WIN2023

The 29th International Workshop on Weak Interactions and Neutrinos

Geo-neutrino Signal at JUNO Predicted by Geological Models

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on behalf of the JUNO collaboration

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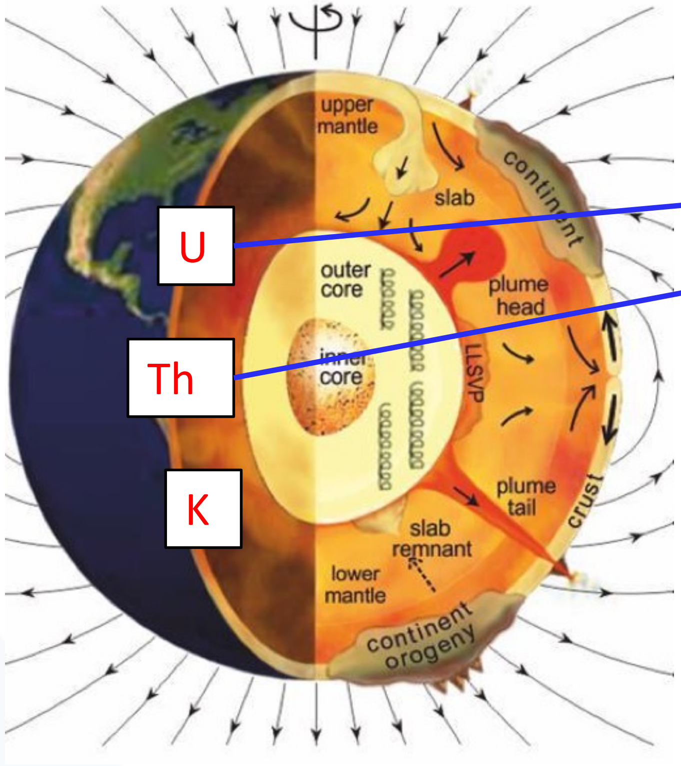
Outline

1. Introduction
2. Global model and predicted signal
3. Local models and predicted signal
4. Conclusions

Probe Earth's interior with geo-neutrino



Production of Geo-neutrino

$$^{238}\mathrm{U} \longrightarrow {}^{206}\mathrm{Pb} + 8\,\alpha + 6\,e^- + 6\,\bar{\nu}_e \quad + 51.698\mathrm{MeV}$$

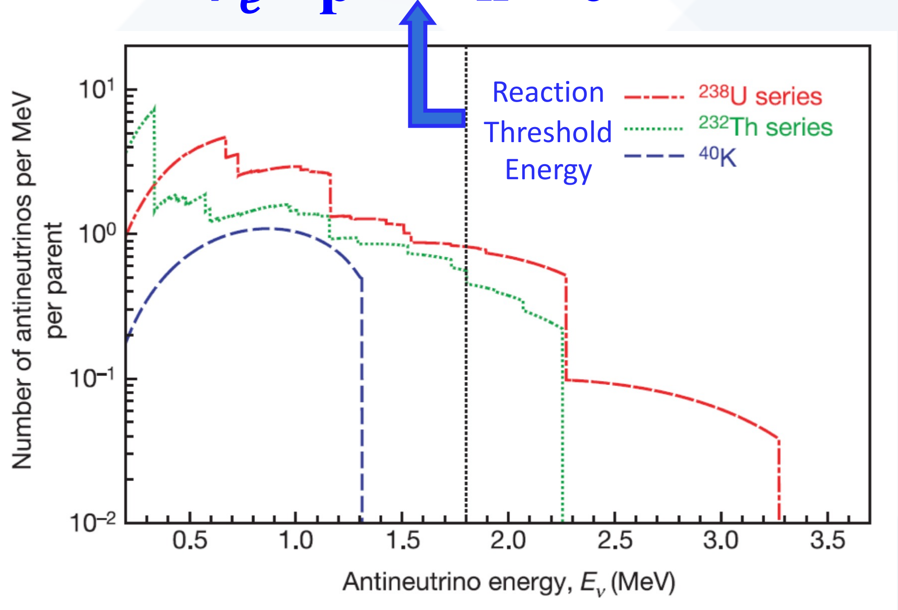
$$^{232}\mathrm{Th} \longrightarrow {}^{208}\mathrm{Pb} + 6\,\alpha + 4\,e^- + 4\,\bar{\nu}_e \quad + 42.652\mathrm{MeV}$$

$$^{40}\mathrm{K} \xrightarrow{89.3\%} {}^{40}\mathrm{Ca} + e^- + \bar{\nu}_e \quad + 1.311\mathrm{MeV}$$

$$^{40}\mathrm{K} + e^- \xrightarrow{10.7\%} {}^{40}\mathrm{Ar} + \nu_e \quad + 1.505\mathrm{MeV}$$

Detection of Geo-neutrino

$$\bar{\nu}_e + p^+ \longrightarrow n + e^+$$



(from S.T. Dye)

Geoscience inputs for geo-neutrino signal calculation

Activity and number of produced geoneutrinos

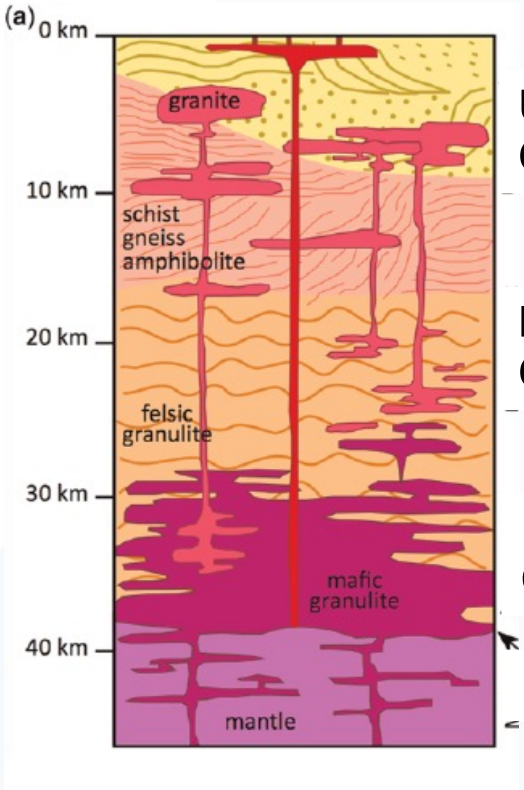
Volume of source unit

$$\Phi_i = A_i \cdot n_i \cdot P_{\nu_e-\nu_e}(E_\nu, |\vec{L}|) \cdot \int_V \frac{a_i(\vec{L}) \cdot \rho_i(\vec{L})}{4\pi|\vec{L}|^2} dV$$

Survival probability function

Abundance and density of the source unit

Distance between source unit and detector



Upper Crust

Middle Crust

Lower Crust

Mantle

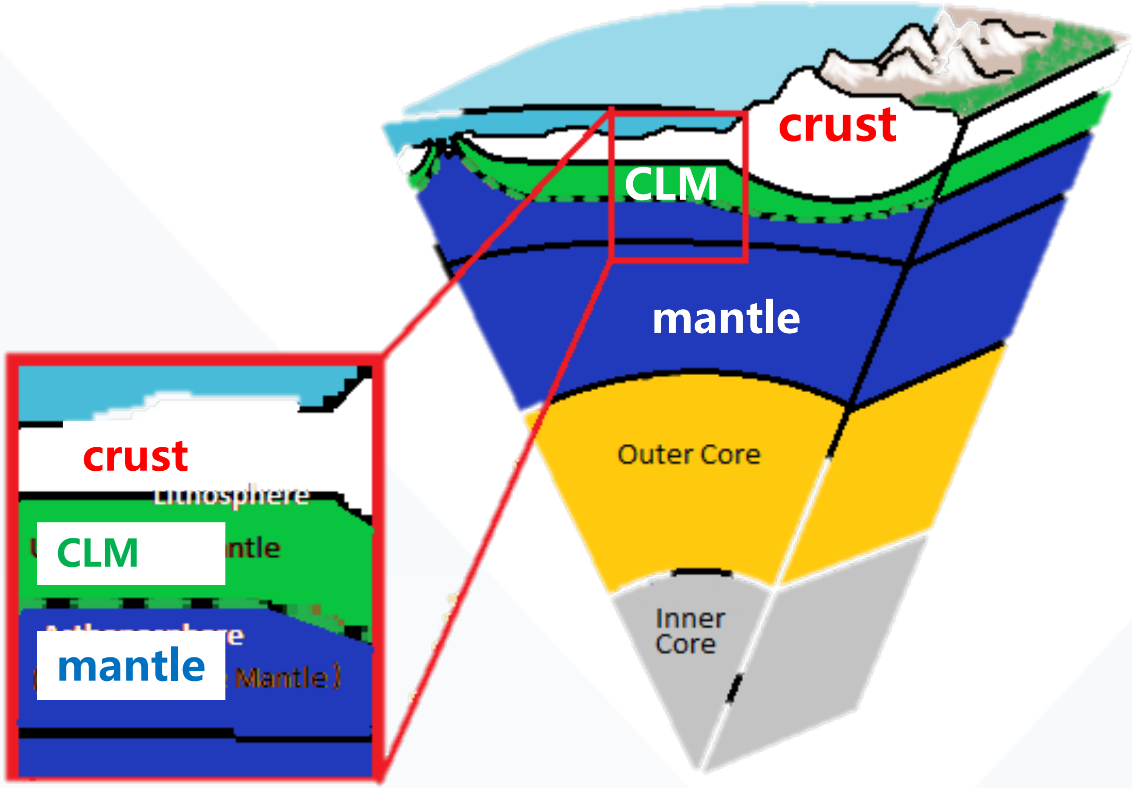
U & Th abundances

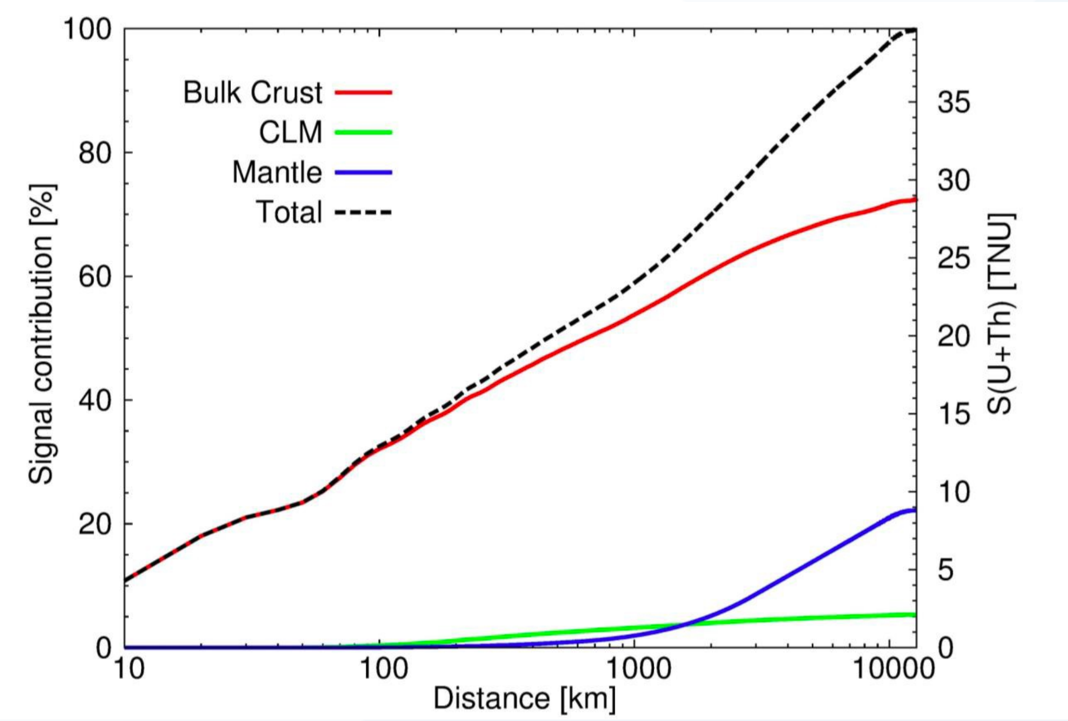
- **Geophysical models**
  - **Density** of source unit
  - **Earth's layers**
- **Geochemical models**
  - **U and Th abundances** of source unit

