JUNO地球中微子与地壳模型研究进展与展望

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中国地质大学（北京）

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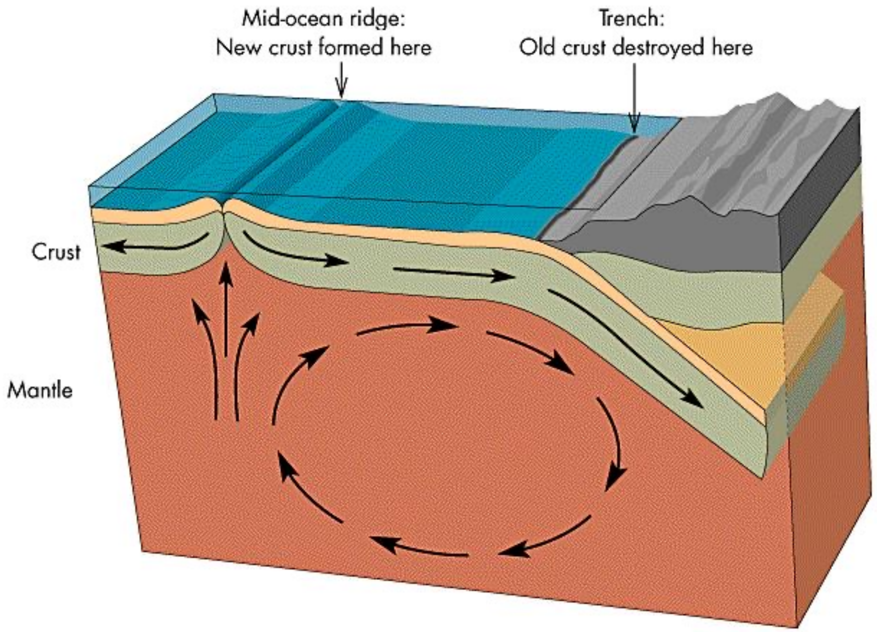
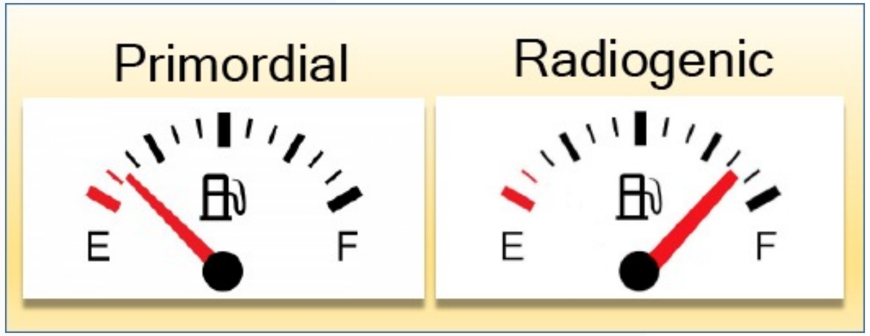
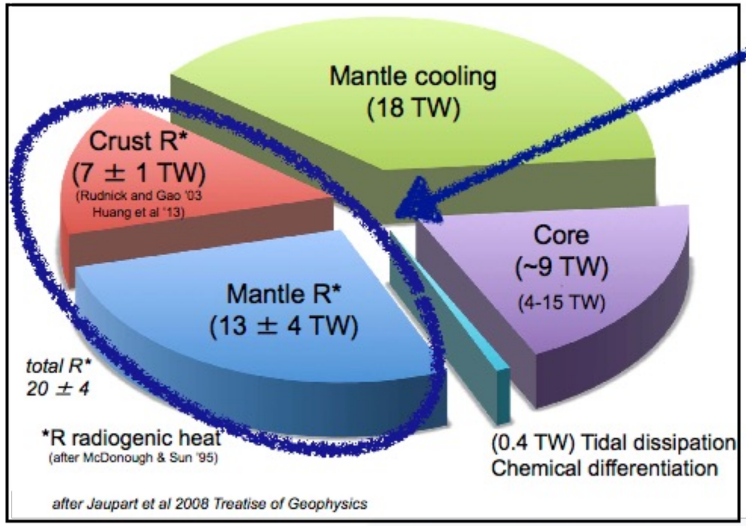
How much fuel is left to drive Plate Tectonics?

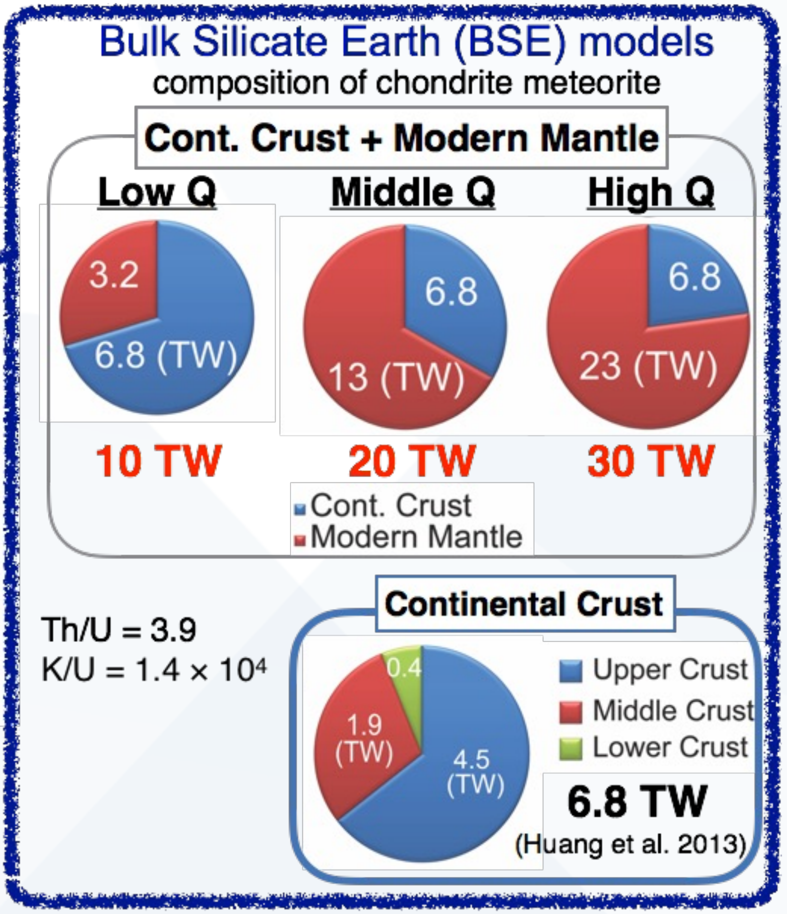




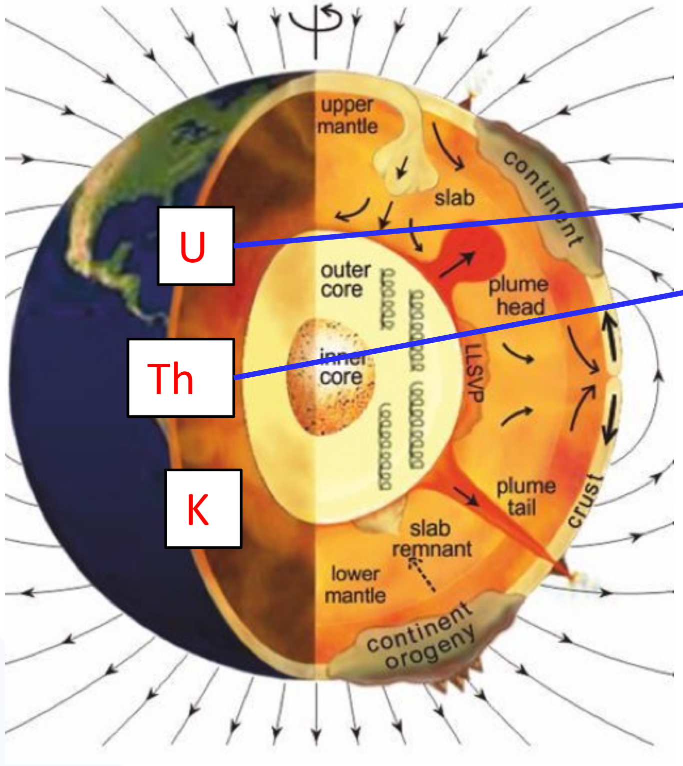
☑ Surface heat flow
46 ± 3 TW
crust heat flux measurement & calculation



Almost half of radiogenic heat contributes to the surface heat flow.



地球中微子的产生与探测



Production of Geo-neutrino

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

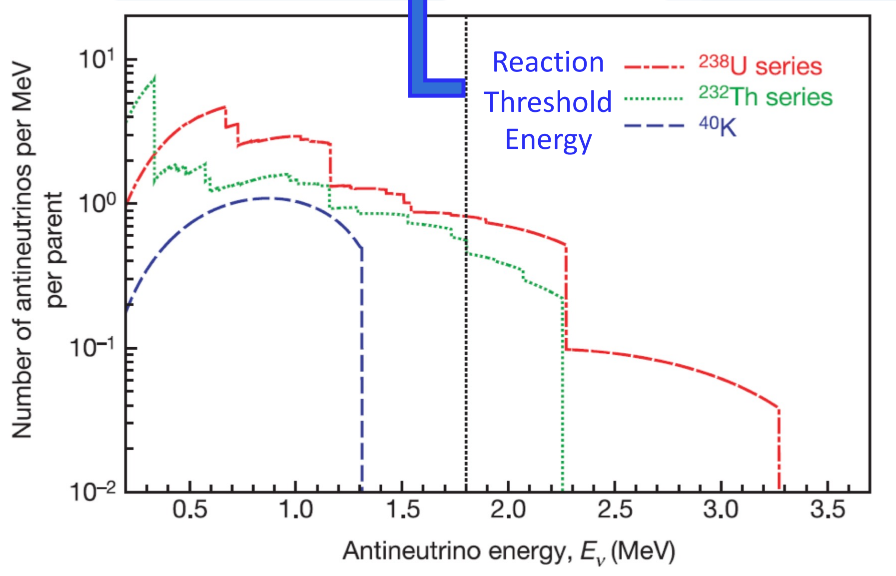
$$^{232}\mathrm{Th} \longrightarrow {}^{208}\mathrm{Pb} + 6\,\alpha + 4\,e^- + \mathbf{4}\,\bar{\nu}_e \quad + 42.652\mathrm{MeV}$$

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

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

Detection of Geo-neutrino

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



(from S.T. Dye)

