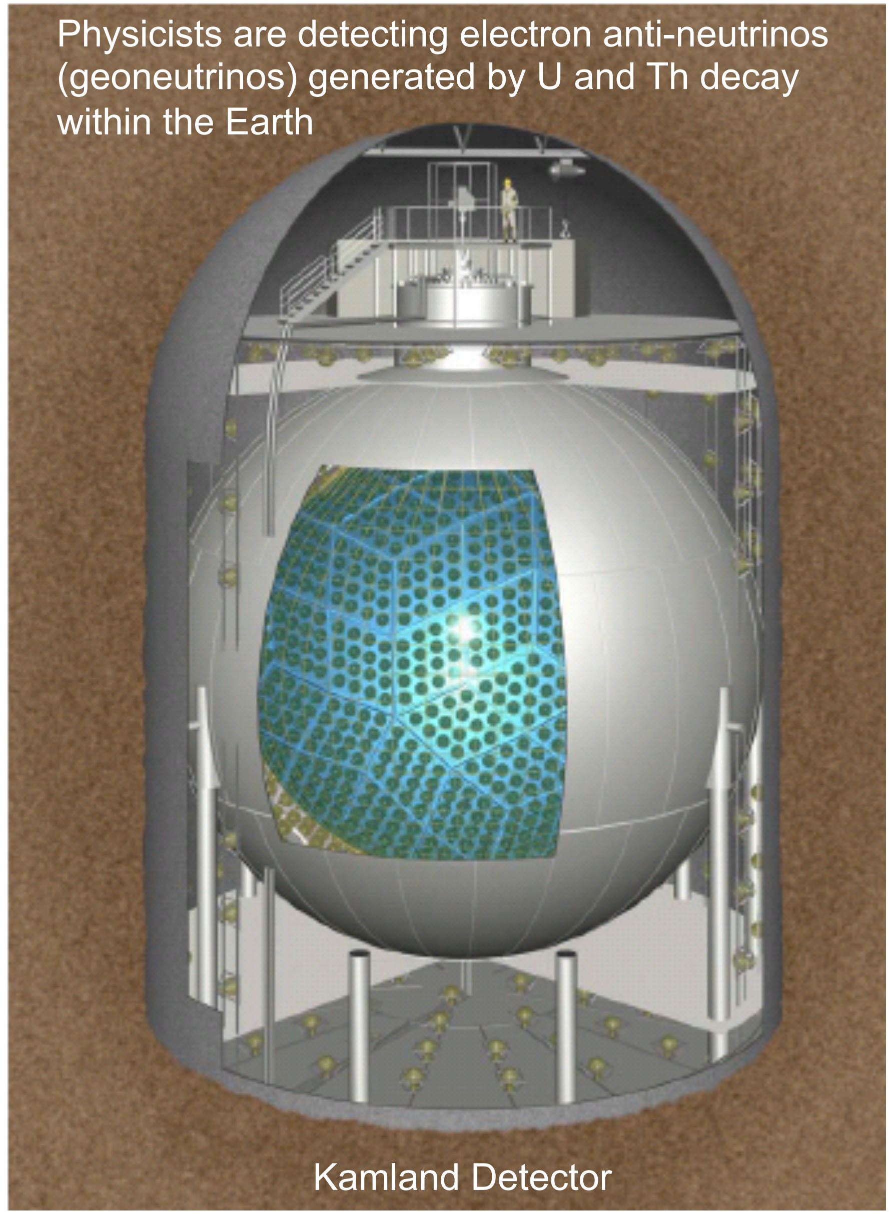
Questions

1) What proportion of the Earth's heat producing elements (K, Th and U) reside today within the continental crust?

2) How has the continental crust composition changed through time?