Earth's layers and their estimated geo-neutrino signal

- **Crust**: **high Th & U**
  - Continental crust
  - Oceanic crust
- **CLM (Continental Lithospheric Mantle)**: **relatively low Th & U**
- **Mantle**: **very low Th & U, large volume**

$$S_{mantle} = S_{total} - (S_{crust} + S_{CLM})$$

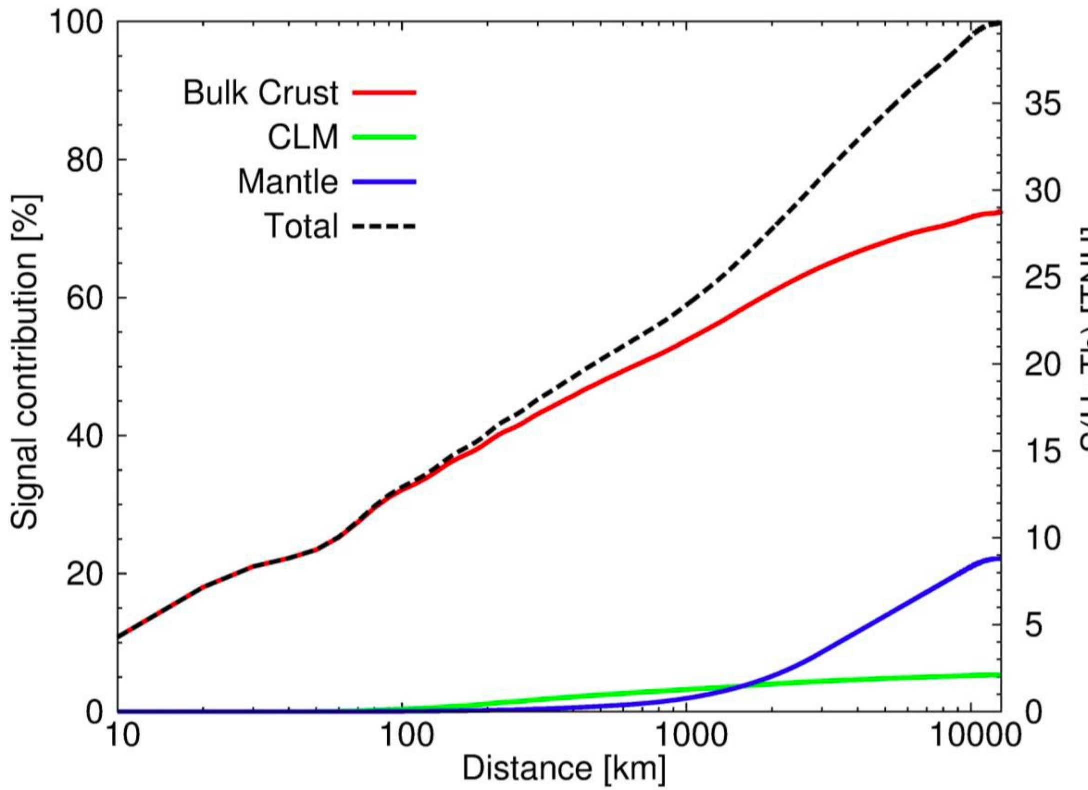




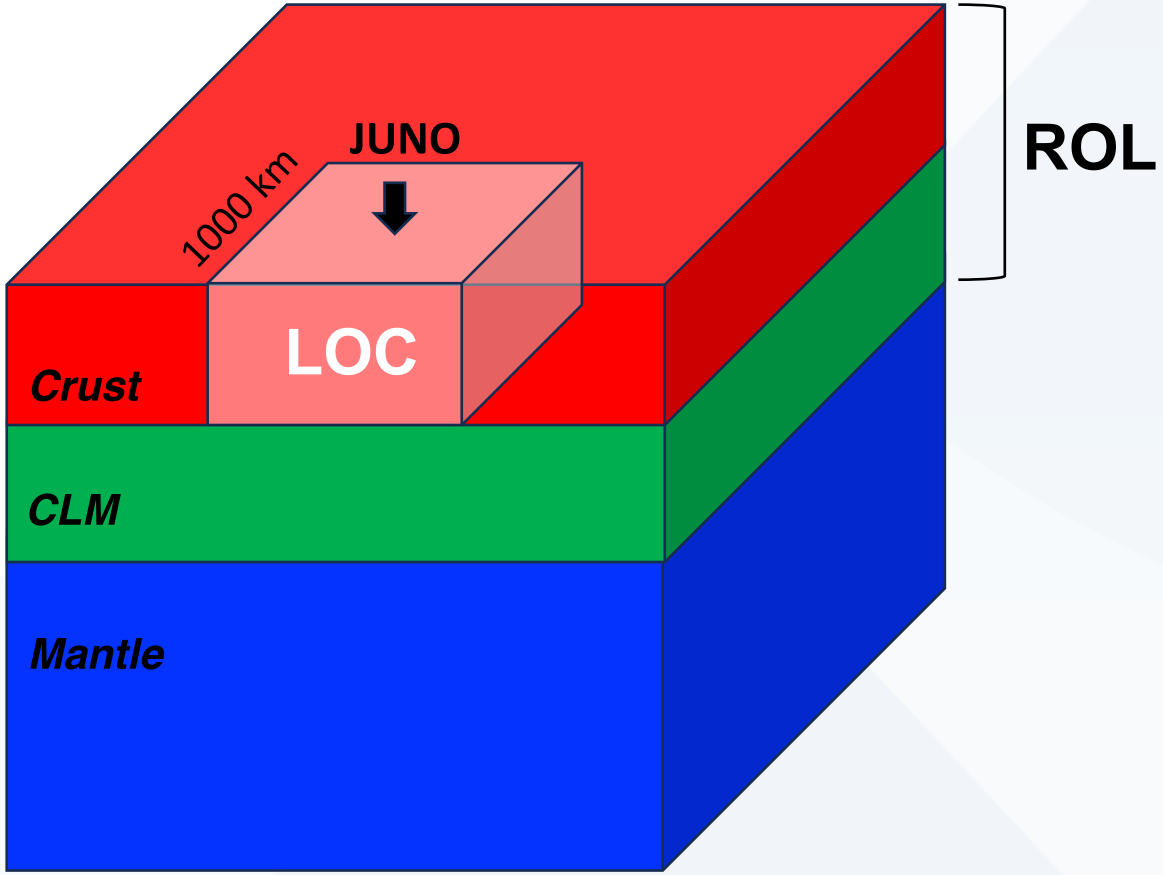
(Strati et al., 2014)

Definition of LOC and ROL

- **LOcalCrust** (**LOC**): a portion of **local crust** centered in JUNO
- **Rest Of Lithosphere** (**ROL**): the **remaining crust** and **CLM**



(Strati et al., 2014)



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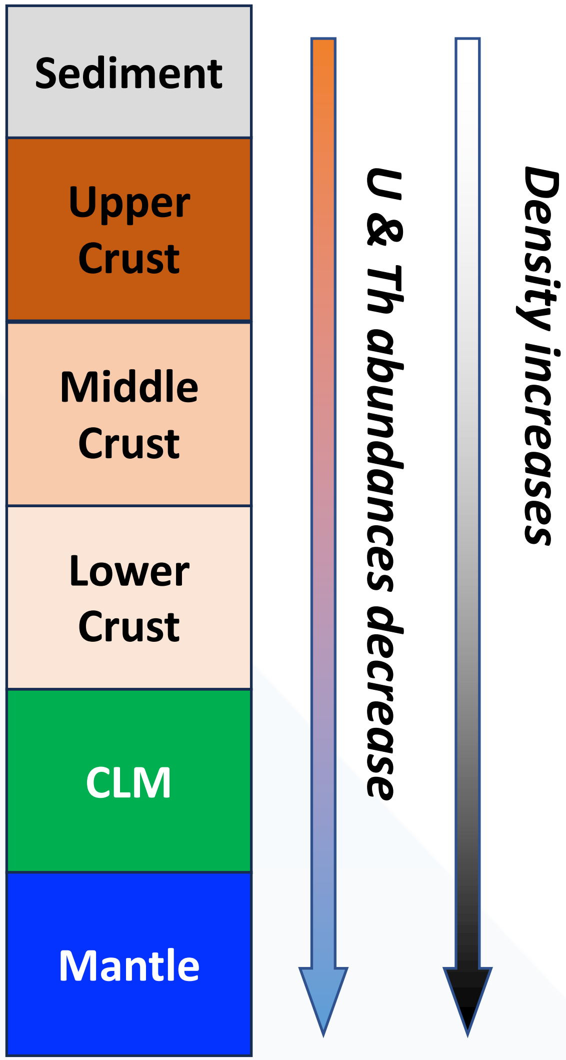
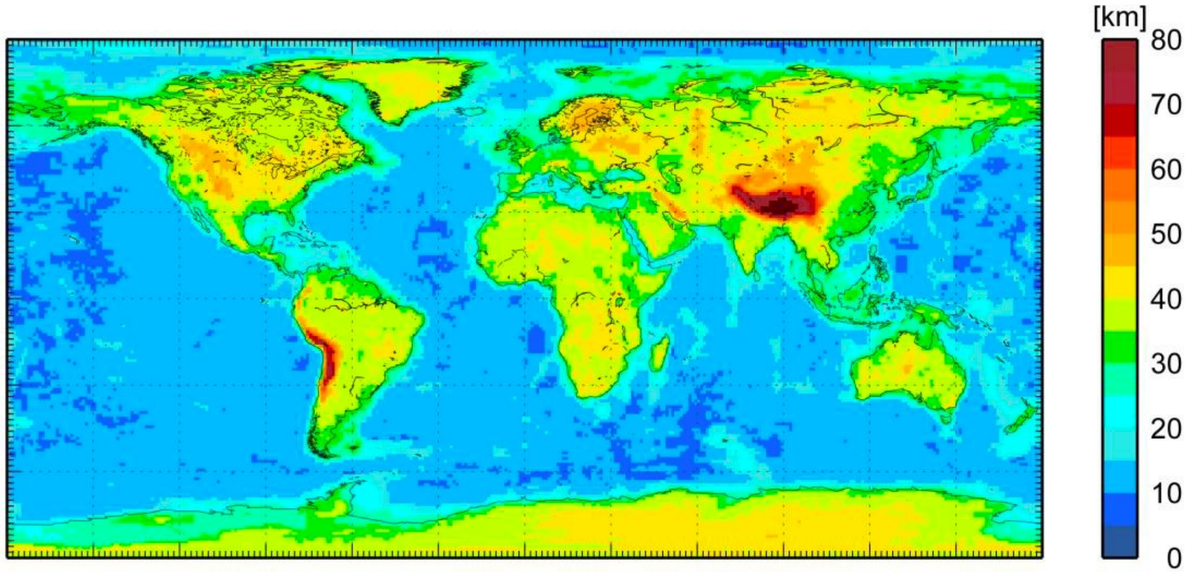
Geophysical models for ROL