地球中微子应用于地学研究

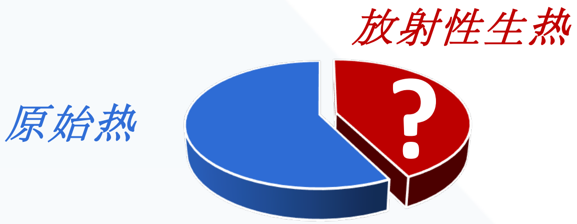
$S_{检测} = S_{地壳} + S_{地幔}$

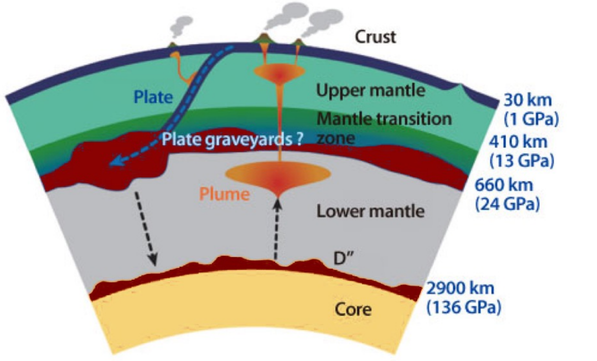
❖ 应用

✓ 探测地球深部信息

✓ 检验地球模型

检验地球中U和Th
(放射性生热元素、不相容元素)
的总量和分布的模型





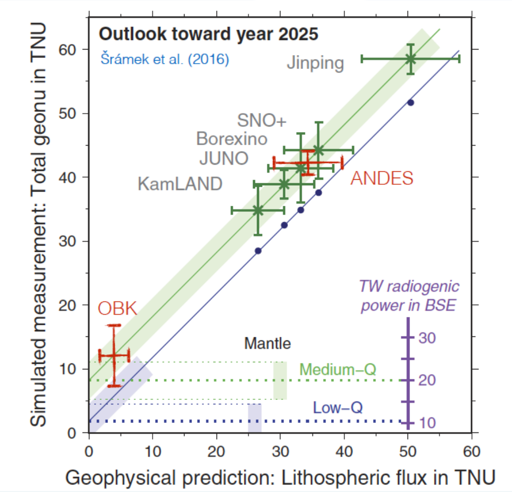
❖ 局限性

✓ 信号没有方向性

✓ 观测站、观测量少

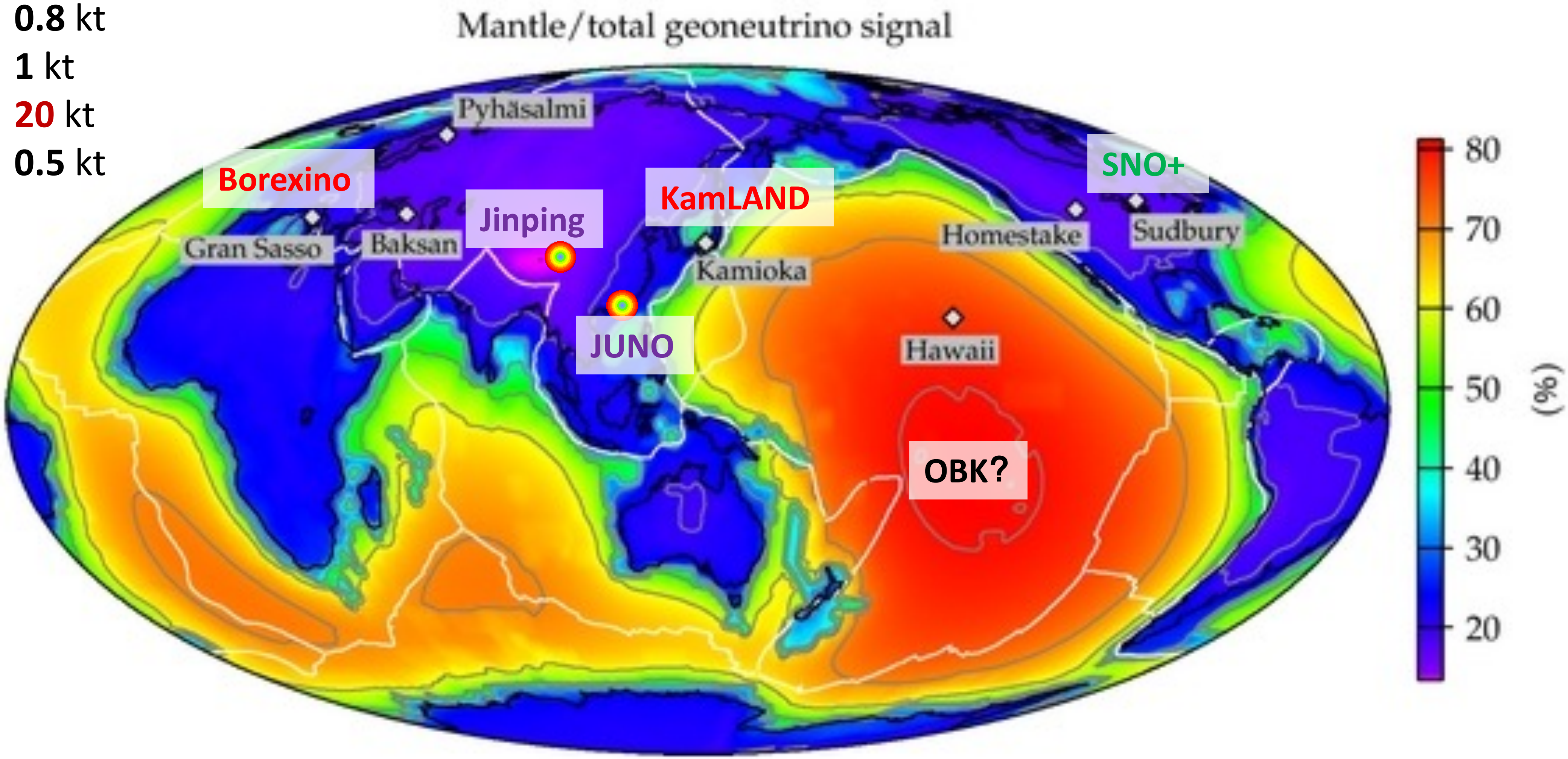
建立更精确的3D地壳模型

多个站点观测结果联合反演



中微子观测站

Borexin	0.28 kt
SNO+	0.8 kt
KamLAND	1 kt
JUNO	20 kt
Jinping	0.5 kt



地球中微子通量计算

Activity and number of produced geoneutrinos

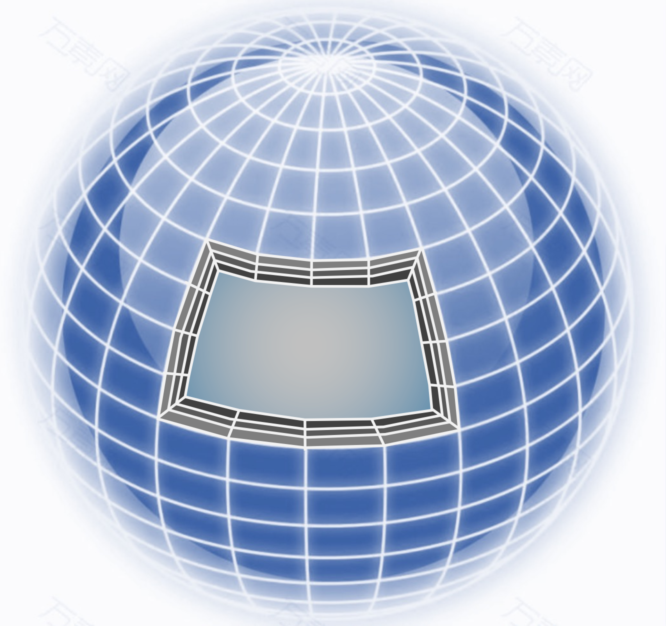
Volume of source unit

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

Survival probability function

Abundance and density of the source unit

Distance between source unit and detector

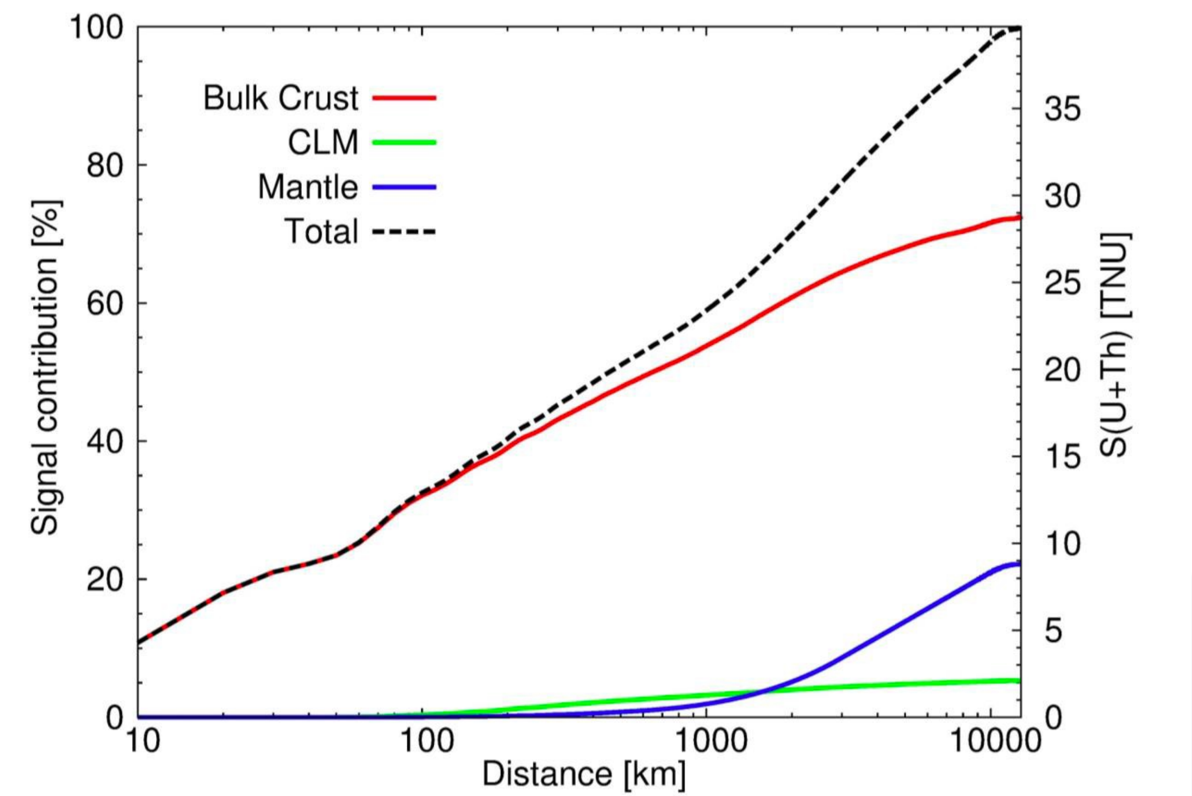


- **Geophysical models**
  - **Density** of source unit
  - Thickness of earth's **layers**
- **Geochemical models**
  - **U and Th abundances** of source unit

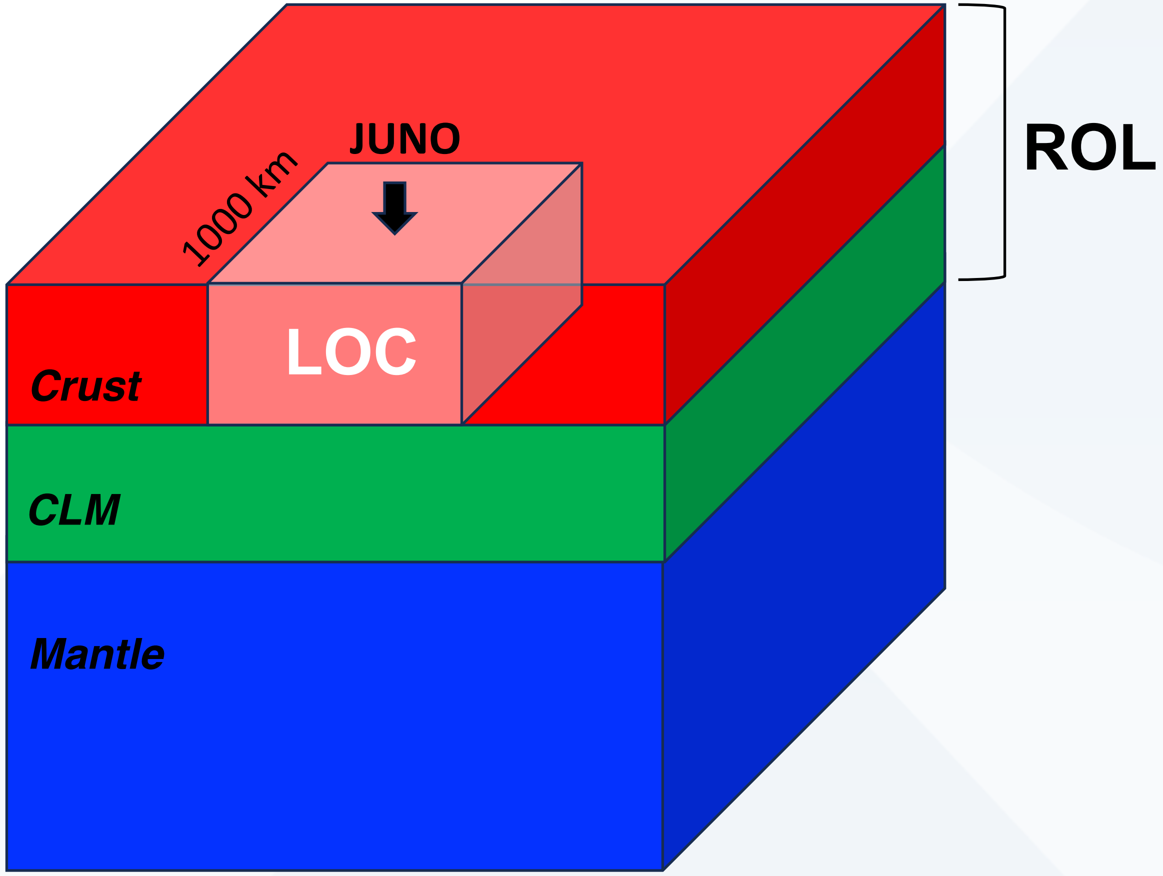
近场 vs 远场地壳模型

$S_{检测} = S_{地壳} + S_{地幔} = S_{近场} + S_{远场} + S_{地幔}$

- **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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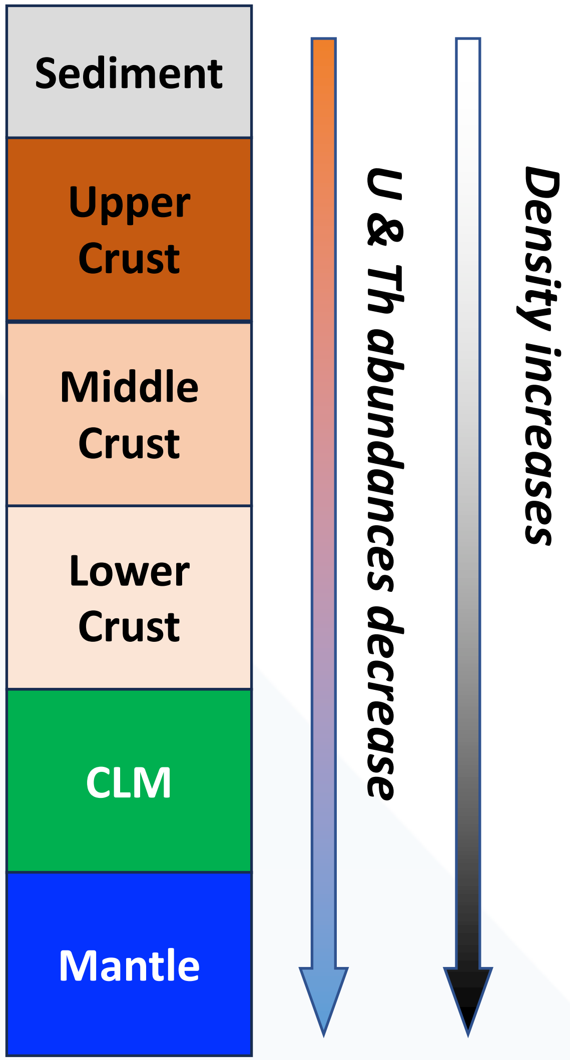
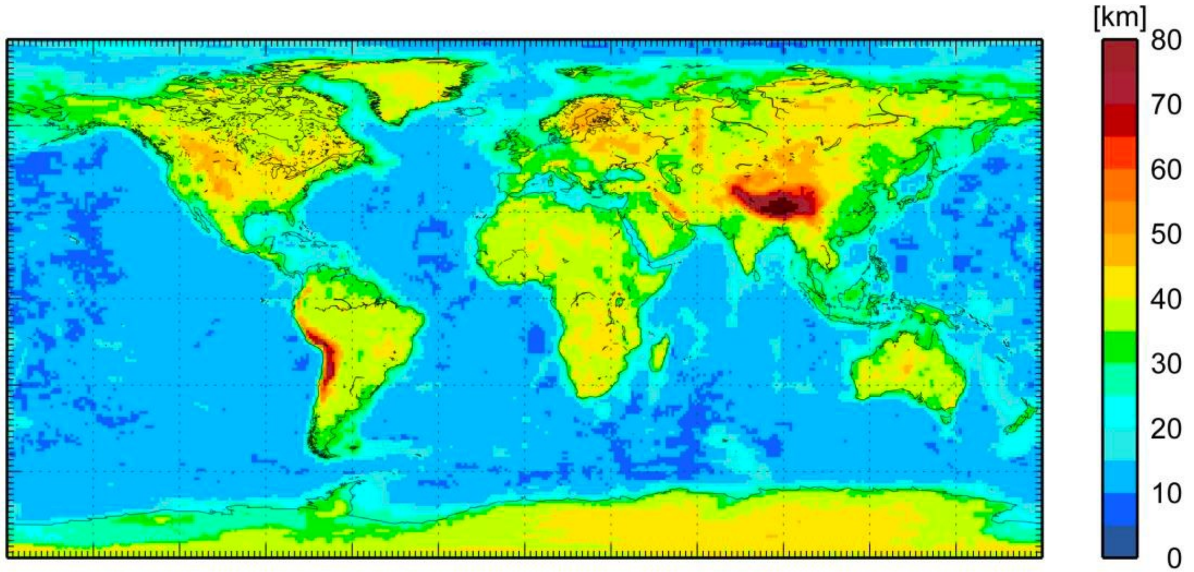
地球物理模型提供的关键

