JULOC：A local 3-D high-resolution crustal model in South China for forecasting geoneutrino measurements at JUNO

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JULOC: JUNO LOcal Crust (C also stand for Chinese Group)

2019-10-22 Prague

Outline

1. Introduction

2. Methods

3. Multi-scale crustal model in South China

   3.1 Ambient noise tomography of local crustal model

   3.2 Receiver function imaging with dense array

   3.3 Ambient noise tomography with dense array

   3.4 Ambient noise tomography of South China Sea

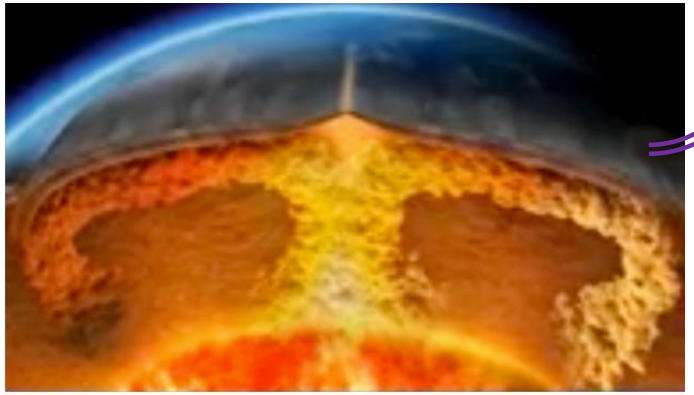
4. Summary

1. Introduction

Different compositional models of BSE individually predicted different mantle geoneutrino fluxes. The detector cannot separate the mantle contribution from the crust contribution.

To test different compositional models of the mantle, an accurate estimation of the crust geoneutrino flux based on the 3-D crust model in advance is necessary.

Bulk Silicate Earth (BSE) models

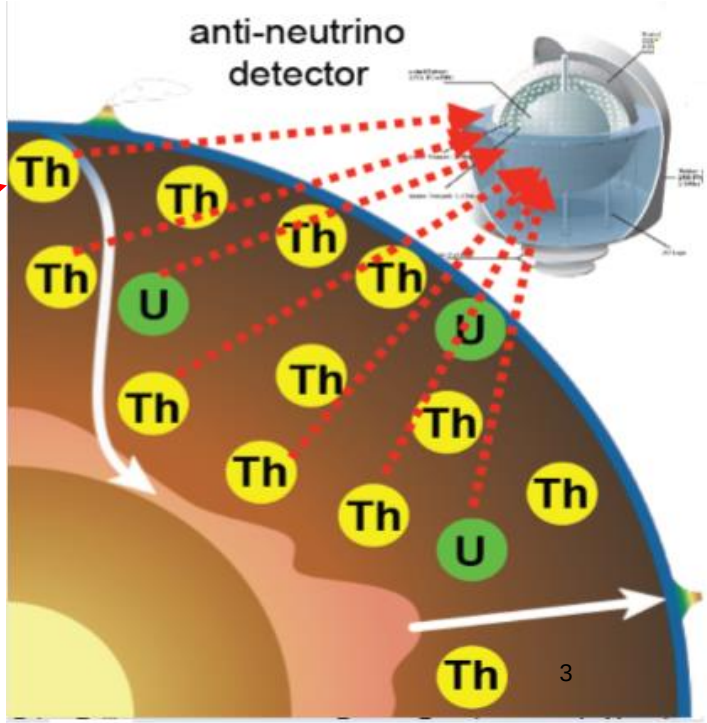


Hybrid Earth's engine

Low Q
~10TW

Middle Q
~20TW

High Q
~30TW



A local 3-D crustal Model, including layering, density and 3-D Abundance

Activity and number of produced geoneutrinos

Volume of source unit

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

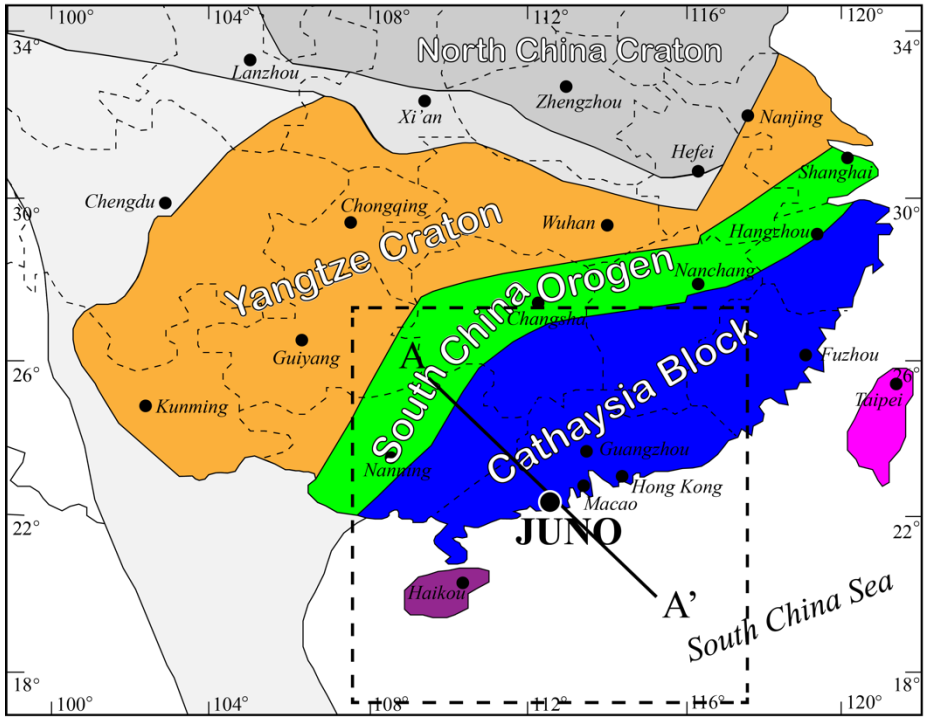
Survival probability function

Abundance and density of the source unit

Distance between source unit and detector

Earth structure (ρ and L) and **chemical composition** (a)

Study Area

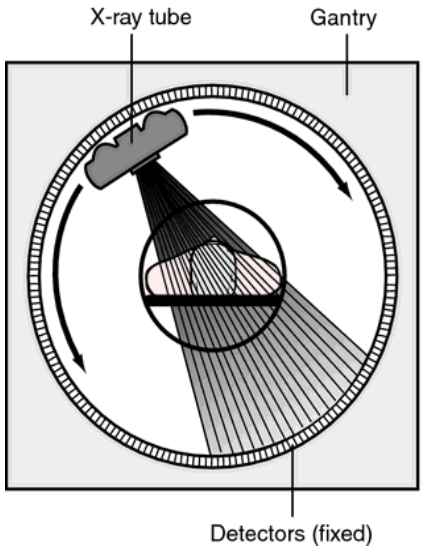


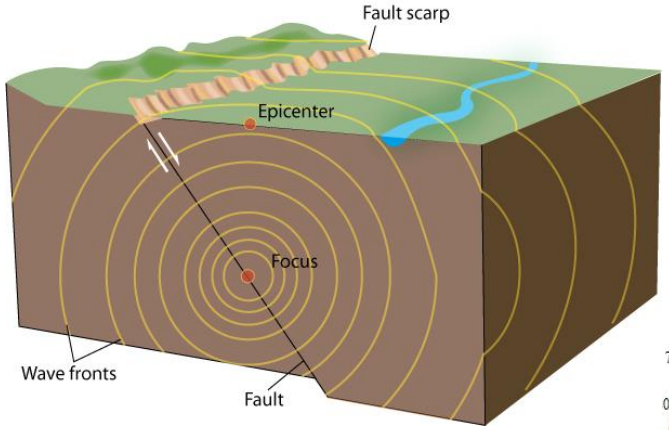
- JUNO is located at continental margin, geologically complex.
- The Cathaysia and Yangtze Blocks.
- Crust thickness varies between ~7-40 km, decreases southward, from about 30 km along the coast to 7-8 km in the central basin

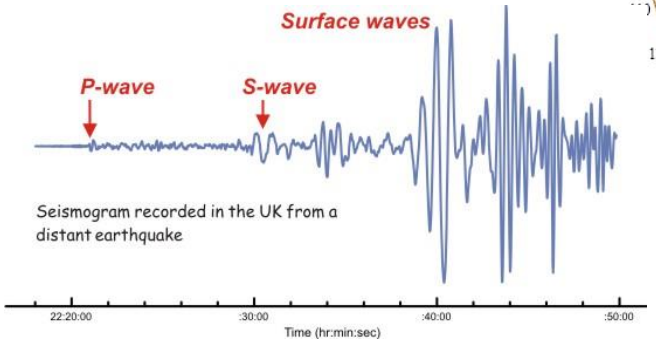
JUNO: ~22ºN, 112.5ºE 17-27ºN, 107.5-117.5ºE (10ºx10º)

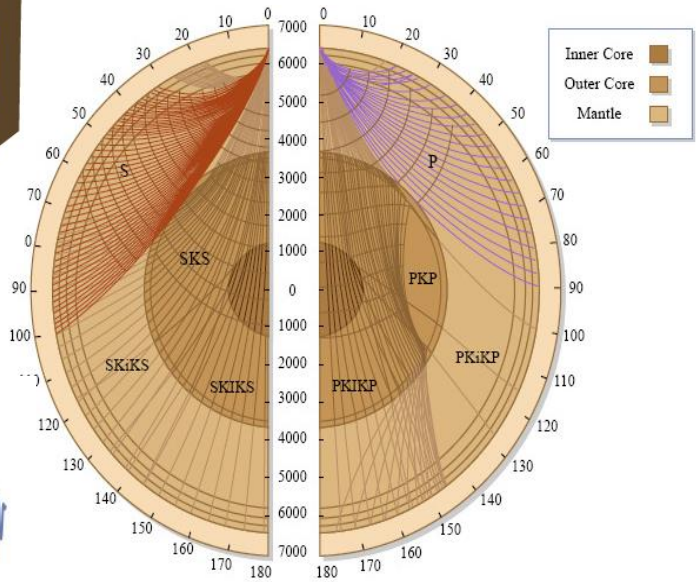
2. Methods

Seismic method is the most effective method to image the 3-D structure of the Earth



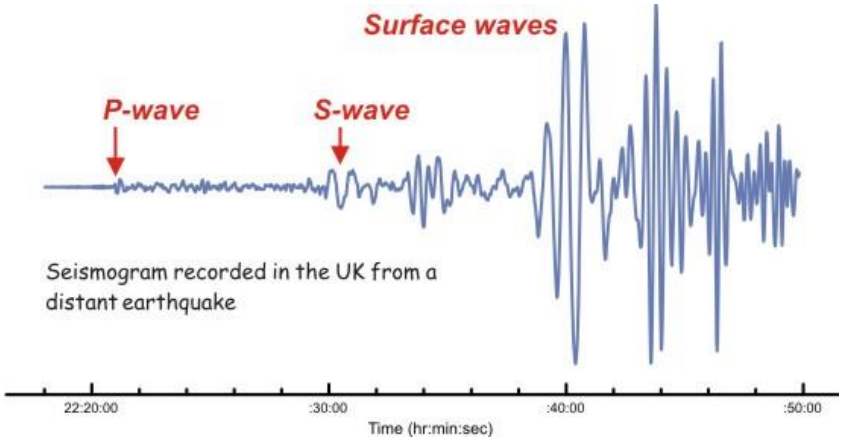


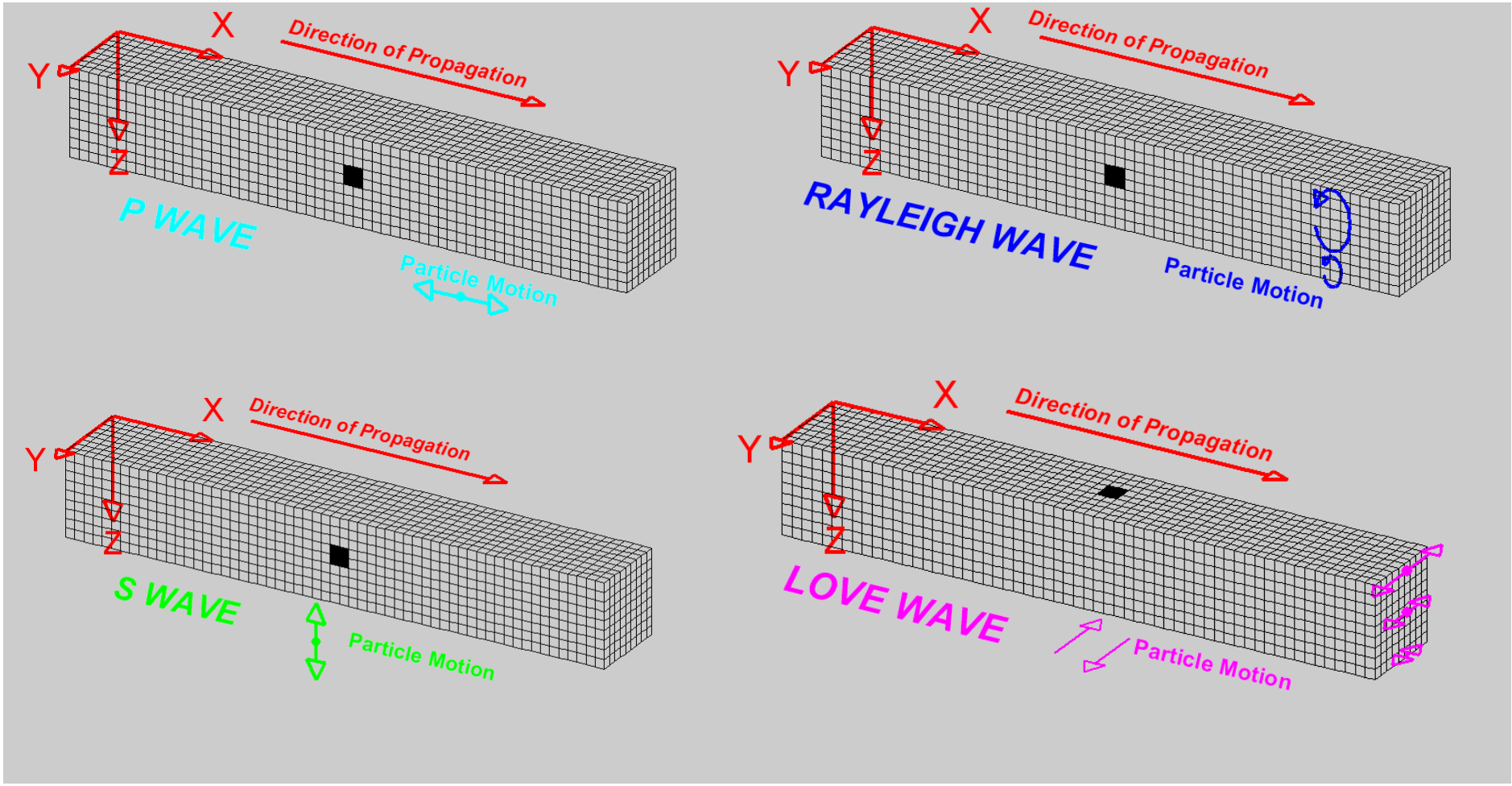




Seismic tomography of the Earth

Seismic body wave and surface wave can be used to imaging the 3-D structures of the Earth.





Seismic methods for imaging crustal structures

1) Seismic refraction/reflection profile (layering, Vp)

2) Earthquake traveltime tomography (Vp, Vs)

3) Ambient noise surface wave tomography (Vs)

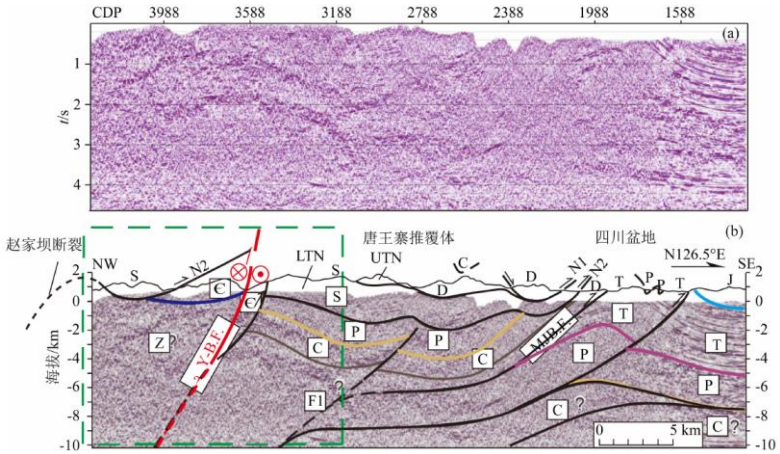
4) Ambient noise tomography with dense array (Vs to 5 km depth)

5) Receiver function imaging with dense array (Vs and Moho)

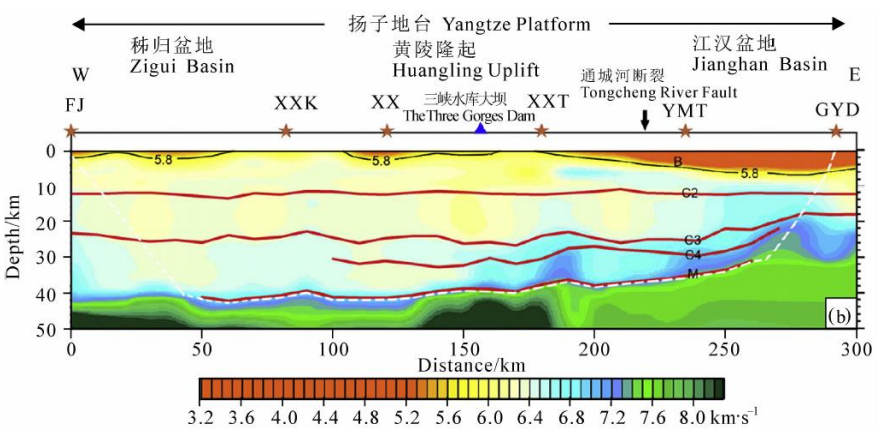
1) Seismic refraction/reflection profile (layering, Vp)

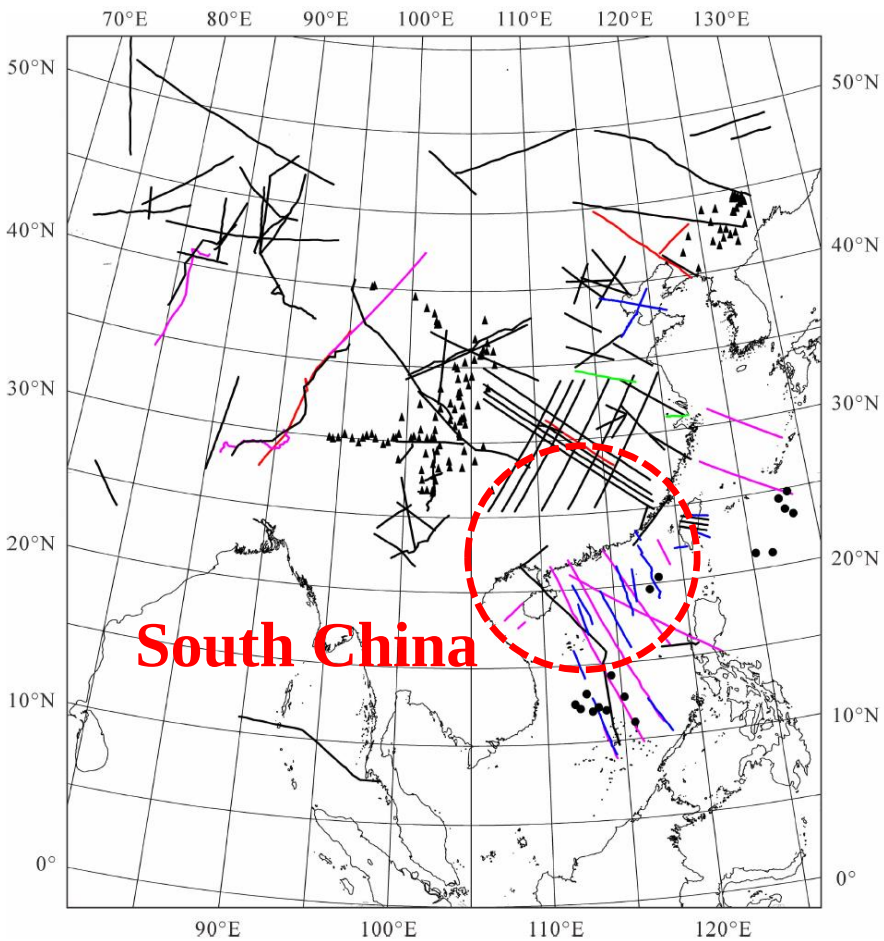
highest resolution, but very expensive, TNT explosion/vibrator are needed.