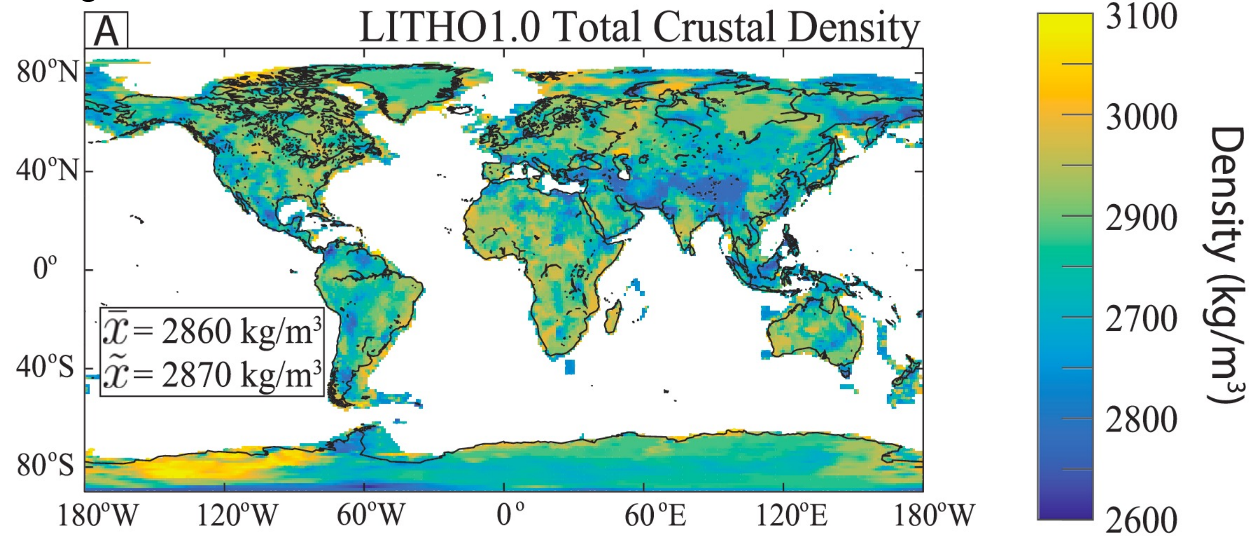


- **Layer** model
  - Sed
  - UC
  - MC
  - LC
  - CLM

- **Density** model



Huang et al., 2013



Wipperfurth et al., 2020

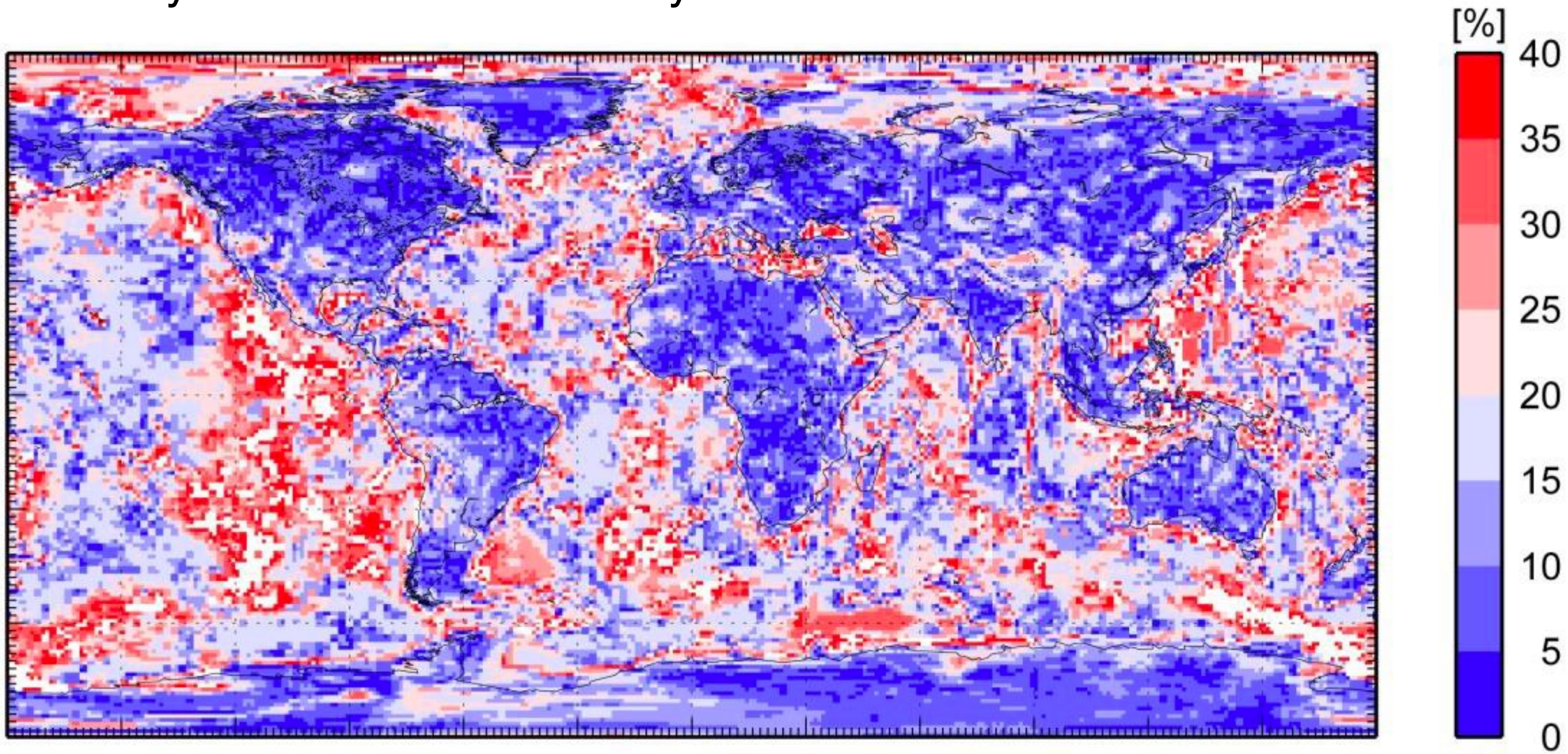
Geophysical models for ROL

Models	GEMMA	CUB 2.0	CRUST2.0	RMM	CRUST 1.0	LITHO 1.0
Author	Negretti et al.	Shapiro and Ritzwoller	Laske et al.	Huang et al.	Laske et al.	Pasyanos et al.
Published year	2012	2002	2001	2013	2013	2014
Resolution	0.5°×0.5°	2°×2°	2°×2°	1°×1°	1°×1°	1°×1°
Methods	**gravity** field data	surface **seismic** wave data	reflection and refraction **seismic** data	average of **GEMMA**, **CUB 2.0** and **CRUST 2.0**	modified from CRUST 2.0	modified from CRUST 1.0 combining surface **seismic** waves data

Uncertainties of geophysical model (RMM) for ROL

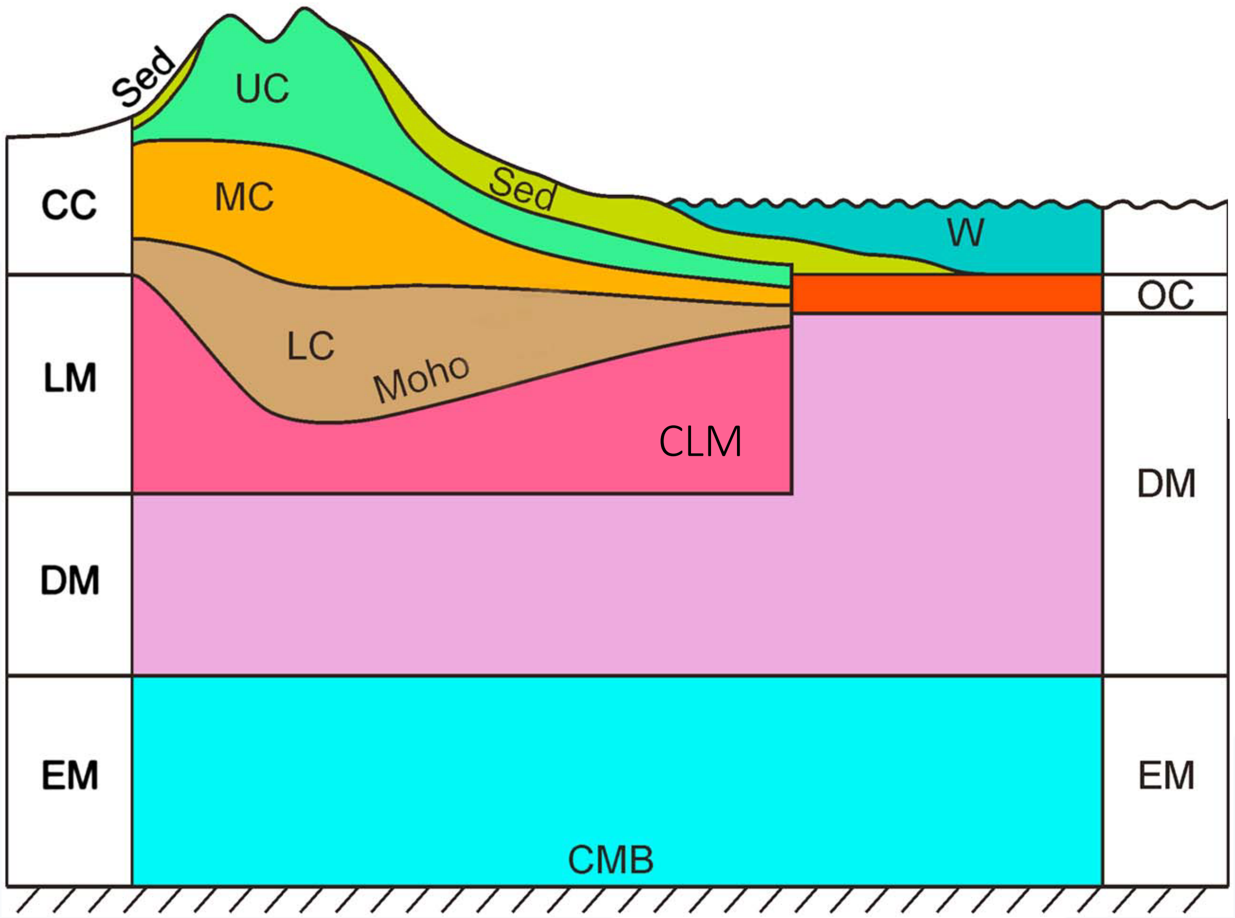
- Crustal thickness shows ~10% uncertainty in continents, and up to 40% uncertainty in oceans and continental margins.

- Density shows ~4% uncertainty.



Huang et al., 2013

Geochemical model for ROL



	a(U) [μg/g]	a(Th) [μg/g]
Sed	1.73 ± 0.09	8.10 ± 0.59
OC	0.07 ± 0.02	0.21 ± 0.06
UC	2.7 ± 0.6	10.5 ± 1.0

	a(U) [μg/g]	a(Th) [μg/g]
MC	$0.97^{+0.58}_{-0.36}$	$4.86^{+4.30}_{-2.25}$
LC	$0.16^{+0.14}_{-0.07}$	$0.96^{+1.18}_{-0.51}$
CLM	$0.03^{+0.05}_{-0.02}$	$0.15^{+0.28}_{-0.10}$

Geo-neutrino signals from ROL

From V. Strati

- Half of the total geoneutrinos signal of the ROL is produced by the Upper Crust **(UC)**
- The contribution of the Continental Lithospheric Mantle **(CLM)** is 15%
- The relative uncertainty on the S(U+Th) of the ROL is about 25%
- Given an average ratio *a*(Th)/*a*(U) = 4.5 in the ROL, the **S(Th)/S(U)** is **0.31**

	Signal [TNU]			S(Th)/S(U)
	U	Th	U + Th	
Sed	0.37 ± 0.06	0.12 ± 0.02	0.40 ± 0.04	0.33
UC	$4.32^{+1.03}_{-1.00}$	$1.17^{+0.16}_{-0.15}$	$5.49^{+1.04}_{-1.01}$	0.27
MC	$1.70^{+1.08}_{-0.66}$	$0.60^{+0.56}_{-0.28}$	$2.43^{+1.23}_{-0.80}$	0.36
LC	$0.26^{+0.23}_{-0.12}$	$0.12^{+0.02}_{-0.02}$	$0.42^{+0.30}_{-0.16}$	0.45
OC	0.05 ± 0.02	0.01 ± 0.01	0.06 ± 0.02	0.21
Bulk Crust	$6.84^{+1.57}_{-1.34}$	$2.09^{+0.65}_{-0.39}$	$9.07^{+1.70}_{-1.48}$	0.31
CLM	$1.32^{+2.52}_{-0.91}$	$0.42^{+0.96}_{-0.30}$	$2.15^{+2.92}_{-1.28}$	0.31
ROL	$\mathbf{8.56^{+3.24}_{-2.01}}$	$\mathbf{2.68^{+1.27}_{-0.70}}$	$\mathbf{11.55^{+3.60}_{-2.32}}$	**0.31**

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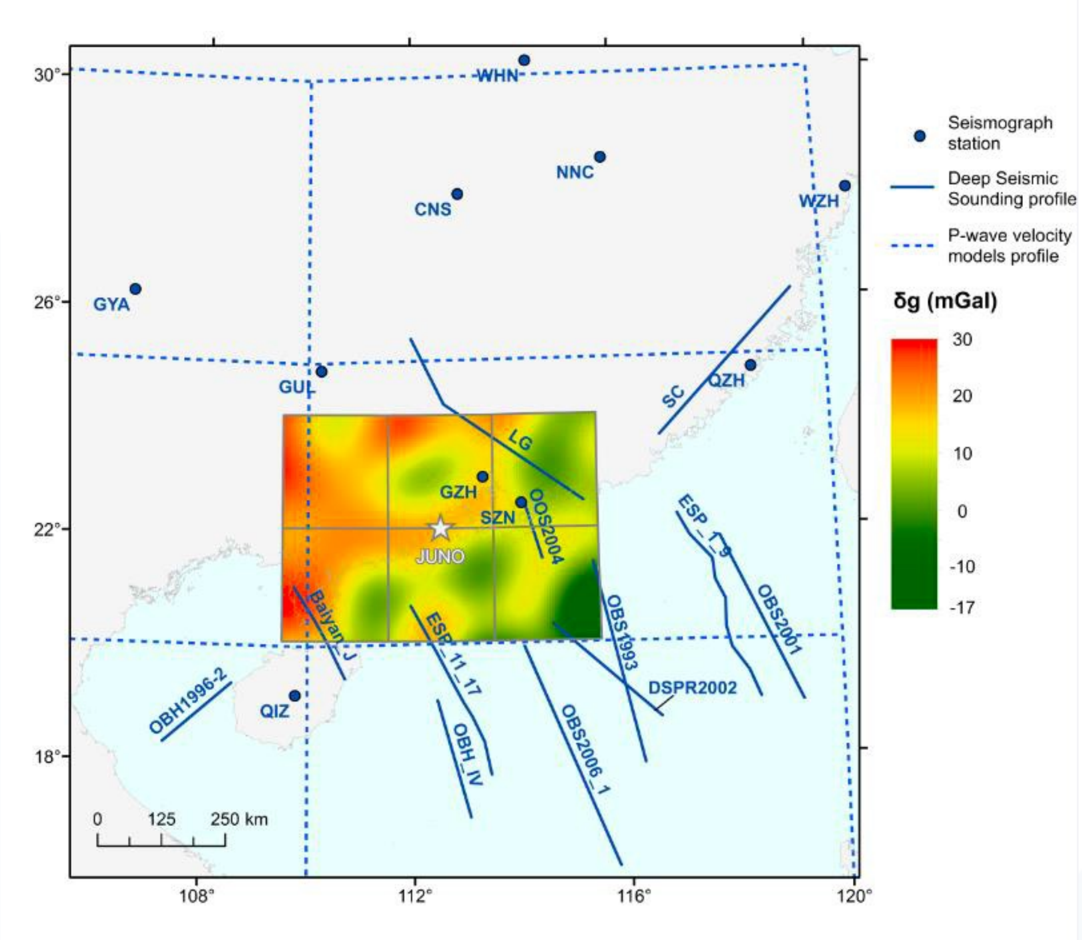
Geophysical models for LOC