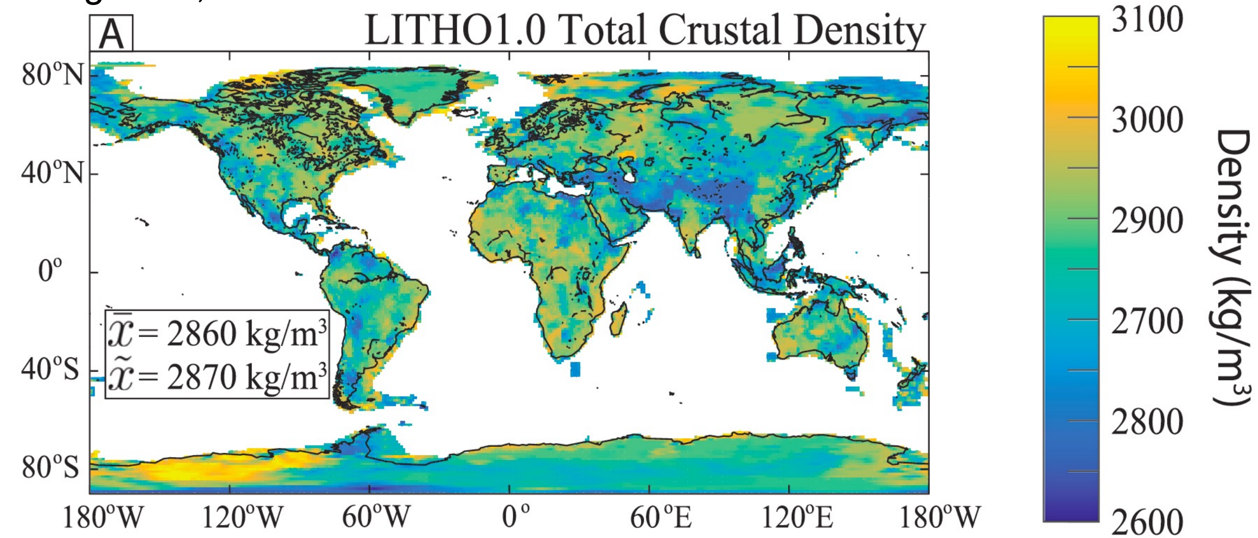


- **地壳分层**
  - Sed
  - UC
  - MC
  - LC

- **地壳密度**



Huang et al., 2013

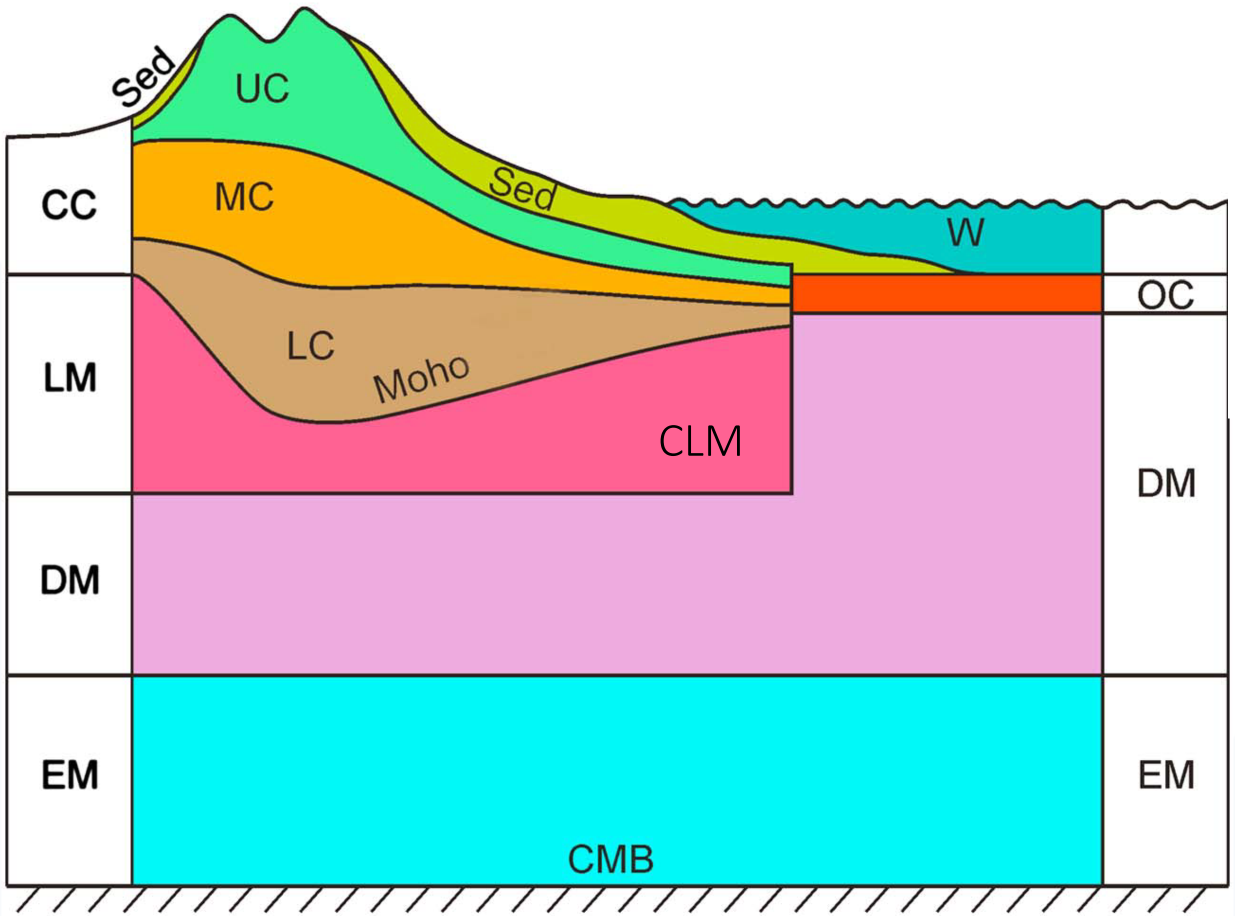


Wipperfurth et al., 2020

全球地壳地球物理模型

Models	GEMMA	CUB 2.0	CRUST2.0	RMM	CRUST 1.0	LITHO 1.0	ECM 1.0
Author	Negretti et al.	Shapiro and Ritzwoller	Laske et al.	Huang et al.	Laske et al.	Pasyanos et al.	Mooney et al.
Published year	2012	2002	2001	2013	2013	2014	2023
Resolution	0.5°×0.5°	2°×2°	2°×2°	1°×1°	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	adding new published data

全球地壳地球化学模型



	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	$0.03^{+0.05}_{-0.02}$	$0.15^{+0.28}_{-0.10}$

Huang et al., 2013

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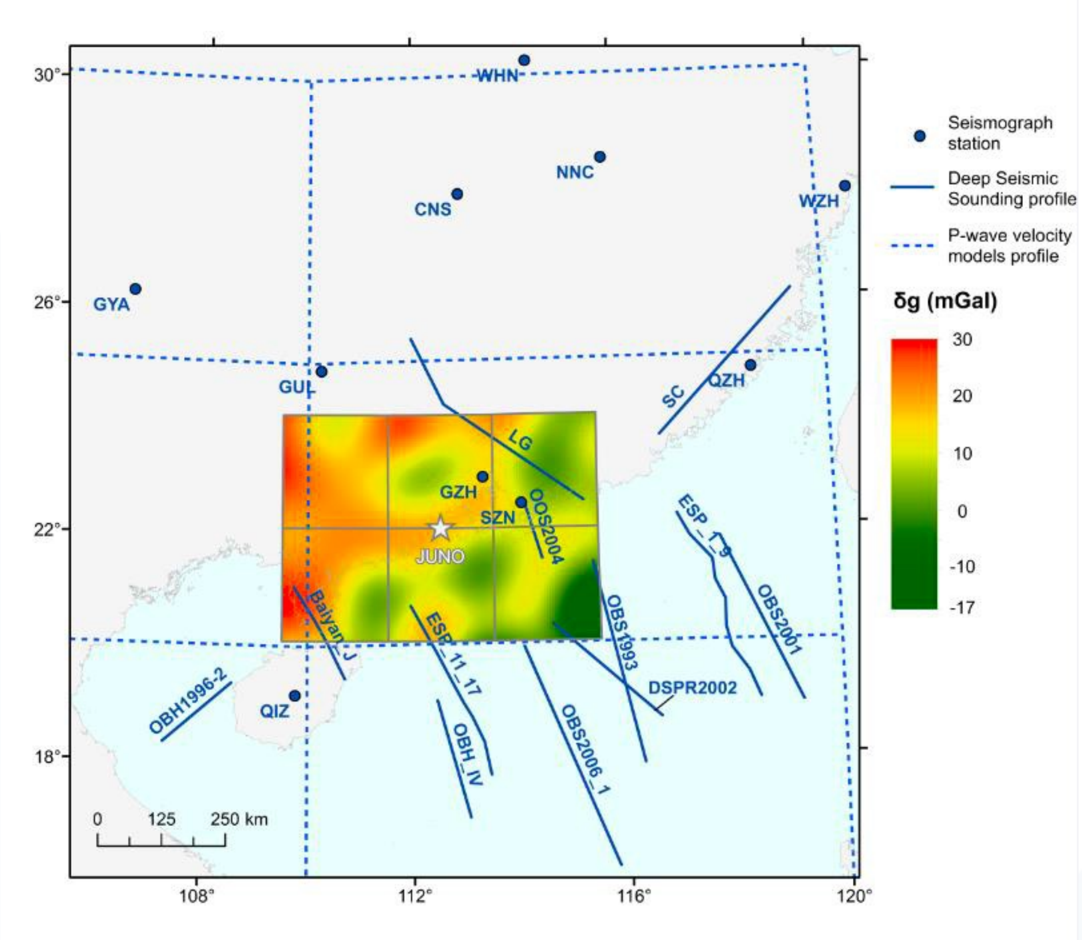
JUNO近场模型

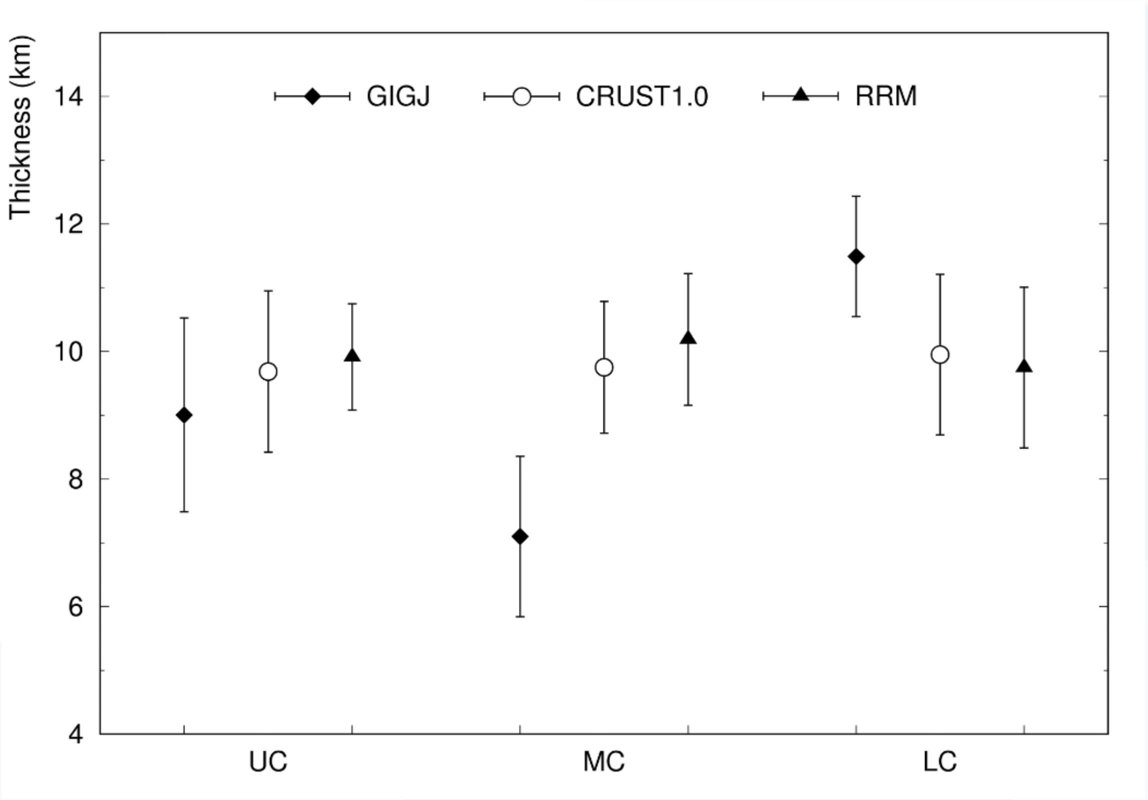
Models	GIGJ	JULOC	JULOC-I
Author	Reguzzoni et al.	Gao et al.	Han et al.
Published year	2019	2020	Under review
Area	6°×4°	10°×10°	10°×11°
Resolution	50×50×0.1 km	0.5°×0.5°×1 km	0.4°×0.4°×1 km
Geophysical model	**gravity** and **seismic** data	**seismic** data	**gravity** and **seismic** data
Geochemical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