No more new seismic reflection profiles in South China.



Yu et al 2018



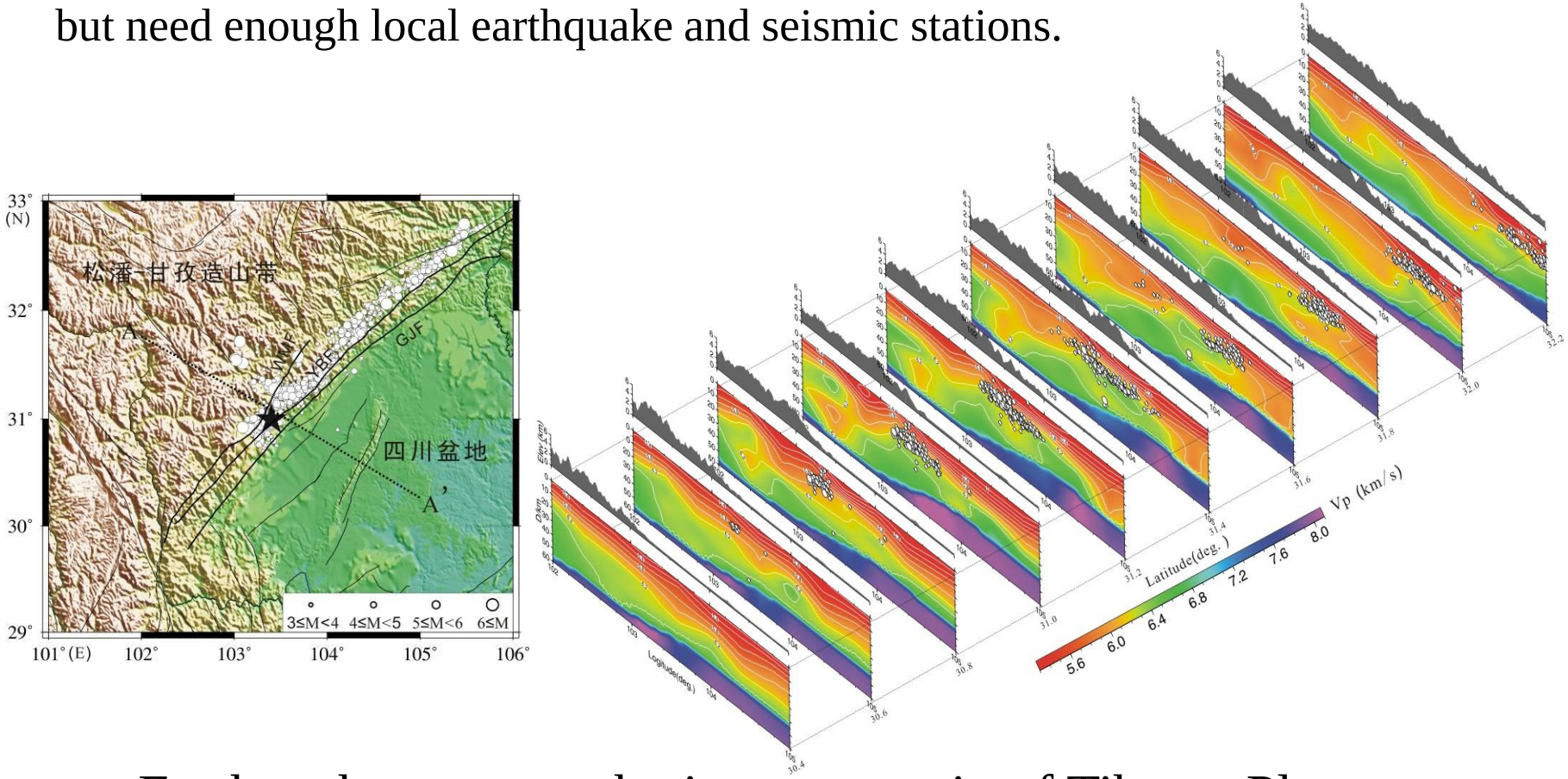


Hao et al 2014

2) Earthquake traveltime tomography (Vp, Vs)

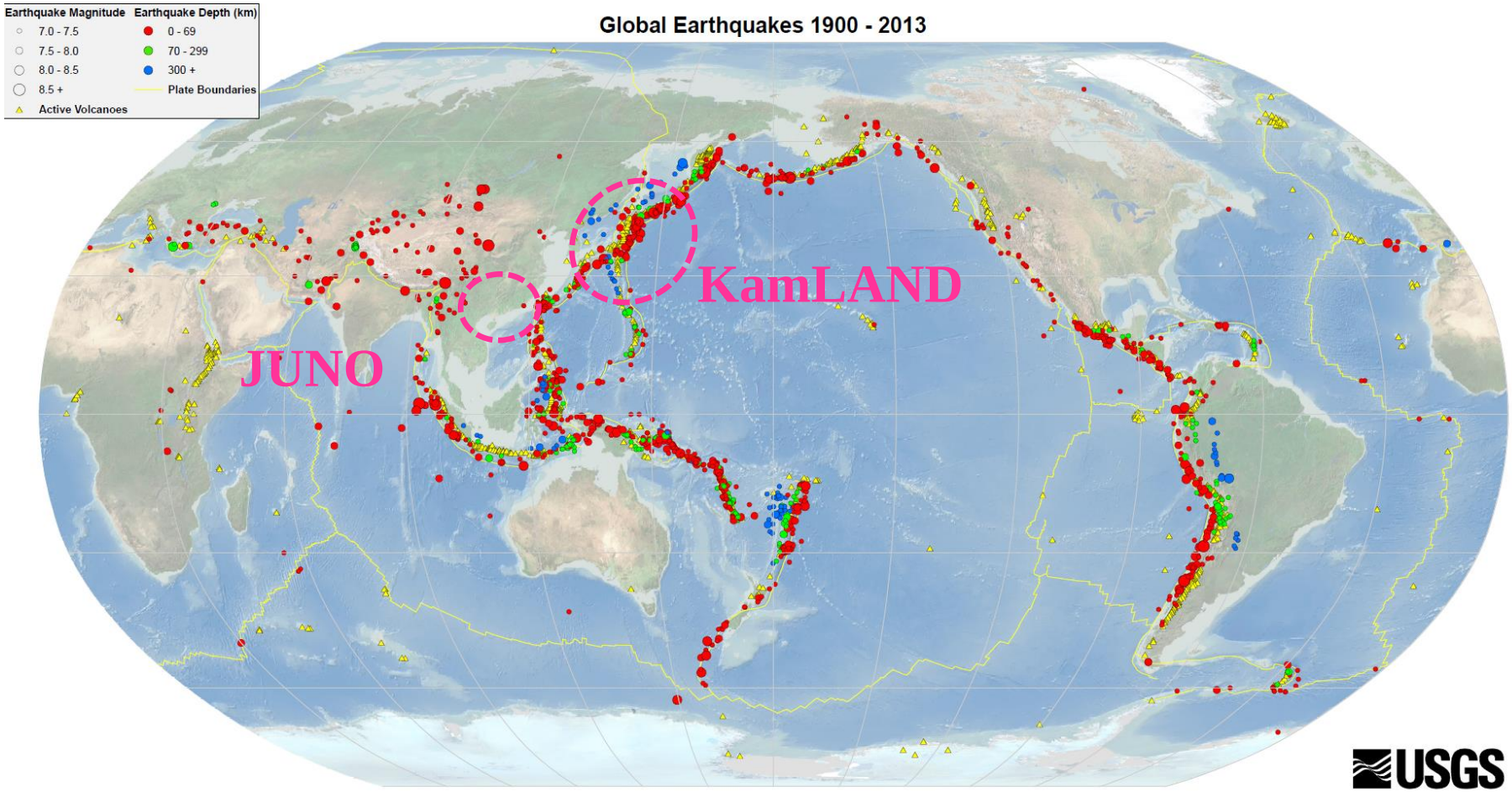
Low-cost, high-resolution seismic imaging method, both Vp and Vs structures can be obtained.

but need enough local earthquake and seismic stations.



Earthquake tomography in east margin of Tibetan Plateau

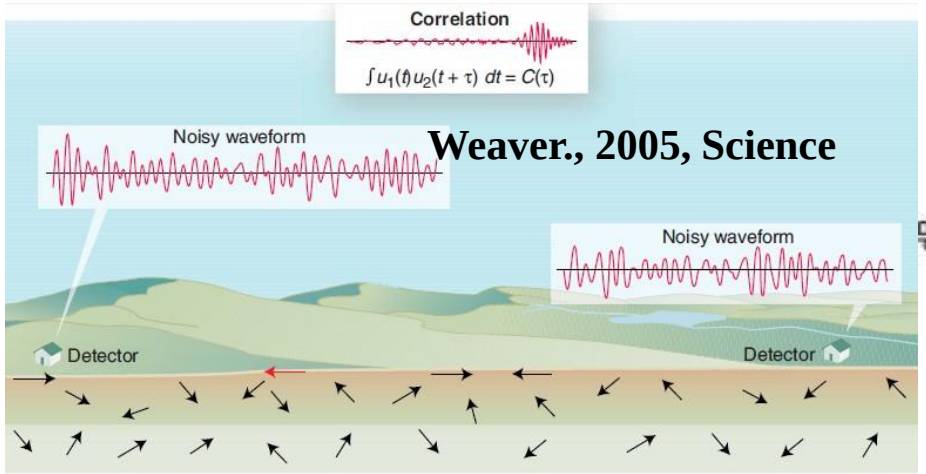
In south China, no enough local earthquakes or regional earthquake in surrounding areas for earthquake tomography



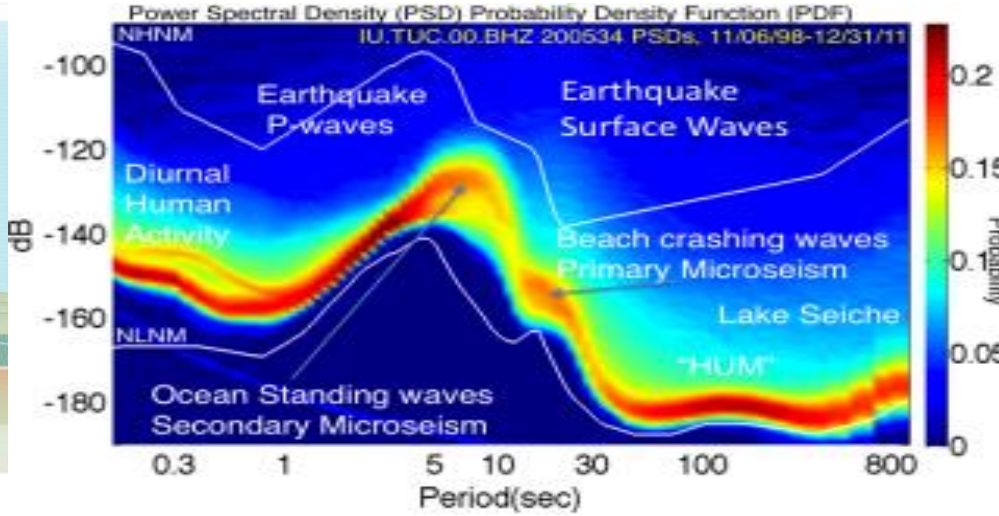
M>7 Earthquake distribution in the last 100 years

3) Seismic ambient noise tomography (Vs)

Seismic surface waves can be obtained with seismic ambient noise data, expecting high-resolution 3-D crustal model beneath seismic array.

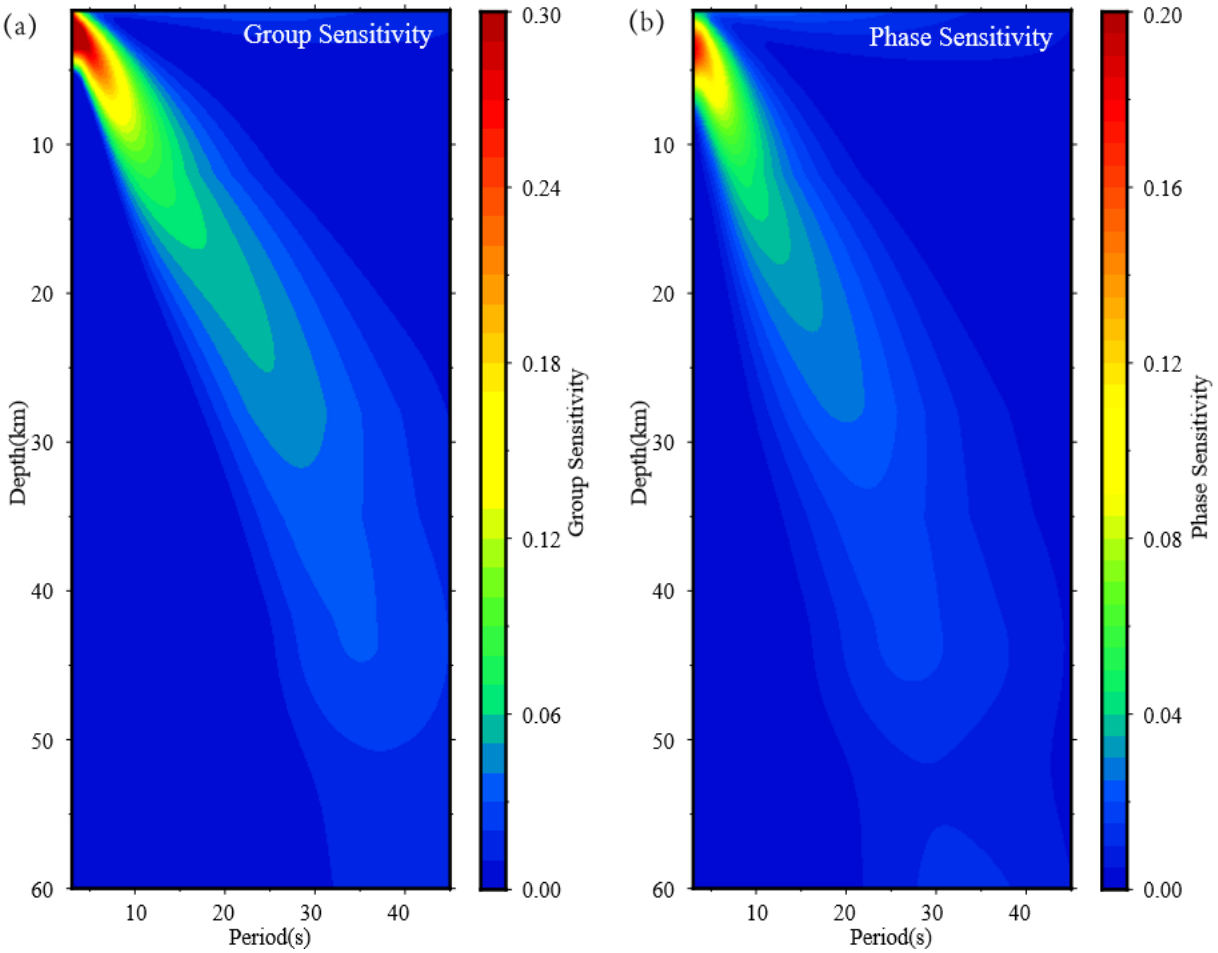


Weaver., 2005, Science



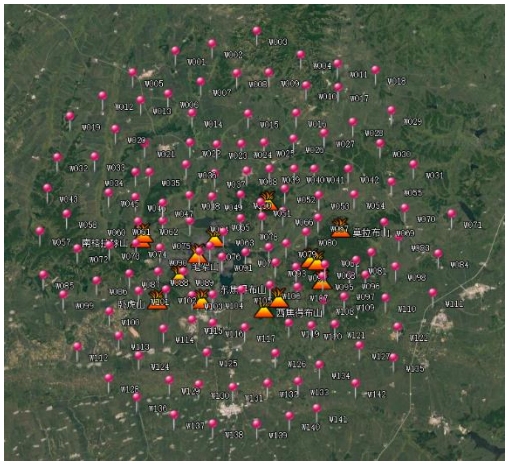
Sensitivity kernel of surface waves to the crustal structures

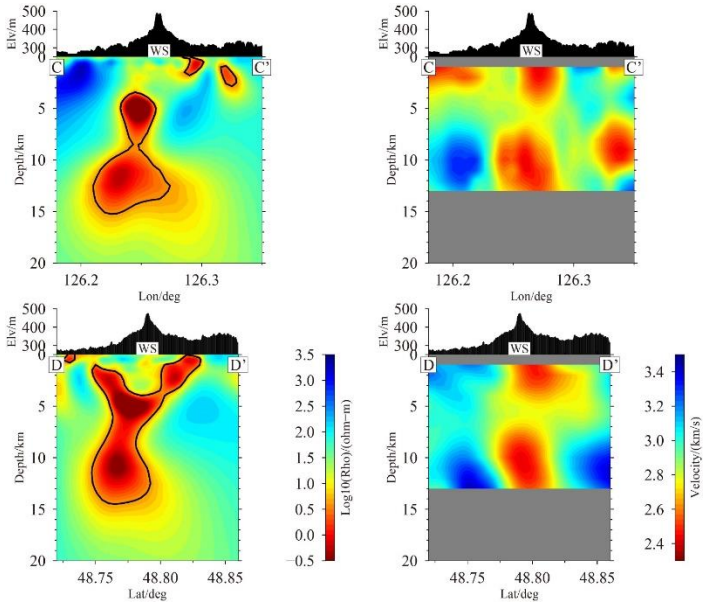
4~ 45 sec surface waves have good constraints of Vs down to ~ 50 km.



4) Ambient noise tomography with dense array (Vs to 5 km depth)

With dense seismic array (~ a few km interstation distance), short period surface waves can be extracted from ambient noise. Shallow Vs down to ~ 5 km depth can be imaged.



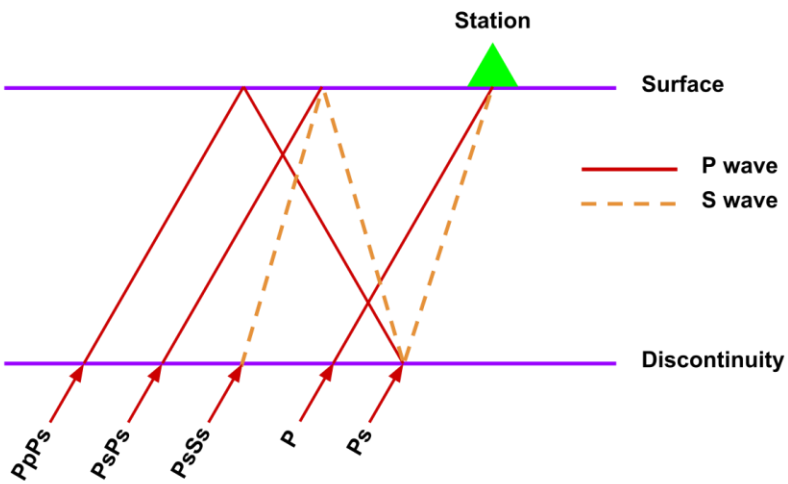


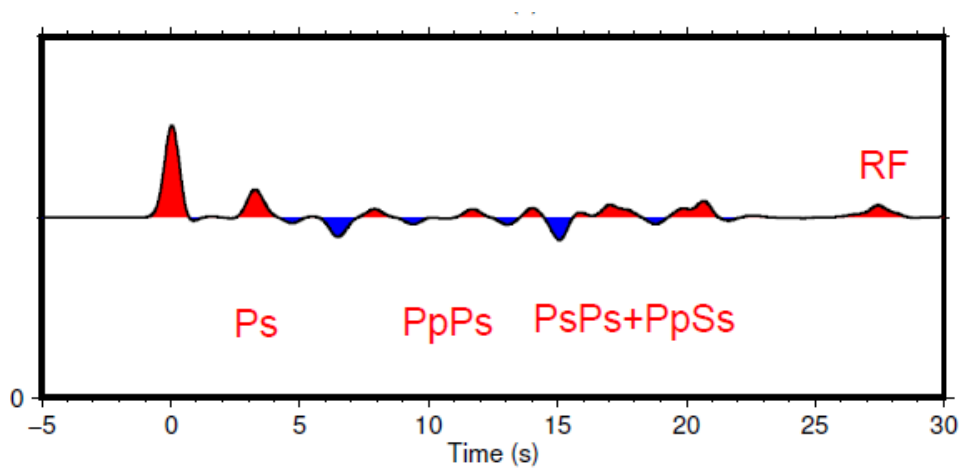
Low-cost 3-C seismometer

5) Receiver function imaging with dense array (Vs and Moho)

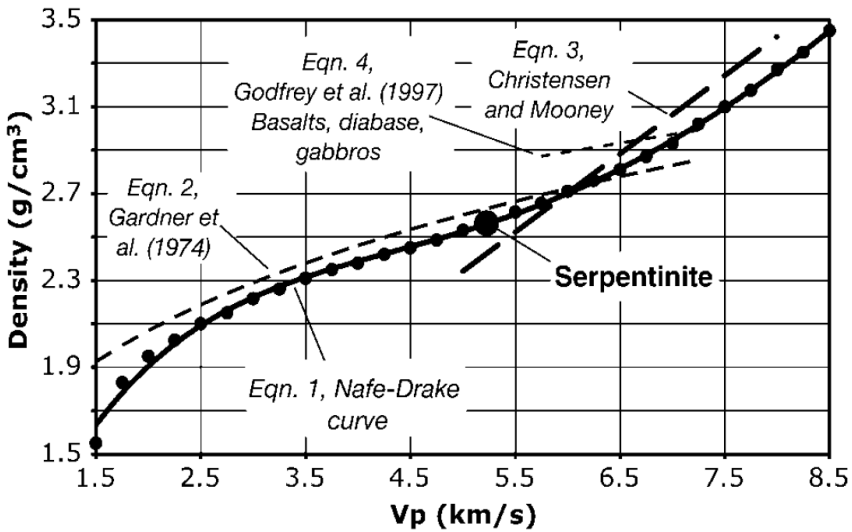
Receiver functions (RFs) are time series, computed from three-component seismograms, which show the relative response of Earth structure near the receiver.