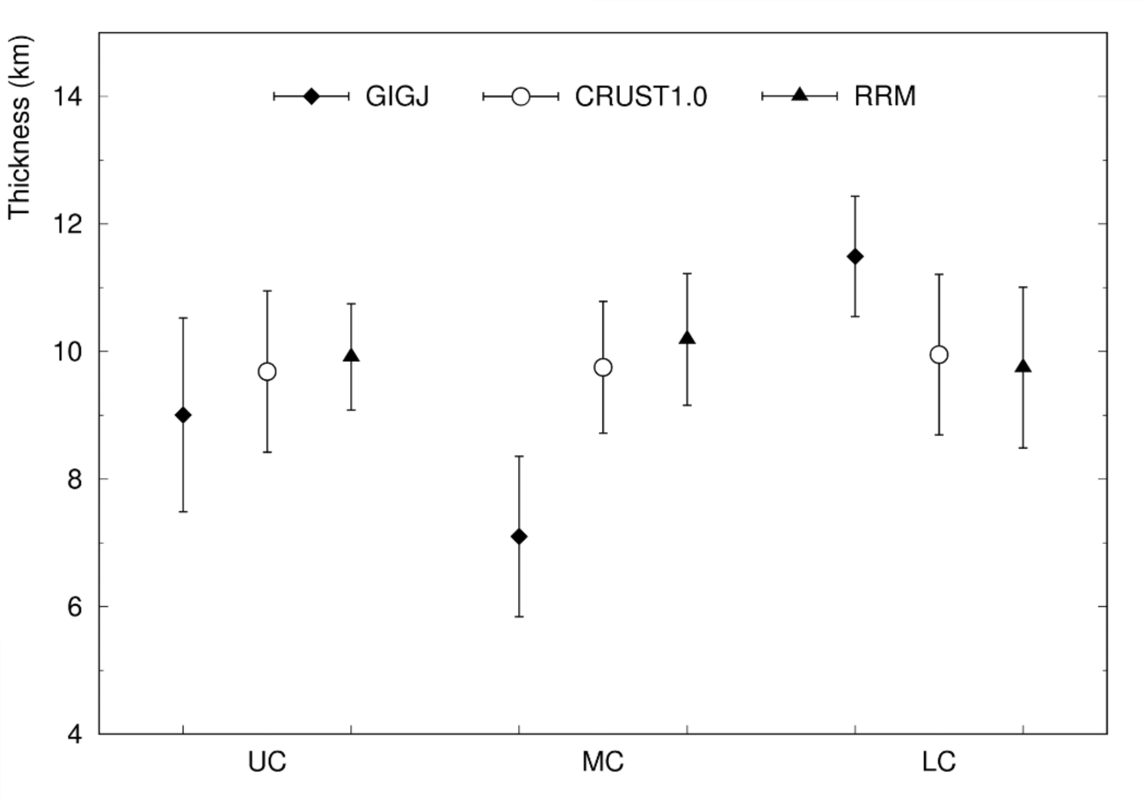
Models	GIGJ	JULOC	JULOC-I
Author	Reguzzoni et al.	Gao et al.	Han et al.
Published year	2019	2020	Under review
Area	6°×4°	10°×10°	10°×11°
Resolution	50×50×0.1 km	0.5°×0.5°×1 km	0.4°×0.4°×1 km
Geophysical model	**gravity** and **seismic** data	**seismic** data	**gravity** and **seismic** data
Geochemical model		**local data**	**local data**