GIGJ model: Reguzzoni et al., 2019, JGR-SE

Inputs: gravity and seismic data

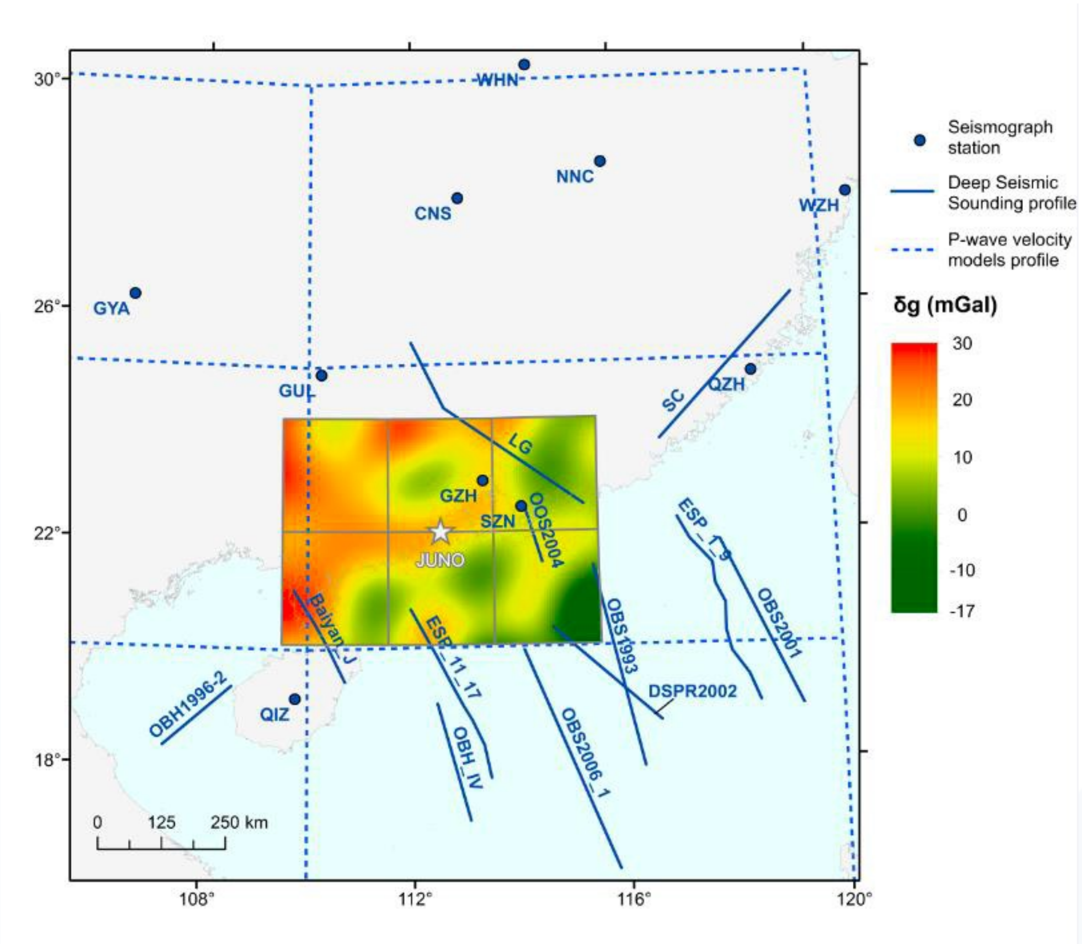


Geophysical model: crustal layers

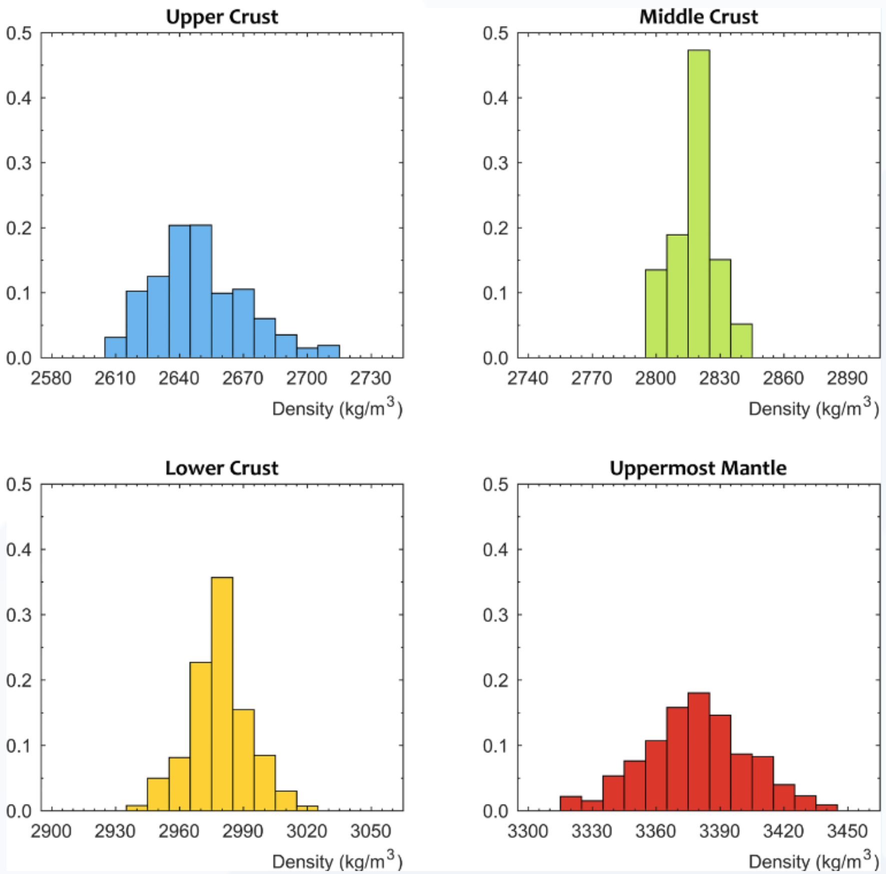


GIGJ model: Reguzzoni et al., 2019, JGR-SE

Inputs: gravity and seismic data

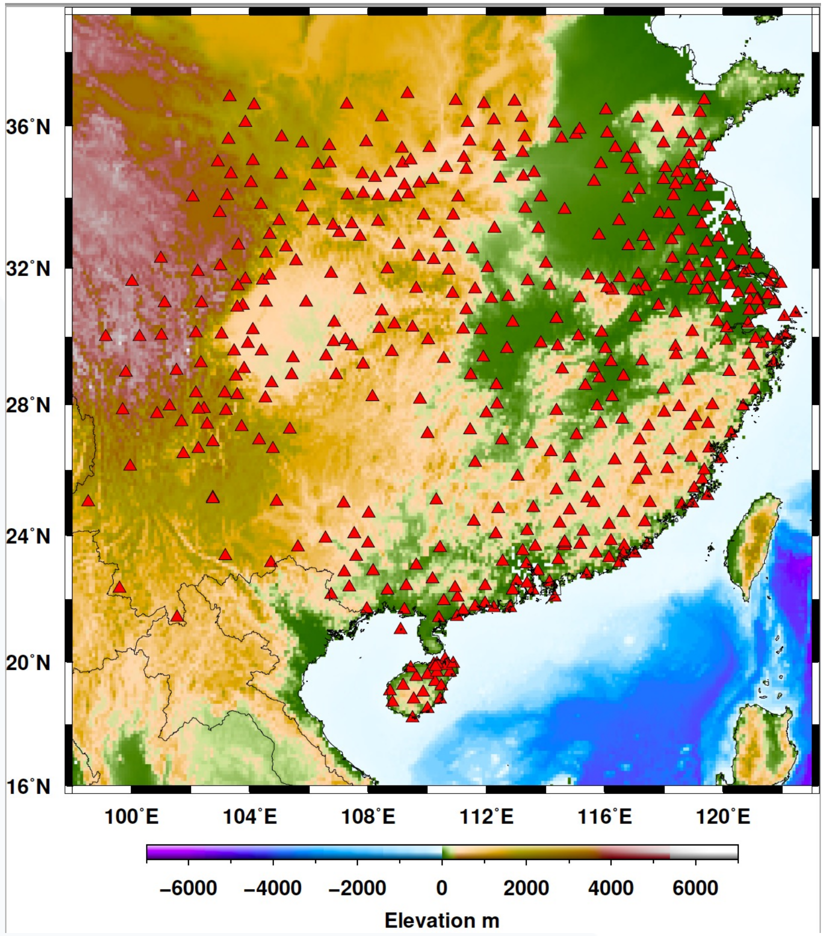


Geophysical model: density

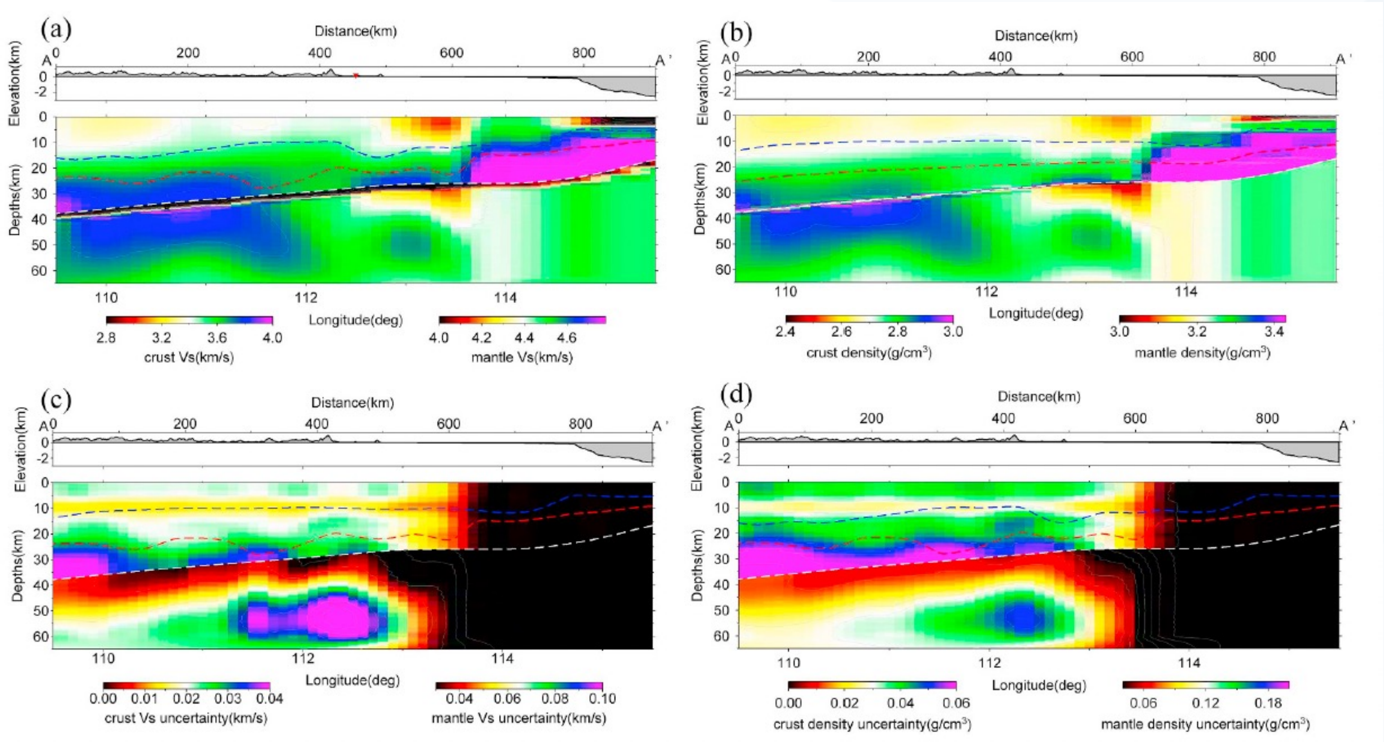


JULOC model: Gao et al., 2020, PEPI

Geophysical inputs: seismic data

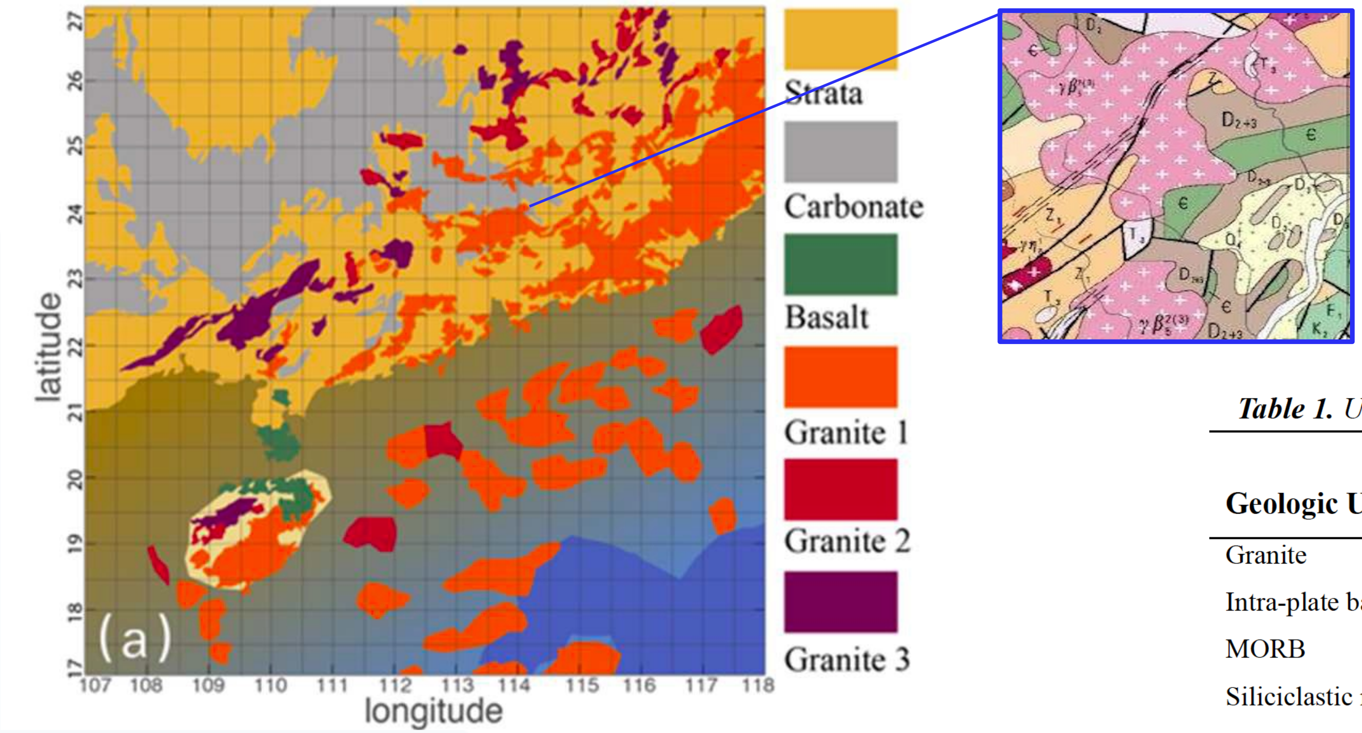


Geophysical model



JULOC model: Gao et al., 2020, PEPI

Geochemical inputs: geological map, rock sample data **(~2000)**



Abundance of each voxel =

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

i: rock type

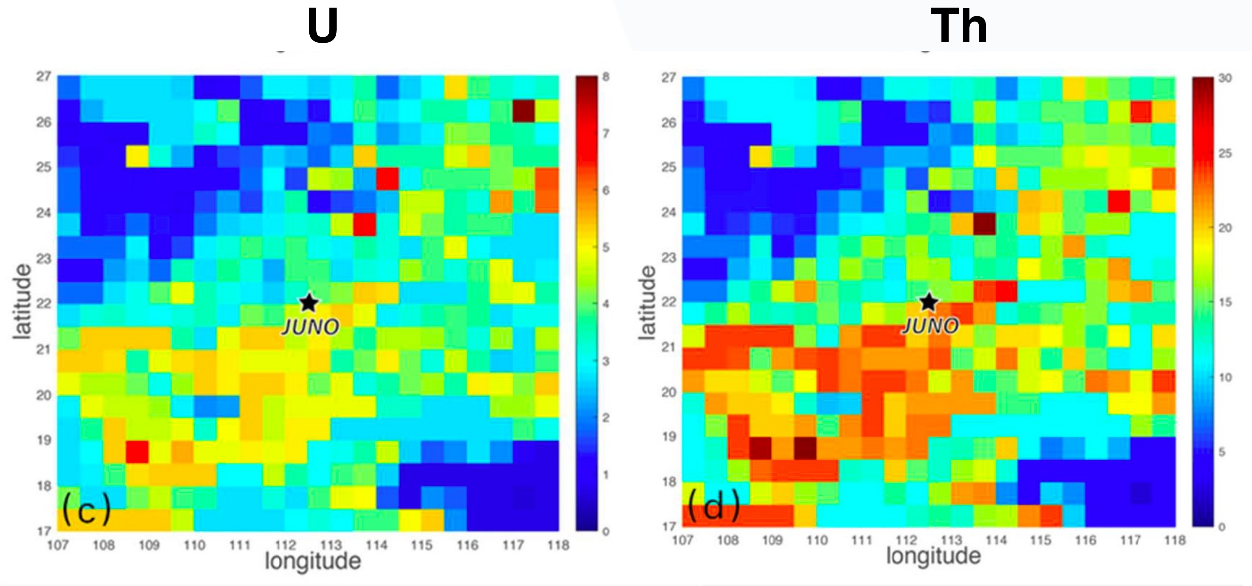
Table 1. *U and Th abundances in geologic units in the regional crust in the 3-D model.*

		1-sigma				1-sigma		
