



Supplement of

Thermal structure of the southern Caribbean and northwestern South America: implications for seismogenesis

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Introduction

This supplementary material provides additional details on the thermal properties selected for the lithospheric layers (Text S1). The sensitivity analysis to the thermal properties is presented in Text S2, Figure S1 and Tables S1 and S2. Table S3 relates the mantle composition used in the conversion of S-wave velocities into mantle temperatures. A brief explanation on the selected earthquake magnitude types is provided in Text S4. Figure S2 shows the evolution of magnitude values versus time in the earthquake catalogue. Figure S3 displays the calculation of the magnitude of completeness of the catalogue in the two periods considered. The spatial variations for the magnitude of completeness are analyzed in Text S5. Figure S4 shows the errors of the Moho depths reported in the GEMMA dataset (Reguzzoni & Sampietro, 2015). Figure S5 depicts the stacked histograms of depth errors for the selected crustal earthquakes. Text S6 reports the magnitude formulae used to calculate the moment magnitude from other magnitude scales. The geothermal gradient every 3 km is shown in Figure S6. Figure S7 represents the sediment thickness in the study area used in the thermal model from the CRUST1.0 dataset (Laske *et al.*, 2013). The resulting depths, temperatures, uncertainties and resolution radius associated to D95 are presented in Figure S8. Lastly, the histograms of standard deviations of D90 and D95 are shown in Figure S9.

Text S1. Thermal properties assigned to the lithospheric layers

Most thermal conductivities were defined by averaging the values reported by Turcotte & Schubert (2014) for particular lithologies. For example, the thermal conductivity for oceanic sediments was obtained by averaging the values of shale, sandstone and limestone. When direct rock samples were available, their composition was taken into account for selecting thermal conductivities, for example in the Aves Ridge.

The radiogenic heat production (H) was mainly assigned considering the values reported by Vilà *et al.* (2010) for each lithology. In some cases, where specific sample analyses were available in the studied area, it was calculated using the actual concentration of the radioactive elements U, Th, and K (Eq. S1). This was the case for rocks of the Caribbean Large Igneous Plateau fragments reported by Kerr (2014), and for a few samples of the Aves Ridge, studied by Neill *et al.* (2011). The radiogenic heat production of the slab and lithospheric mantle were defined based on the average concentration of mantle rocks reported by Turcotte & Schubert (2014). In those cases, the equation that relates the radiogenic heat production ($\mu\text{W m}^{-3}$) with the radioactive composition is (Vilà *et al.*, 2010):

$$H = 10^{-5}\rho(9.52C_U + 2.56C_{Th} + 3.48C_K), \quad \text{Eq. S1}$$

where ρ is the density (kg m^{-3}) obtained from the forward modelling of the gravity anomalies for each layer (Table 1, after Gómez-García *et al.*, 2020, 2021), and C_U , C_{Th} , and C_K the concentration of uranium (ppm), thorium (ppm), and potassium (%), respectively.

A sensitivity test was performed to different thermal properties, and 25 models were executed, aiming to find the best fitting model considering the broad range of feasible thermal configurations given the lithologies of the study area. The best-fitting model (whose parameters are presented in Table 1) was selected as the one minimizing the misfit between the measured downhole borehole temperatures and the modelled ones, which also reproduces to a large extent the surface heat flow measurements (Figure 4).

Text S2. Sensitivity analysis of thermal properties

We explored the sensitivity of the thermal field in the study area using 25 different thermal configurations, presented in Tables S1 and S2. Although the thermal parameters of several layers were considered in this sensitivity test, particular attention was given to the radiogenic heat production (Table S1) and thermal conductivity (Table S2) of the continental upper and lower crusts, the slabs and lithospheric mantle.

Figure S1 shows the statistics of the residual borehole temperature (modelled values minus observed ones) for each model. We selected model 24 (M24) as the best-fitting one, because its residuals have a mean value close to zero (-4.99°C) and the minimum standard deviation (9.21°C) among all the models tested.

This test demonstrates that the modelled temperatures are highly sensitive to the thermal properties assigned to the lithospheric layers. Consequently, fitting the observed temperatures indeed constrains the model parameters and validates the resulting 3D thermal field. This also highlights the importance of eventually gathering more temperature observations, as they would provide more control points to constrain future models.

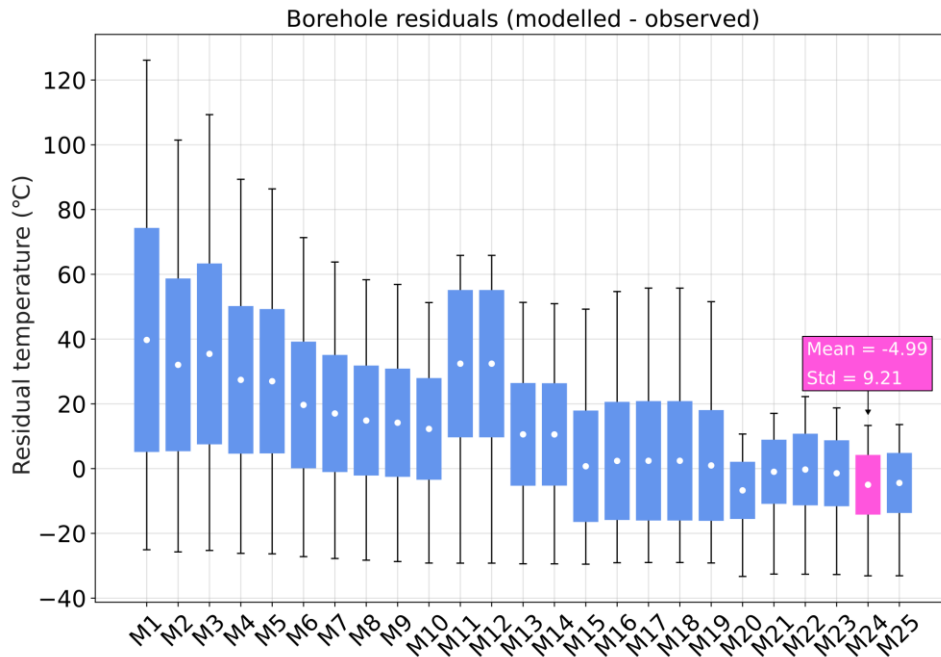


Figure S1. Residuals of the borehole temperatures (modelled values minus observed ones) obtained from the 25 thermal models tested. Model details are provided in Tables S1 and S2. *White dots*: Mean value of the residuals. *Bars*: Range of plus/minus one standard deviation. *Black lines*: Whole range of the residuals. The location of the boreholes is presented in Figure 3.

Table S1. Values of radiogenic heat production assumed for the different layers of the tested models.