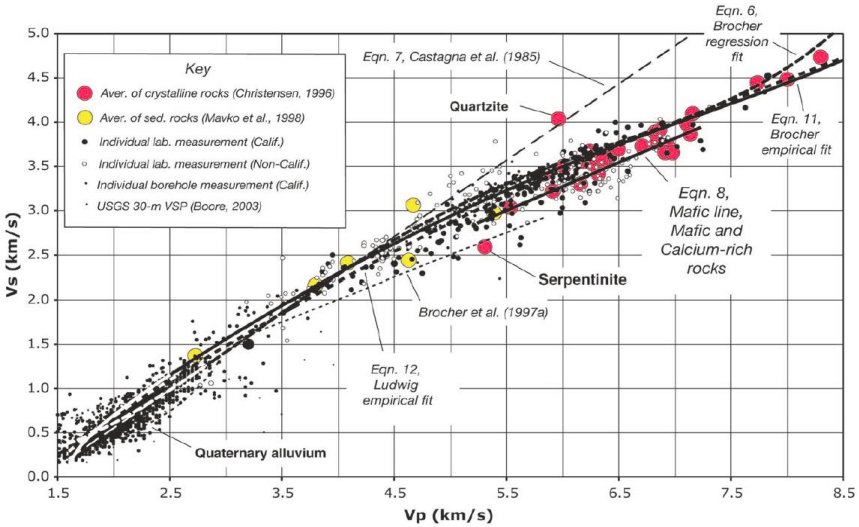
RFs can provide good constraints on Vs and Moho of crust.





Empirical relations for crustal velocity and density





Brocher, 2005 BSSA

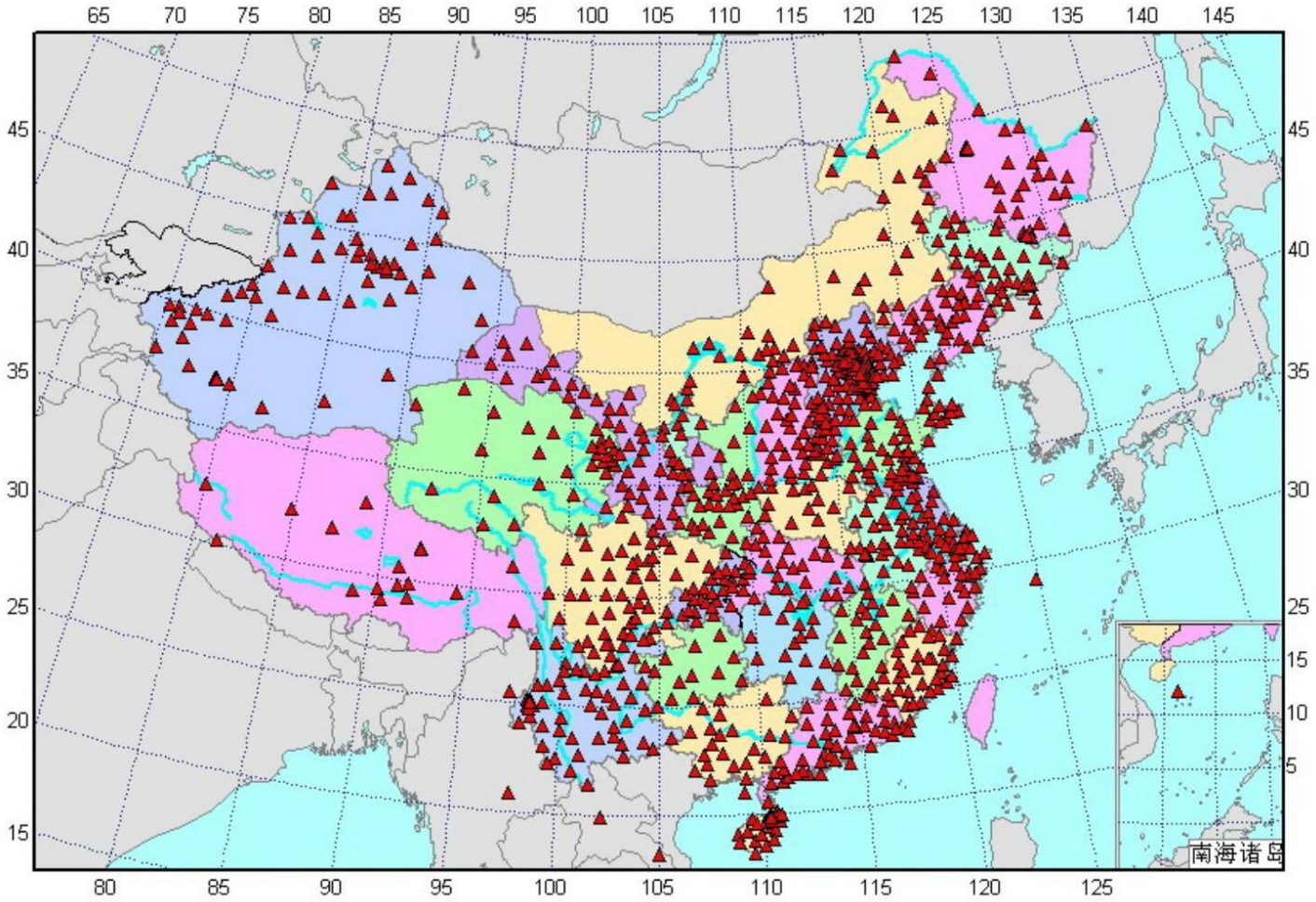
$$\rho(\mathrm{g/cm^3}) = 1.6612V_\mathrm{p} - 0.4721V_\mathrm{p}^2 + 0.0671V_\mathrm{p}^3 - 0.0043V_\mathrm{p}^4 + 0.000106V_\mathrm{p}^5.$$

$$V_\mathrm{p}(\mathrm{km/sec}) = 0.9409 + 2.0947V_\mathrm{s} - 0.8206V_\mathrm{s}^2 + 0.2683V_\mathrm{s}^3 - 0.0251V_\mathrm{s}^4.$$

3. Multi-scale crustal model in South China

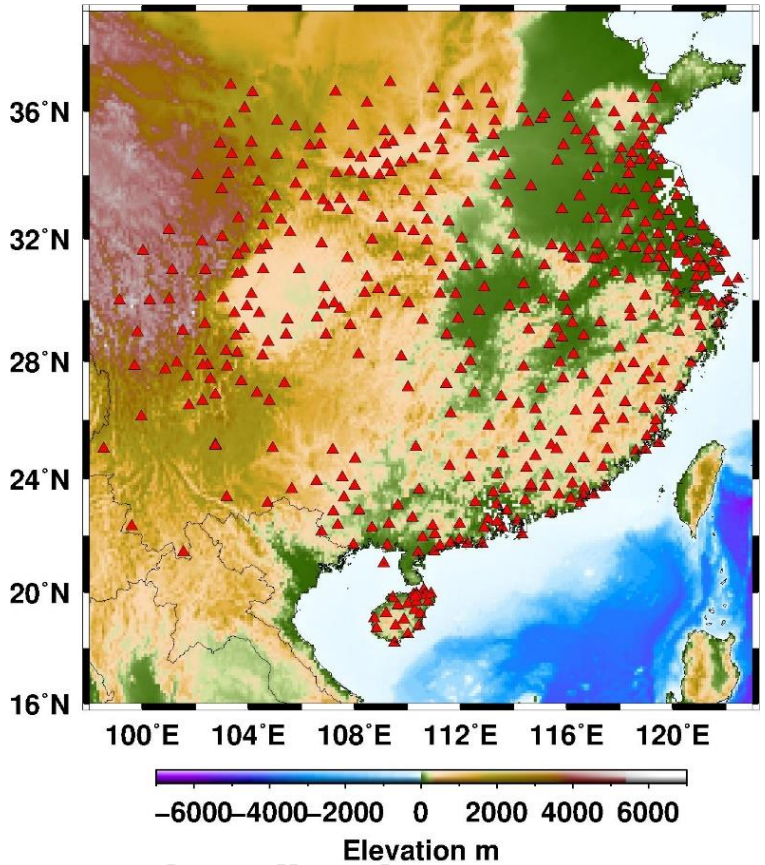
~1000 seismic stations in China

~ 450 stations in and around South China, ~ 70 km interstation distance

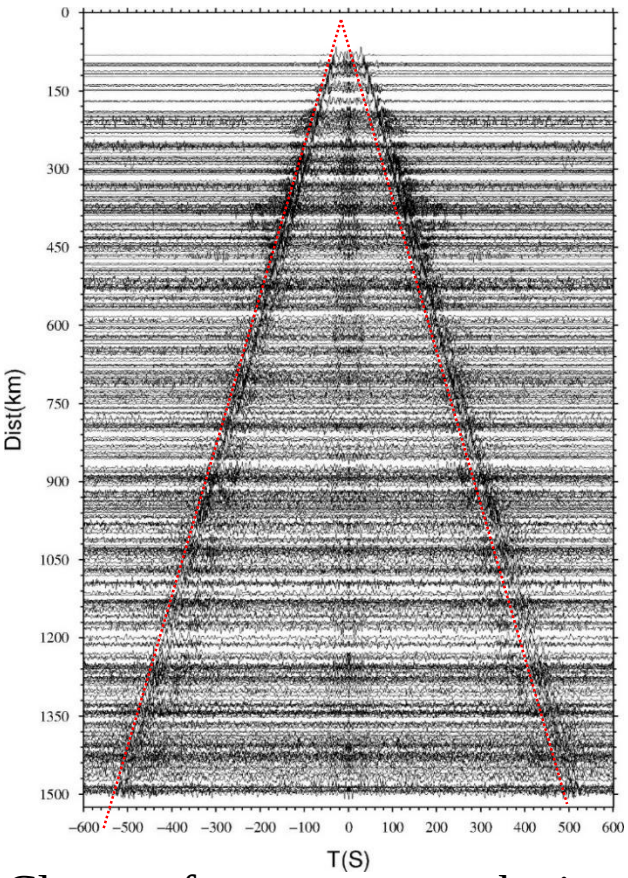


3.1 Ambient noise tomography of local crustal model

With continuous seismic waveforms from 450 seismic stations in South China, ~ 100,000 noise cross-correlation functions (NCF) are obtained to extract the surface wave dispersions.