Geologic Unit	**U mean**	**+**	**-**	**N**	**Th mean**	**+**	**-**	**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, PEPI

Geochemical model:

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

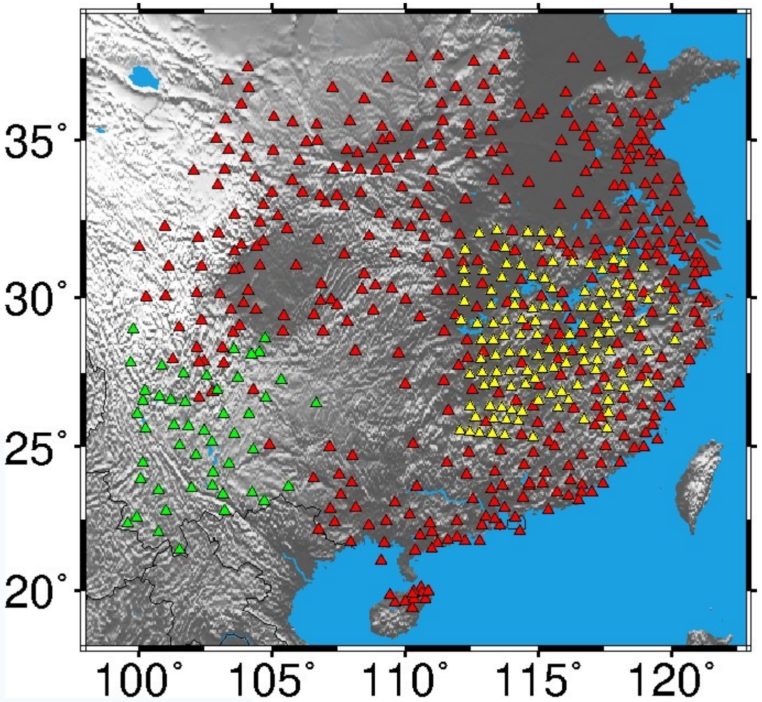


		1-sigma				1-sigma		
Geologic Unit	**U mean**	**+**	**-**	**N**	**Th mean**	**+**	**-**	**n**
Upper crust basement	3.0	2.1	1.2	57	15.4	10.7	6.3	57
Middle crust	0.6	0.4	0.4	10	1.9	1.4	1.4	10
Lower crust	0.04	0.08	0.03	55	0.1	0.3	0.08	55

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

陆区地物模型

Data source

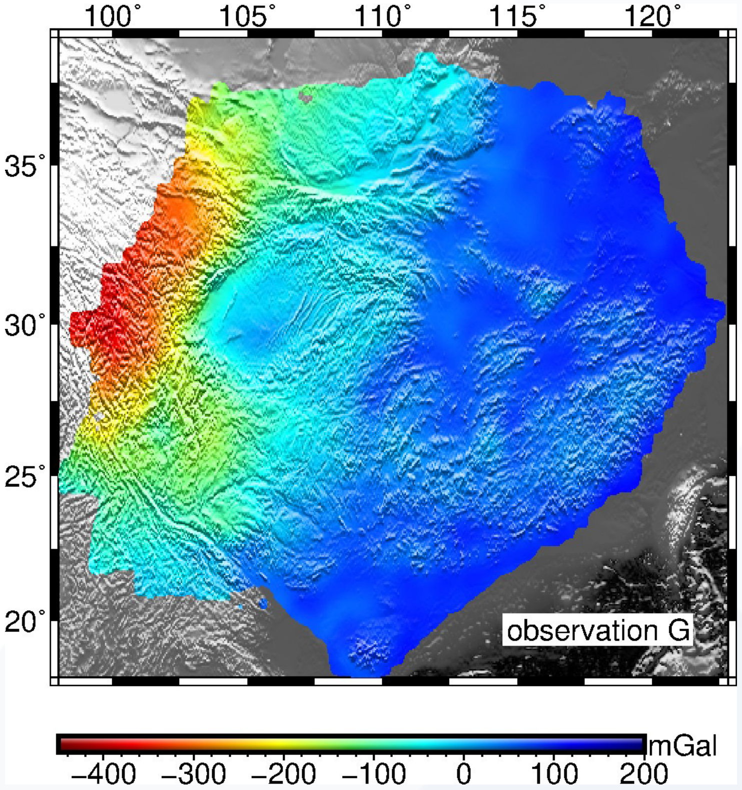


39 broadband seismometer

131 mobile seismometer

421 broadband seismometer from the China National Seismic Network

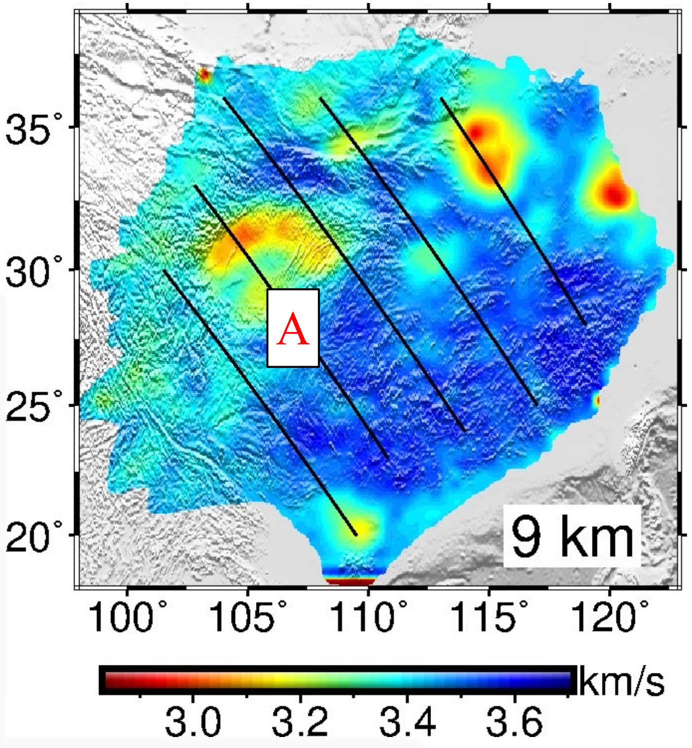
Geophysical model from joint inversion

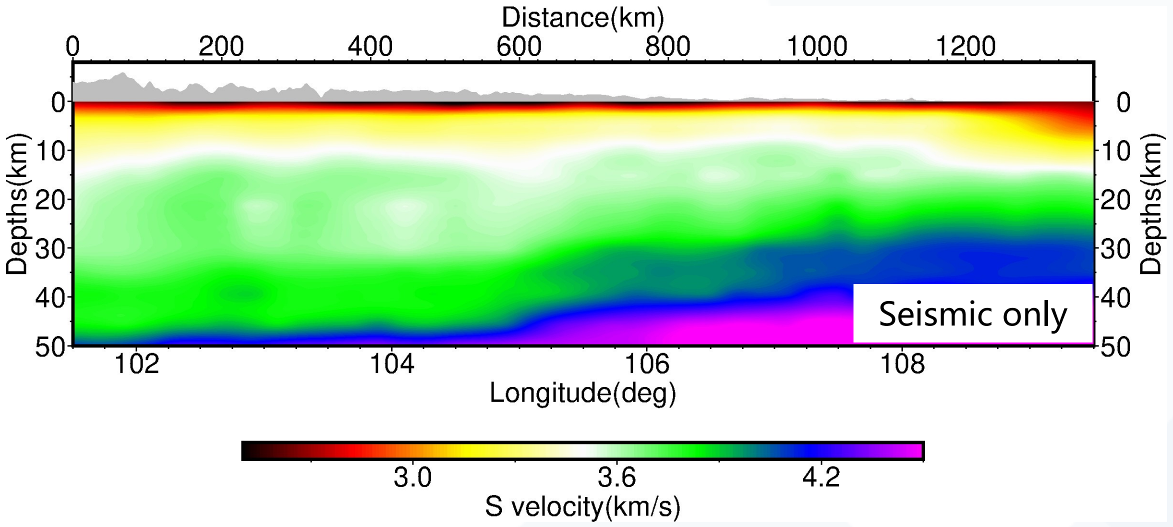


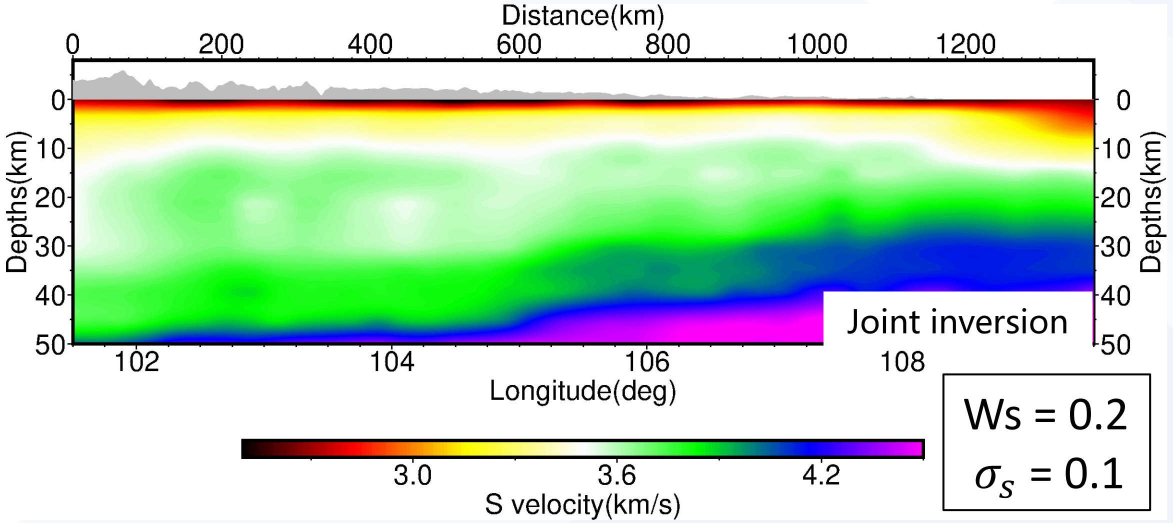
WGM2012
Global satellite Bouguer gravity anomaly data