Radiogenic heat production ($\mu\text{W m}^{-3}$)																									
Layer	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12	M13	M14	M15	M16	M17	M18	M19	M20	M21	M22	M23	M24	M25
Oceanic sediments	1.1																								
Continental sediments	1.19																							1.6	
Oceanic upper crust	0.358																								
Low density bodies (Aves Ridge)	1.07																								
High density bodies in the upper oceanic crust	0.057																								
Oceanic lower crust	0.468																								
Low density bodies in the lower oceanic crust (Aves Ridge)	1.07																								
High density bodies in the lower oceanic crust	0.057																								
Continental upper crust	3.233	1.741	0.903																			0.6	0.9	0.6	

Radiogenic heat production ($\mu\text{W m}^{-3}$)																									
Layer	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12	M13	M14	M15	M16	M17	M18	M19	M20	M21	M22	M23	M24	M25
Low density bodies in the upper continental crust	0.85									0.7									0.4						
High density body in the upper continental crust (Santa Marta massif)	0.677																								
Continental lower crust	0.85						0.7		0.5																
High density subcrustal bodies	0.01																								
Slab	0.03		0.258		0.001																				
Lithospheric mantle	0.03			0.012																					

Table S2. Values of thermal conductivity assumed for the different layers of the tested models.

Thermal conductivity ($W m^{-1} K^{-1}$)																										
Layer	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12	M13	M14	M15	M16	M17	M18	M19	M20	M21	M22	M23	M24	M25	
Oceanic sediments	1.49																			2.55	2.3	2.55				
Continental sediments	2.55										1.5		2.55		3.5					3	3.5					
Oceanic upper crust	2.1																									
Low density bodies (Aves Ridge)	2.6																									
High density bodies in the upper oceanic crust	2.93																									
Oceanic lower crust	2.95																									
Low density bodies in the lower oceanic crust (Aves Ridge)	2.6																									
High density bodies in the lower oceanic crust	2.93																									
Continental upper crust	3.1					2.4					2.2					2.1					2.4					

Thermal conductivity ($W m^{-1} K^{-1}$)																									
Layer	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12	M13	M14	M15	M16	M17	M18	M19	M20	M21	M22	M23	M24	M25
Low density bodies in the upper continental crust	2.82										2.5	2.87	2.5	2.1											
High density body in the upper continental crust (Santa Marta massif)	2.95																								
Continental lower crust	2.82						2.4			1.9						2.4									
High density subcrustal bodies	4.15																								
Slab	4					3														4		3.3			
Lithospheric mantle	3.75							3.5		3															

Phase	Fraction
Olivine	0.75
Clinopyroxene	0.035
Orthopyroxene	0.21
Garnet	0
Jadeite	0.005
XFe	0.01

Table S3. Mantle composition assumed in the conversion of S-wave velocities (Schaeffer & Lebedev, 2013) to temperatures at 75 km depth. The composition is based on Shapiro & Ritzwoller (2004).

Text S4. Selection of earthquake magnitude types

We adopted the hierarchy proposed by ISC for selecting the most reliable, preferred magnitude (Di Giacomo & Storchak, 2016) for earthquakes taken from ISC datasets (ISC-EHB or ISC Bulletin). Namely, using the acronyms reported in this Bulletin, the hierarchy of magnitude types is: 1) moment magnitude (acronym starting with MW or Mw); 2) surface-wave magnitude (acronym starting with MS or Ms), including MsBB, the equivalent from broad-band records (Di Giacomo & Storchak, 2022); 3) broadband body-wave magnitude (mB; Bormann and Saul, 2008); 4) short-period body-wave magnitude (acronym starting with mb or Mb); 5) local magnitude (acronym starting with ML, MI, mL, or ml); 6) duration magnitude (MD, Md, or md) and 7) any other magnitude type.

If more than one value was available for the chosen magnitude type, preference was given: 1) to the moment magnitude MW provided by the Global CMT catalogue (following the recommendation by Di Giacomo & Storchack, 2016), which is also listed in the ISC Bulletin; 2) to magnitudes MS or mb recomputed by ISC (also following Di Giacomo & Storchack, 2016) or 3) to the largest value of that type, for simplicity.

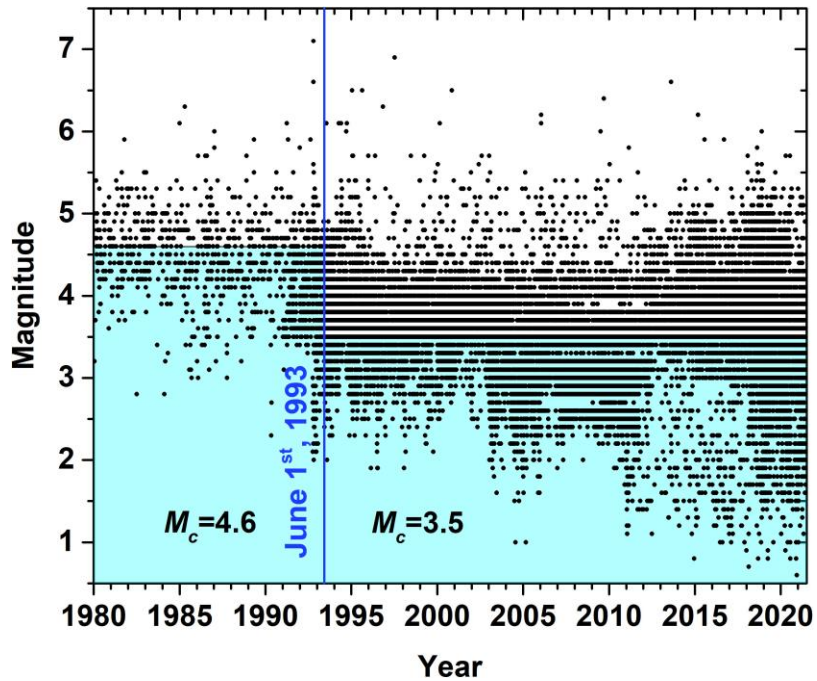


Figure S2. Preferred magnitude versus time of earthquakes with depth ≤ 50 km in the study area. This kind of scatterplot is useful for identifying heterogeneities and different periods in the compilation of an earthquake catalog (e.g.: Gentili *et al.*, 2011; González, 2017). The depth range used encompasses all crustal seismicity. Note that few earthquakes with magnitude <4.0 were recorded before 1991, indicating incompleteness at least below this value for that period. Earthquakes with magnitudes <3.5 have been recorded only irregularly, and more frequently since June 1993, when the Colombian national seismic network started to compile its earthquake catalog (Arcila *et al.*, 2020) and reporting data to ISC. This date (vertical line) was chosen for separating the whole catalogue in two sub-periods, with different magnitude of completeness (M_c , see Figure S3).