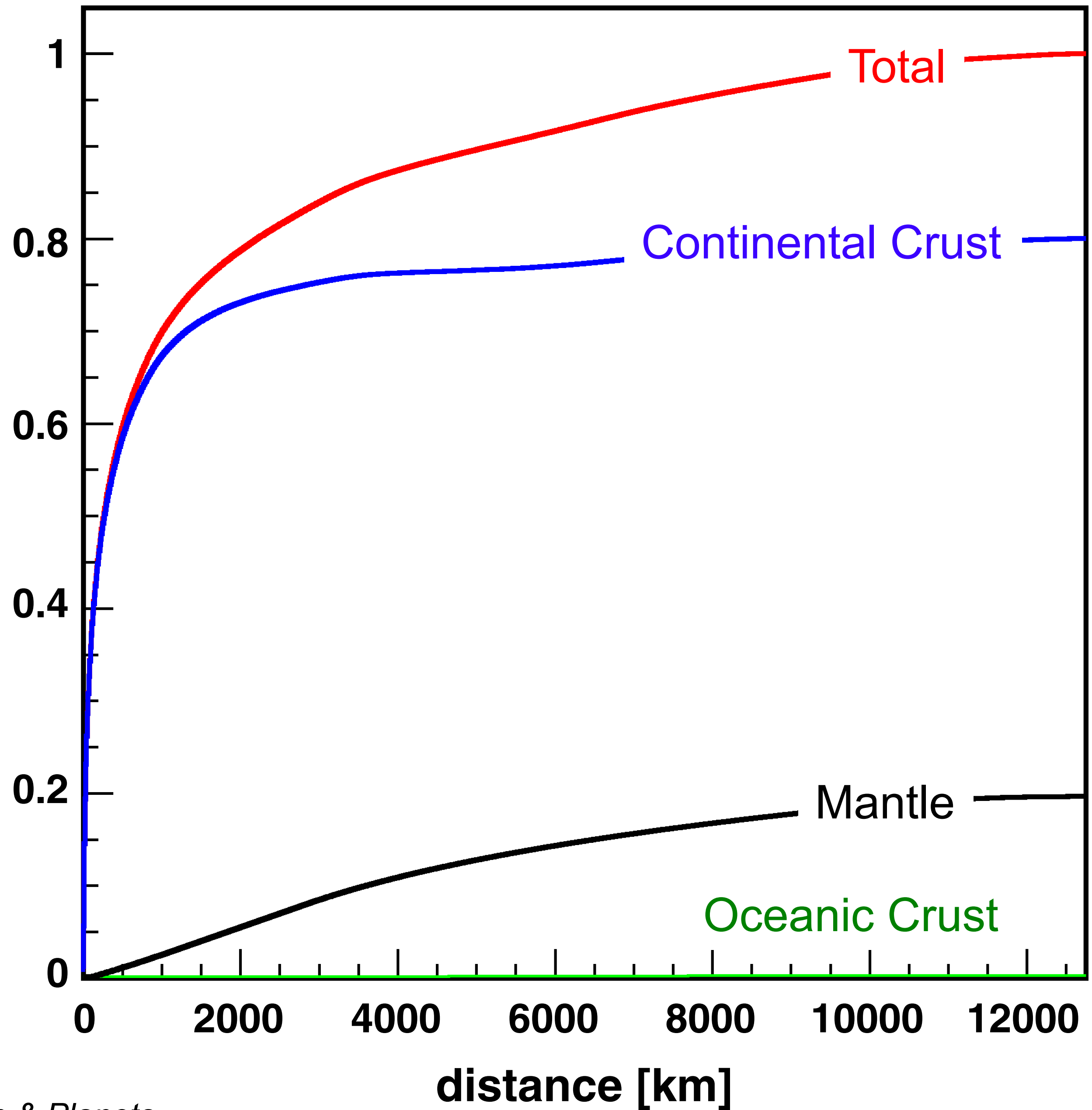
3) When was the continental crust extracted from the mantle? [setting the mantle's heat budget!]