陆区地物模型

Comparison of Vs at vertical slice







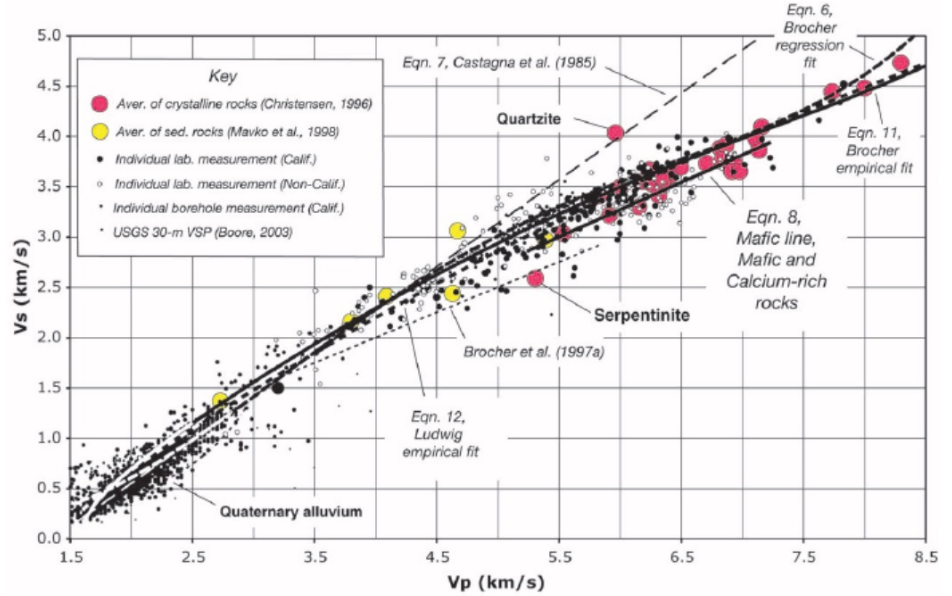
Ws = 0.2
σ_s = 0.1

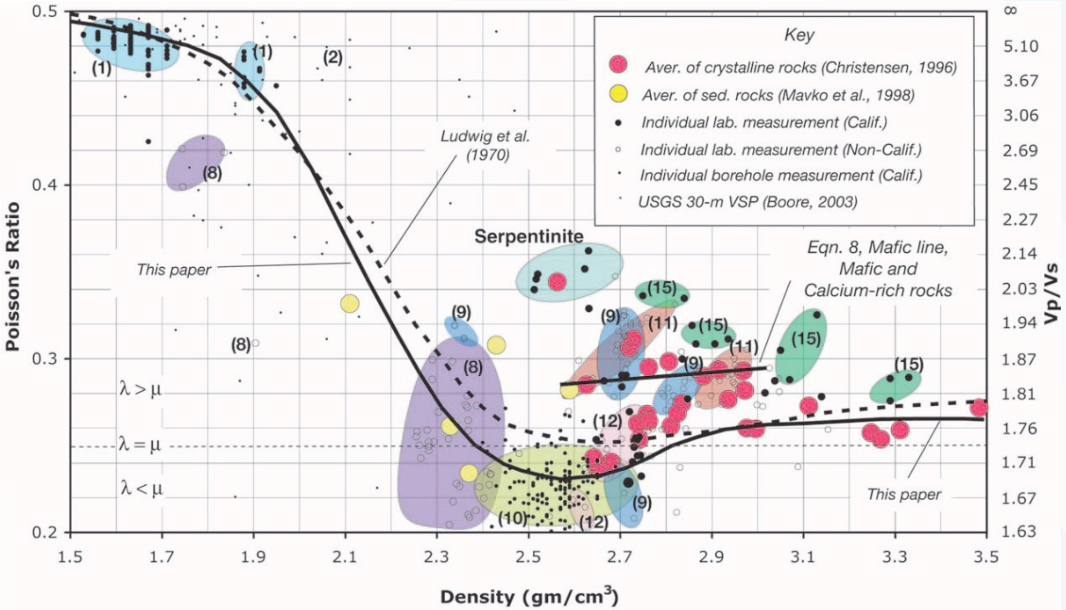
陆区地物模型

Empirical relations between the seismic velocity and density

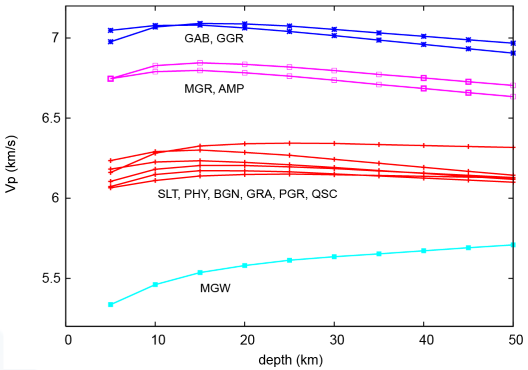
$$V_p(\text{km/sec}) = 0.9409 + 2.0947V_s - 0.8206V_s^2 + 0.2683V_s^3 - 0.0251V_s^4.$$

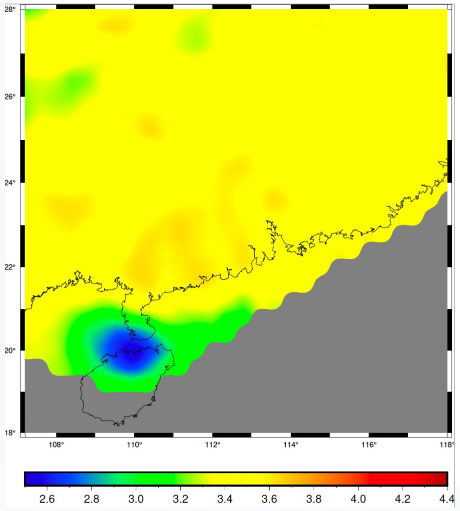
$$\rho(\text{g/cm}^3) = 1.6612V_p - 0.4721V_p^2 + 0.0671V_p^3 - 0.0043V_p^4 + 0.000106V_p^5.$$





陆区地化模型: Sun et al., 2022, JGR-SE





Constraints from crustal Vp

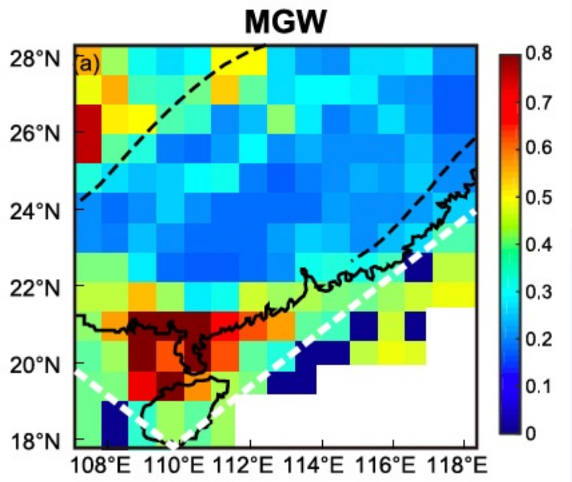
Prior probability

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

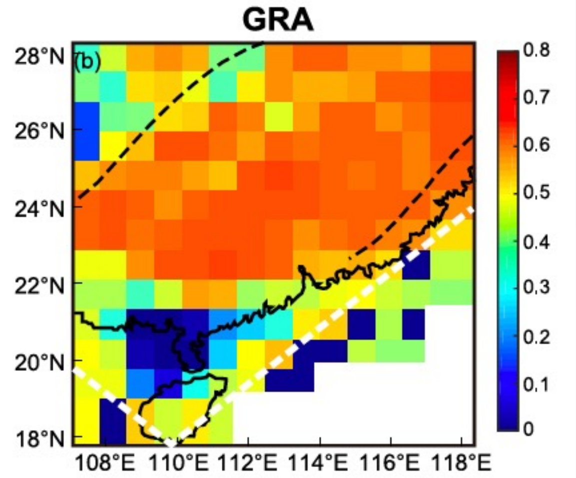
Posterior probability

Constraints from crustal Vp

3km



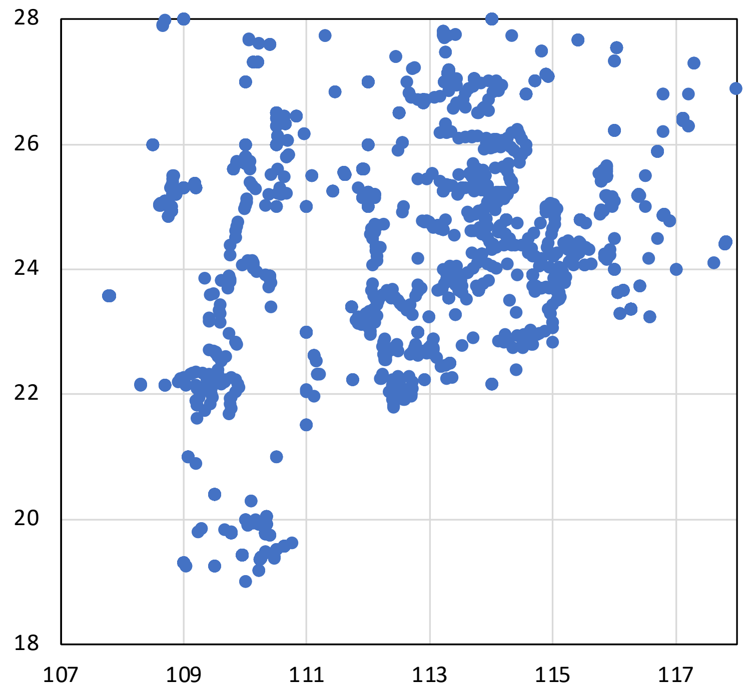
3km



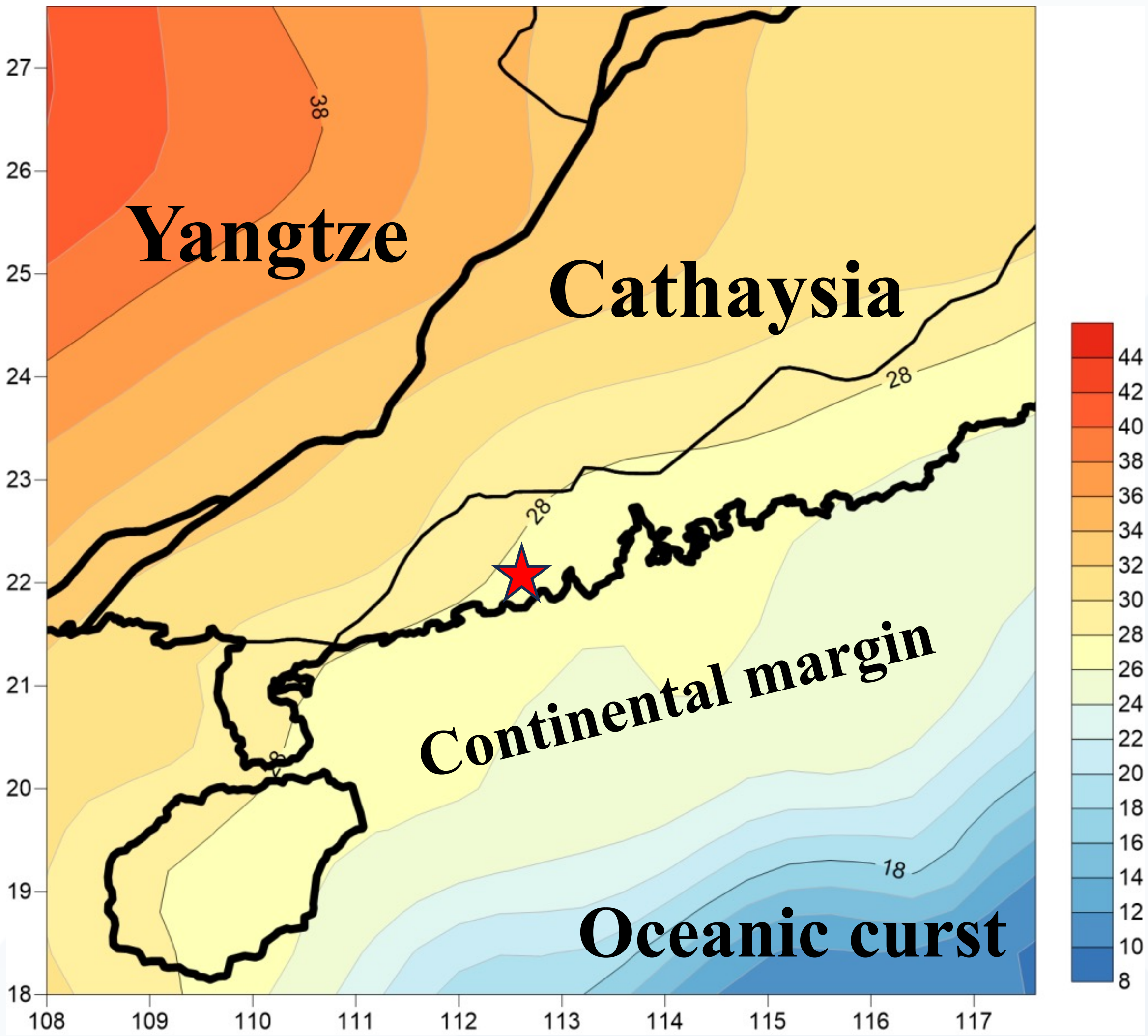
- 利用贝叶斯公式和波速的限制，计算出了每个网格里不同岩石类型的占比。

陆区地化模型

Rock U-Th abundance

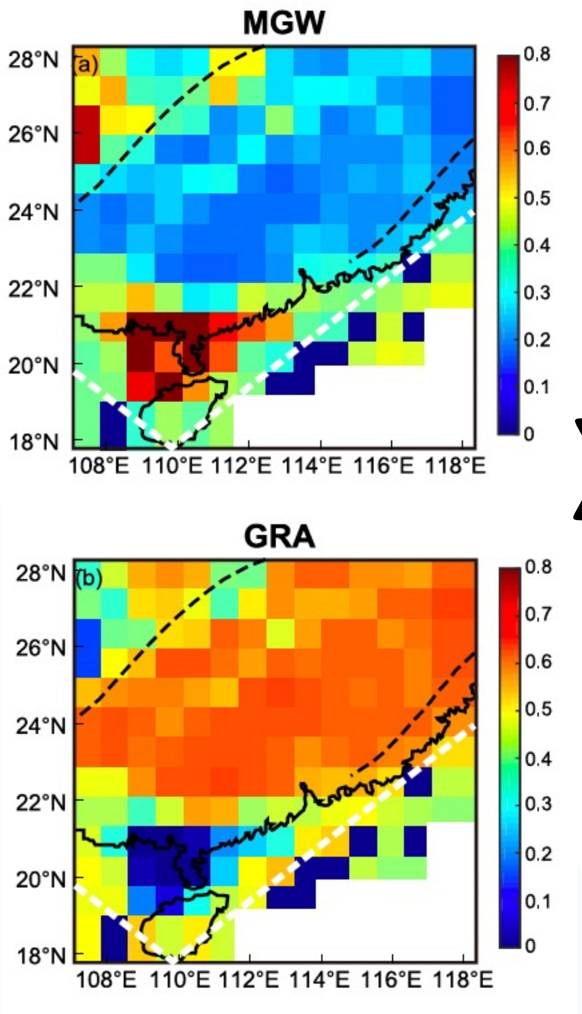


U and Th abundance data: rock sample data collected from literature and measured in lab.