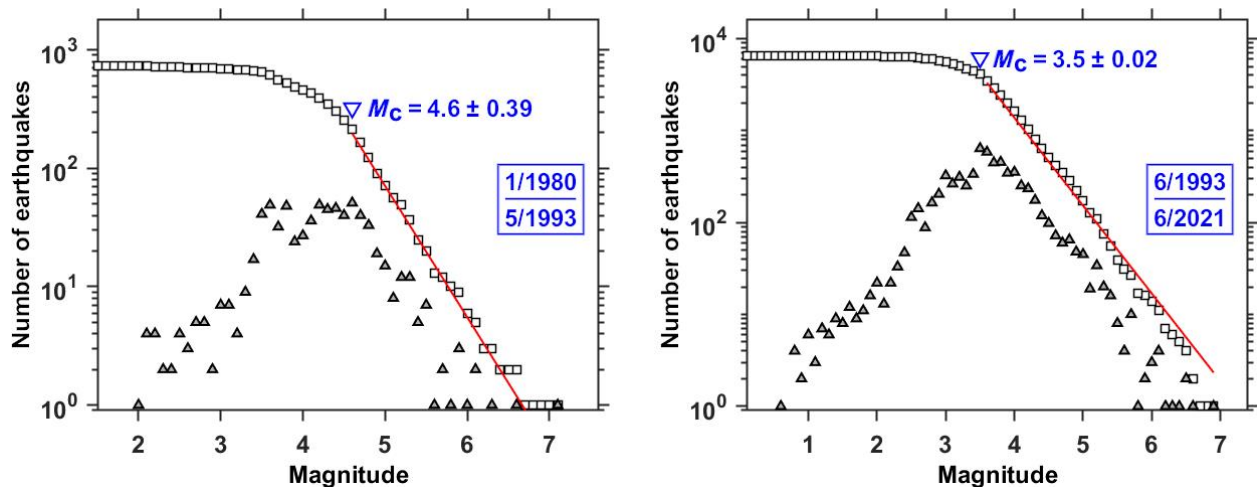


Figure S3. Magnitude of completeness of the earthquake catalogue (Fig. S1) in the two sub-periods considered. *Triangles*: Number of earthquakes in each magnitude bin (0.1 units wide). *Squares*: Cumulative number of earthquakes with magnitude greater than or equal to the value in the abscissas. M_c : Magnitude of completeness calculated with the maximum curvature method (Wiemer & Wyss,

1997), with uncertainty calculated using 1000 bootstrap samples (Woessener & Wiemer, 2005). This is the same method used by Woessener & Wiemer (2005) with the ISC Bulletin. *Red lines*: Maximum-likelihood Gutenberg-Richter fits to the cumulative distributions, for the complete part of each catalogue subset. The fits are not used for calculating M_c with this method, and are only shown as reference, to indicate that they hold for magnitude $\geq M_c$. Note the different scales in both plots. Calculations and plots were made with ZMAP v. 6.0 (Wiemer, 2001).

Text S5. Spatial variations of the magnitude of completeness

The calculated spatial variations of M_c in the region are smaller than the temporal ones. The number of earthquakes, particularly in the first period, was too low to calculate M_c with as much spatial detail as D90, given that M_c requires a very minimum of 60 events in the sample (e.g. Woessner & Wiemer, 2005, González, 2017). An attempt was made of mapping M_c in detail in each period, with a fixed radius of 120 km around the nodes of a latitude/longitude grid in steps of 0.1 degrees of latitude and longitude and the maximum curvature method, with uncertainties calculated with 200 bootstrap samples (Woessner & Wiemer, 2005). In the first period, no region had significantly higher M_c (where it could be calculated) than the mean. In the second period, M_c was significantly higher than the mean ($M_c \sim 4$) only south of Panama and at the volcanic San Andrés Archipelago, areas whose results are not interpreted in this work. So in all of the sub-regions analyzed in the main text, M_c was not significantly higher (worse) than the mean values used for the analysis

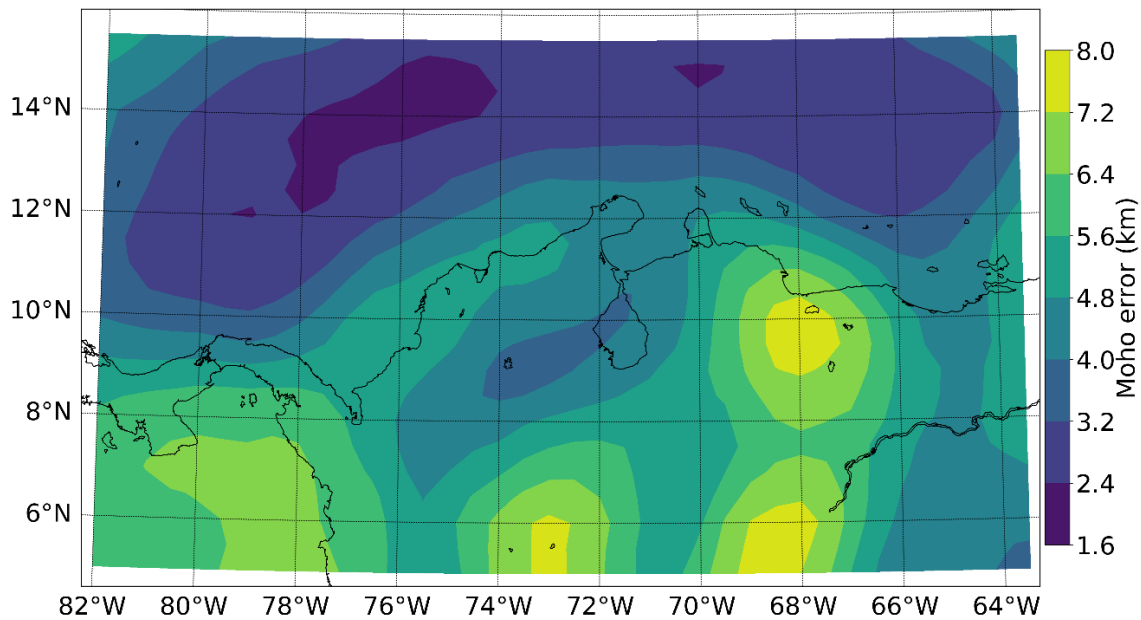


Figure S4. Errors associated to the Moho depths used in this study according to the GEMMA dataset. The original model (Reguzzoni & Sampietro, 2015) was interpolated to a resolution of 0.5°.