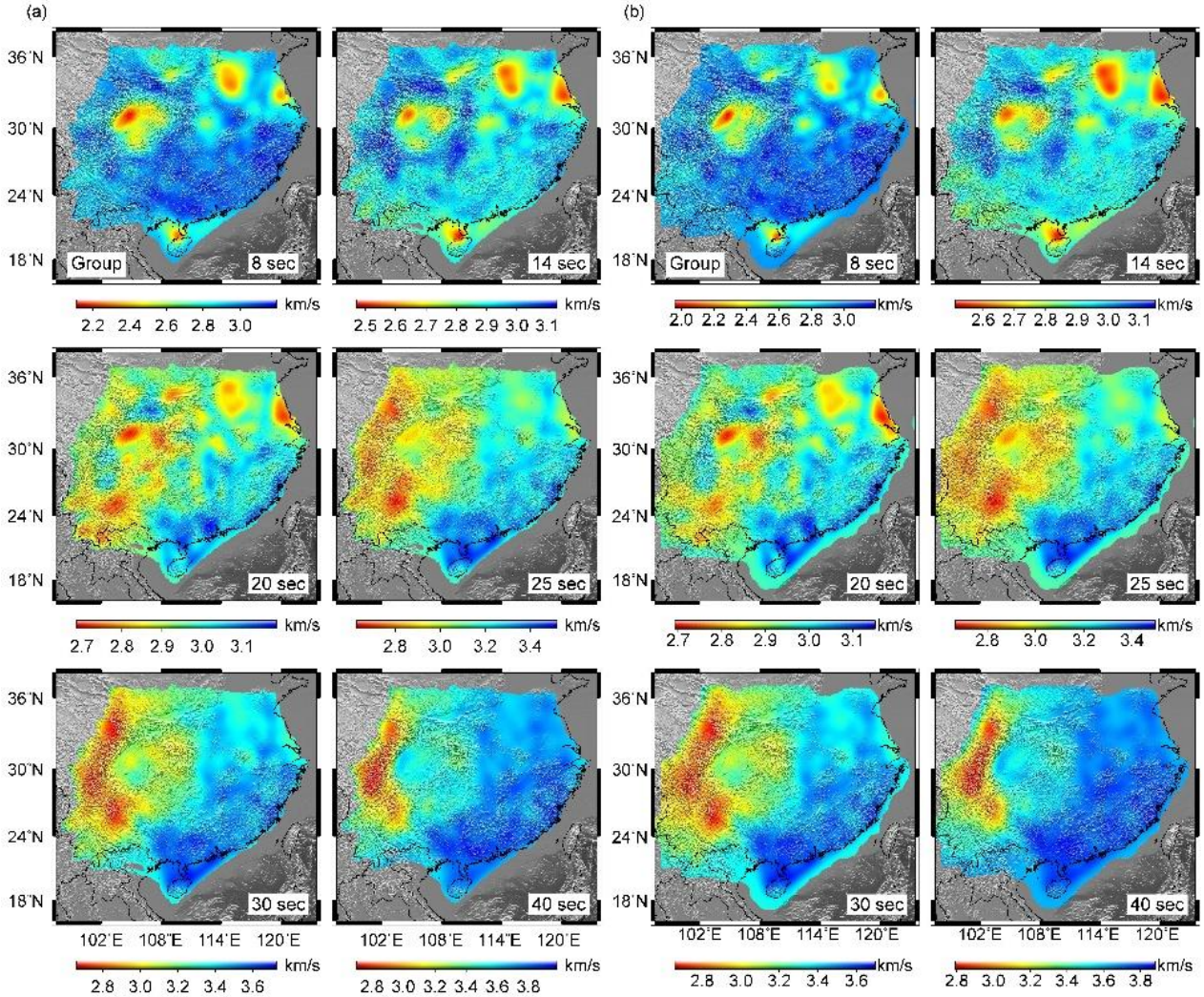


450 broadband seismic stations

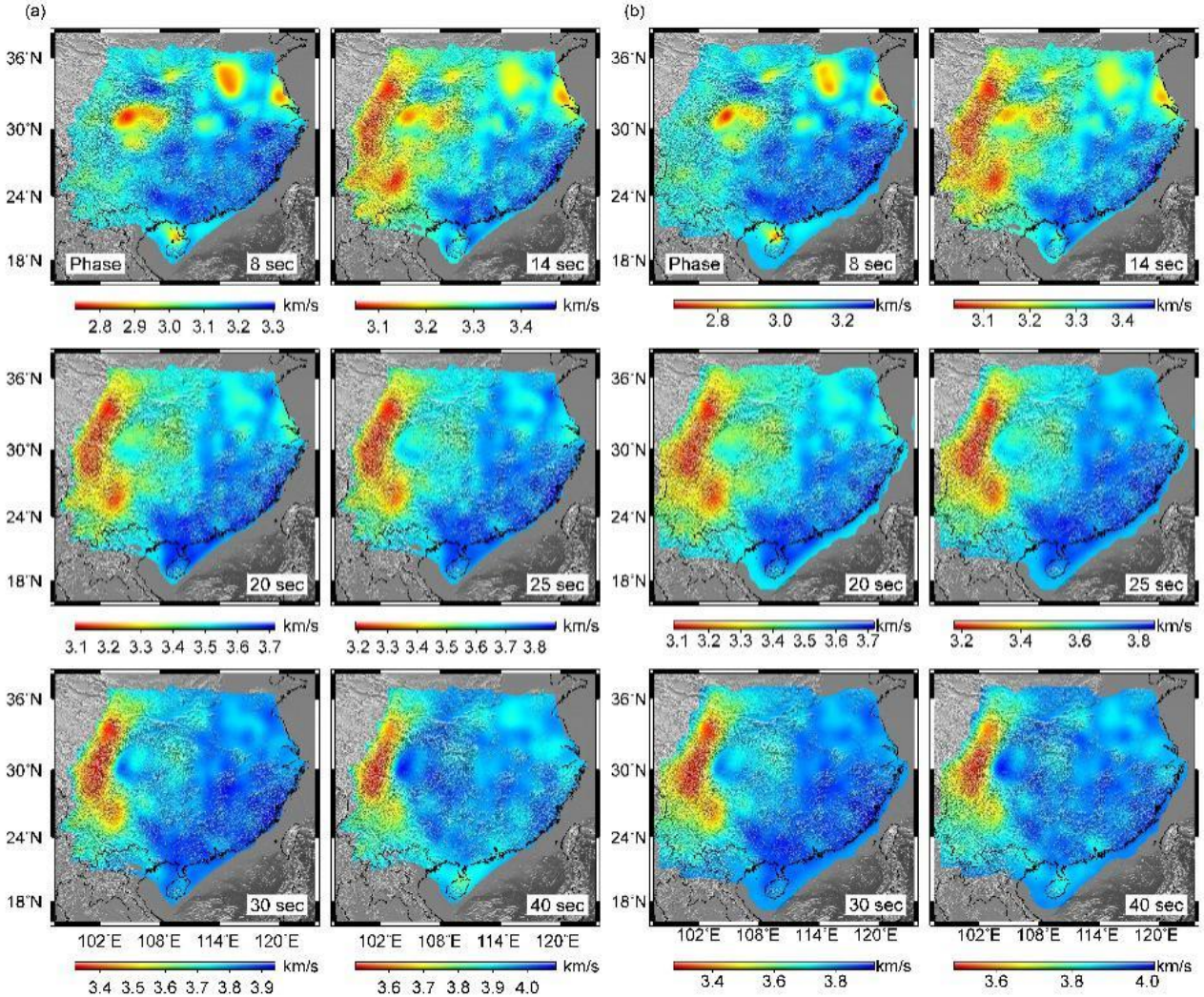


Clear surface waves are obtained

Observed Group velocity **Predict Group velocity**

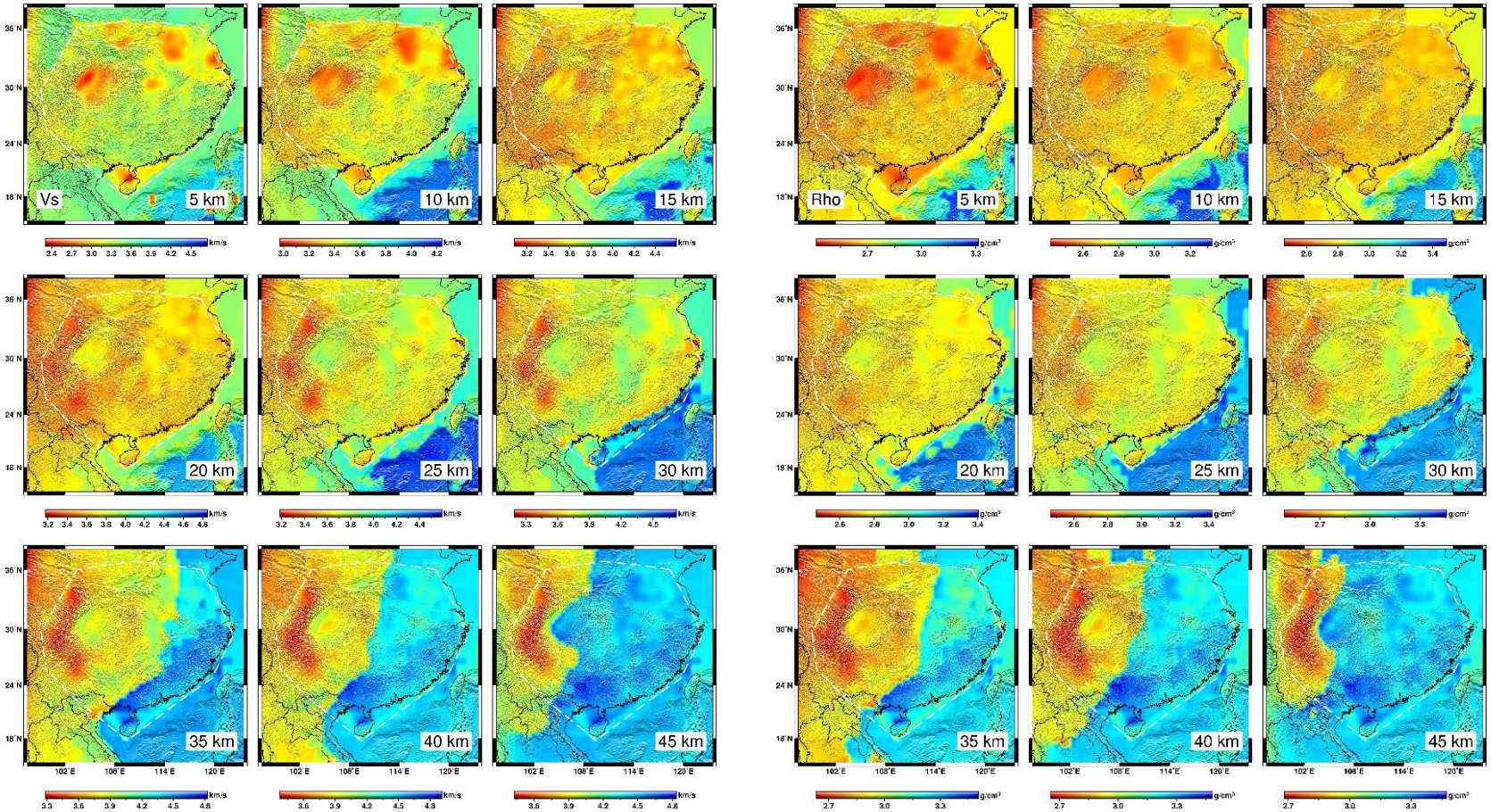


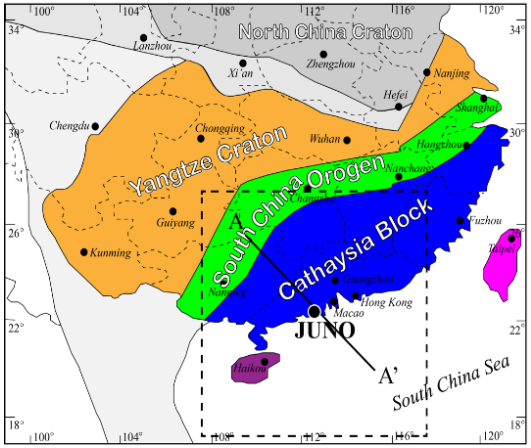
Observed Phase velocity **Predict Phase velocity**



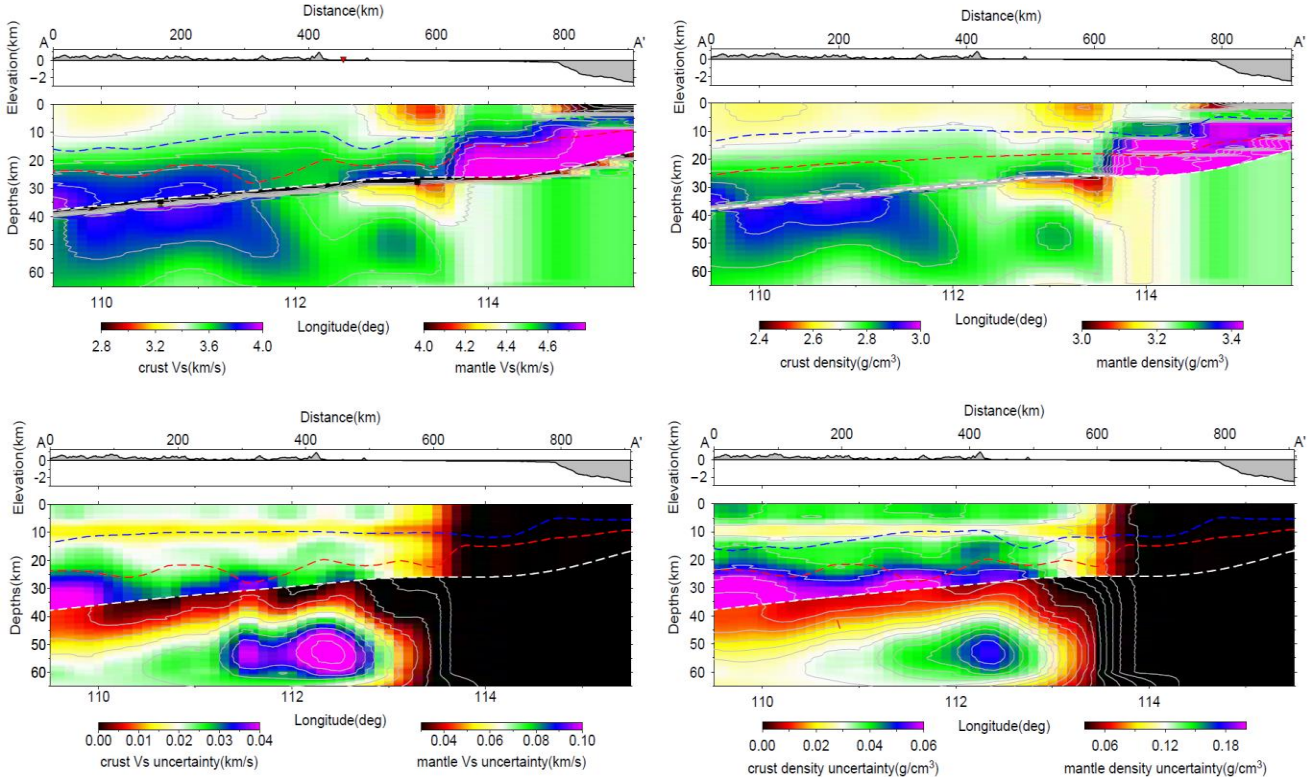
3-D high-resolution Vs structures in the South China

spatial resolution: **~ 40 km in horizontal and 3~4 km in vertical directions**.





Cross-sections for shear-wave velocity and density structures in NW-SE directions through the JUNO site



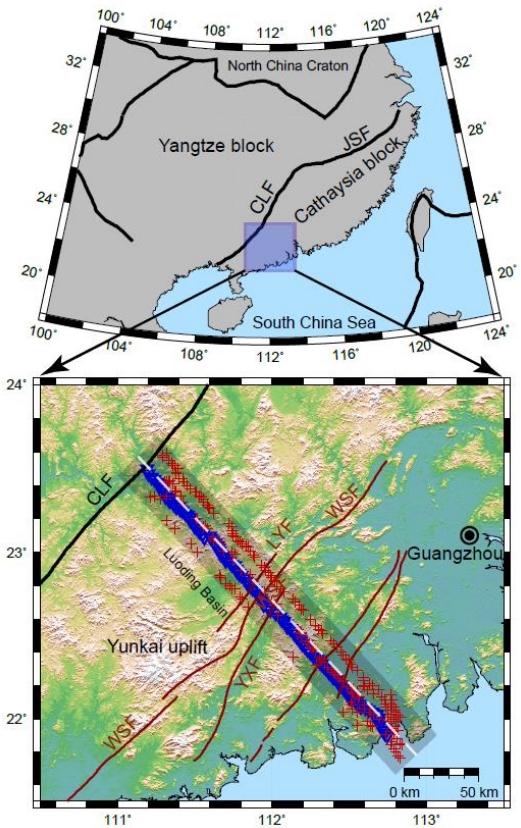
White dashed lines are Moho from gravity and DSS.

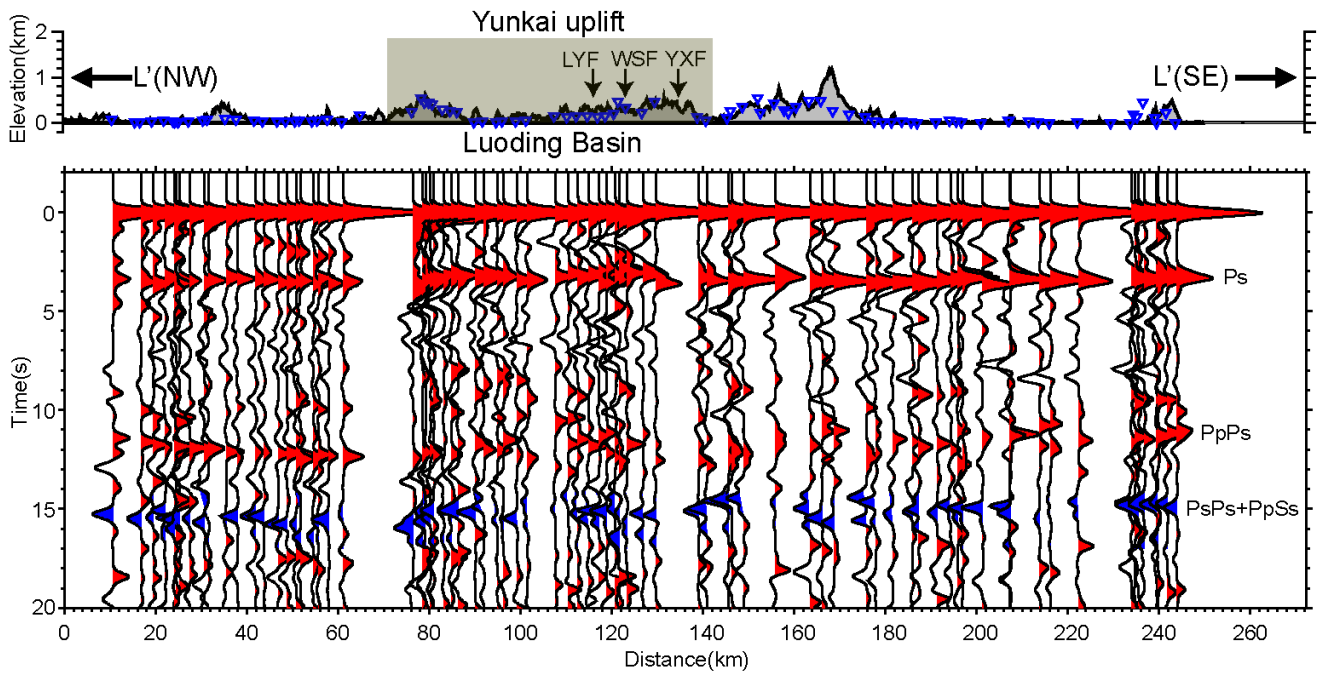
uncertainties for Vs and density structures

3.2 Receiver function imaging with dense array

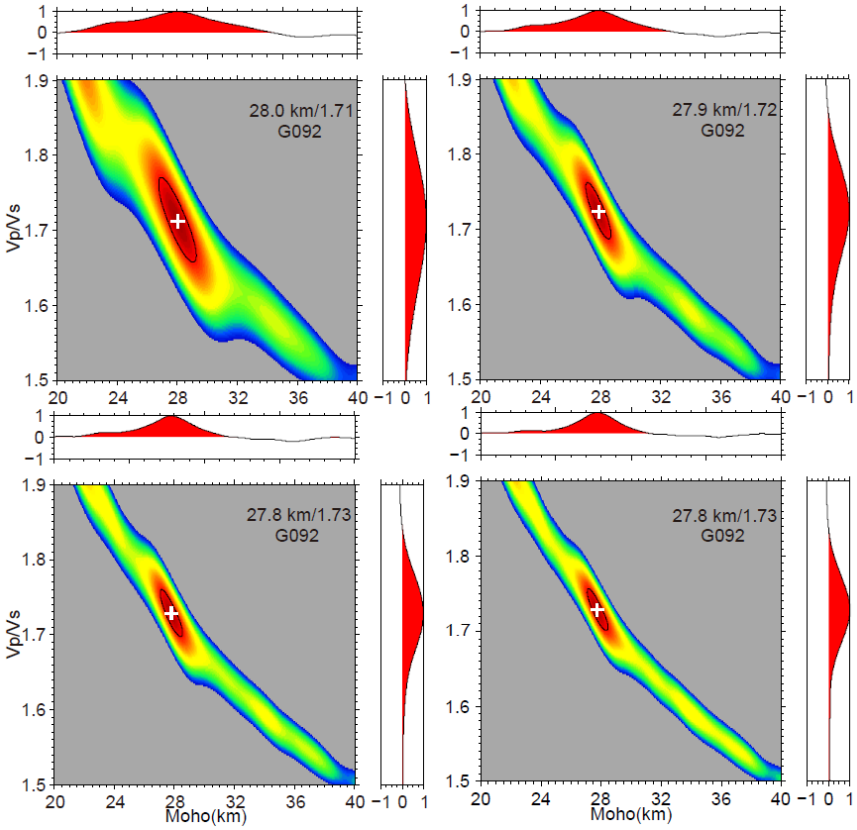
260 km profile with 110 seismometers and ~ 2.5 km interstation distances crossing JUNO.

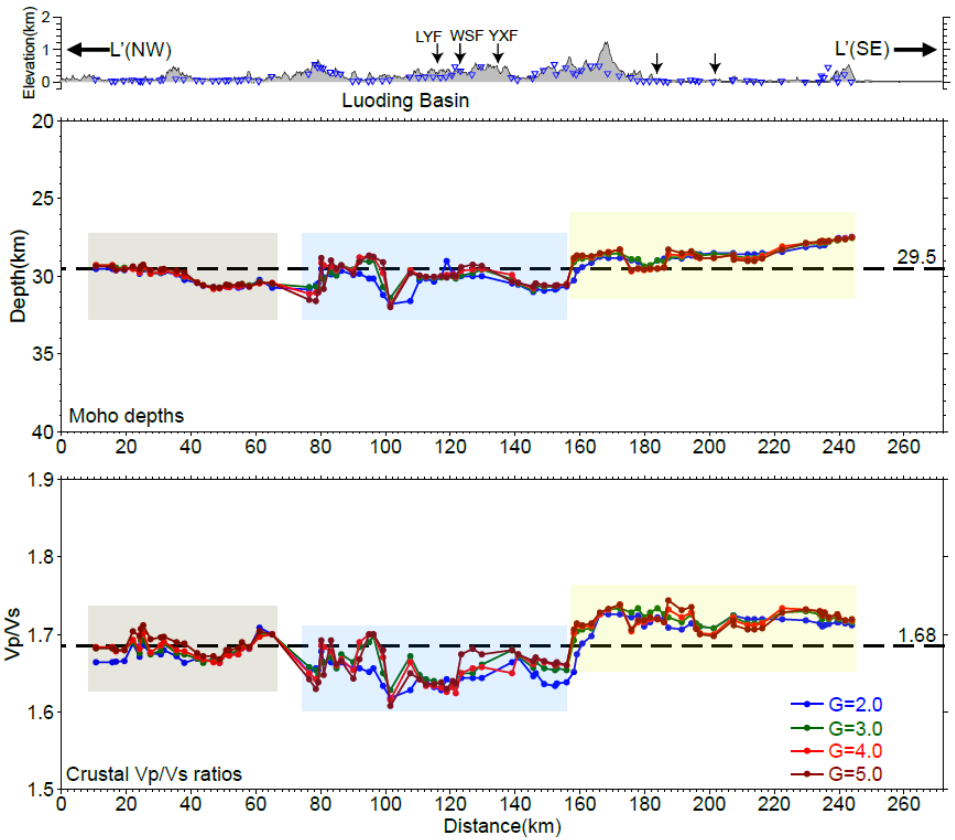
spatial resolution: **2~3 km in both horizontal and vertical directions**



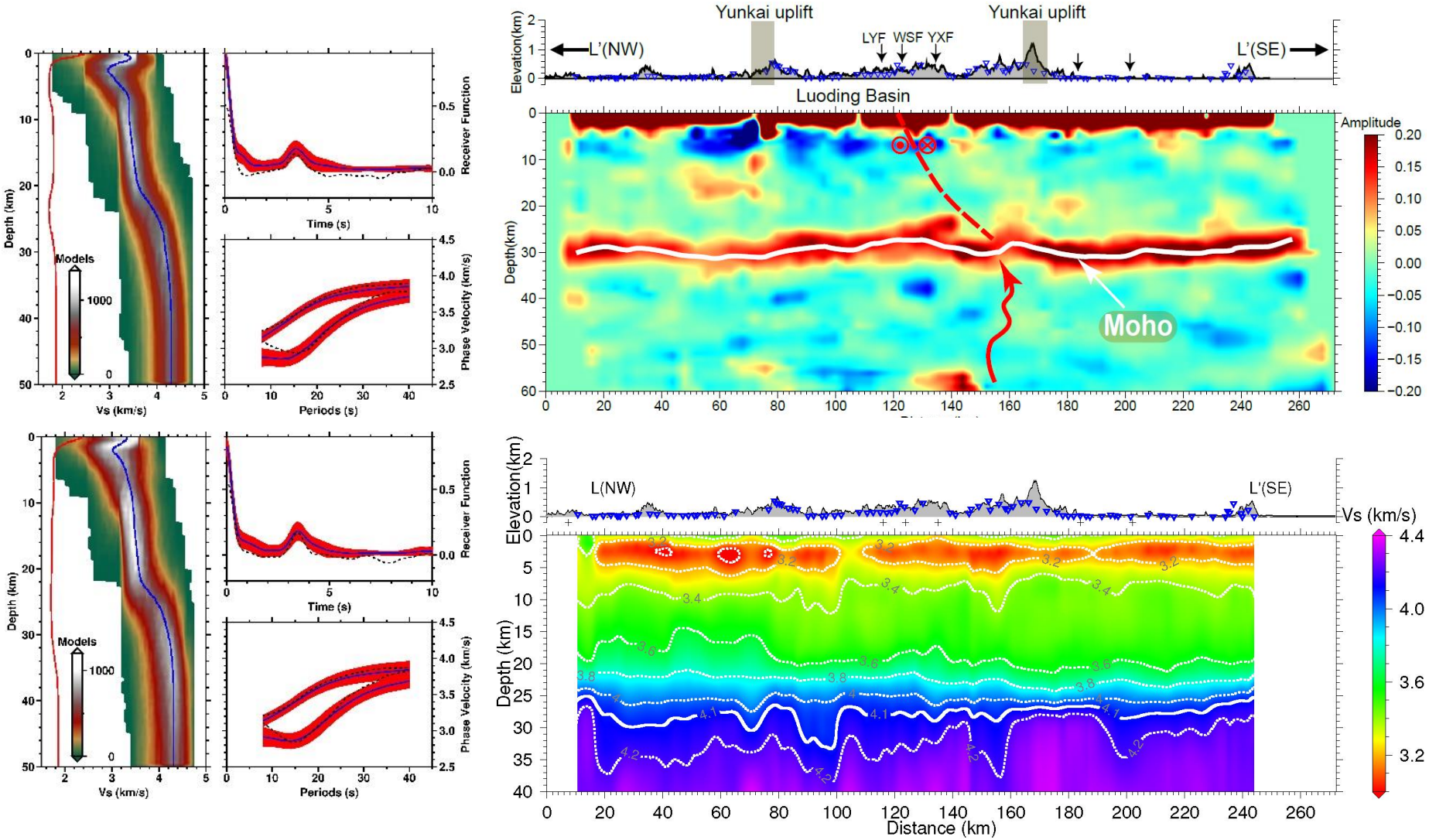


H-k method for crustal thickness and average Vp/Vs along profile





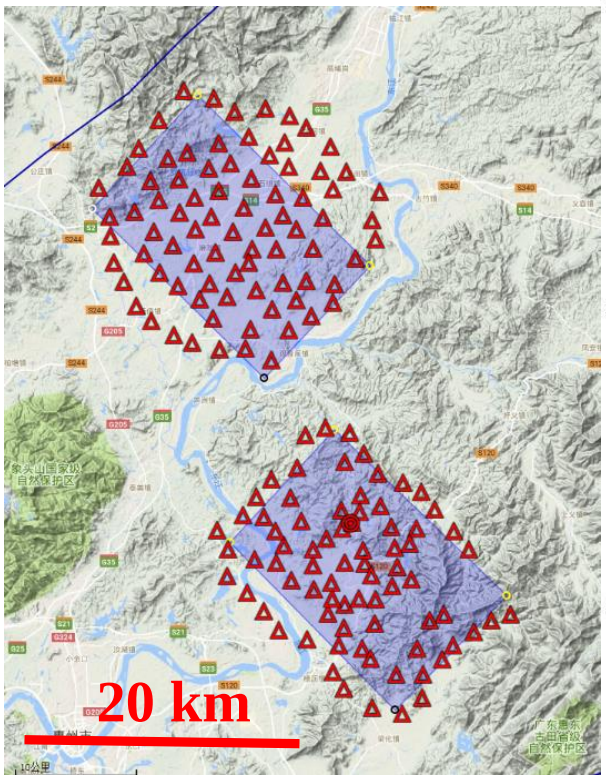
common conversion point stacking, and joint inversion of surface wave and RFs for 2-D crustal structures.