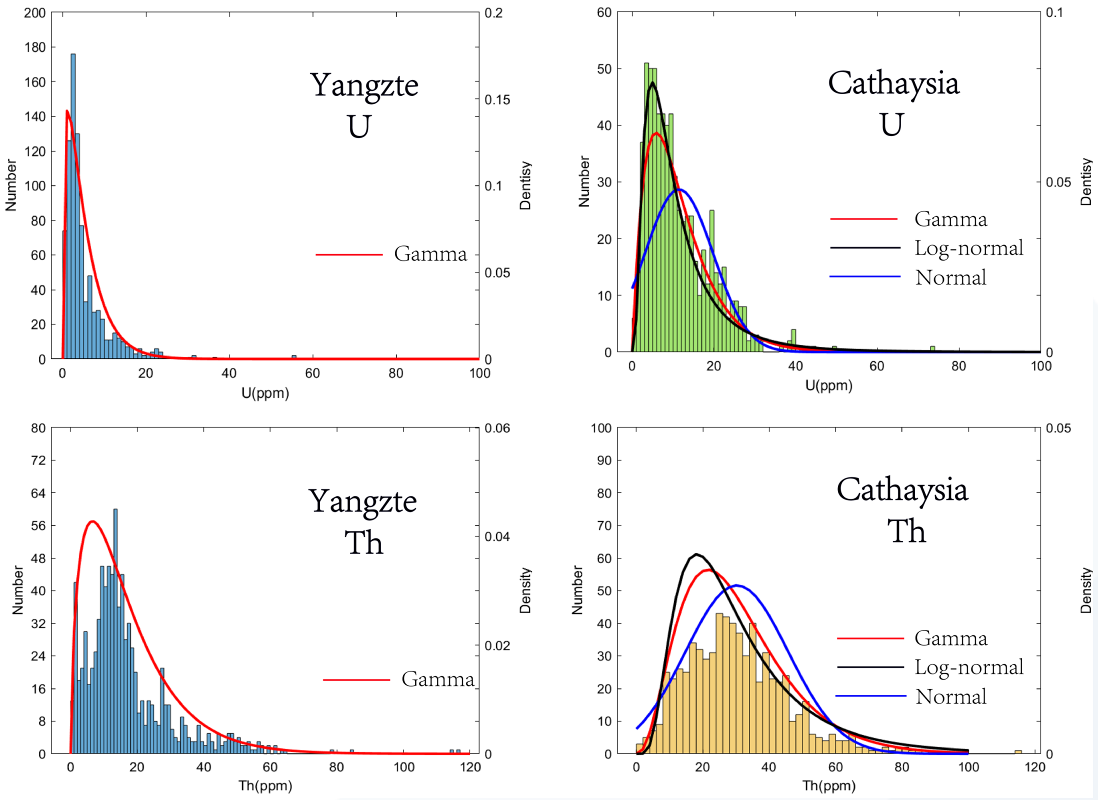


陆区地化模型

Abundance of each voxel $= \sum_{i=1}^{n} Proportion\%(i) * Abundance(i)$



X



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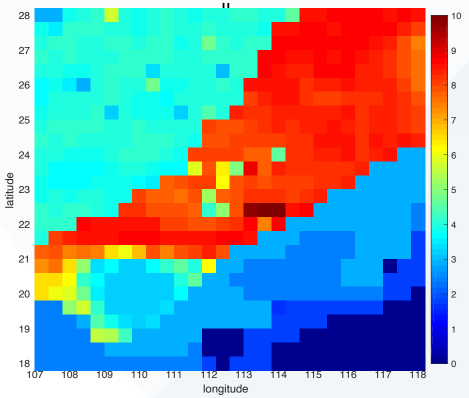
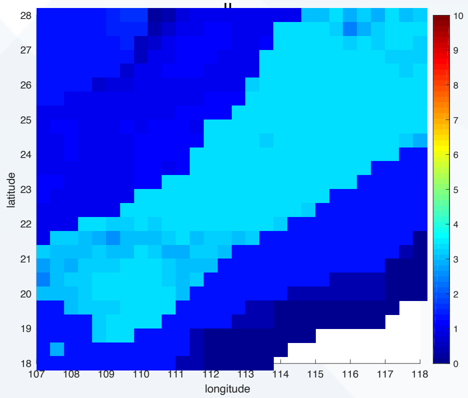
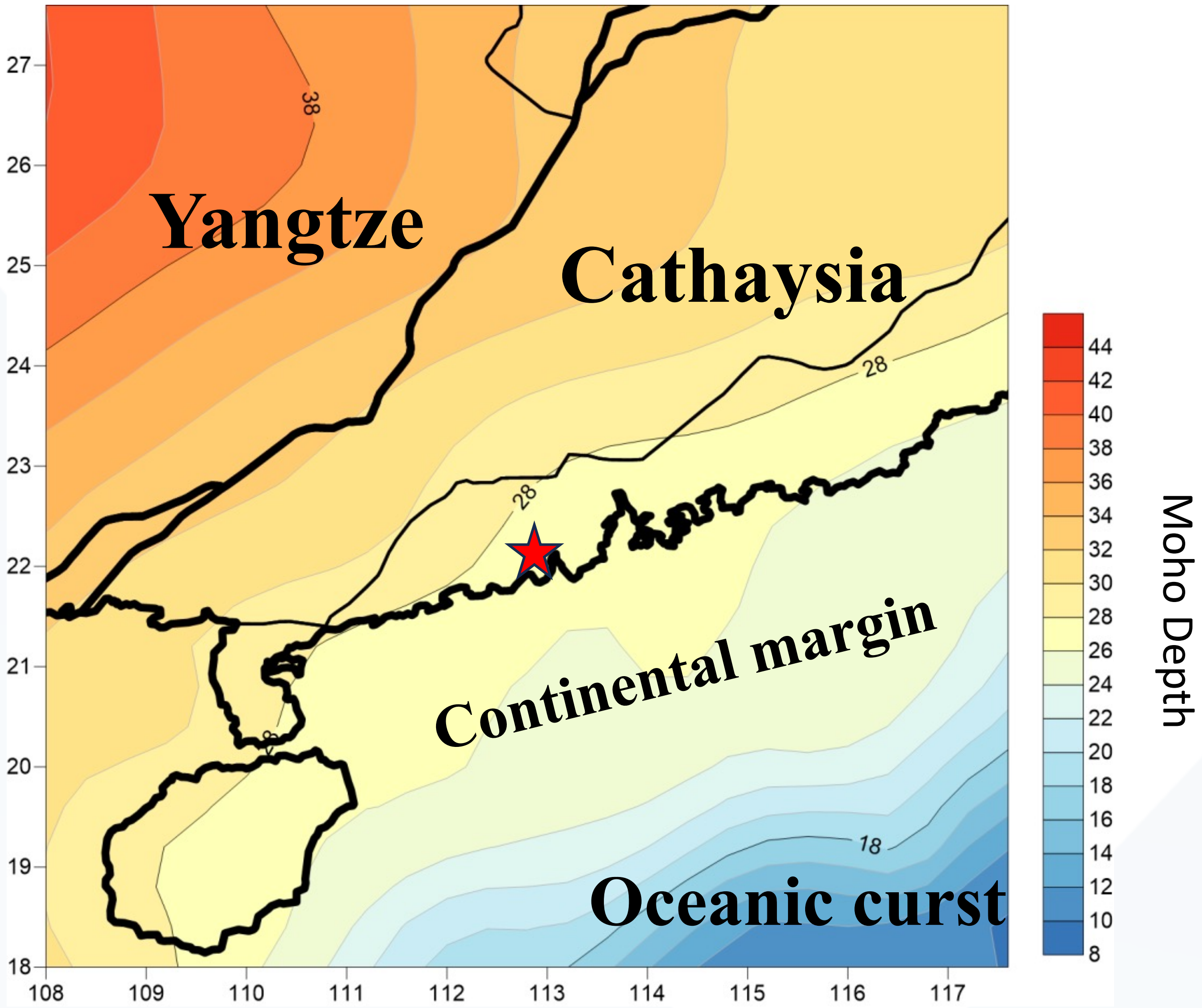
3 km



15 km



过渡带和洋壳简化模型



Geophyical model: Crust 1.0

Geochemical model

过渡带

	U	Th
沉积层	2.38±0.15	9.50±0.59
上地壳	2.99±0.62	11.96±2.49
中地壳	1.25±0.5	4.98±2
下地壳	0.42±0.15	1.67±0.59

洋壳

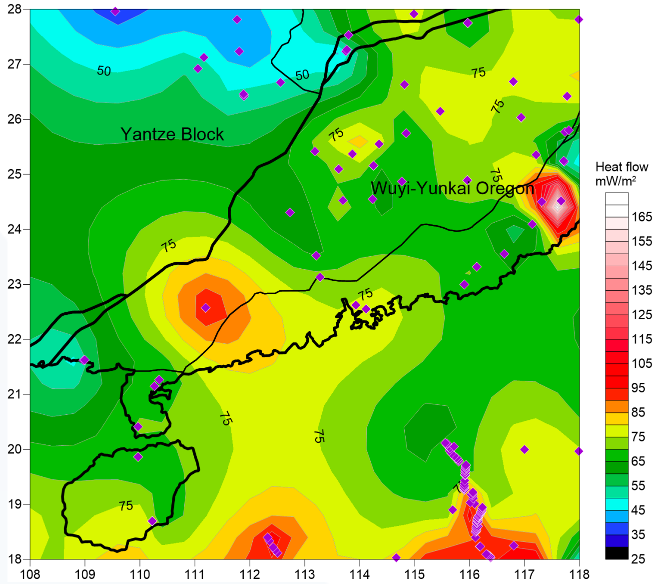
	a(U) [μg/g]	*a*(Th) [μg/g]
Sed	1.73 ± 0.09	8.10 ± 0.59
OC	0.07 ± 0.02	0.21 ± 0.06

地表热流对模型的检验

Surface heat flow map

Crustal heat production

Mantle flux



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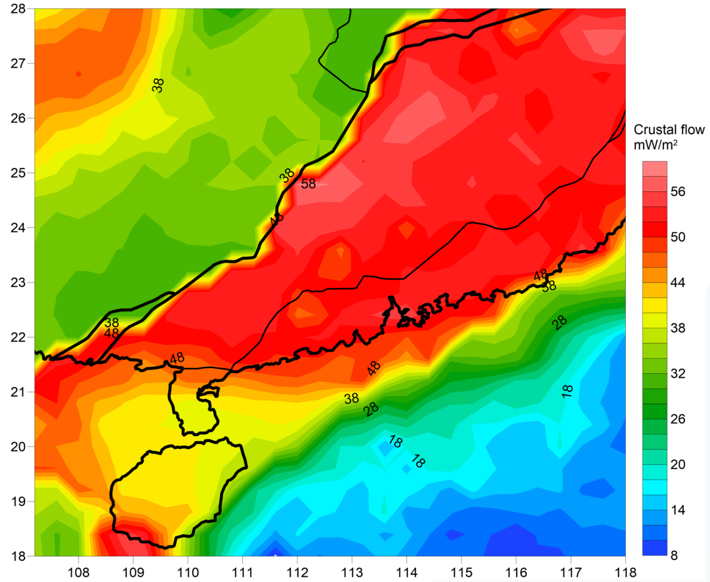

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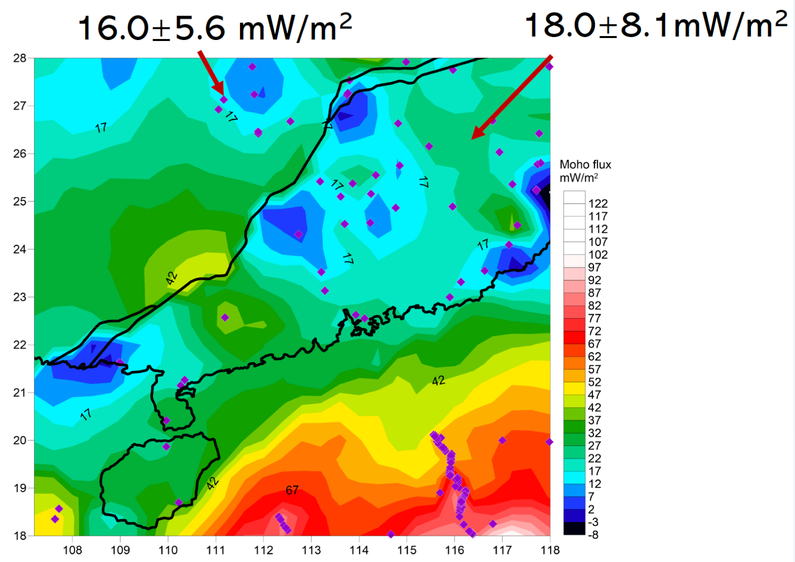