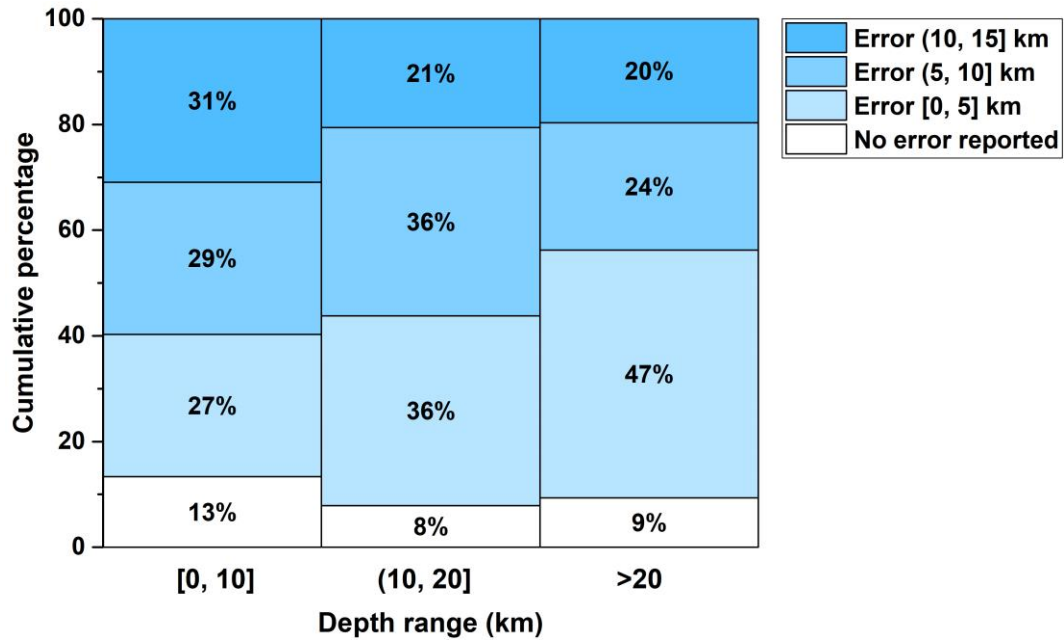
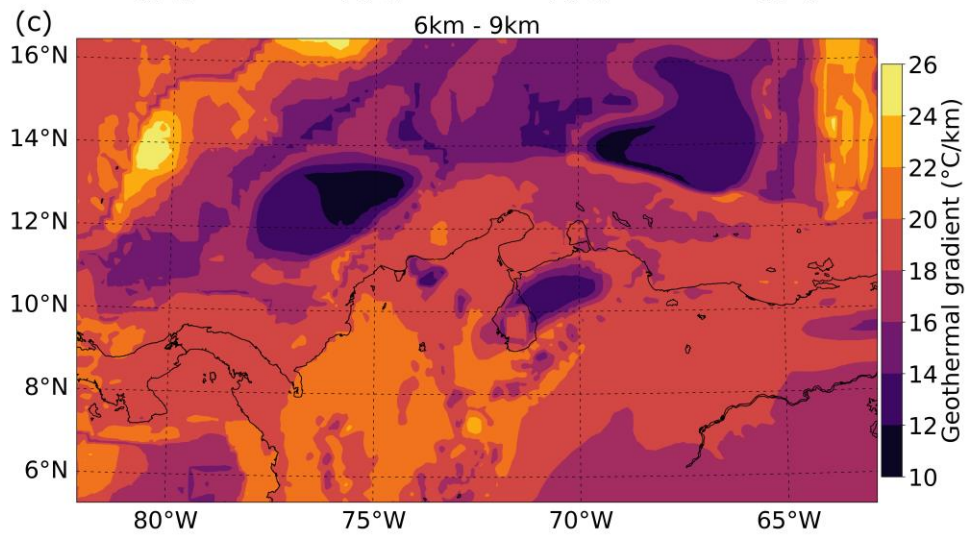
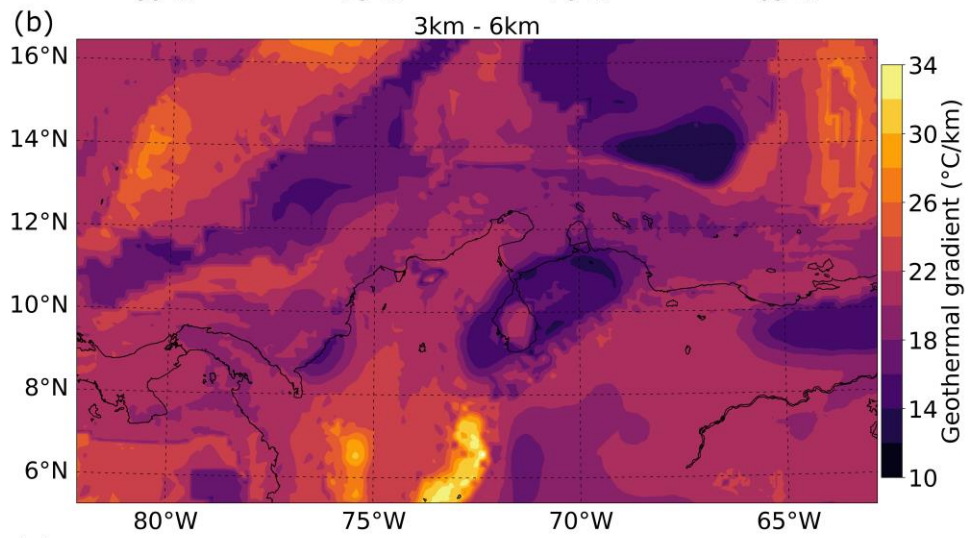
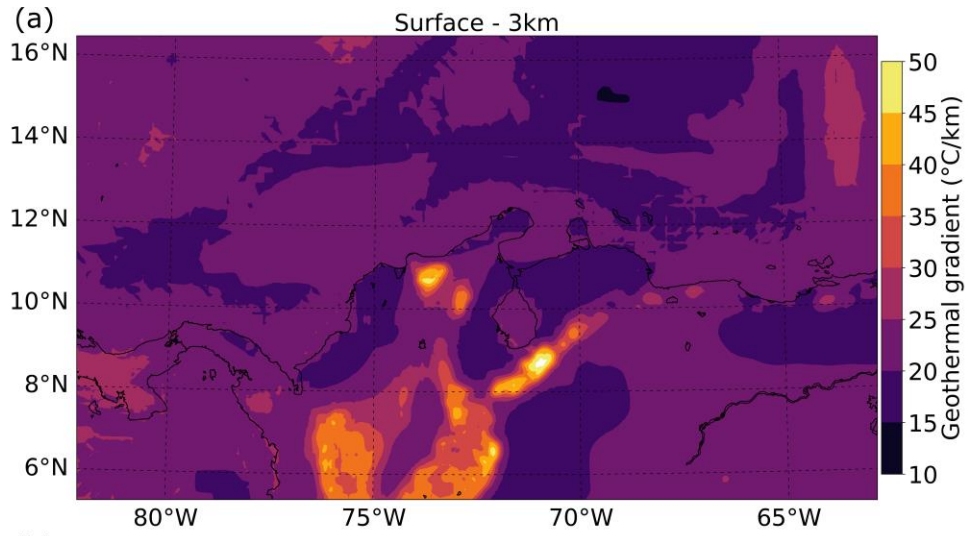