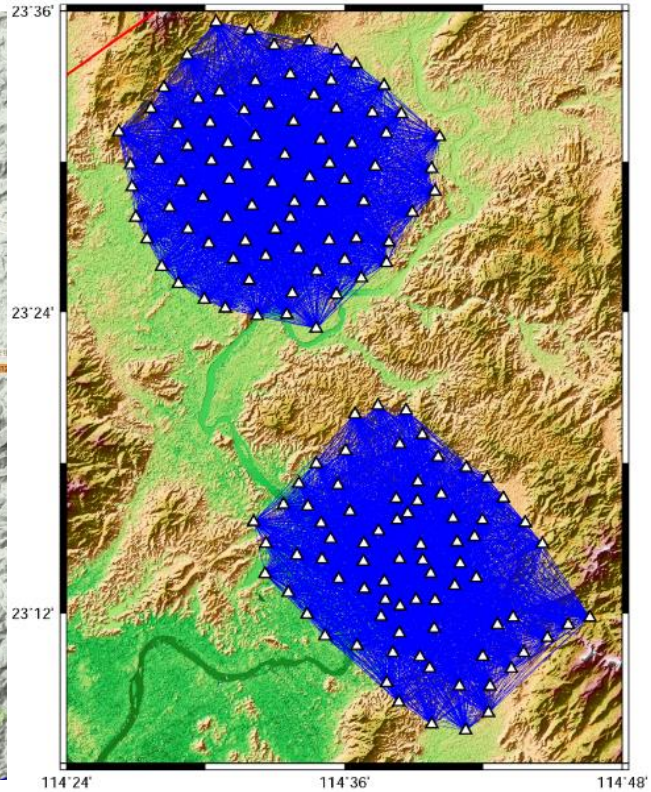


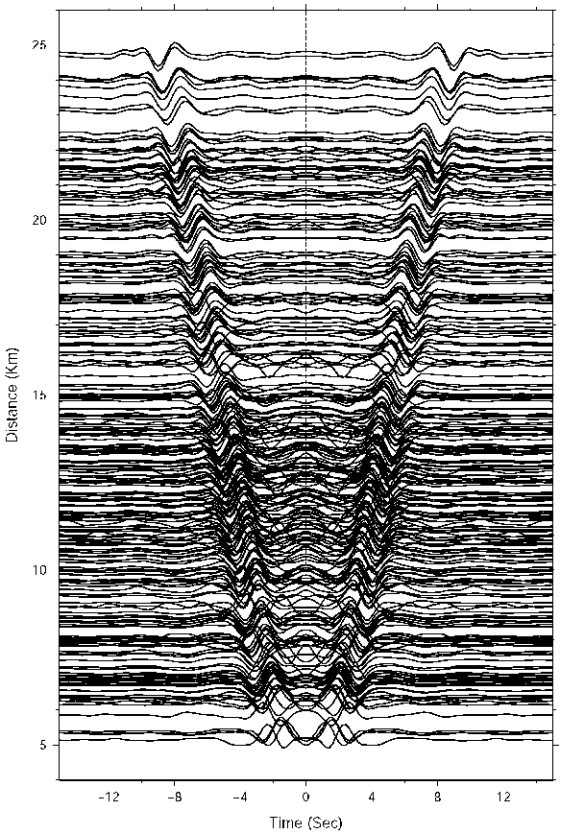
3.3 Ambient noise tomography with dense array

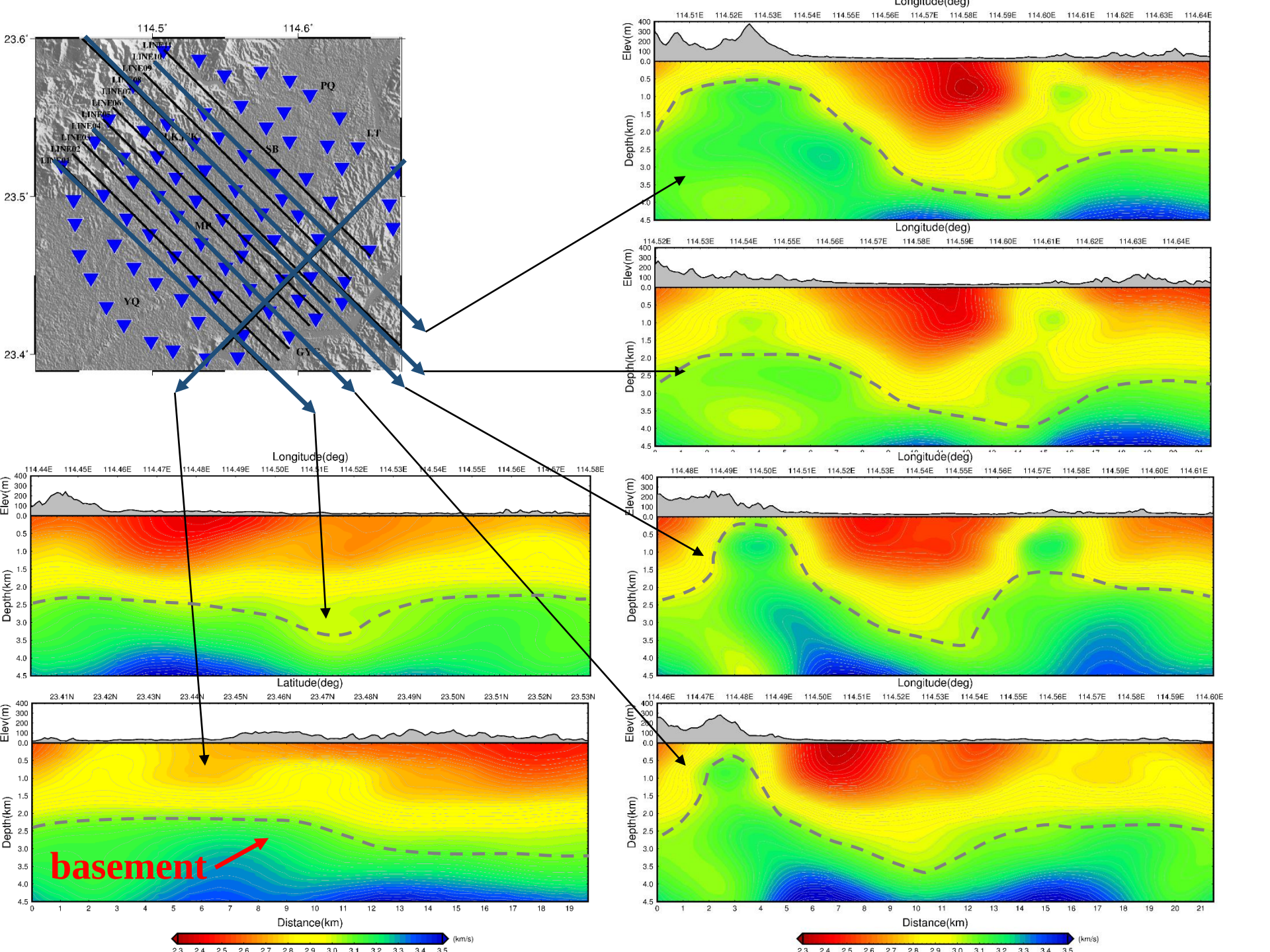
Two dense arrays ~ 100 km away from JUNO (Huizhou, Guangdong).

Small basin structures are obtained with high-resolution **(~ 1 km**)

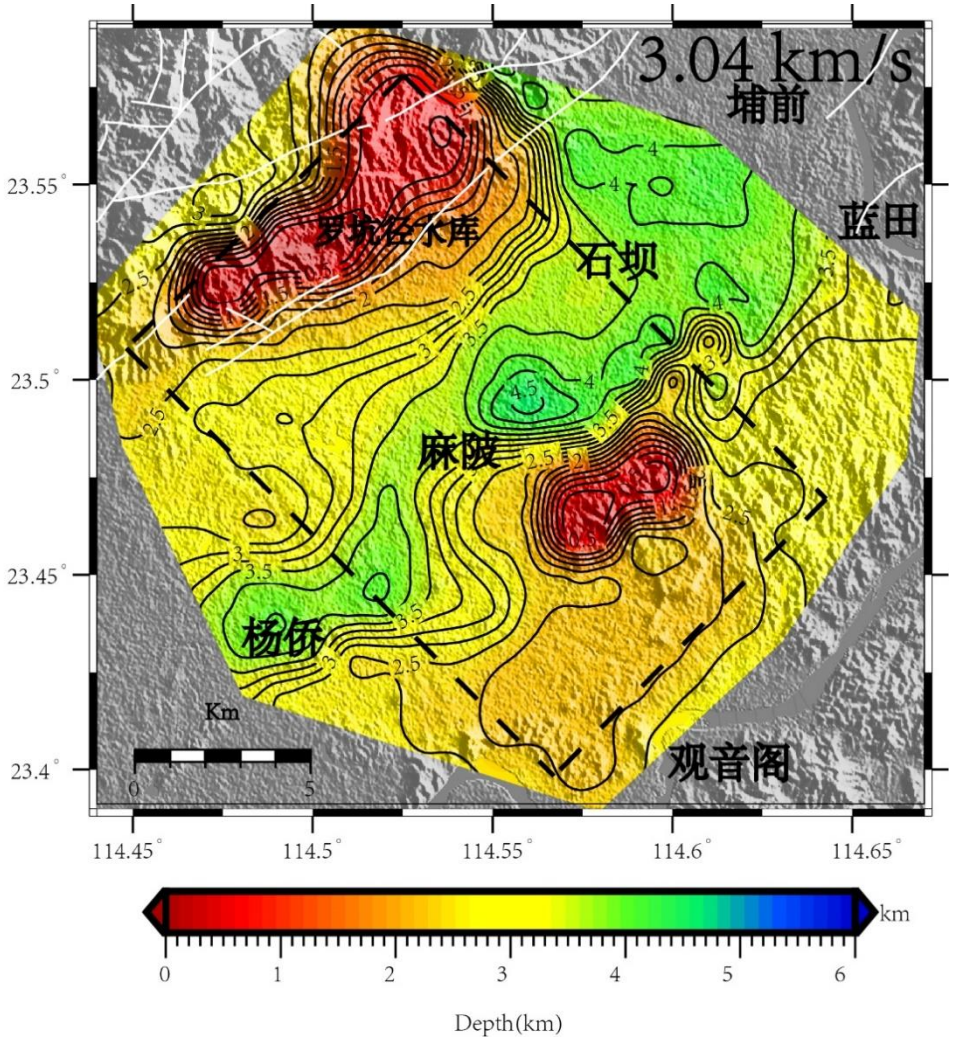







114.5°
114.6°
23.6°
23.5°
23.4°
LINE11
LINE10
LINE09
LINE08
LINE07
LINE06
LINE05
LINE04
LINE03
LINE02
LINE01
PQ
LT
SB
MP
YQ
GYC
Longitude(deg)
Latitude(deg)
Elev(m)
Depth(km)
Distance(km)
basement
(km/s)

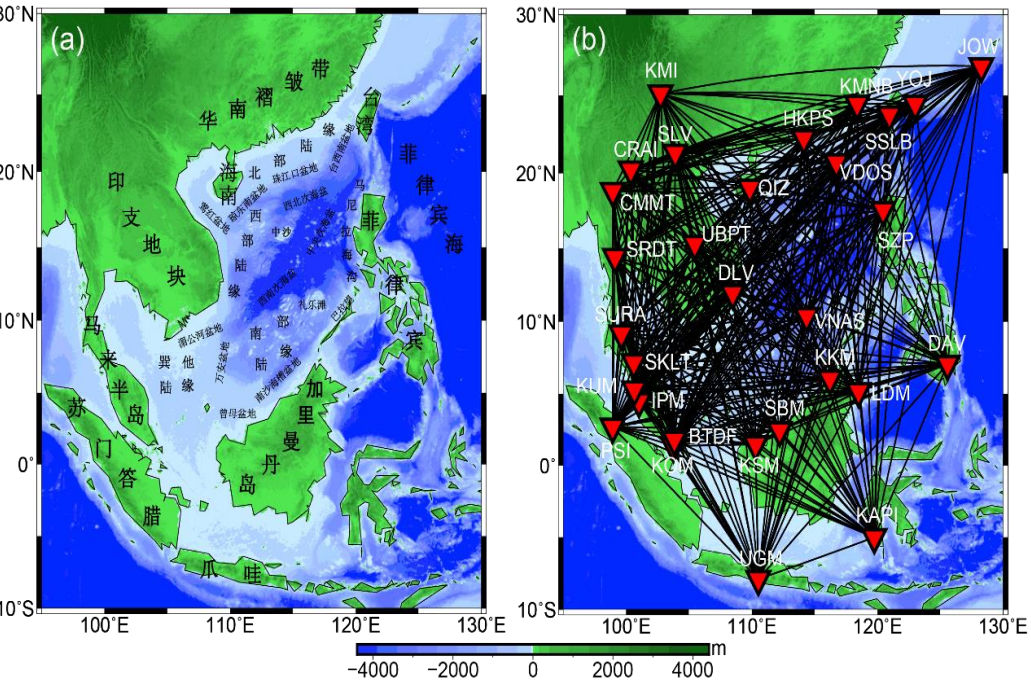
Basin basement estimated from isosurface of Vs beneath dense array

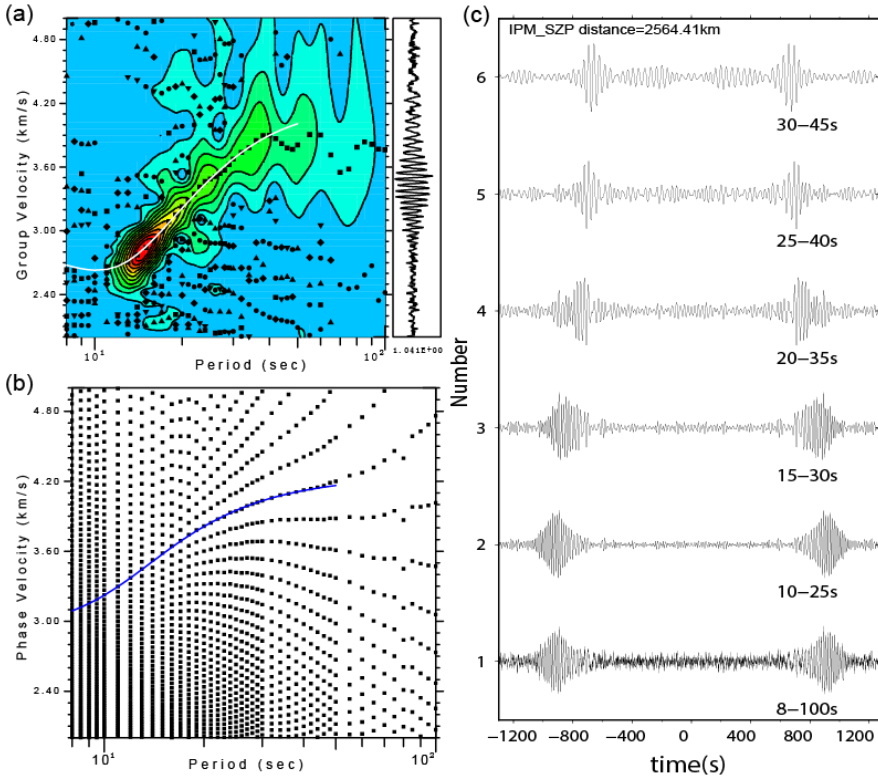


3.4 Ambient noise tomography of South China Sea

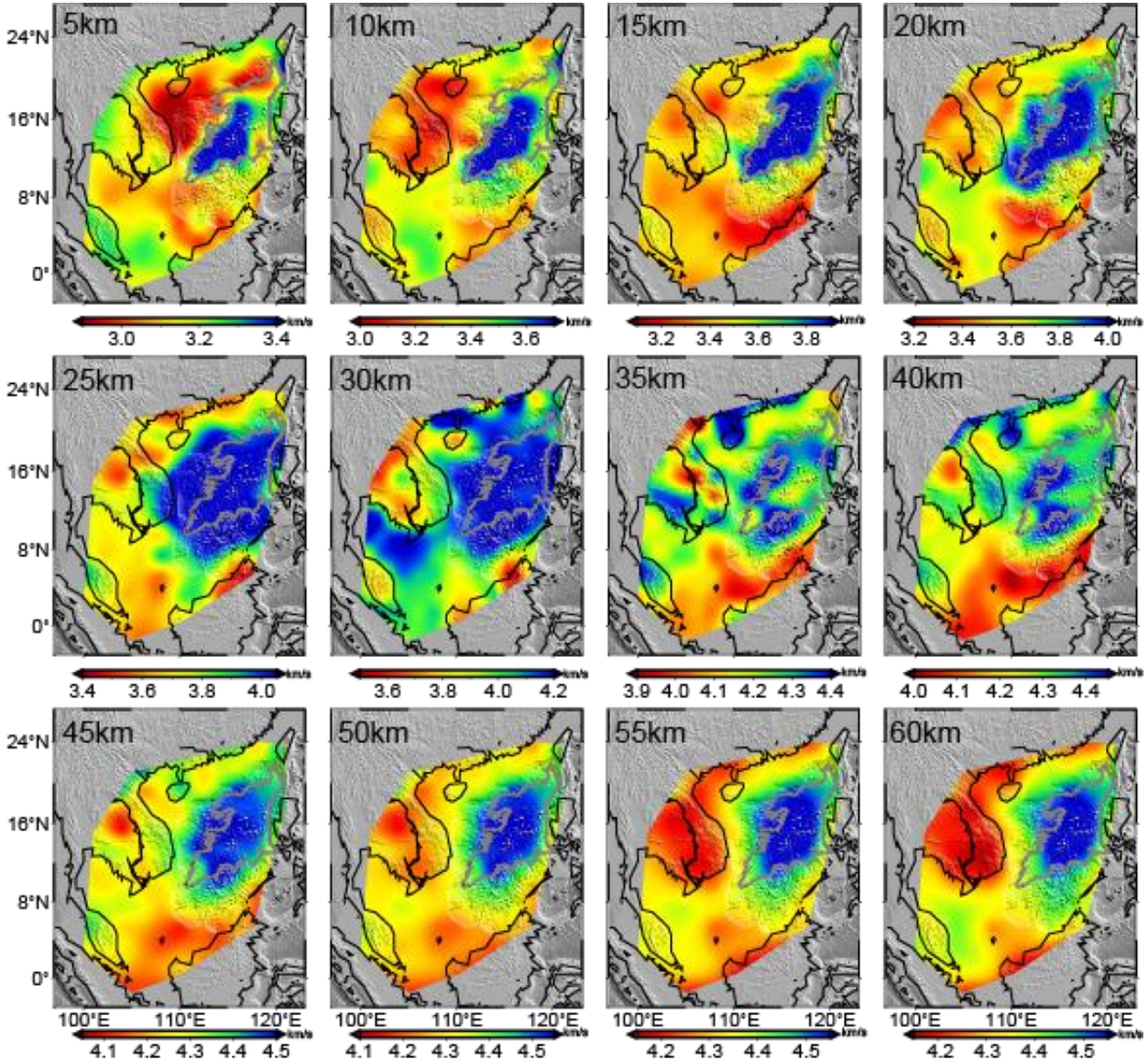
Large-scale surface wave tomography, ~ 300 km horizontal resolution

Deep to 60 km. A model better than CRUST1.0 for South China Sea.