Geoneutrinos: trying to see the mantle from the crust



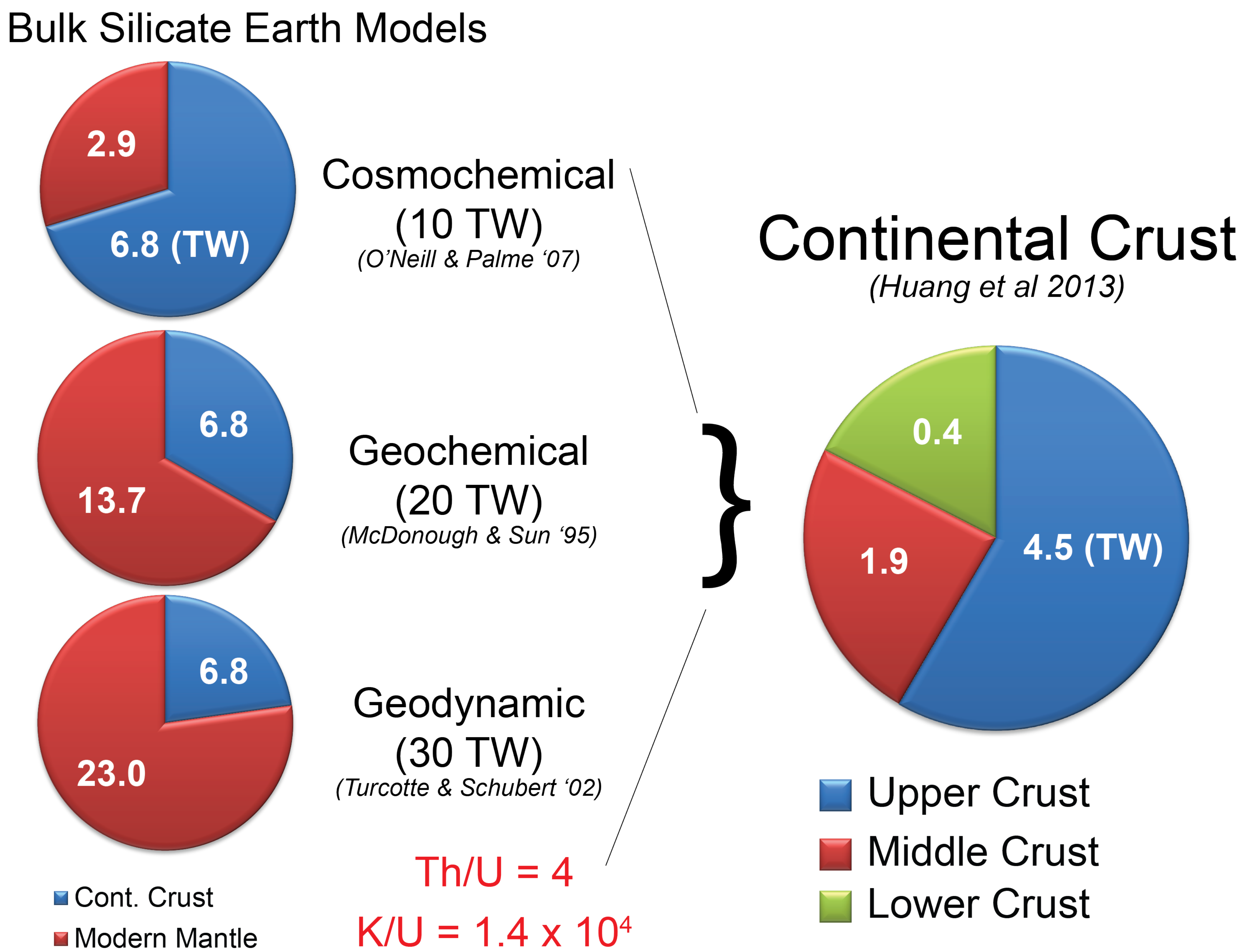
Most of the geoneutrino signal in continental-based detectors originates in the continental crust

Fractional geo-neutrino flux at SNO+*



**Calculated assuming seismological and geochemical reference models*

From Chen, 2006, Earth, Moon & Planets



Bulk Silicate Earth Models
2.9
6.8 (TW)
Cosmochemical
(10 TW)
(O'Neill & Palme '07)
6.8
13.7
Geochemical
(20 TW)
(McDonough & Sun '95)
6.8
23.0
Geodynamic
(30 TW)
(Turcotte & Schubert '02)
Cont. Crust
Modern Mantle
Th/U = 4
K/U = 1.4 x 10^4
Continental Crust
(Huang et al 2013)
0.4
1.9
4.5 (TW)
Upper Crust
Middle Crust
Lower Crust

Estimates of the flux of Geoneutrinos at ongoing and proposed detectors

	Global model Huang et al ’13	Site specific surveys
KamLAND	$31.5^{+4.9}_{-4.1}$	38.1 (Enomoto et al 2007)
Borexino	$40.3^{+4.9}_{-4.1}$	36.2 ± 4.9 (Coltorti et al 2011)
SNO+	$45.4^{+4.9}_{-4.1}$	40^{+6}_{-4} (Huang et al 2014)
Hanohano	$12.0^{+0.7}_{-0.6}$	