GIGJ model: Reguzzoni et al., 2019

Geophysical inputs: gravity and seismic data

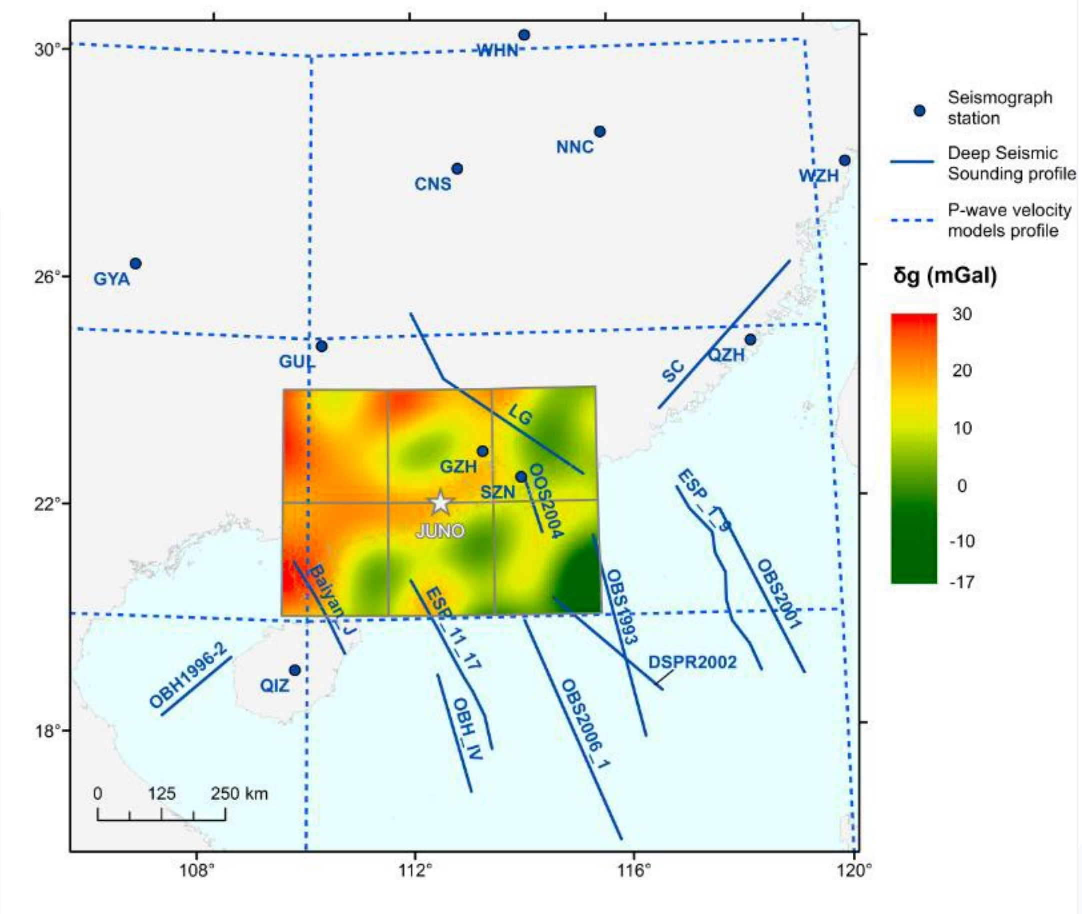


Geophysical model: **crustal layers**

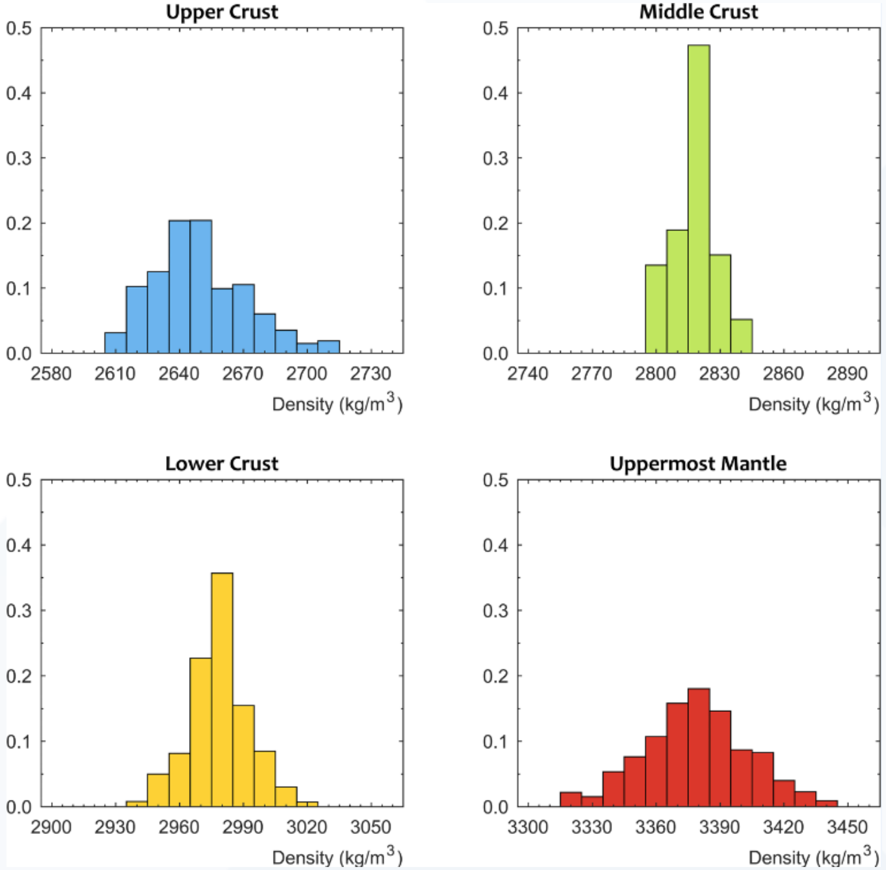


GIGJ model: Reguzzoni et al., 2019

Geophysical inputs: gravity and seismic data

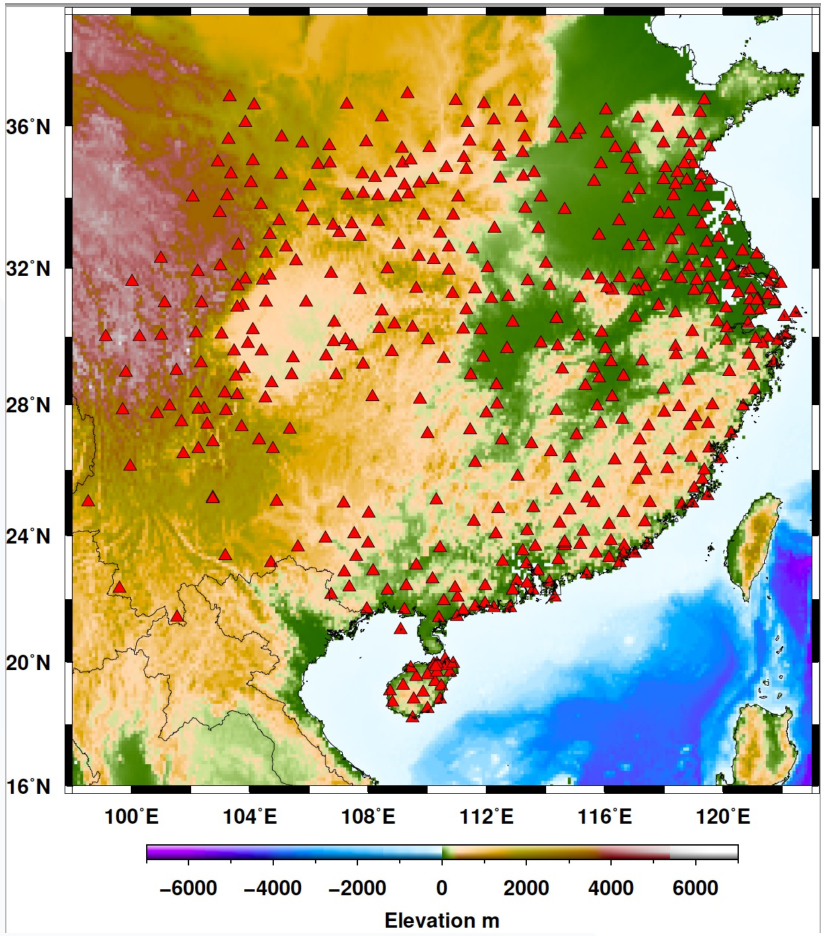


Geophysical model: density

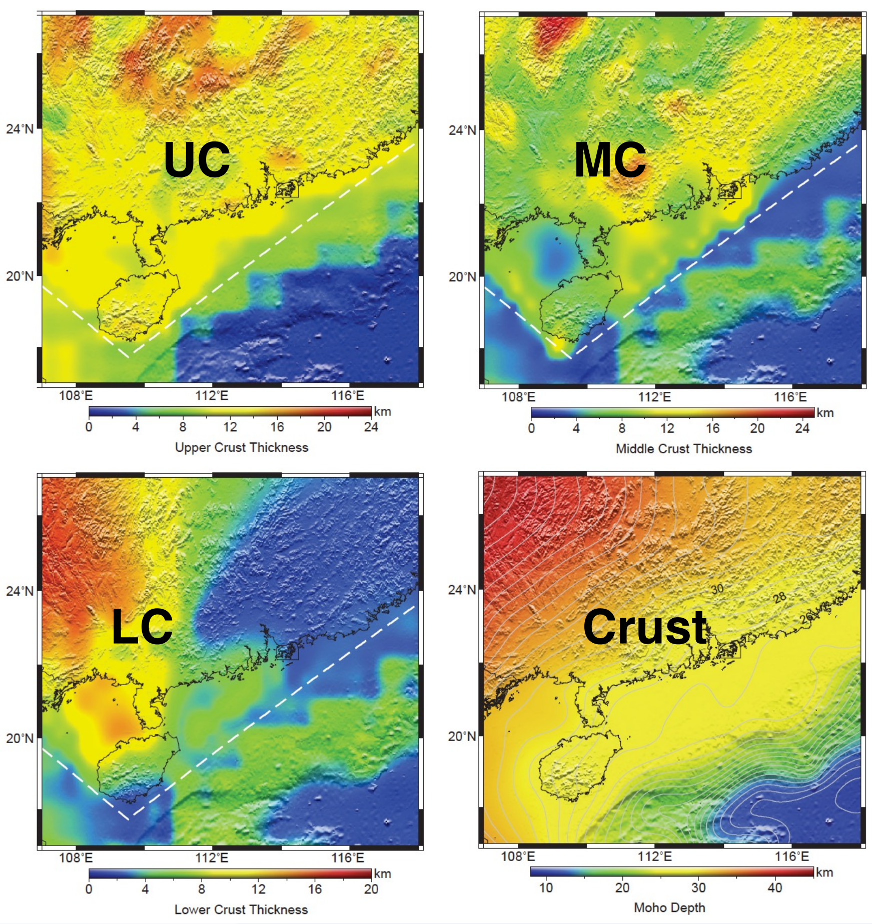


JULOC model: Gao et al., 2020

Geophysical inputs: seismic data

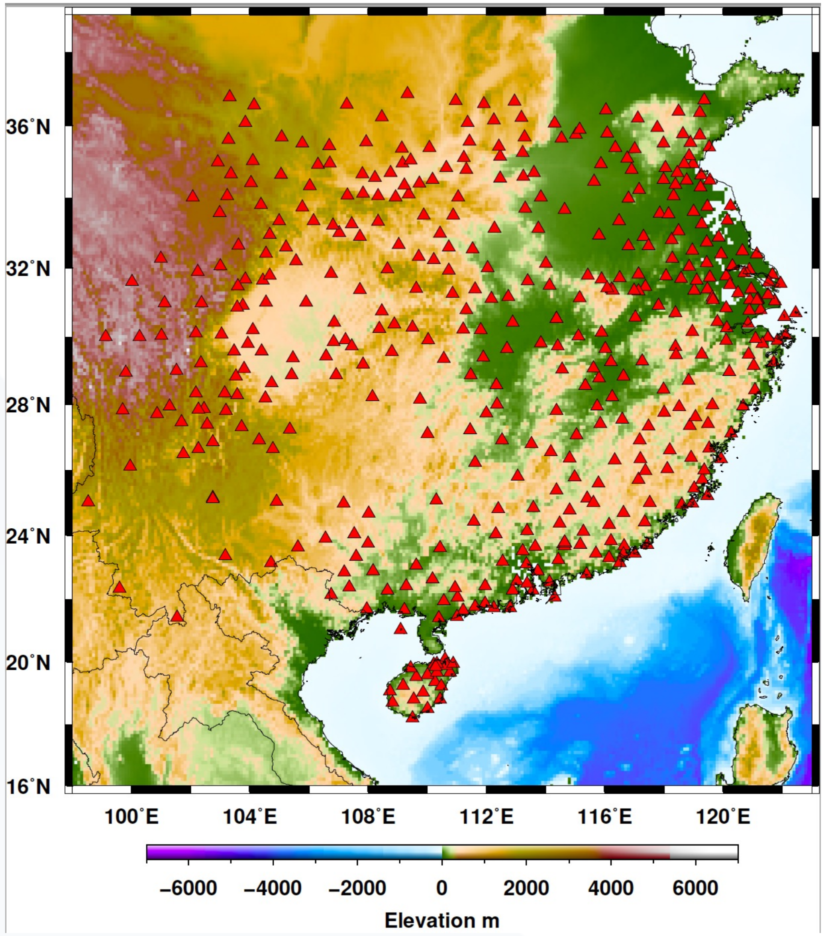


Geophysical model: crustal layers

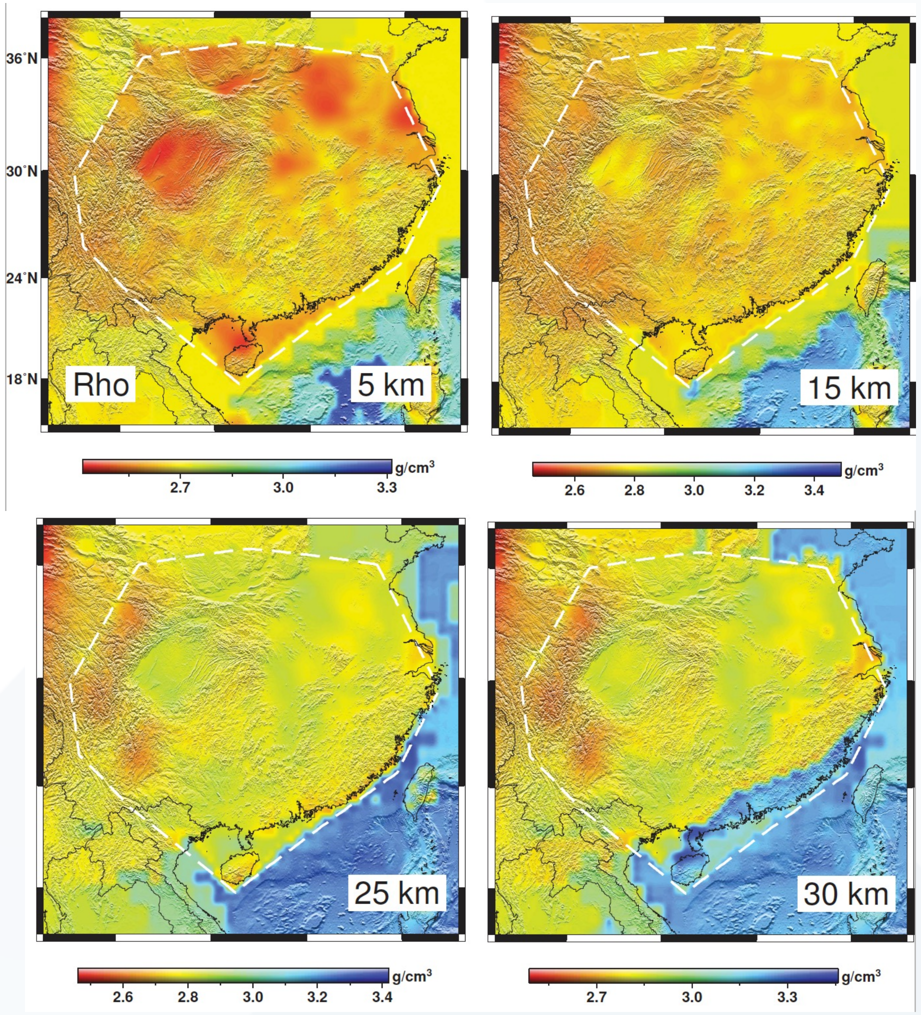


JULOC model: Gao et al., 2020

Geophysical inputs: seismic data

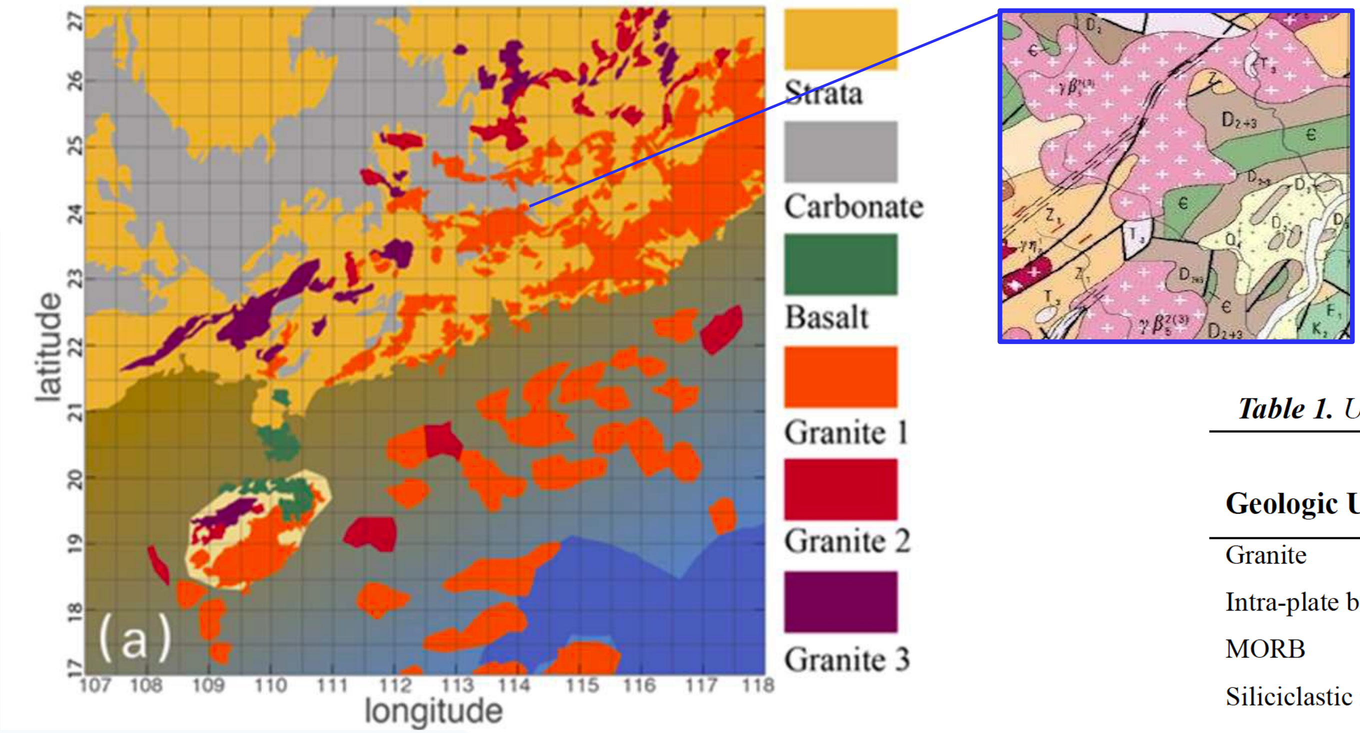


Geophysical model: density



JULOC model: Gao et al., 2020

Geochemical inputs: geological map, rock sample data



Abundance of each voxel =

$$\sum_{i=1}^{n} \boldsymbol{Area\%(i) * Abundance(i)}$$

i: rock type

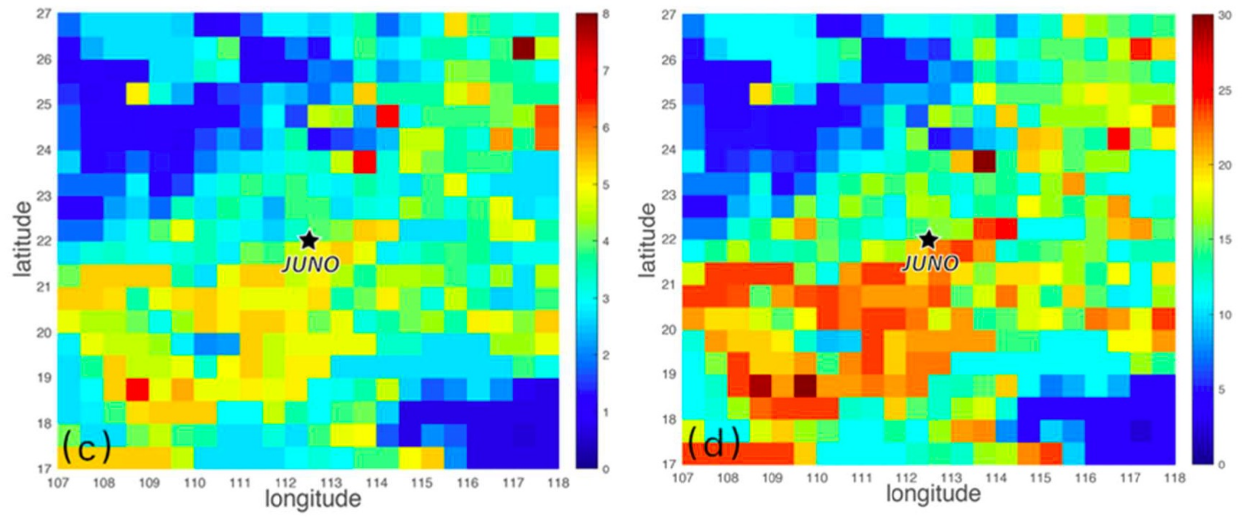
Table 1. *U and Th abundances in geologic units in the regional crust in the 3-D model.*

Geologic Unit	U mean	1-sigma +	1-sigma -	N	Th mean	1-sigma +	1-sigma -	n
Granite	5.4	5.6	2.7	2200	23.7	16.2	9.6	2200
Intra-plate basalt	0.7	0.7	0.5	255	3.7	3.2	1.8	255
MORB	0.7	0.8	0.4	332	2.6	1.8	1.2	332
Siliciclastic rocks	2.7	1.2	0.8	391	11.1	12.8	5.9	391
Carbonites	0.9	0.5	0.3	31	3.6	2.9	1.6	31
Upper crust basement	3.0	2.1	1.2	57	15.4	10.7	6.3	57
Middle crust	0.6	0.4	0.4	10	1.9	1.4	1.4	10
Lower crust	0.04	0.08	0.03	55	0.1	0.3	0.08	55
Oceanic crust	0.7	0.8	0.4	332	2.6	1.8	1.2	332

JULOC model: Gao et al., 2020

Geochemical model:

Top layer (5 km)