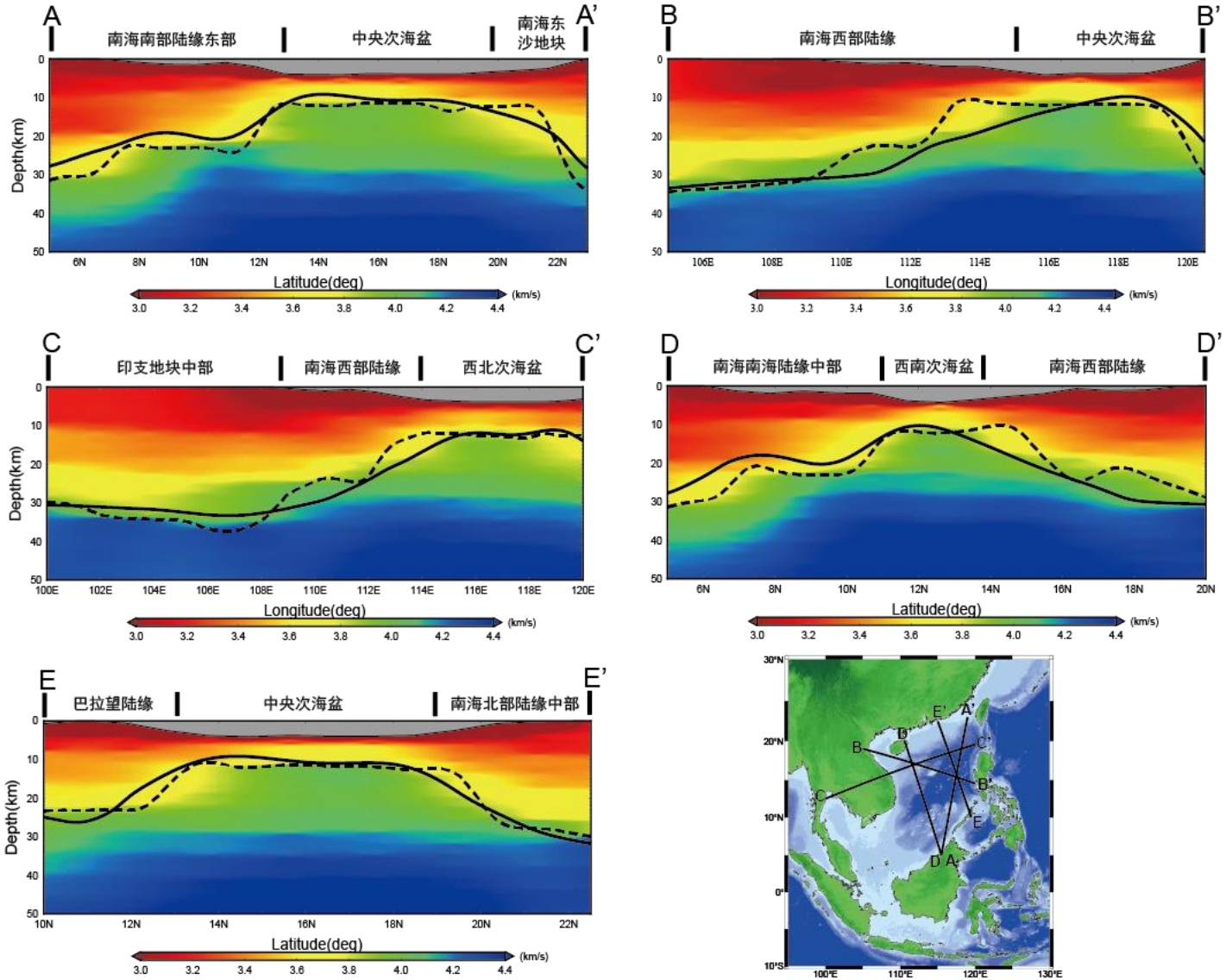


Vs model deep to 60 km depth.



Cross-sections of Vs model

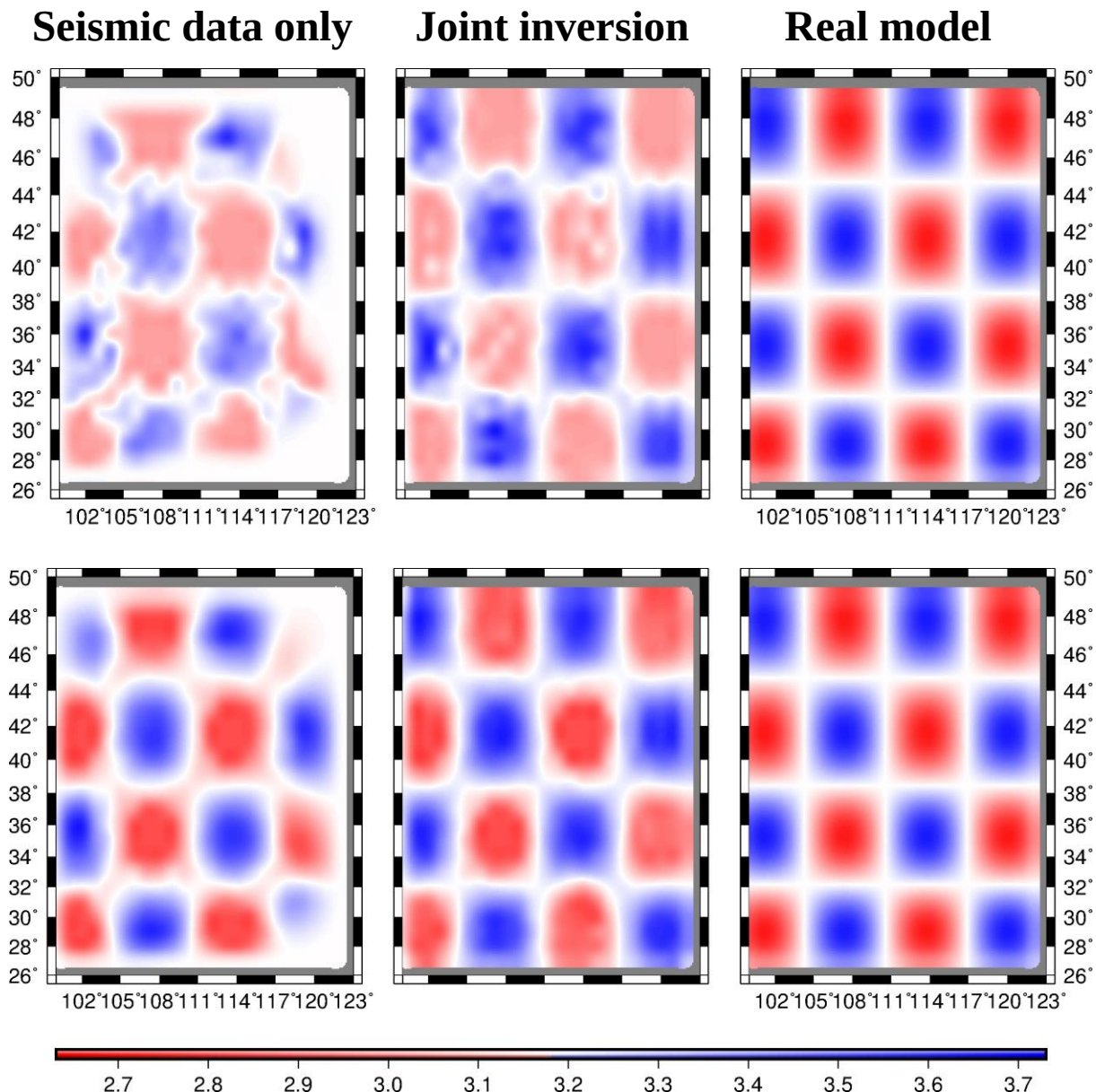
dashed line: CRUST1.0 Moho; solid line: Moho in this study



4. Summary

- Local high-resolution (~ 40 km) crustal model in South China is obtained with data from ~ 450 seismic stations, higher resolution than CRUST1.0 global model.
- Local models for crust and sediment basins with much higher resolution can be obtained by deploying more dense temporary seismometers.
- we are planning to update the local crust model by joint inversion with more geophysical data (e.g., seismic and gravity data). Testing algorithms in Sichuan basin, then apply to South China.

Trials of joint inversion of seismic and gravity data in Sichuan Baisn



Thanks!

Backup

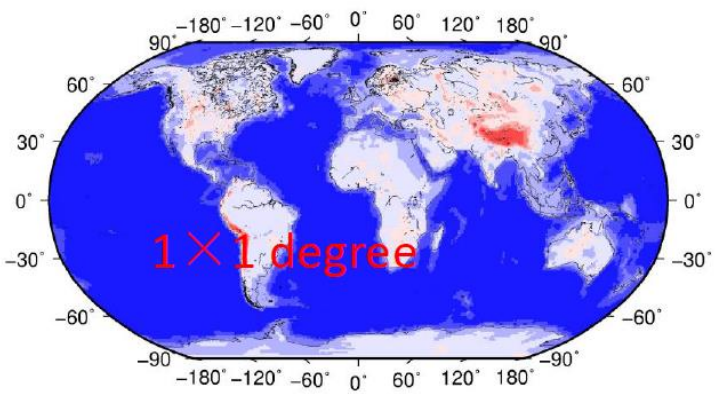
Why a new local model for South China

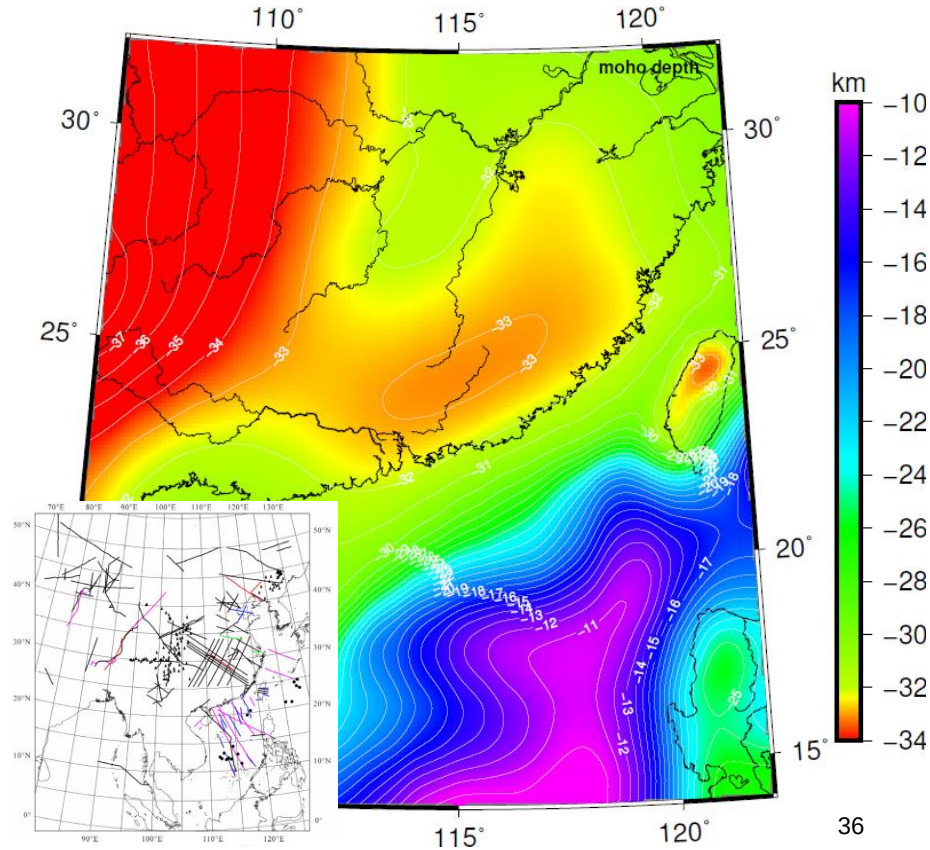
Global CRUST1.0 model has low-resolution (~1° x1 °, ~ 100 km). it also is a compiled model based on many independent models. A new local refined 3-D crustal model with higher resolution is needed for South China around the JUNO.

CRUST 1.0

latitude, longitude, crustal type
89.5 , -178.5 A1
elevetion: 0.0000000
layers: vp, vs, rho, bottom

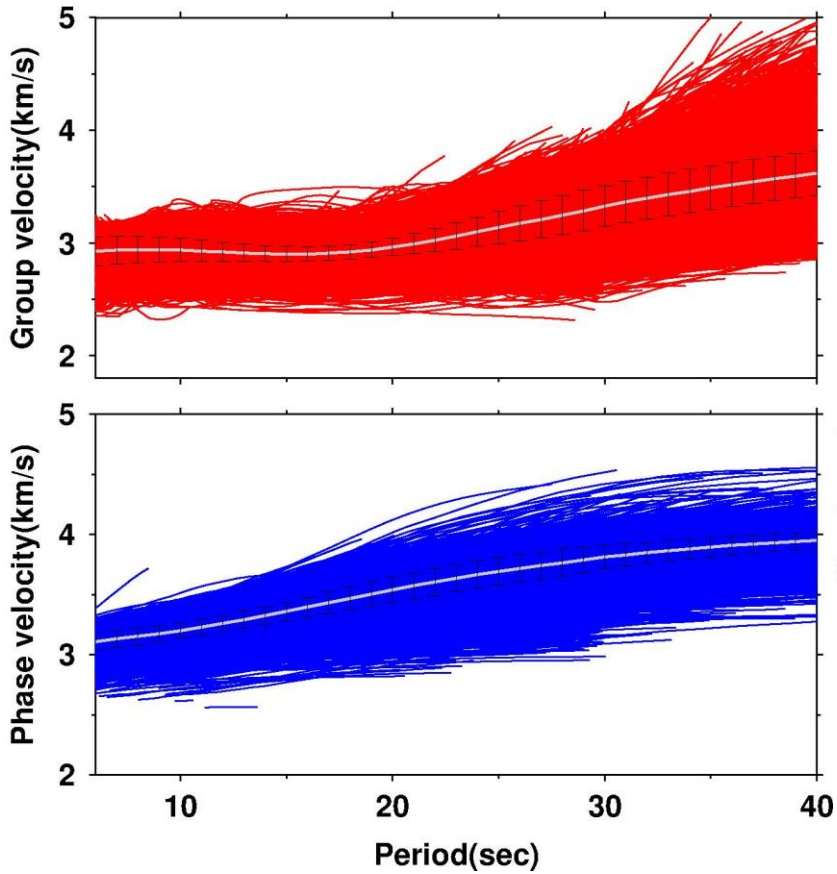
1.50	0.00	1.02	-3.66	1- water
3.81	1.94	0.92	-3.66	2- ice
2.00	0.55	1.93	-4.96	3- upper sediments
0.00	0.00	0.00	-4.96	4- middle sediments
0.00	0.00	0.00	-4.96	5- lower sediments
5.00	2.70	2.55	-5.64	6- upper crust
6.50	3.70	2.85	-7.13	7- middle crust
7.10	4.05	3.05	-11.74	8- lower crust

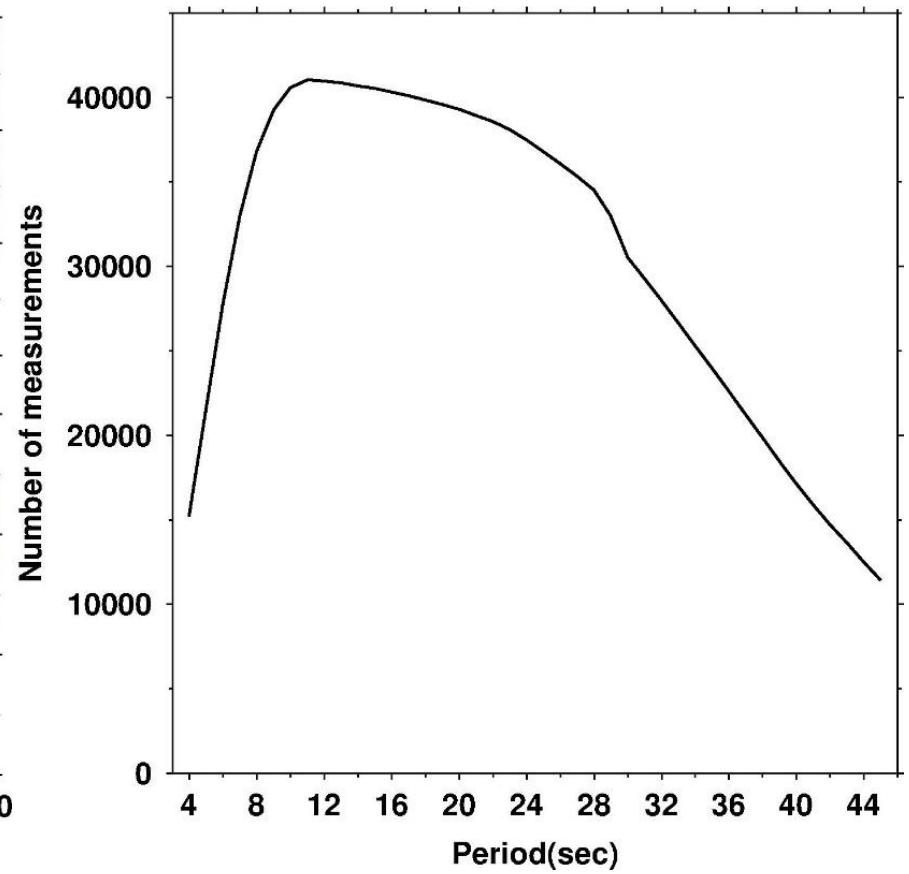




New Moho depth from Bouguer gravity inversion

Using Automatic Frequency-Time Analysis method (AFTAN), totally 41,041 dispersion curves are extracted from 76,689 Rayleigh wave dispersion curves after quality control.