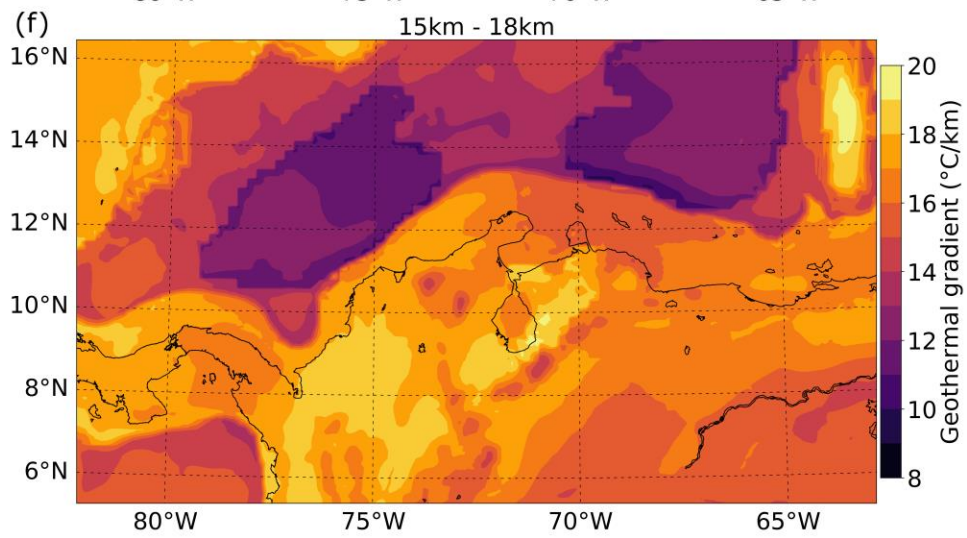
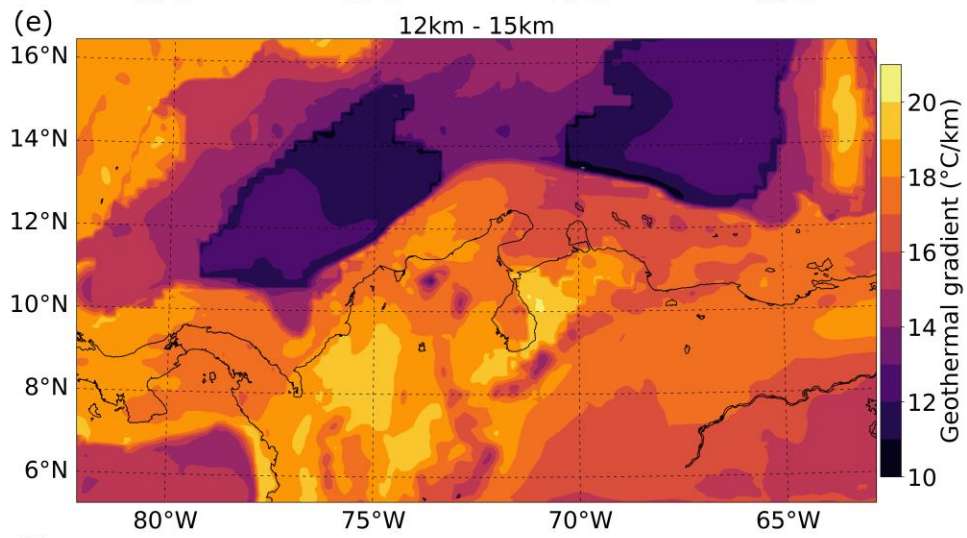
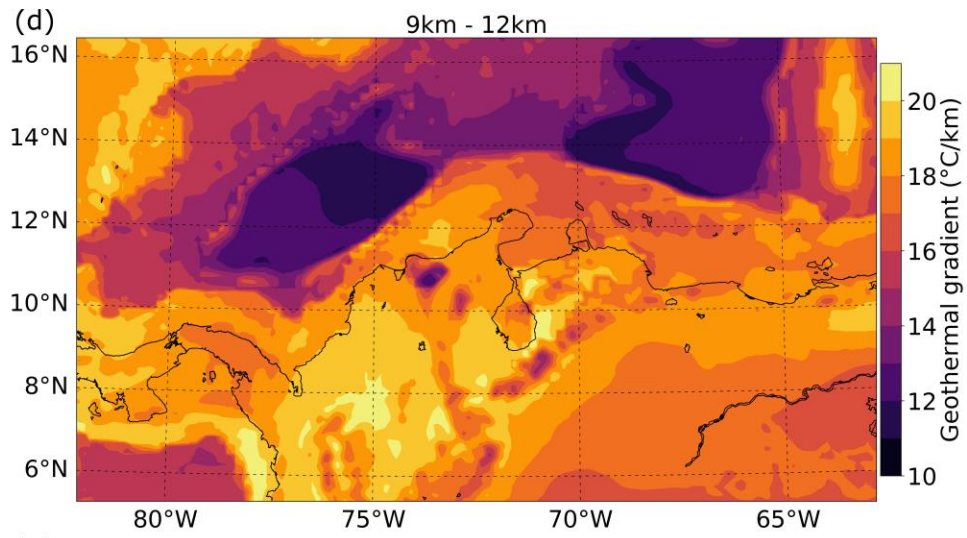
Figure S5. Stacked histograms of depth errors for the selected (best located) crustal earthquakes within the study area, for different depth ranges. Note that the errors are typically larger for shallower earthquakes.