Top layer (5 km): 0.5°×0.5° resolution

Upper crust basement: mean value

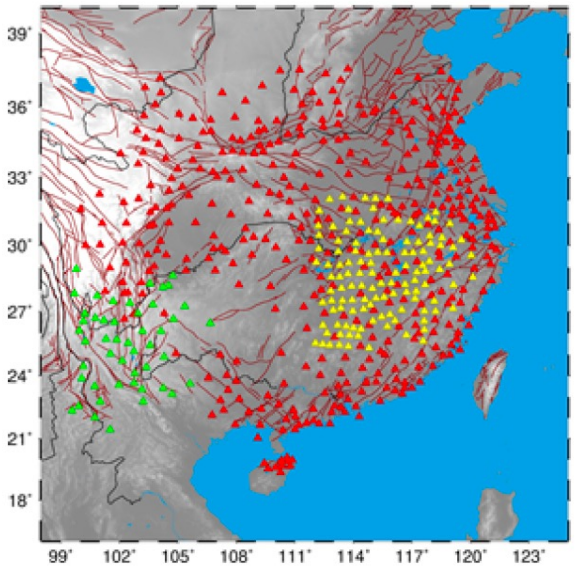
Middle crust: mean value

Lower crust: mean value

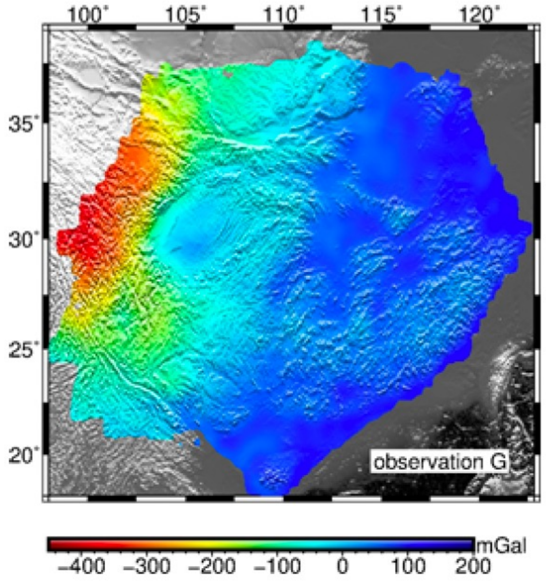
Geologic Unit	U mean	1-sigma +	1-sigma -	N	Th mean	1-sigma +	1-sigma -	n
Upper crust basement	3.0	2.1	1.2	57	15.4	10.7	6.3	57
Middle crust	0.6	0.4	0.4	10	1.9	1.4	1.4	10
Lower crust	0.04	0.08	0.03	55	0.1	0.3	0.08	55

JULOC-I model: Han et al., under review

Geophysical inputs: seismic and gravity data

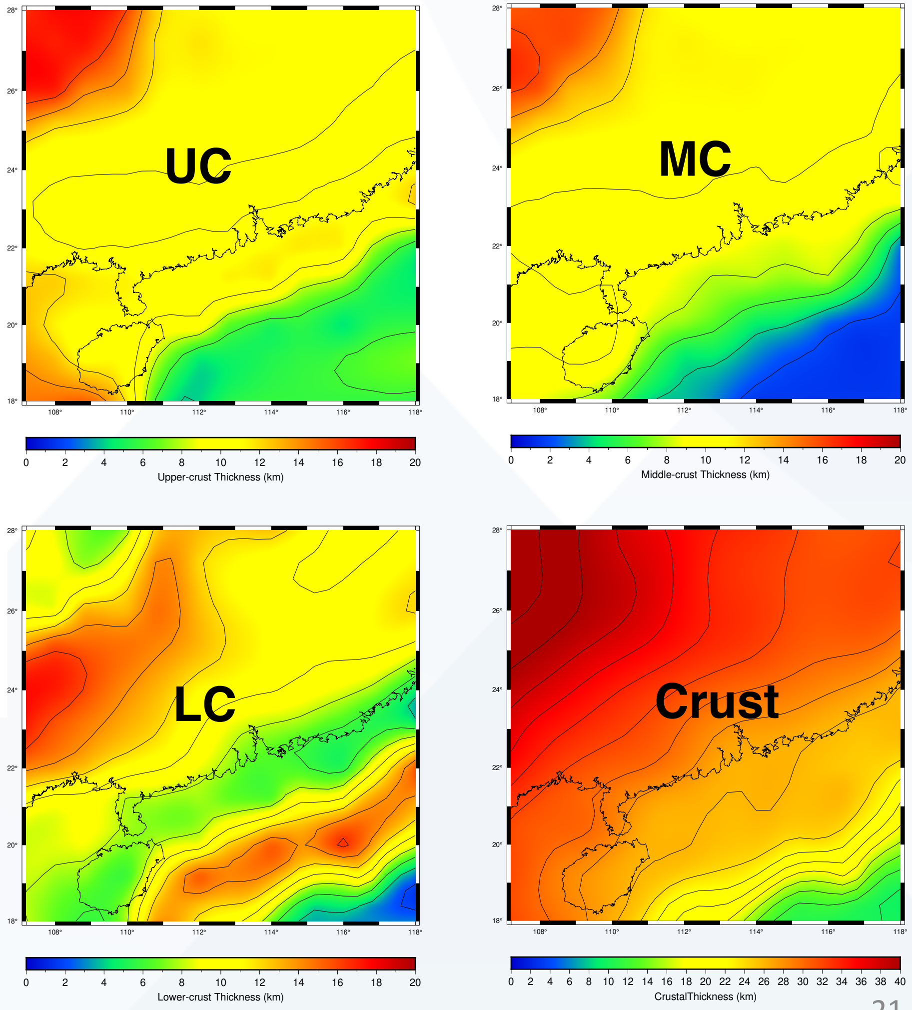


Seismograph stations



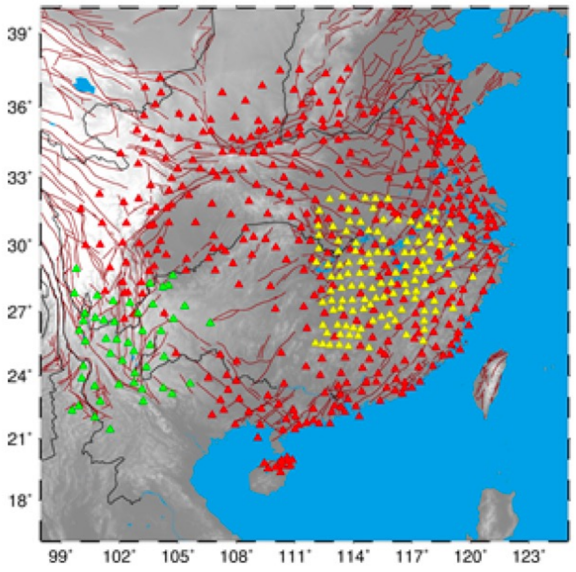
Gravity anomaly data

Geophysical model: crustal layers

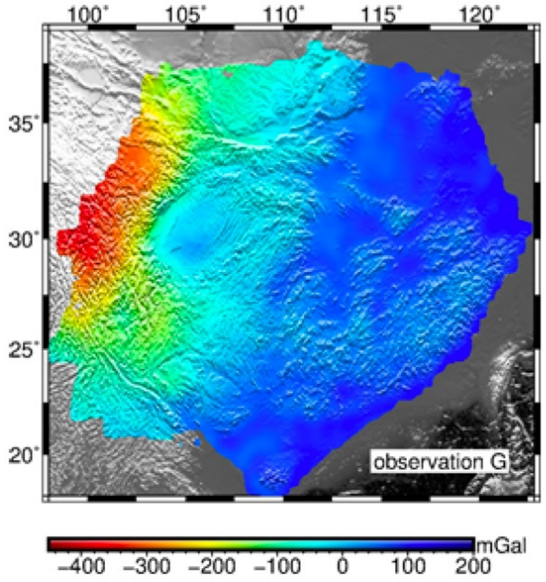


JULOC-I model: Han et al., under review

Geophysical inputs: seismic and gravity data

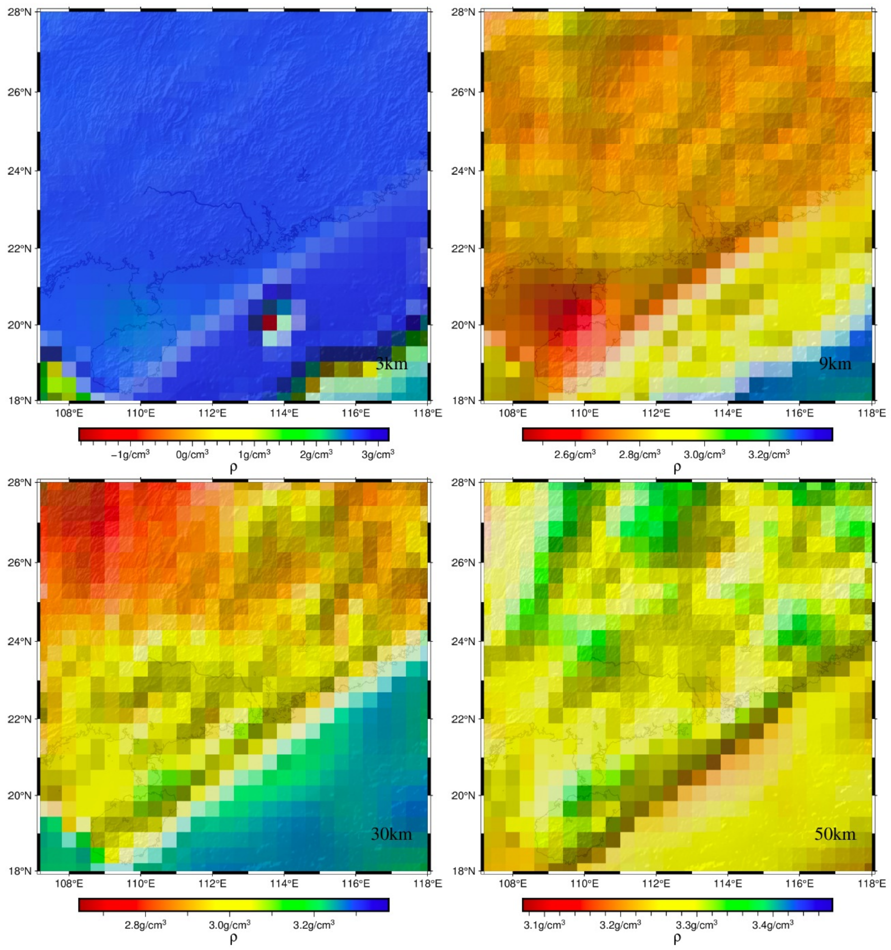


Seismograph stations



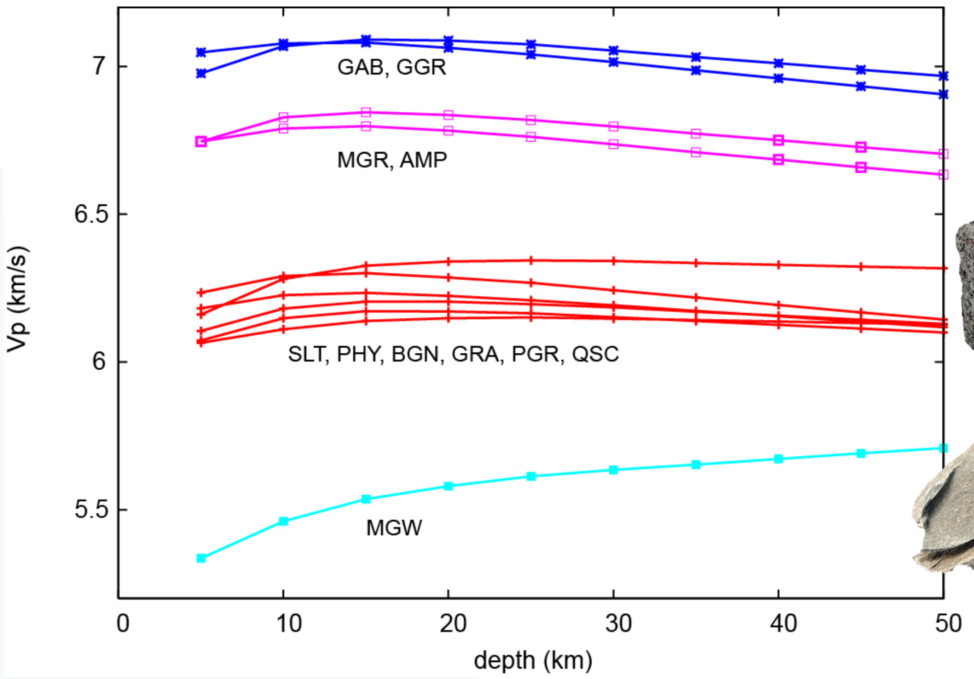
Gravity anomaly data

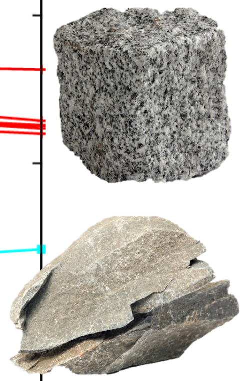
Geophysical model: density



JULOC-I model: Han et al., under review

Geochemical inputs: seismic data, prior, rock sample data





Constraints from crustal Vp

Prior probability

$$P\left(i \middle| V_P^{obs}\right) = \frac{P\left(V_P^{obs} \middle| i\right) P_{(i)}}{\sum_{i=1}^{n} P\left(V_P^{obs} \middle| i\right) P_{(i)}}$$