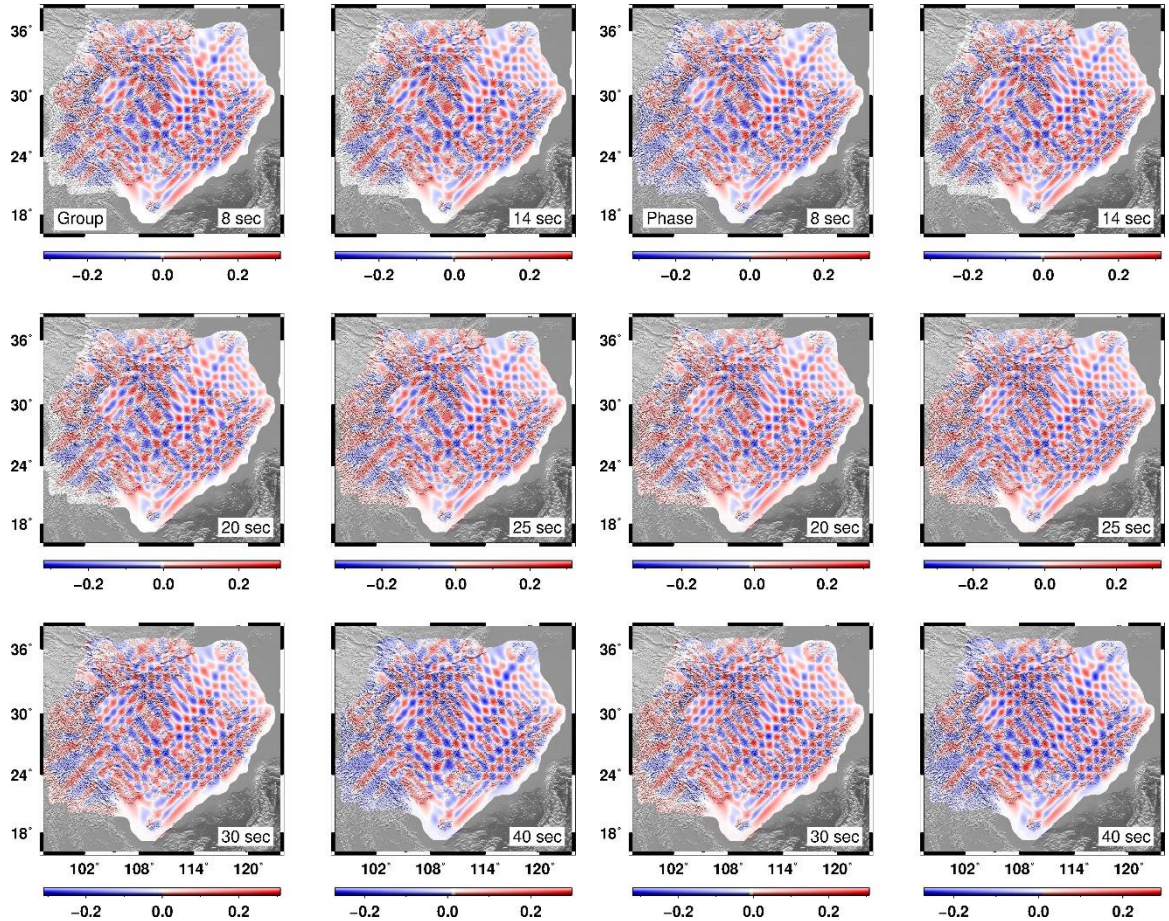


Dispersion curves of Rayleigh waves

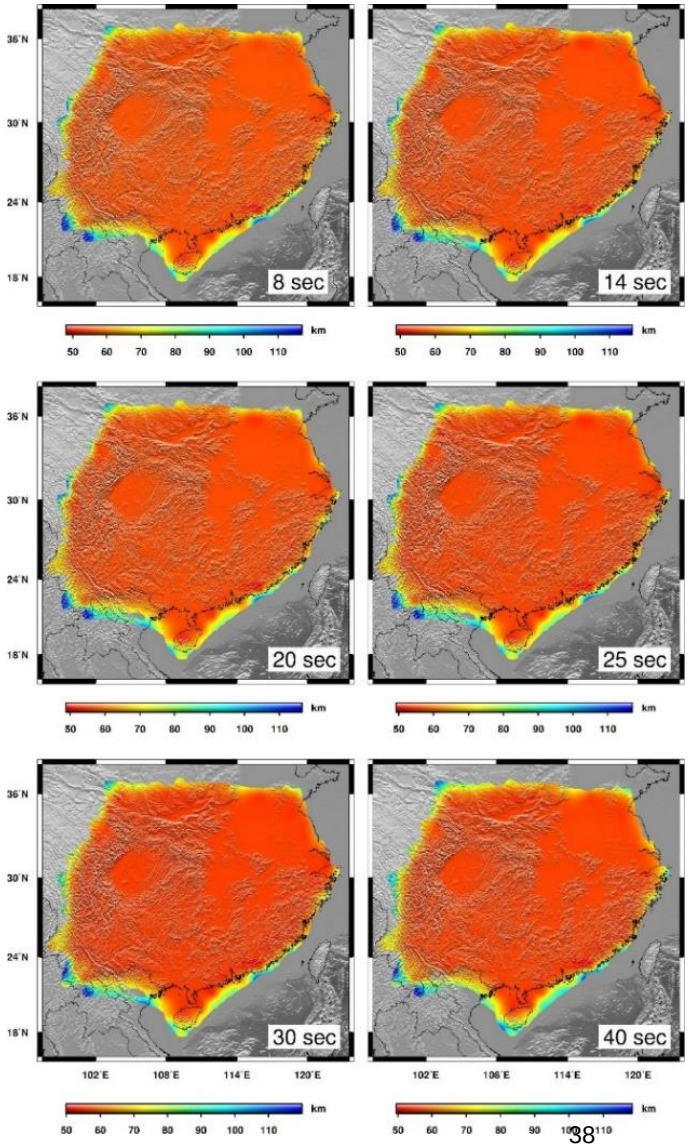
Numbers of dispersion curves at 4-45 s

Surface wave tomography with Fast March Method (FMM)

Resolution is better than ~50 km for most areas.

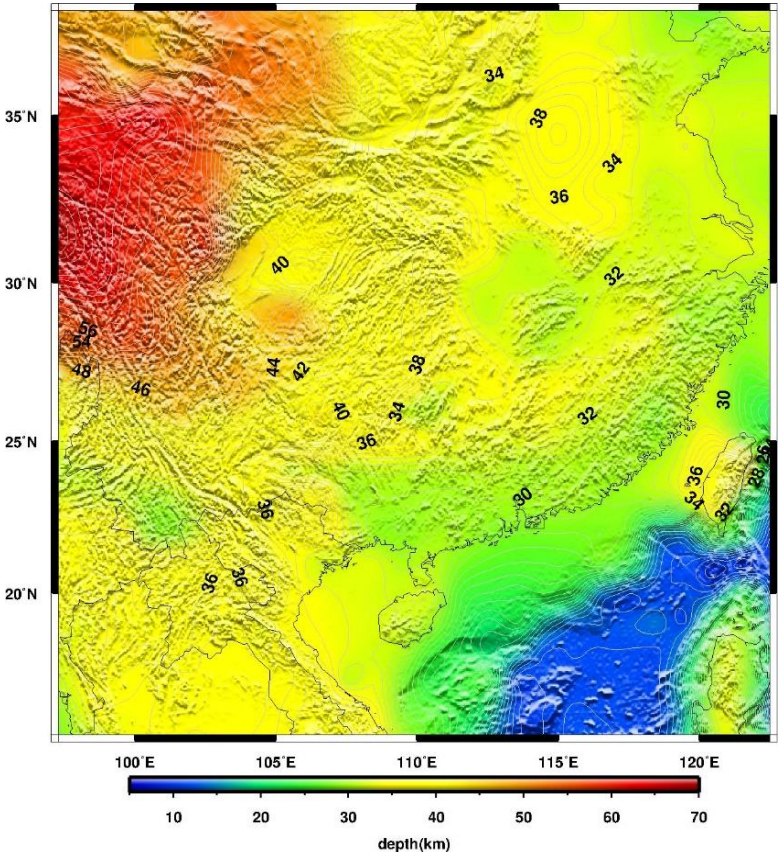


Checkerboard resolution tests for 0.8x0.8 degree

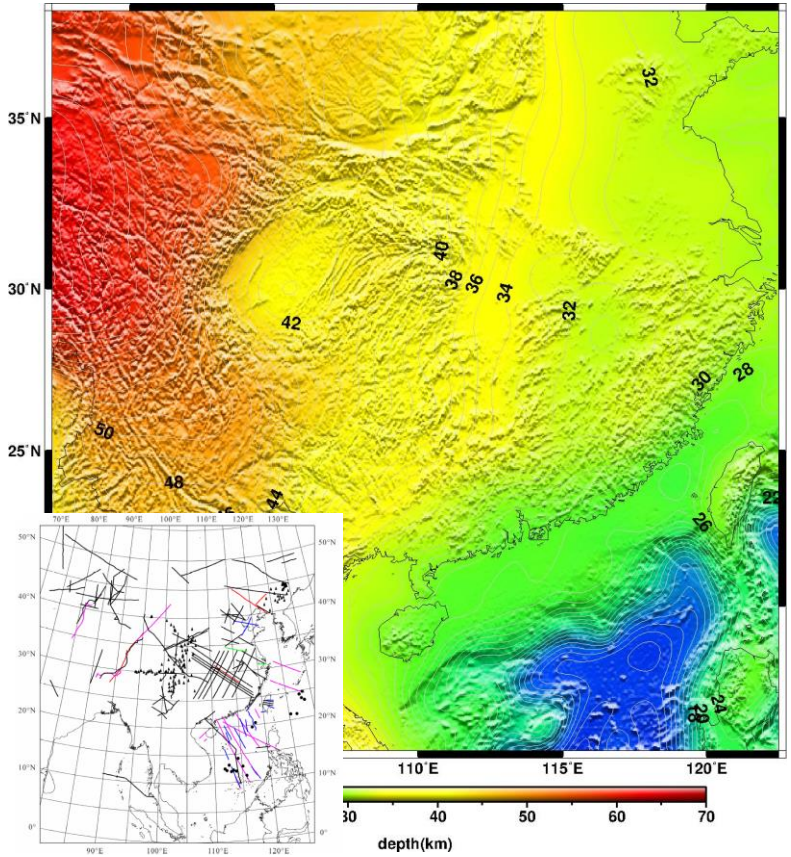


Spatial resolution

Better crustal thickness model is used to build starting model for 3-D Vs model inversion.



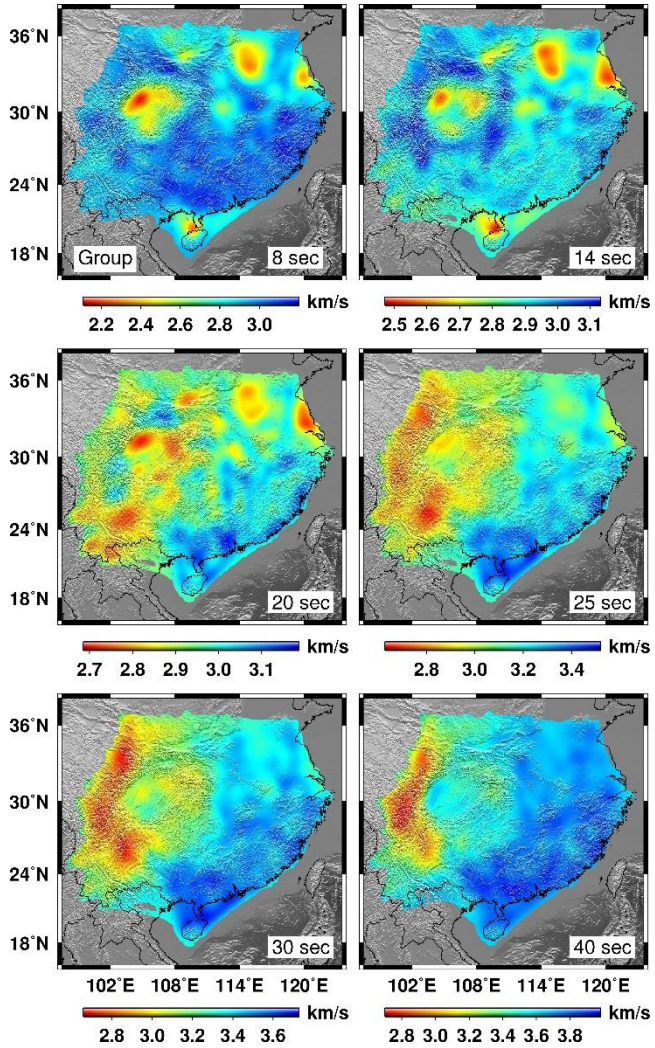
Crustal thickness from CRUST1.0 model



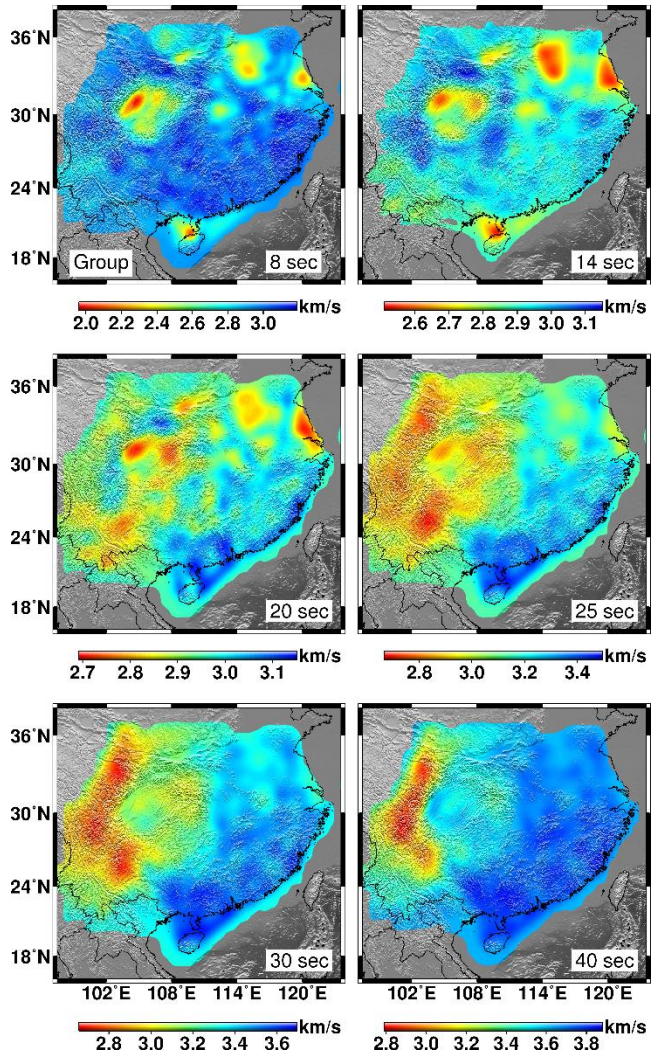
Crustal thickness model in this study

Consistency shows the inverted 3-D model can fit the observations pretty good.

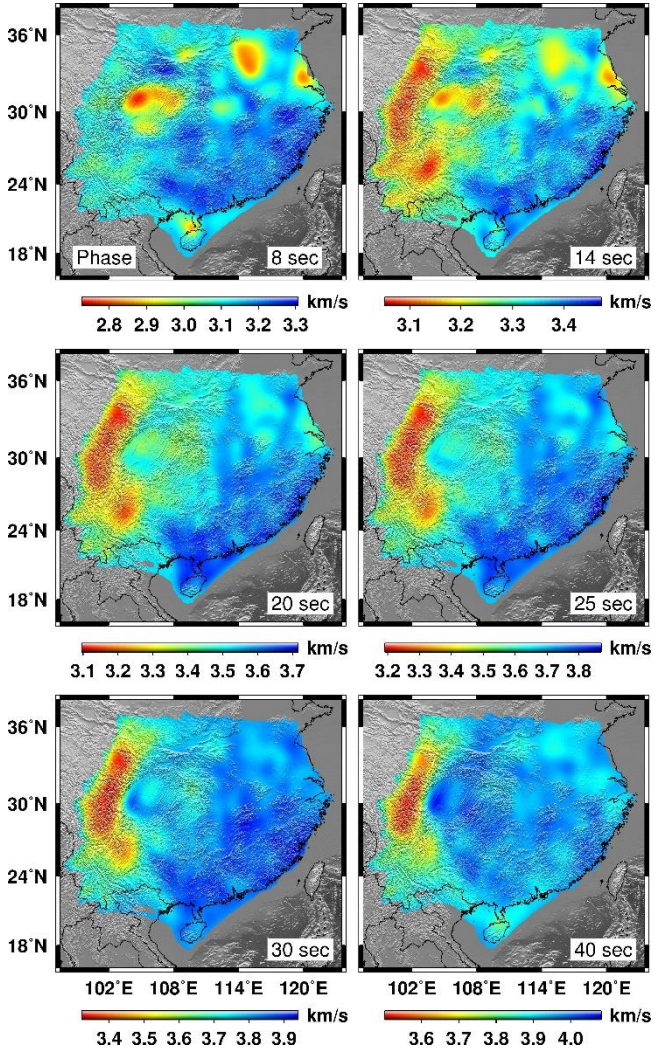
Group velocity from data



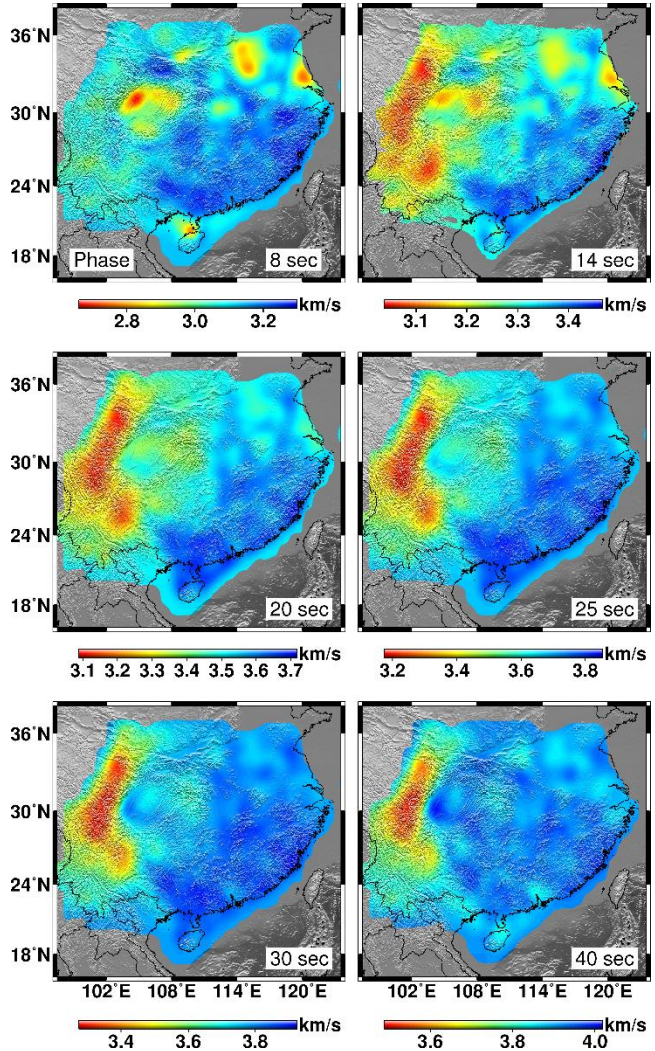
Group velocity from inverted 3-D model



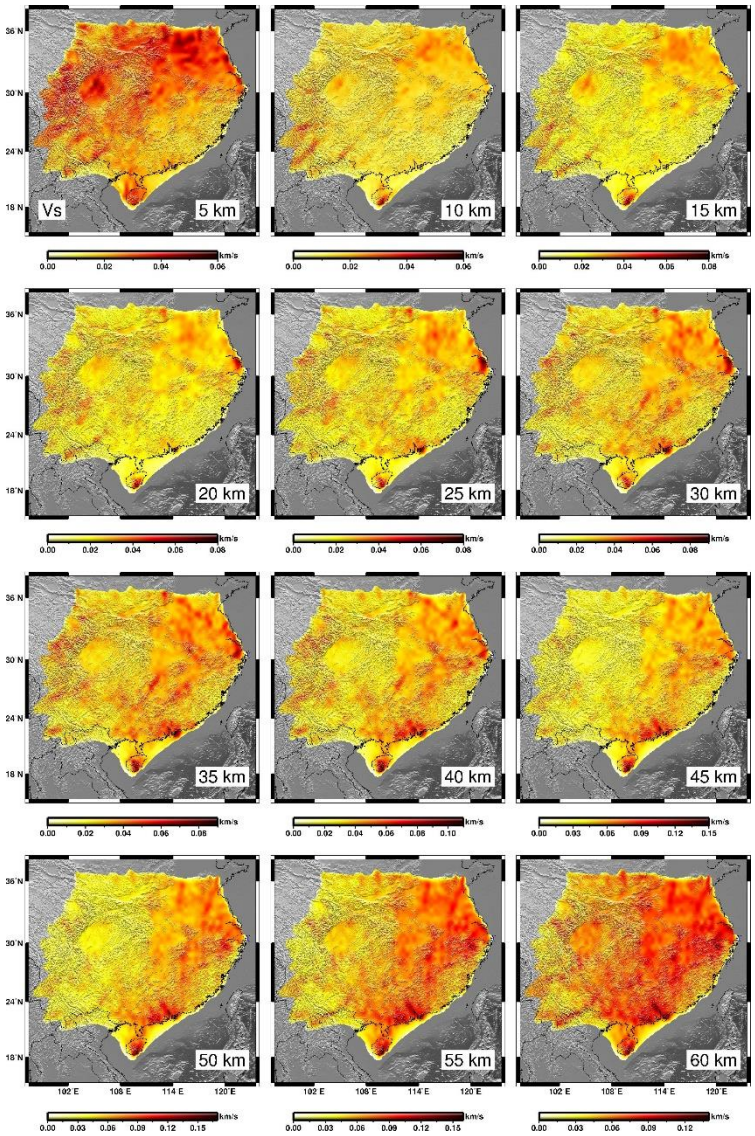
Phase velocity from data



Phase velocity from inverted 3-D model

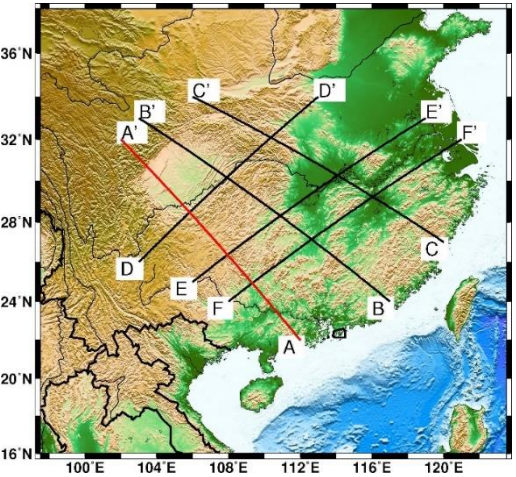


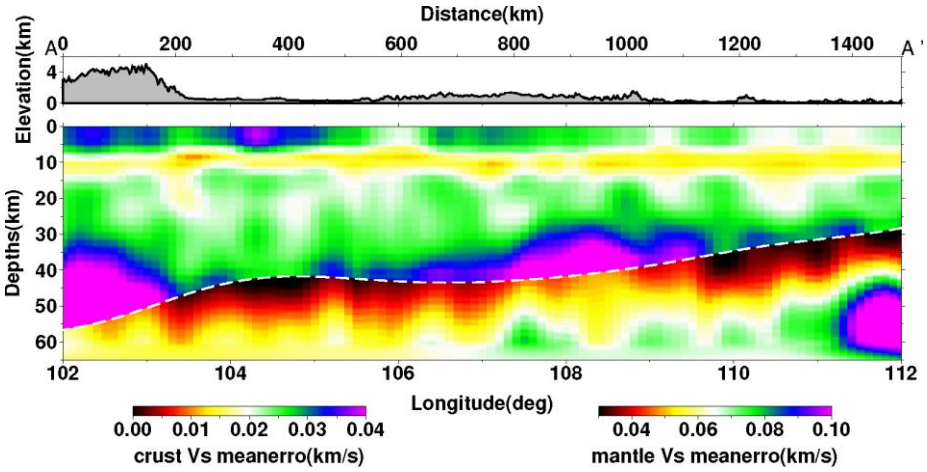
Using bootstrap method to evaluate the model uncertainty. It is less than ~ 1% for most areas at depths from 0 ~ 60 km.