Jiang et al., 2019, Tectonophysics

Calculated based on JULOC-I model

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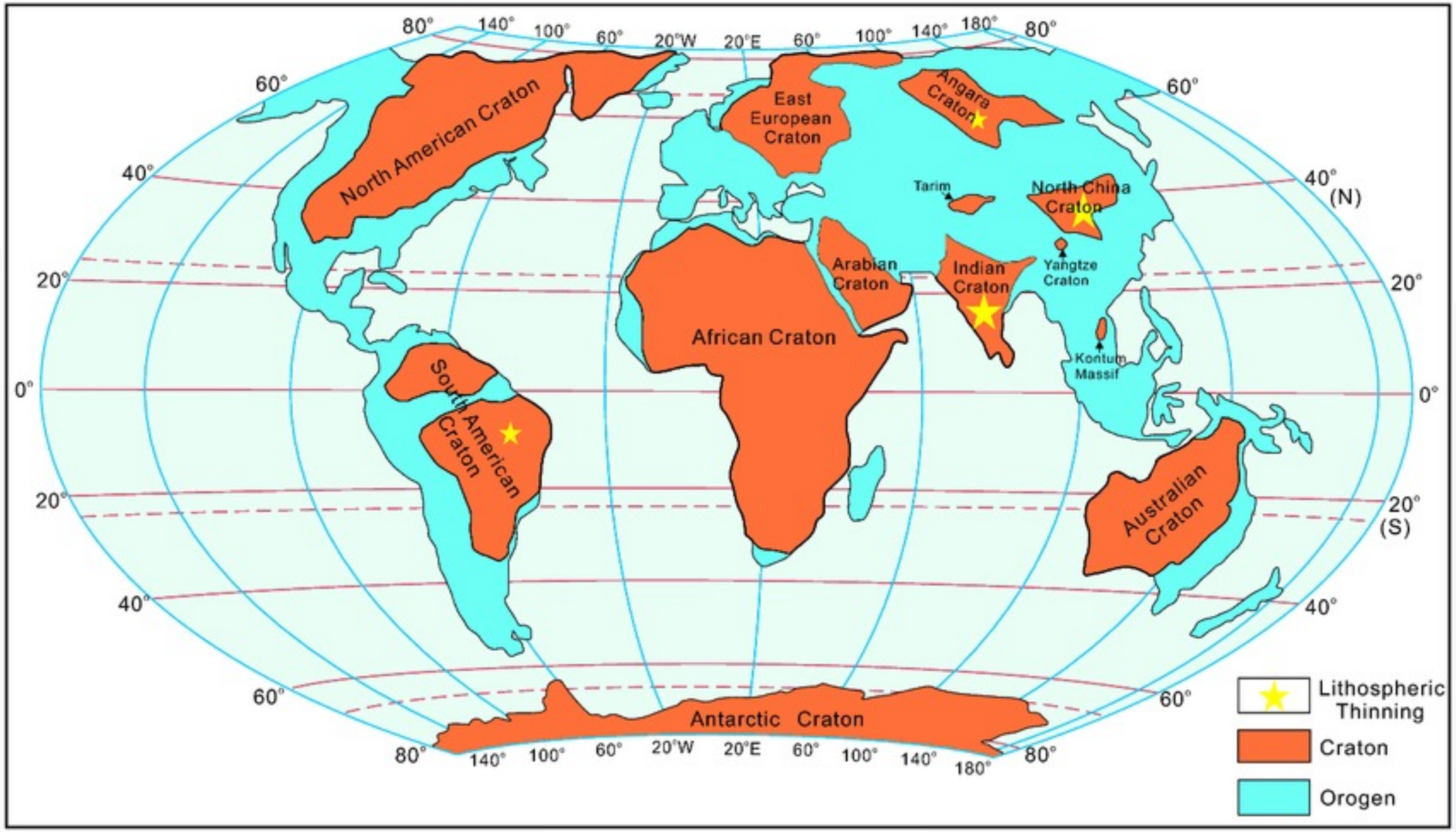
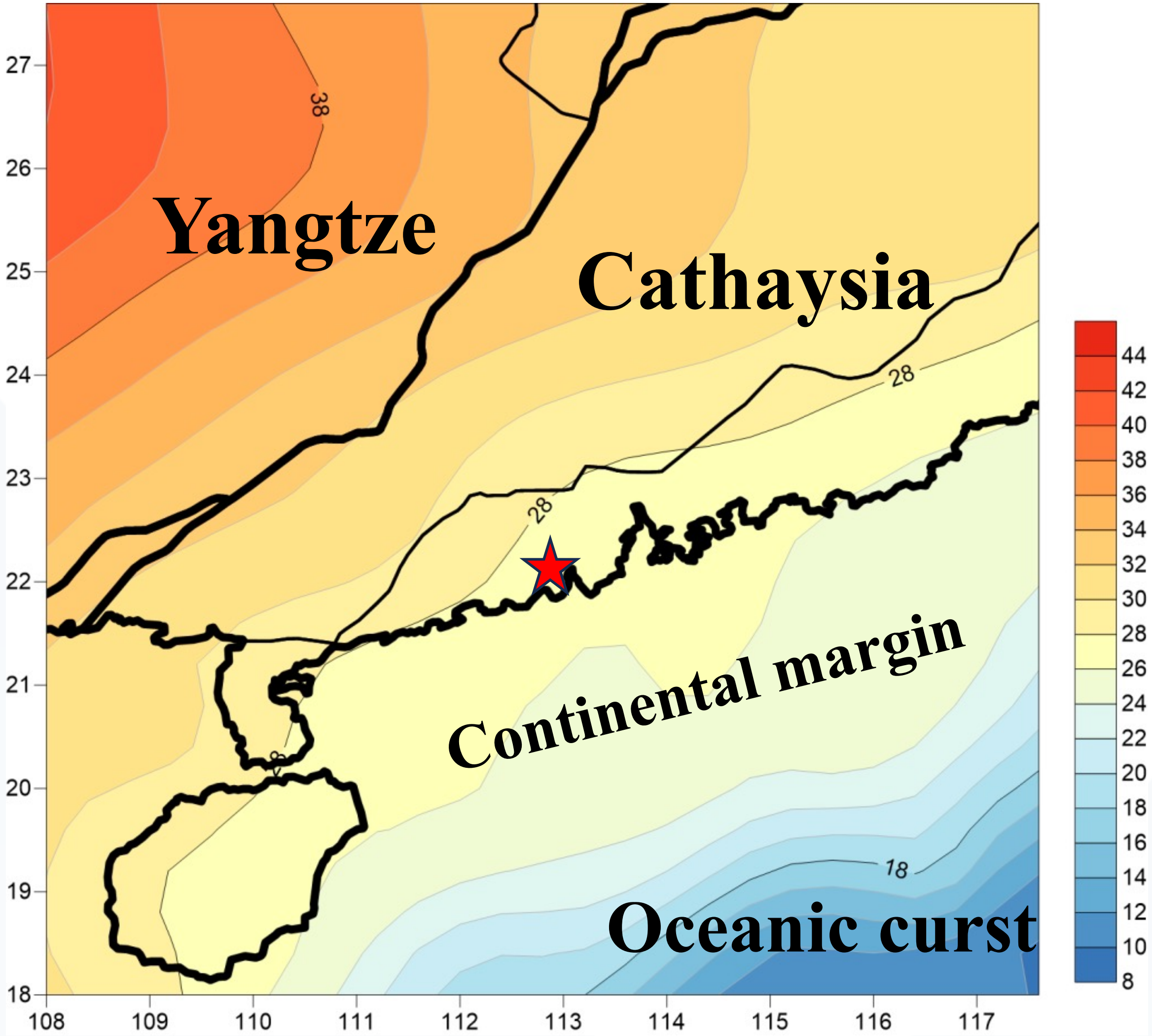
全球模型的优化



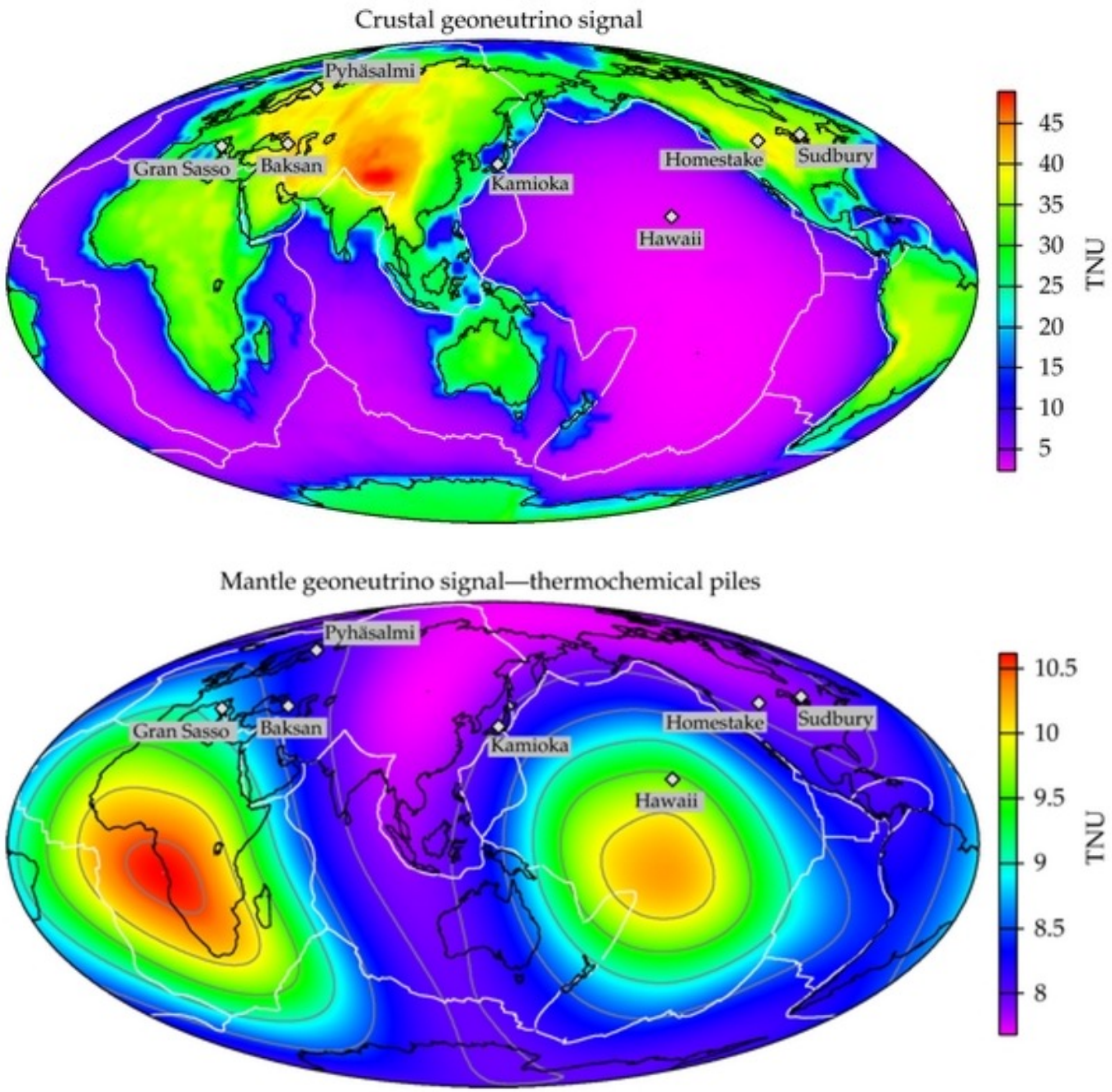
- 地球物理模型的更新
- 分区域的地球化学模型

区域模型的优化

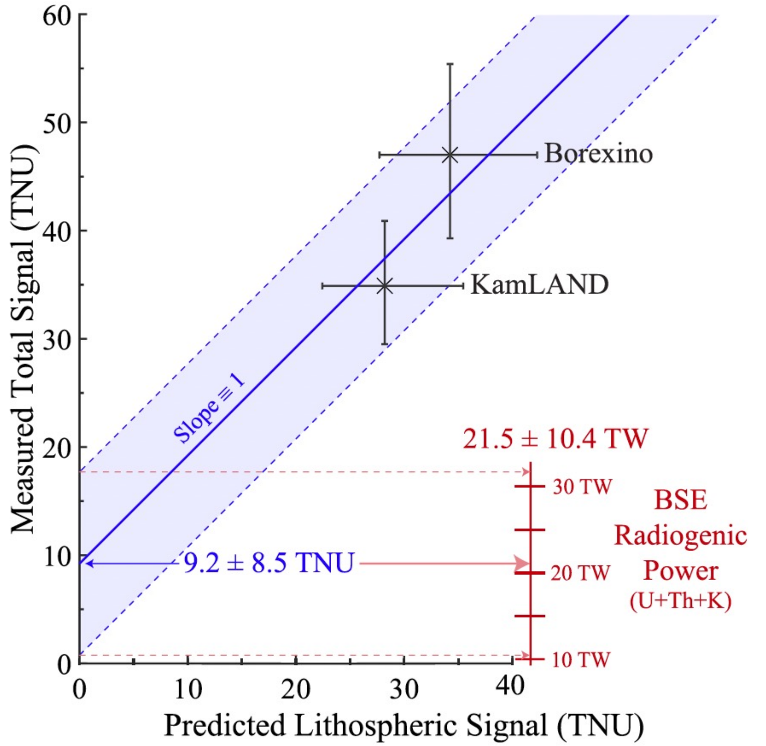


- **海区模型的建立**
- **陆区模型的优化**
  - 花岗岩（极富U、Th）延伸深度
  - 地壳岩石U、Th丰度垂向变化
  - 机器学习等新技术在数据处理和建模中的应用
  - ……

地球中微子与地壳模型研究展望



- **2024取数在即**
  - 对数据的解释
  - 学科交叉应用



Thank you!