Posterior probability

Constraints from crustal Vp

- **Different rock has different typical Vp.**
- **With the constraints from crustal Vp (geophysical model), we can estimate the proportion of different rock types in each voxel.**

JULOC-I model: Han et al., under review

Geochemical inputs: seismic data, **prior**, rock sample data

Upper crust	Middle crust	Lower crust
SED 0.08 **BAS** 0.02 **BGN-GGN** 0.1 **GRA** 0.4 **MGW** 0.25 **SLT-PHY-QSC** 0.15	**BGN-GGN** 0.1 **AMP** 0.9	**IGR** 0.6 **MGR** 0.2 **MPE** 0.2

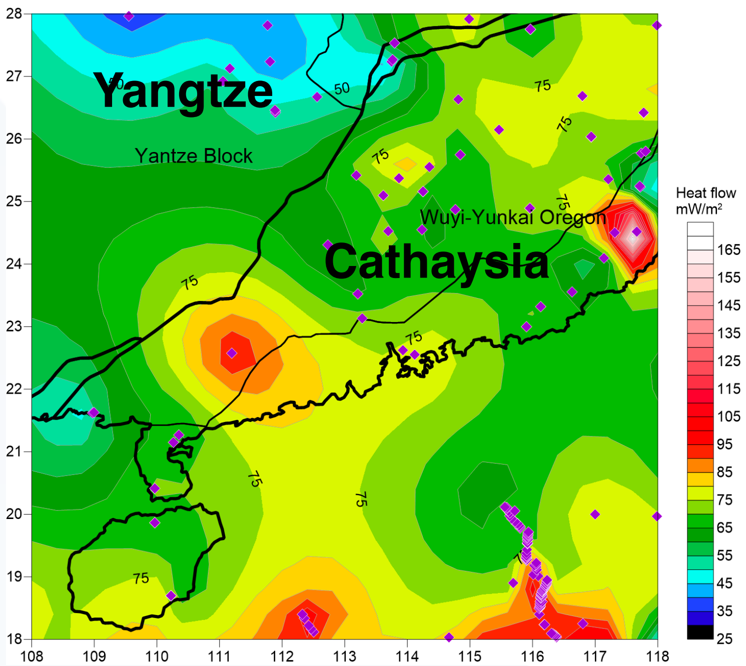
Estimated from geological map

Based on the study on Central East China

Gao et al., 1998

JULOC-I model: Han et al., under review

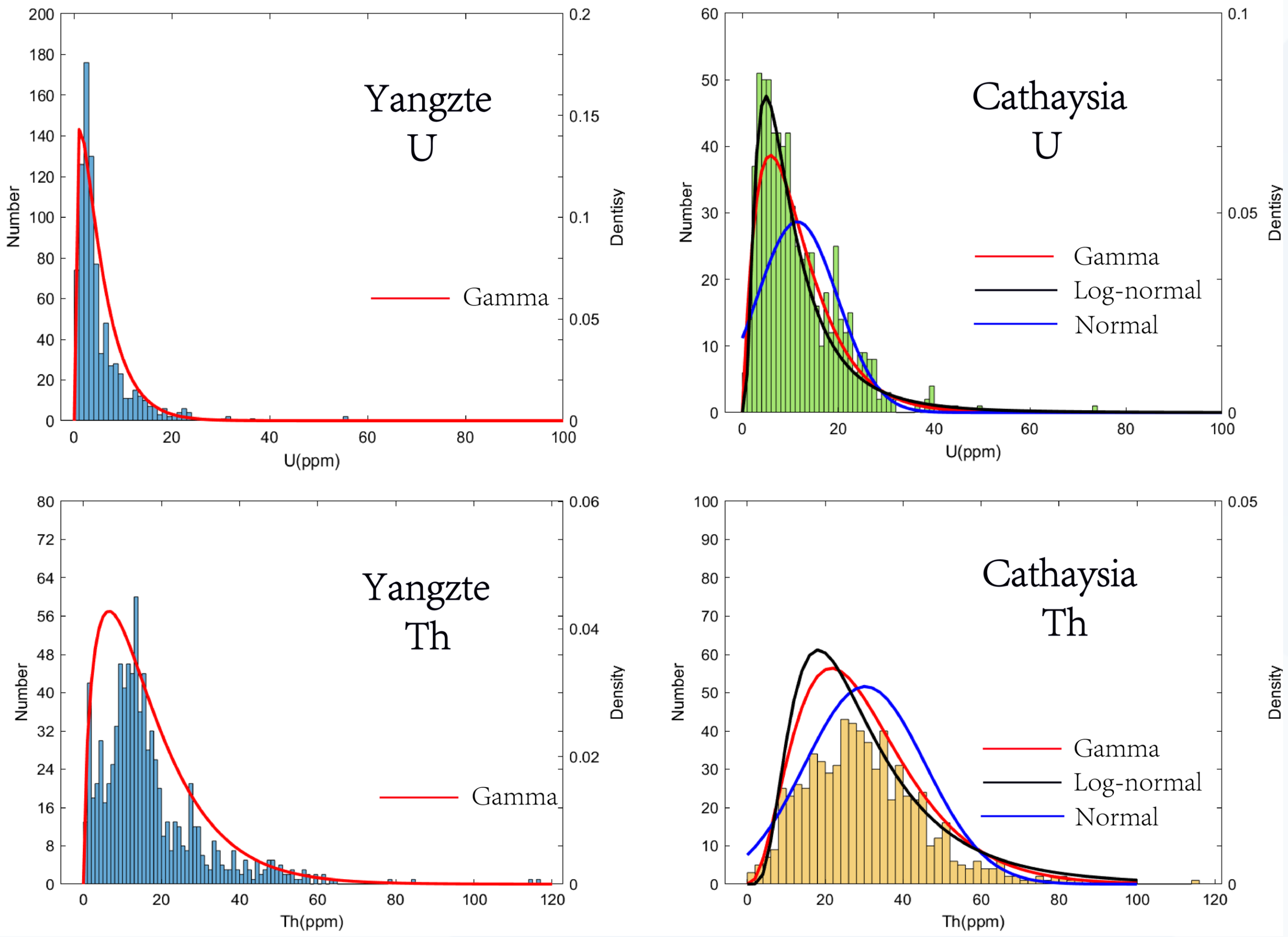
Geochemical inputs: seismic data, prior, **rock sample data**