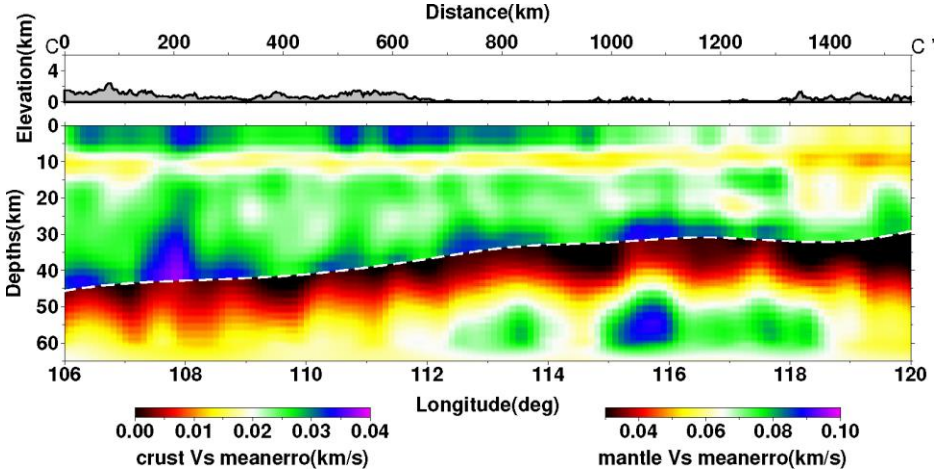


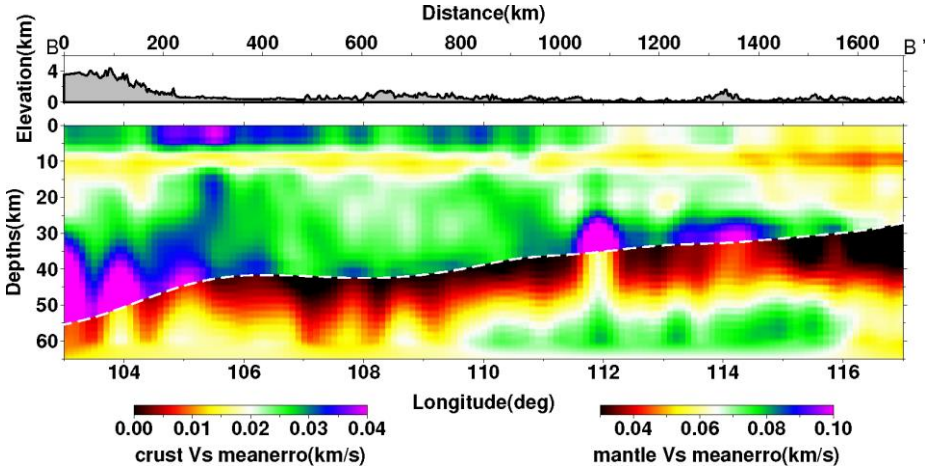
S波模型的均方差分布图

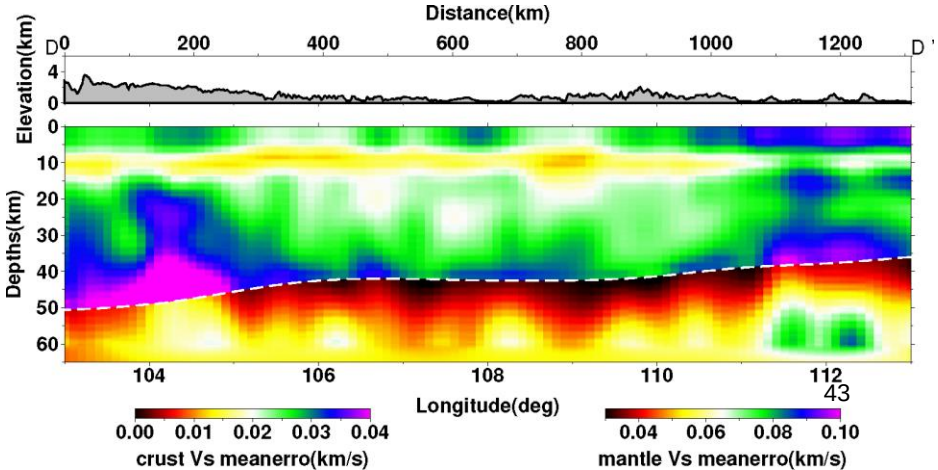
Uncertainties along the vertical cross sections.





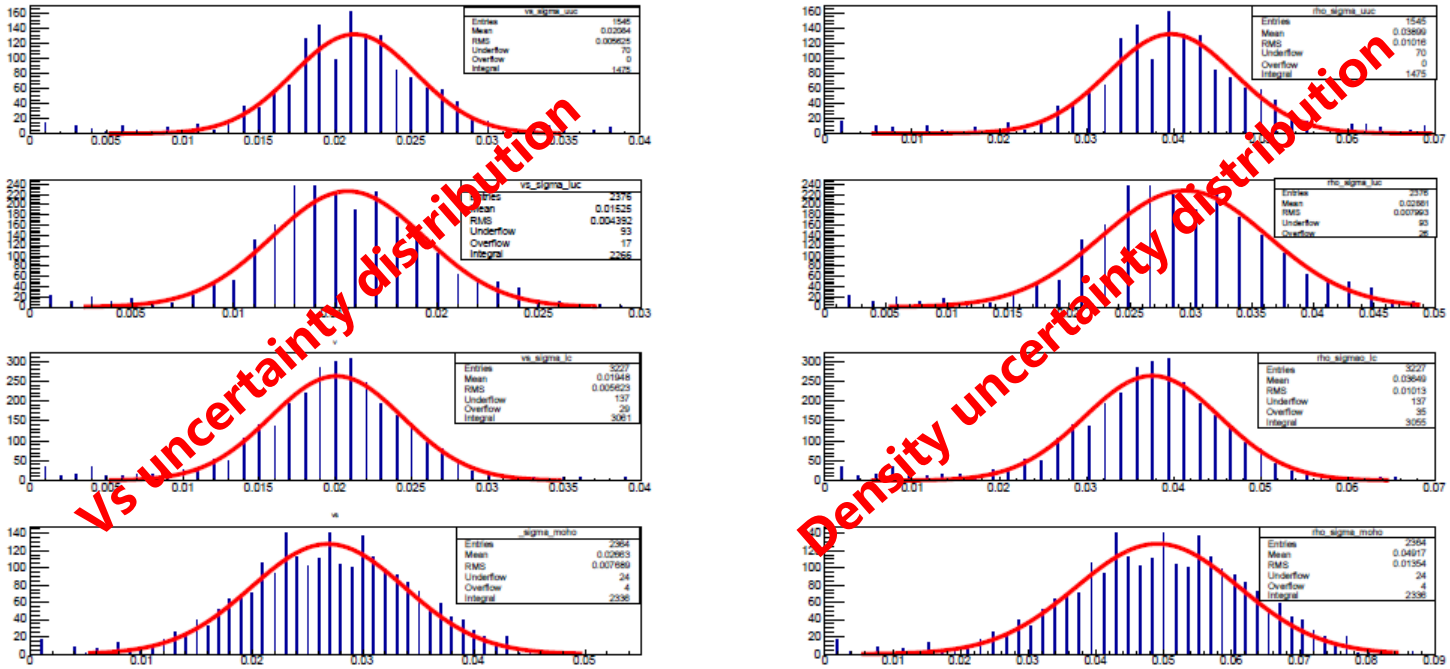






The Density Uncertainty

The density uncertainty are from Vs uncertainty by Error Propagation



The uncertainty of depth is not considered for this moment

Appendix C: Geoneutrino Signal, Mass of Uranium and Radiogenic Heat

This relationship between geoneutrino signal and masses of heat generating elements like uranium will be developed in the following way:

(1) After excluding the region, the proximity argument provides for the signal from the rest of the world:

$$S_{RW}(U) = (4.2 + 14.76 \times m(U)) \pm (-2.56 + 2.61 \times \mathrm{m}(U))$$

where the signal is in TNU, the mass is in units of 10^{17} kg and the interval within the $\pm$ sign corresponds to the full range of models which have been considered (Fiorentini.G et al. 2007).

(2) The regional contribution, calculated in the previous section is

$$S_{reg}(U) = 21.40 \pm 3.98$$

(3) Combining the regional contribution and rest of the world result, then the uranium geoneutrino signal as a function of uranium mass in the Earth is given by:

$$S(U) = S_0(U) \pm \delta(U)$$

Where $S_0(U) = 25.6 + 14.76 \times m(U)$ and $\delta(U) = sqrt((2.61 \times \mathrm{m}(U) - 2.56)^2 + 3.98^2)$

From the signal of U, the Th contribution can be calculated based on an assumed chondritic Th/U ratio. Given the abundances of U and Th and mass of a given layer in the Earth, the radiogenic heat production can be calculated as:

$$H_R(U + Th) = 9.85 \times \mathrm{m}(U) + 2.67 \times \mathrm{m}(Th)$$

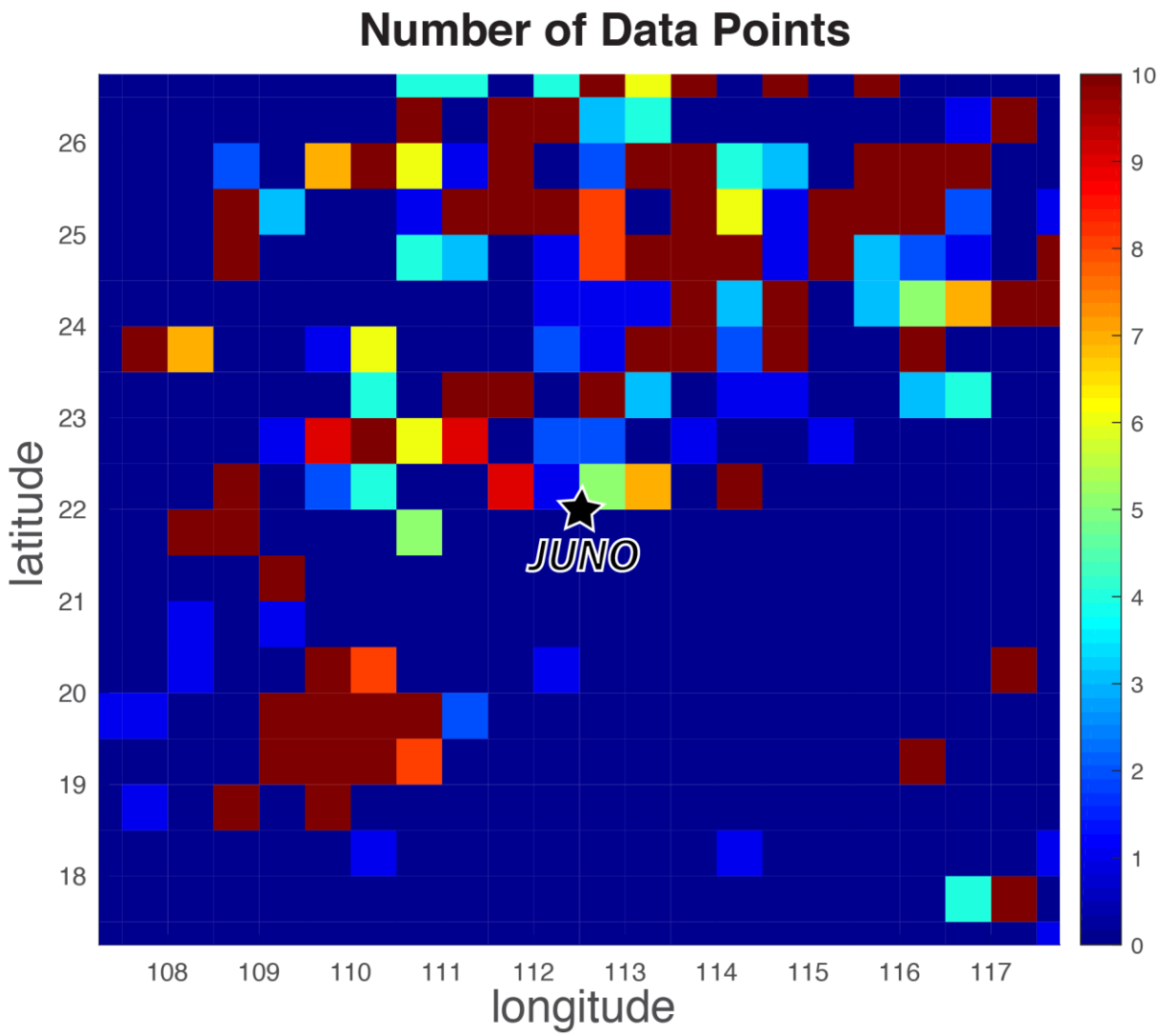
This Study

	U (ppm)	Th (ppm)
Upper Crust	3.2	15
Middle Crust	0.5	1.8
Lower Crust	0.07	0.2

Global Average

	U (ppm)	Th (ppm)	Reference
Upper Crust	2.7	10.5	R&G, 2003, 2014
Middle Crust	1.3	6.5	R&G, 2003, 2014
Lower Crust	0.2	1.2	R&G, 2003, 2014

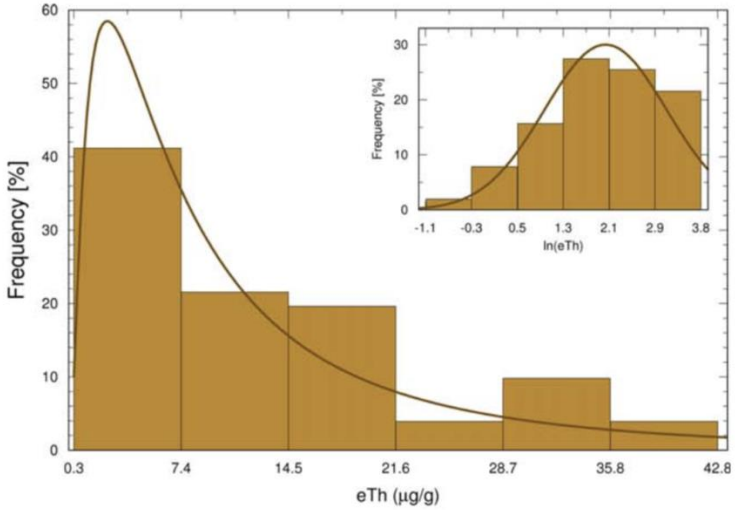
Data points in each cell



Error estimate

For the six units with more than 10 samples (Table 3), the distribution of U and Th concentrations is graphically evaluated using univariate statistics by means of frequency histograms. In order to discriminate the normal and lognormal distributions, the Kolmogorov-Smirnov (K-S) statistical test was applied, providing a *p*-value for rejecting the null hypothesis. The mean and standard deviation are calculated and used for the geochemical modeling of the other three units (CM, OW, and CT), characterized with less than five samples, corresponding approximately to 1% of the total volume of the CUC.

(Strati et al., 2017)

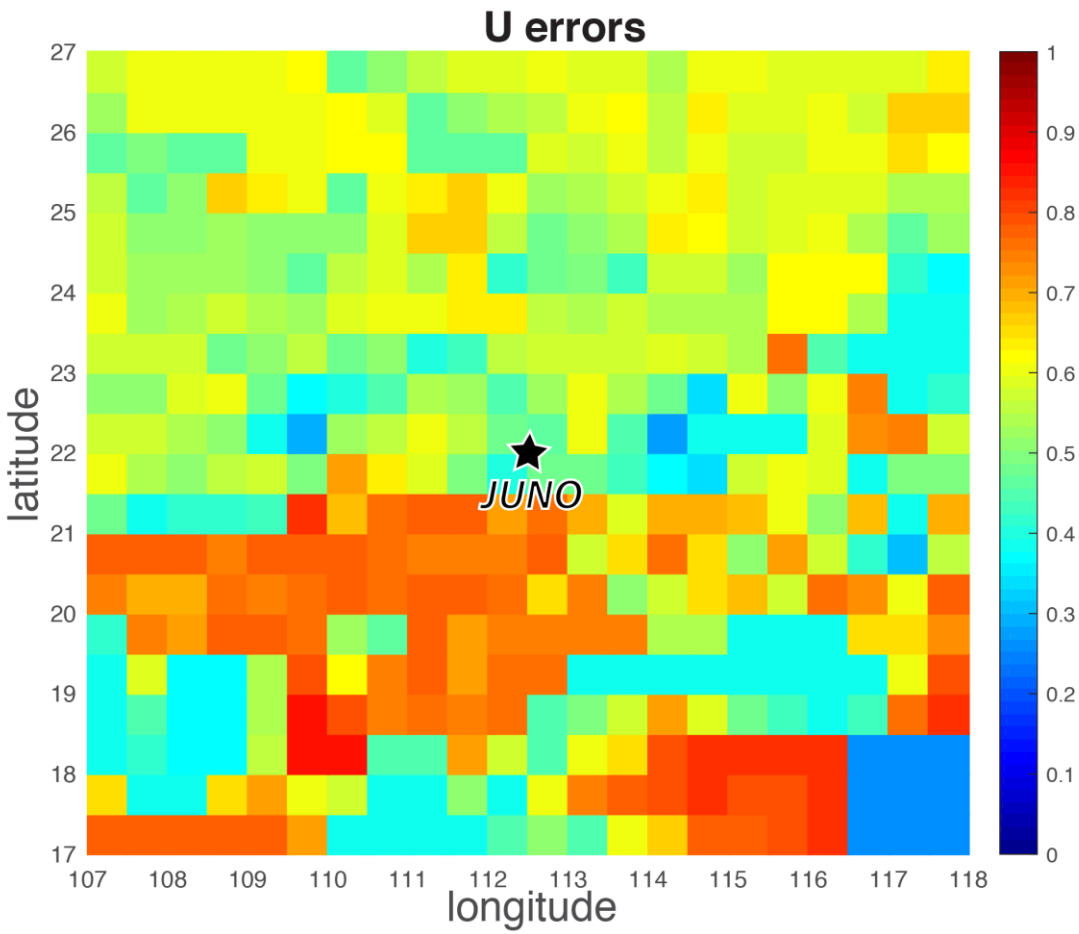


$$\text{样本标准差：} s = \sqrt{s^2} = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n-1}}$$

n ≥ 10

n < 10

Error estimate



U ± σ (μg/g)	Th ± σ (μg/g)
$0.7^{+1.0}_{-0.4}$	$2.7^{+6.0}_{-1.9}$
$2.3^{+4.0}_{-1.5}$	$8.0^{+15.3}_{-5.3}$
$1.2^{+0.6}_{-0.4}$	$5.9^{+2.1}_{-1.6}$
3.3 ± 0.3	15.0 ± 1.5
3.1 ± 0.6	8.2 ± 1.0
$2.7^{+3.4}_{-1.5}$	$10.9^{+17.3}_{-6.7}$
1.1 ± 0.01	5.2 ± 1.5
1.1 ± 0.1	5.1 ± 0.7
1.8 ± 1.1	56.9 ± 27.3

(Strati et al., 2017)

每个格子的误差部分关联，部分独立