Geoneutrino Flux on Earth Surface

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

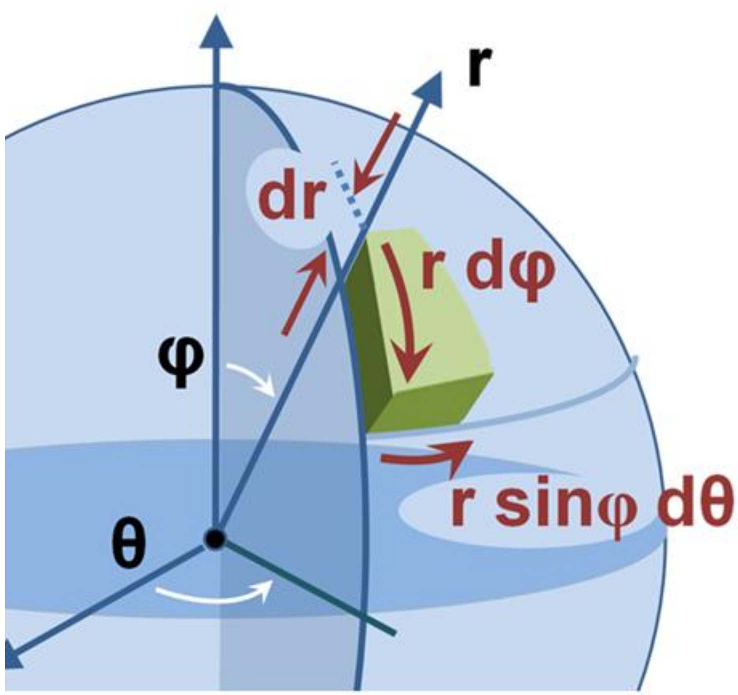
Abundance and density of the source unit

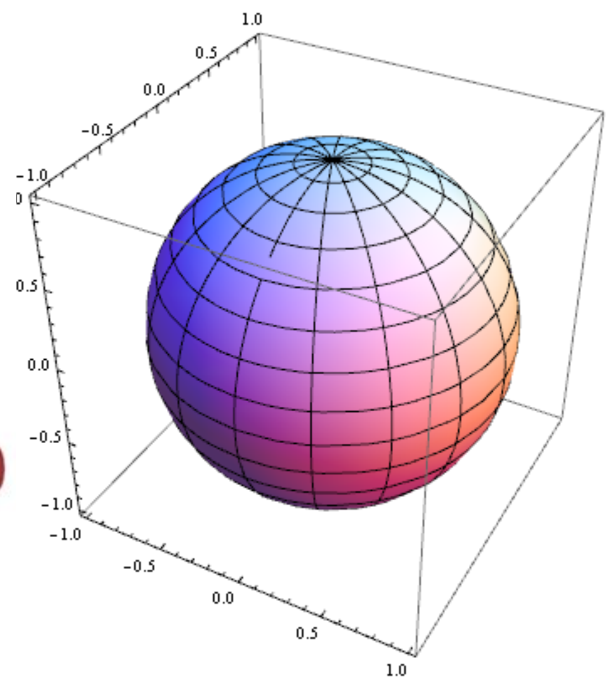
Distance between source unit and detector

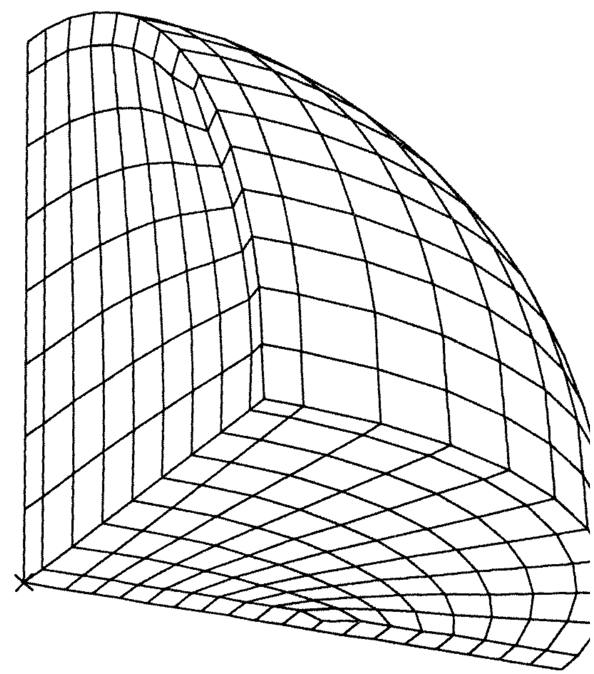
Earth structure (ρ and L) and **chemical composition** (a)