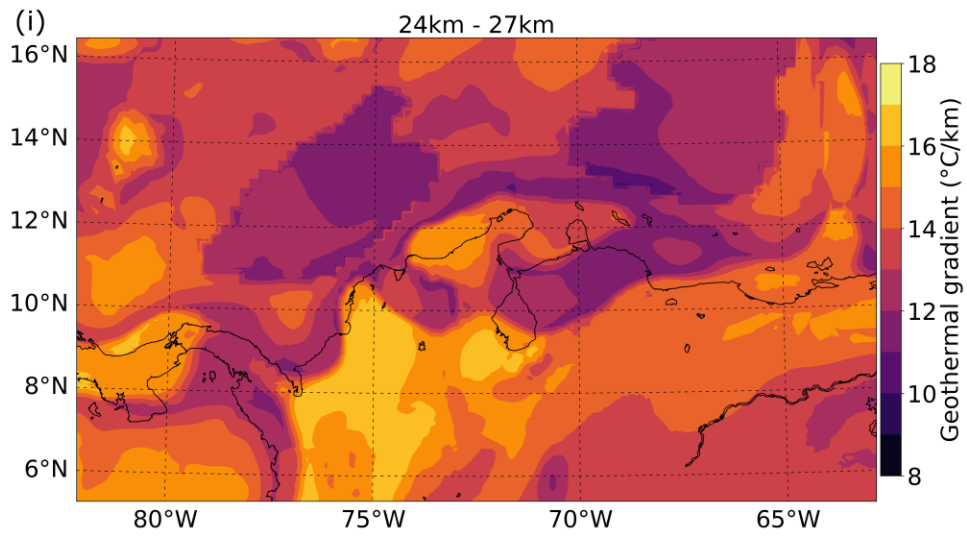
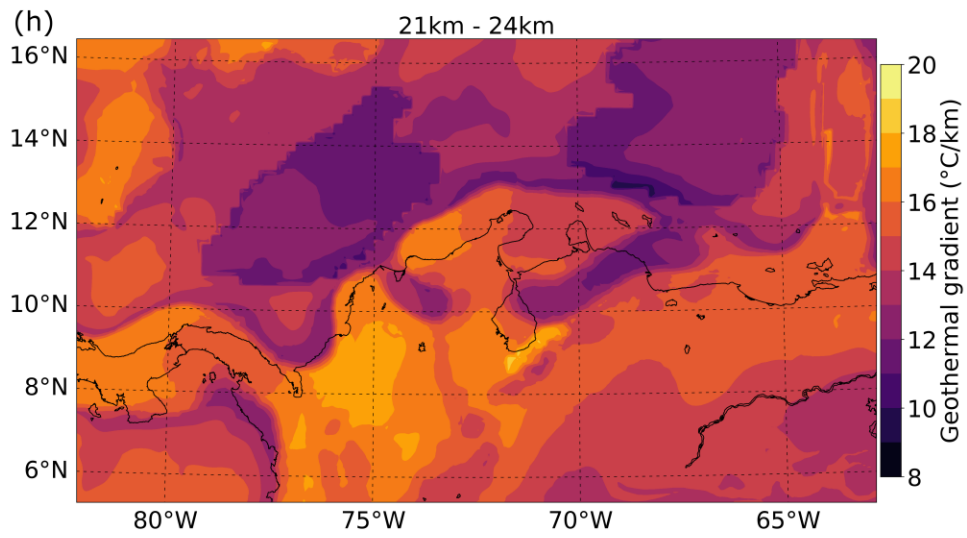
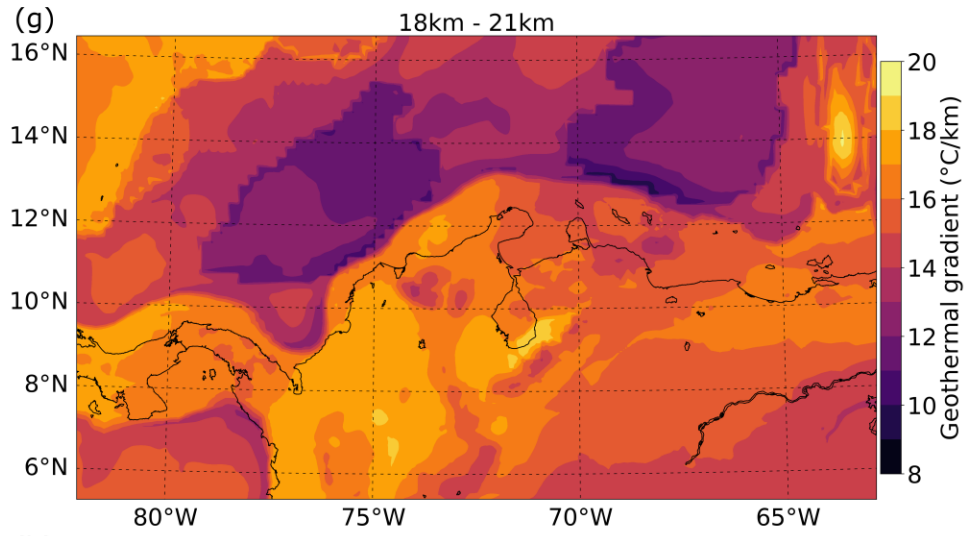
Text S6. Formulae used for calculating moment magnitude from other magnitude scales

If the preferred magnitude for an earthquake was not already M_W , it was converted using these relations:

- From body-wave magnitude (m_b): $M_W = e^{(-4.664+0.859 \times m_b)} + 4.555$ (Di Giacomo *et al.*, 2015)
- From surface-wave magnitude (M_S): $M_W = e^{(-0.222+0.233 \times M_S)} + 2.863$ (Di Giacomo *et al.*, 2015)
- From local magnitude (M_L): $M_W = 0.958 \times M_L + 0.1$ (Arcila *et al.*, 2020)
- From duration magnitude (M_D): $M_W = 2.189 + 0.660 \times M_D$ (Salazar *et al.*, 2013).







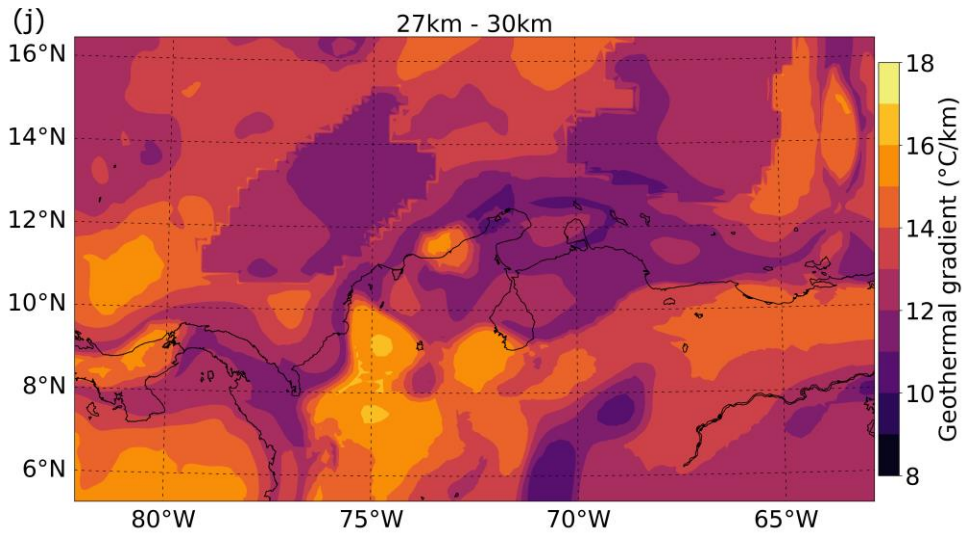


Figure S6. Geothermal gradient computed at different depth intervals based on the resulting thermal field. The depth ranges are: (a) from the solid Earth surface down to 3 km below. (b) 3 km to 6 km. (c) 6 km to 9 km. (d) 9 km to 12 km. (e) 12 km to 15 km. (f) 15 km to 18 km. (g) 18 km to 21 km. (h) 21 km to 24 km. (i) 24 km to 27 km. (j) 27 km to 30 km. Note that the range of values in the color bars, chosen to increase contrast in each map, is not the same for all figures.