Surface heat flow map

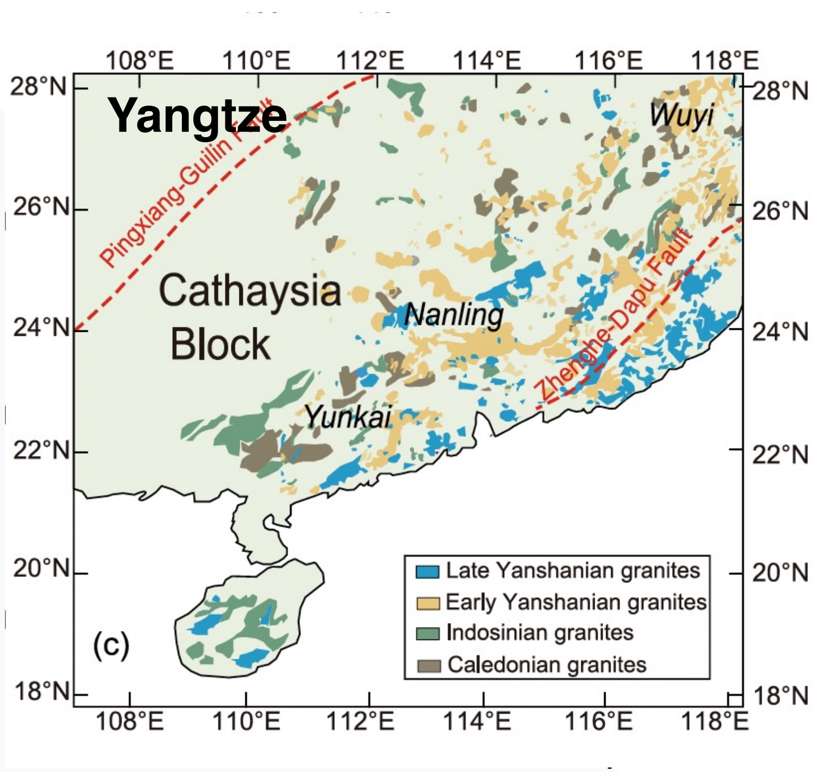
Granites

in Yangtze vs Cathaysia



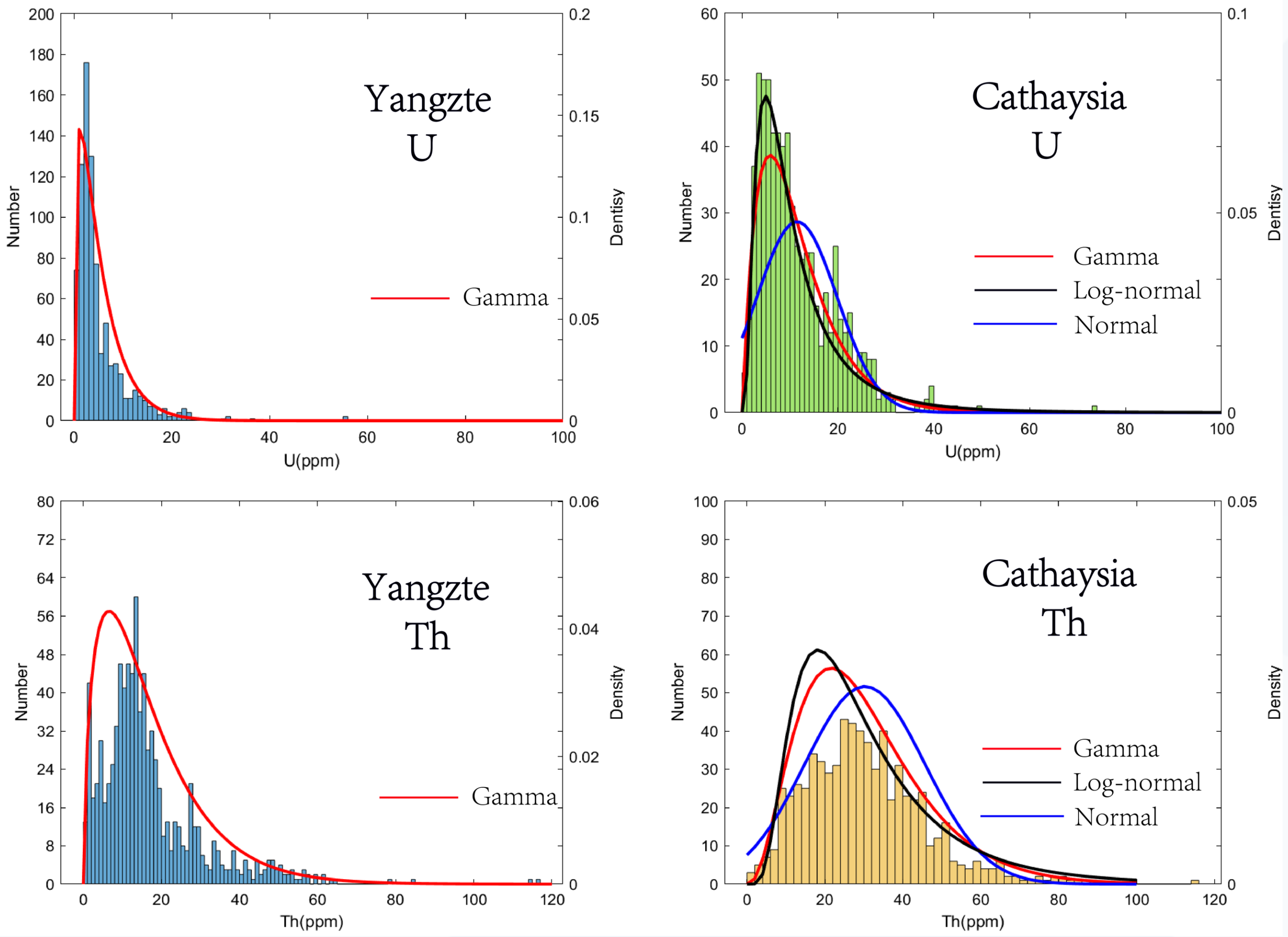
JULOC-I model: Han et al., under review

Geochemical inputs: seismic data, prior, **rock sample data**



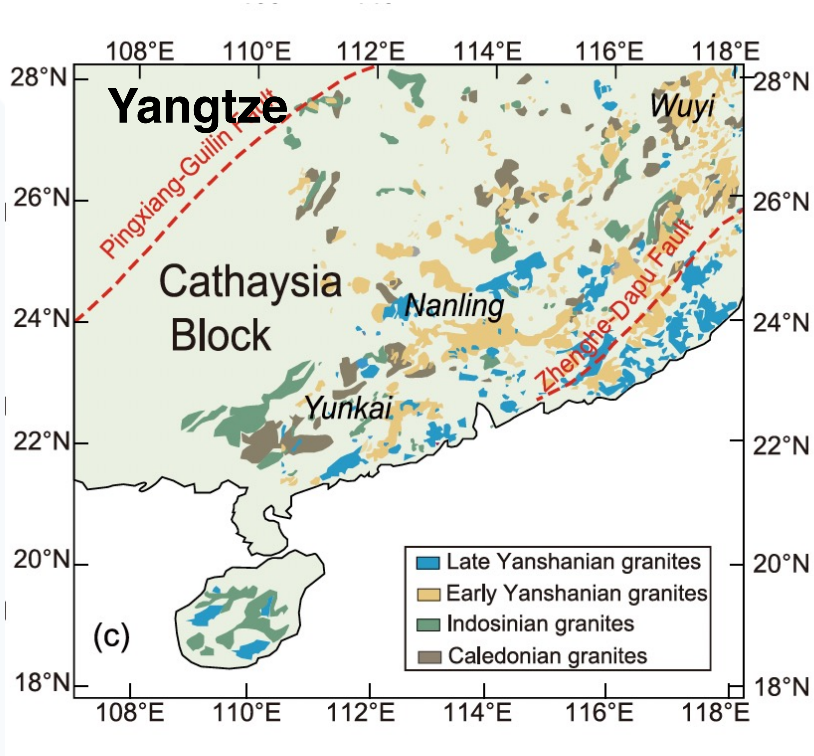
Granites

Yangtze vs Cathaysia



JULOC-I model: Han et al., under review

Geochemical inputs: seismic data, prior, **rock sample data**



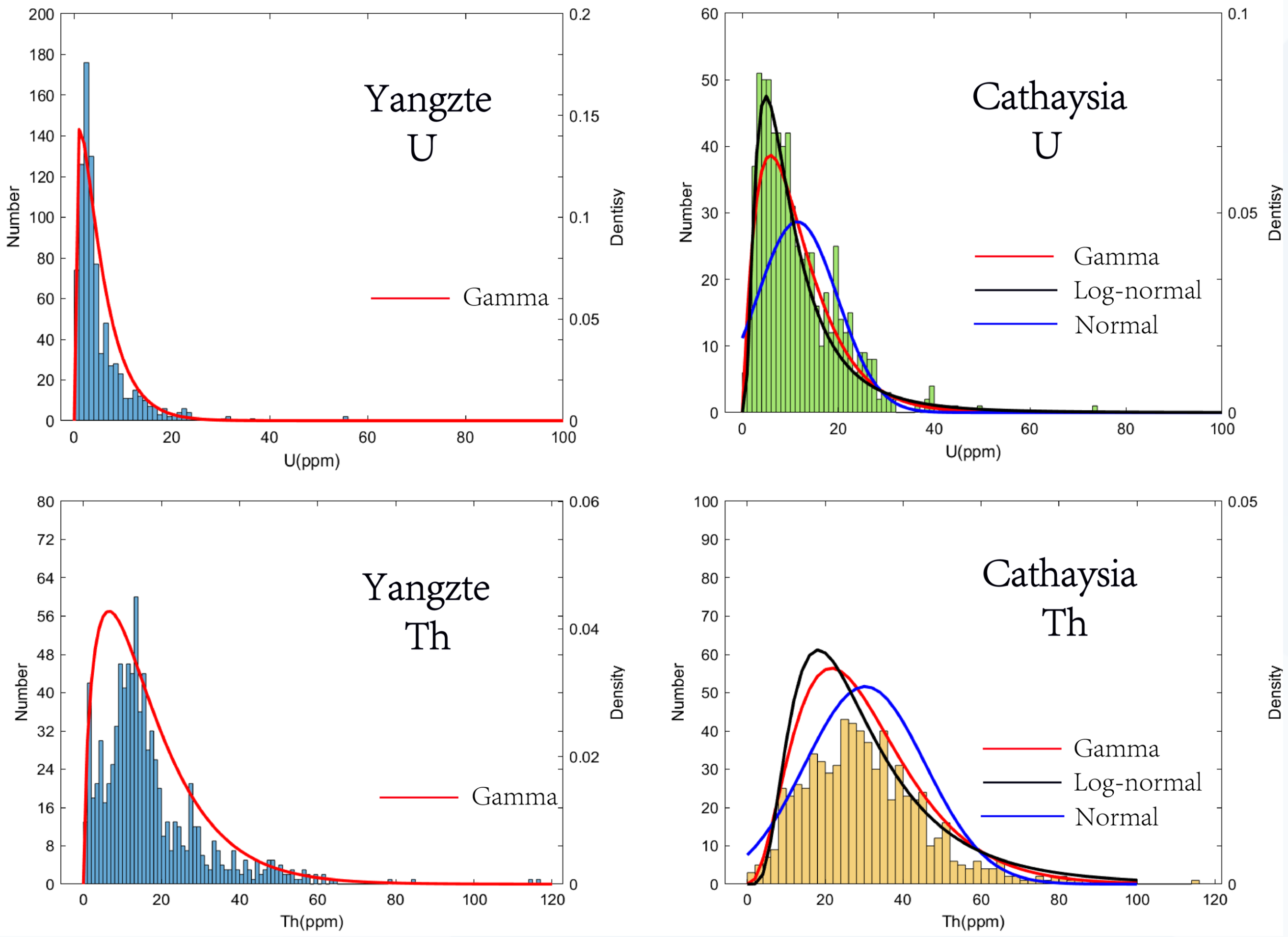
Granites

Yangtze vs Cathaysia

Average UC

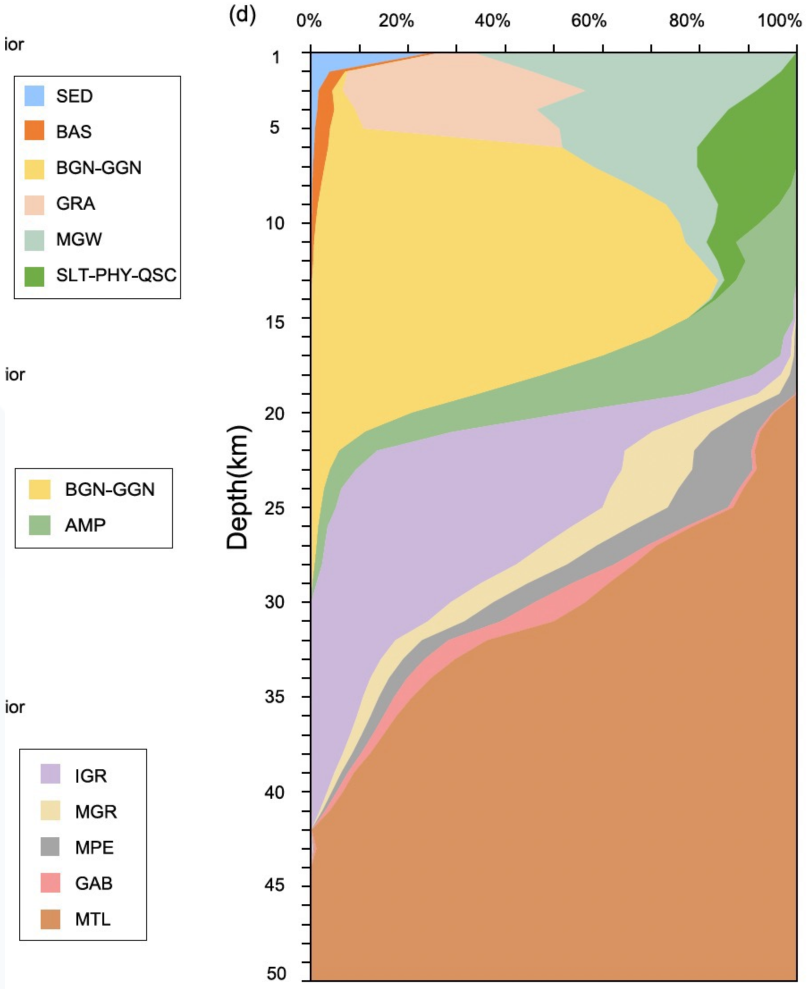
U: 2.7±1.6 $\mu g/g$

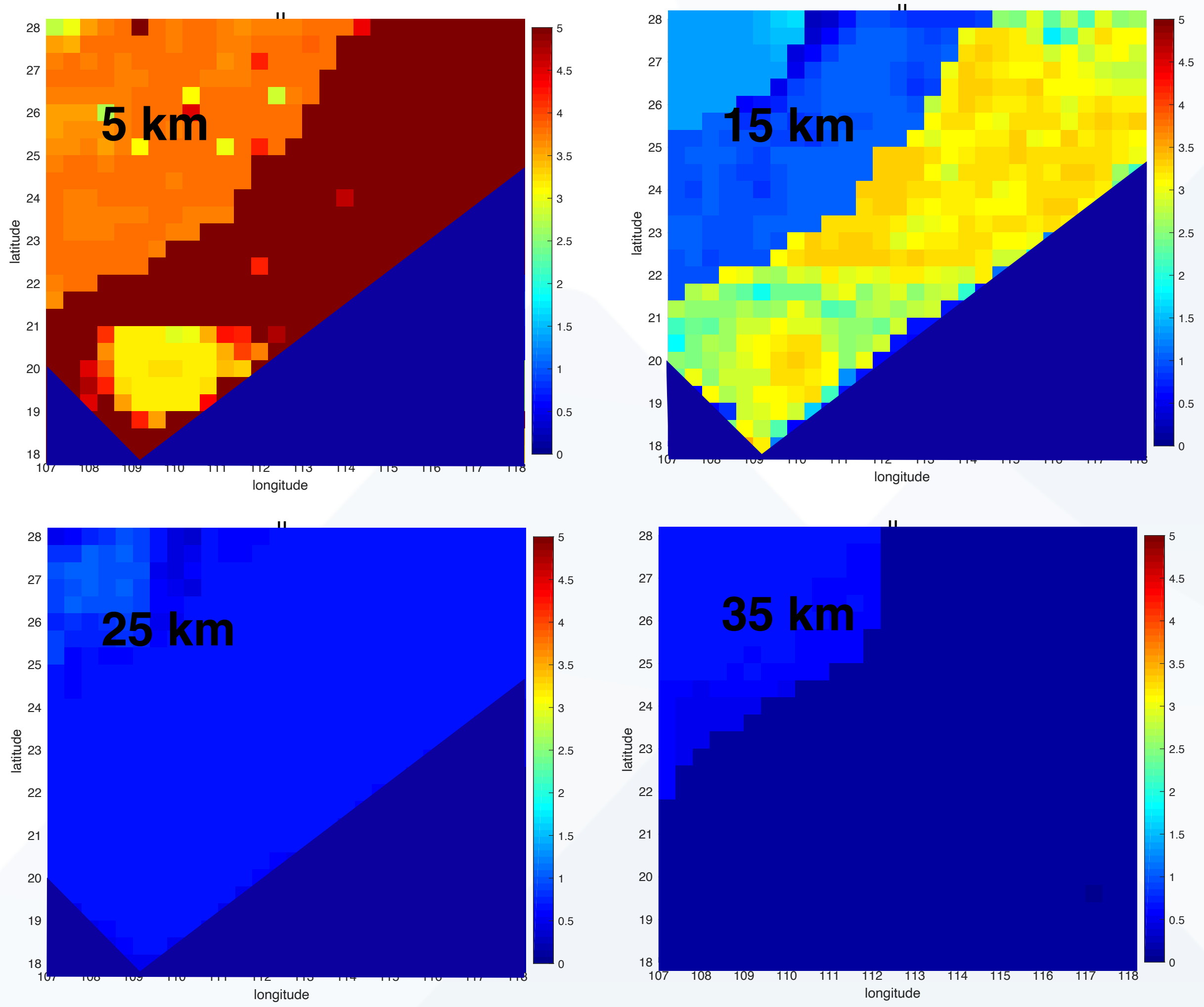
Th: 10.5±1.0 $\mu g/g$



JULOC-I model: Han et al., under review

Geochemical model: 0.4°×0.4°×1 km resolution





Geo-neutrino signals from LOC

JULOC

		$S_U \pm \sigma$	$S_{Th} \pm \sigma$	$S_{U+Th} \pm \sigma$
Upper Crust	Top layer	$10.5_{-0.7}^{+0.7}$	$3.2_{-0.3}^{+0.3}$	$13.8_{-0.7}^{+0.8}$
	Basement	$8.1_{-3.7}^{+7.0}$	$2.6_{-1.1}^{+1.8}$	$11.0_{-3.9}^{+5.9}$
Middle Crust		1.7 ± 1.0	0.4 ± 0.3	2.1 ± 1.1
Lower Crust		$1.9_{-1.3}^{+3.8}$	$0.8_{-0.7}^{+5.7}$	$1.7_{-1.2}^{+4.0}$
Oceanic Crust		0.2 ± 0.05	0.1 ± 0.01	0.3 ± 0.05
Total		21.3 ± 4.0	6.6 ± 1.3	28.5 ± 4.5

JULOC-I

Preliminary results

	S_U	S_{Th}	S_{U+Th}
Continental Crust	22.1	6.7	28.8
Oceanic Crust	0.2	0.1	0.3
Total	22.3	6.8	29.1

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Conclusions

1. Geochemical model has larger influence on geo-neutrino signal prediction than geophysical model, as the earth's continental crust is highly heterogenous in terms of U and Th abundances.

2. Local crust model (JULOC/JULOC-I) predicts higher geoneutrino signal than global models.

3. This is consistent with the wide distribution of high U/Th granite intrusions in the Cathaysia region around JUNO.

Thank you!