Constructing a 3-D reference model Earth

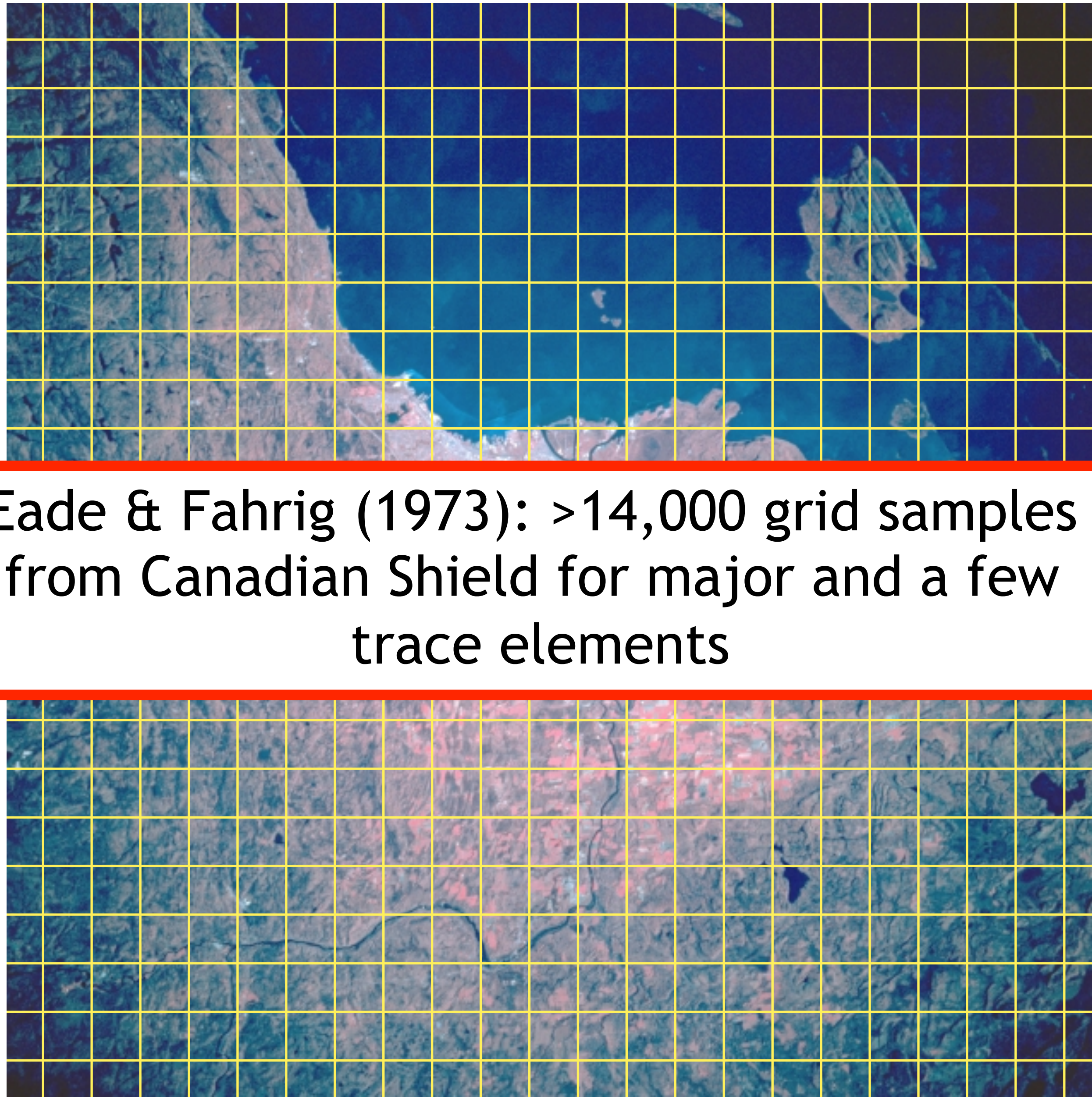
assigning chemical and physical states to Earth voxels