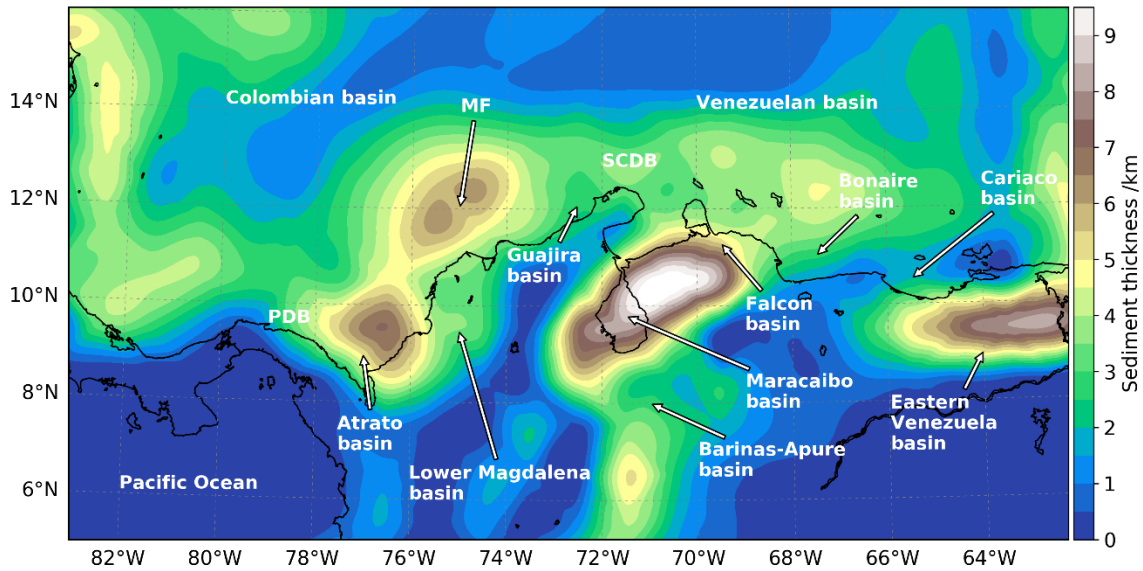


Figure S7. Sediment thickness in the study area (Laske *et al.*, 2013) as parametrized in the thermal calculation. MF = Magdalena Fan. PDB = Panamá Deformed Belt. SCDB = South Caribbean Deformed Belt.

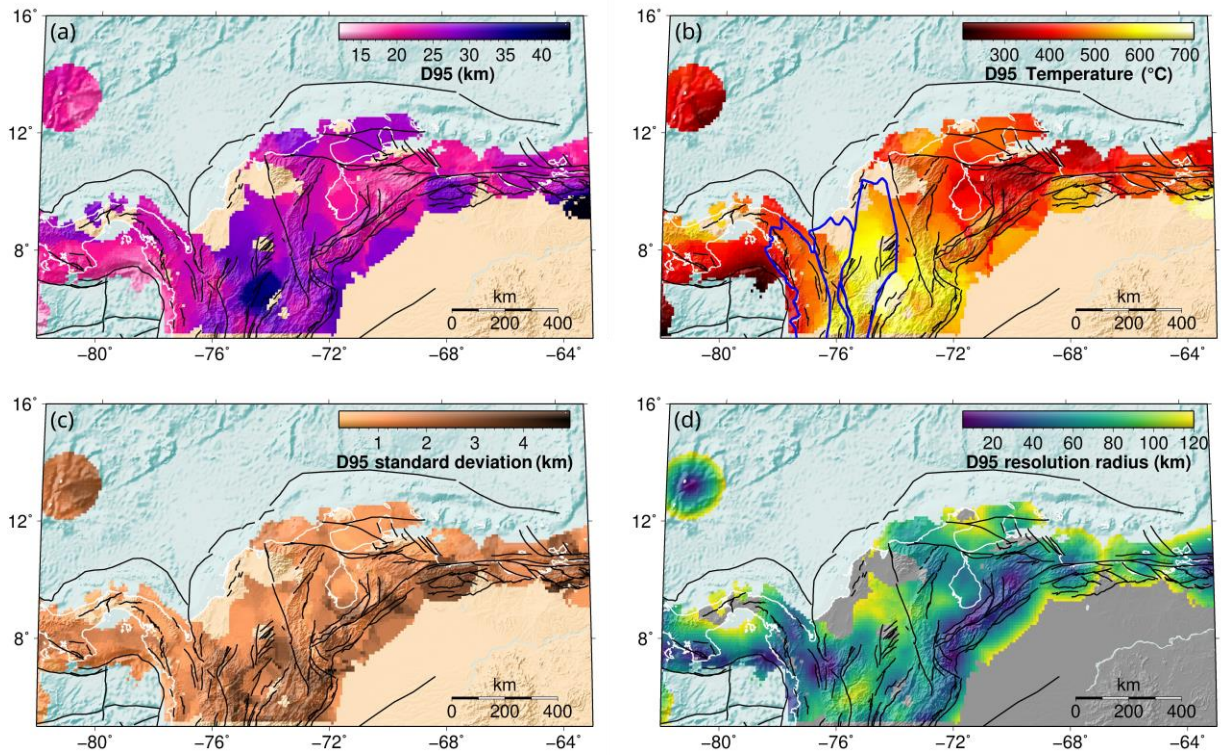


Figure S8. Results on D95. (a) D95 depths. (b) D95 temperature. Blue polygons: terranes in NW South America after Boschman *et al.*, 2019 and Kennan and Pindell, 2009. (c) Uncertainties in D95. (d) Resolution radius used to compute D95. Black lines: active fault traces, as in Fig. 1a. Coastlines are depicted as white lines.

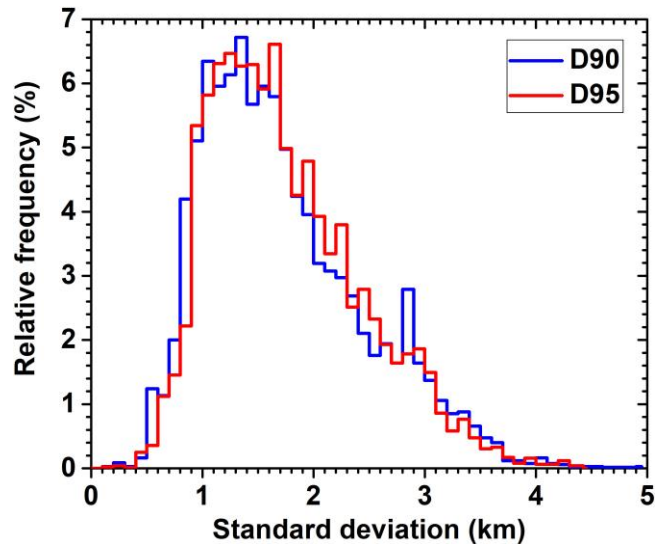


Figure S9. Histogram of standard deviations of D90 and D95 in the study area, calculated from the combined Monte Carlo simulation and bootstrapping.

References

- Arcila, M., García, J., Montejó, J., Eraso, J., Valcarcel, J., Mora, M., Viganò, D., Pagani, M., & Díaz, F. (2020). *Modelo nacional de amenaza sísmica para Colombia*. Ed.: Servicio Geológico Colombiano & Global Earthquake Model Foundation. Bogotá (Colombia). 308 p. <http://doi.org/10.32685/9789585279469>
- Bormann, P., & Saul, J. (2008). The new IASPEI standard broadband magnitude m_B . *Seismological Research Letters*, 79(5), 698–705. <https://doi.org/10.1785/gssrl.79.5.698>
- Boschman, L. M., van Hinsbergen, D. J., Torsvik, T. H., Spakman, W., & Pindell, J. L. (2014). Kinematic reconstruction of the Caribbean region since the Early Jurassic. *Earth-Science Reviews*, 138, 102–136. <https://doi.org/10.1016/j.earscirev.2014.08.007>
- Di Giacomo, D., Bondár, I., Storchak, D. A., Engdahl, E. R., Bormann, P., & Harris, J. (2015). ISC-GEM Global Instrumental Earthquake Catalogue (1900-2009), III. Re-computed M_S and m_b , proxy M_w , final magnitude composition and completeness assessment. *Physics of the Earth and Planetary Interiors*, 239, 33–47. <https://doi.org/10.1016/j.pepi.2014.06.005>
- Di Giacomo, D., & Storchak, D. A. (2016). A scheme to set preferred magnitudes in the ISC Bulletin. *Journal of Seismology*, 20(2), 555–567. <https://doi.org/10.1007/s10950-015-9543-7>
- Di Giacomo, D., & Storchak, D. A. (2022). One hundred plus years of recomputed surface wave magnitude of shallow global earthquakes. *Earth System Science Data*, 14(2), 393–409. <https://doi.org/10.5194/essd-14-393-2022>
- Gentili, S., Sukan, M., Peruzza, L. & Schorlemmer, D. (2011). Probabilistic completeness assessment of the past 30 years of seismic monitoring in northeastern Italy. *Physics of the Earth and Planetary Interiors*, 186(1–2), 81–96, doi:10.1016/j.pepi.2011.03.005.
- Gómez-García, Á. M., Le Breton, E., Scheck-Wenderoth, M., Monsalve, G., & Anikiev, D. (2020). 3D lithospheric structure of the Caribbean and north South American Plates and rotation files of

- kinematic reconstructions back to 90 Ma of the Caribbean Large Igneous Plateau. *GFZ data services*, <https://doi.org/https://doi.org/10.5880/GFZ.4.5.2020.003>
- Gómez-García, Á. M., Le Breton, E., Scheck-Wenderoth, M., Monsalve, G., & Anikiev, D. (2021). The preserved plume of the Caribbean Large Igneous Plateau revealed by 3D data-integrative models. *Solid Earth*, *12*(1), 275–298. <https://doi.org/10.5194/se-12-275-2021>
- González, Á. (2017). The Spanish National Earthquake Catalogue: Evolution, precision and completeness. *Journal of Seismology*, *21*(3), 435–471, doi:10.1007/s10950-016-9610-8
- Kennan, L., & Pindell, J. L. (2009). Dextral shear, terrane accretion and basin formation in the Northern Andes: best explained by interaction with a Pacific-derived Caribbean Plate? *Geological Society, London, Special Publications*, *328*(1), 487–531. <https://doi.org/10.1144/SP328.20>
- Kerr, A. C. (2014). Oceanic Plateaus. In *Treatise on Geochemistry: Second Edition* (2nd ed., Vol. 4, pp. 631–667). Oxford: Elsevier Ltd. <https://doi.org/10.1016/B978-0-08-095975-7.00320-X>
- Laske, G., Masters, G., Ma, Z., & Pasyanos, M. E. (2013). CRUST1.0: An updated global model of Earth's crust. *Geophys. Res. Abstracts*, *15*, Abstract EGU2013--2658. Retrieved from <http://igppweb.ucsd.edu/~gabi/rem.html>
- Neill, I., Kerr, A. C., Hastie, A. R., Stanek, K.-P., & Millar, I. L. (2011). Origin of the Aves Ridge and Dutch-Venezuelan Antilles: interaction of the Cretaceous “Great Arc” and Caribbean-Colombian oceanic plateau? *Journal of the Geological Society*, *168*(2), 333–348. <https://doi.org/10.1144/0016-76492010-067>
- Reguzzoni, M., & Sampietro, D. (2015). GEMMA: An Earth crustal model based on GOCE satellite data. *International Journal of Applied Earth Observation and Geoinformation*, *35*(PA), 31–43. <https://doi.org/10.1016/j.jag.2014.04.002>
- Salazar, W., Brown, L., Hernández, W., & Guerra, J. (2013). An earthquake catalogue for El Salvador and neighboring Central American countries (1528-2009) and its implication in the seismic hazard assessment. *Journal of Civil Engineering and Architecture*, *7*(8), 1018-1045. <https://doi.org/10.17265/1934-7359/2013.08.011>
- Schaeffer, A. J., & Lebedev, S. (2013). Global shear speed structure of the upper mantle and transition zone. *Geophysical Journal International*, *194*(1), 417–449. <https://doi.org/10.1093/gji/ggt095>
- Shapiro, N. M., & Ritzwoller, M. H. (2004). Thermodynamic constraints on seismic inversions. *Geophysical Journal International*, *157*(3), 1175–1188. <https://doi.org/10.1111/j.1365-246X.2004.02254.x>
- Turcotte, D. L., & Schubert, G. (2014). *Geodynamics* (3rd ed.). Cambridge: Cambridge University Press. <https://doi.org/10.1017/CBO9780511843877>
- Vilà, M., Fernández, M., & Jiménez-Munt, I. (2010). Radiogenic heat production variability of some common lithological groups and its significance to lithospheric thermal modeling. *Tectonophysics*, *490*(3–4), 152–164. <https://doi.org/10.1016/j.tecto.2010.05.003>
- Wiemer, S. (2001). A software package to analyze seismicity: ZMAP. *Seismological Research Letters*, *72*, 373–382, <https://doi.org/10.1785/gssrl.72.3.373>
- Wiemer, S. and Wyss, M. (1997). Minimum magnitude of completeness in earthquake catalogs: Examples from Alaska, the western United States, and Japan. *Bulletin of the Seismological Society of America*, *90*, 859–869, <https://doi.org/10.1785/0119990114>

Woessner, J. & Wiemer, S. (2005): Assessing the quality of earthquake catalogues: Estimating the magnitude of completeness and its uncertainty. *Bulletin of the Seismological Society of America*, 95, 684–698, <https://doi.org/10.1785/0120040007>