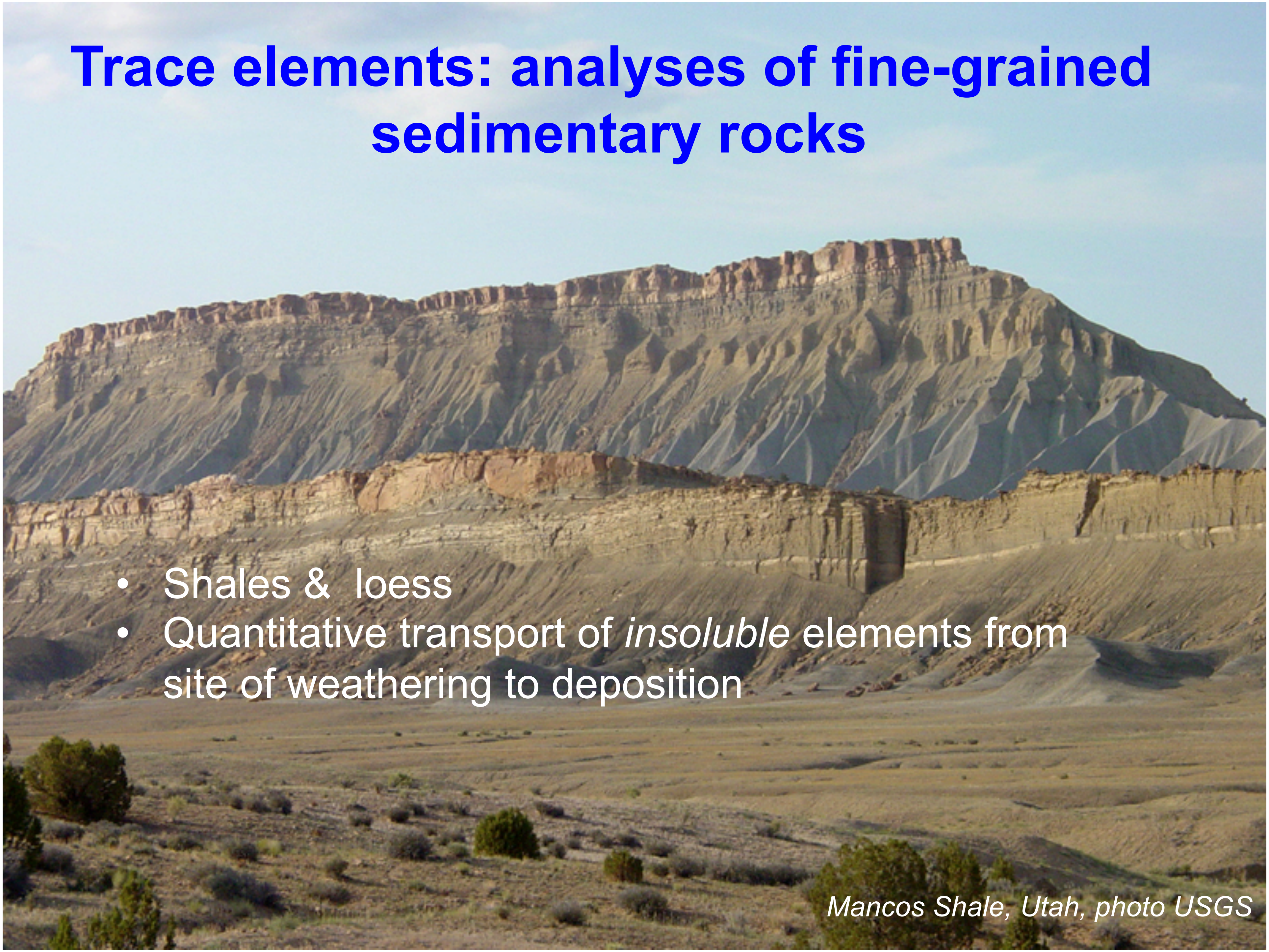
Upper crust major elements: grid sampling



Eade & Fahrig (1973): >14,000 grid samples from Canadian Shield for major and a few trace elements

Space shuttle view of Thunder Bay, Ontario

Trace elements: analyses of fine-grained sedimentary rocks



- Shales & loess
- Quantitative transport of *insoluble* elements from site of weathering to deposition

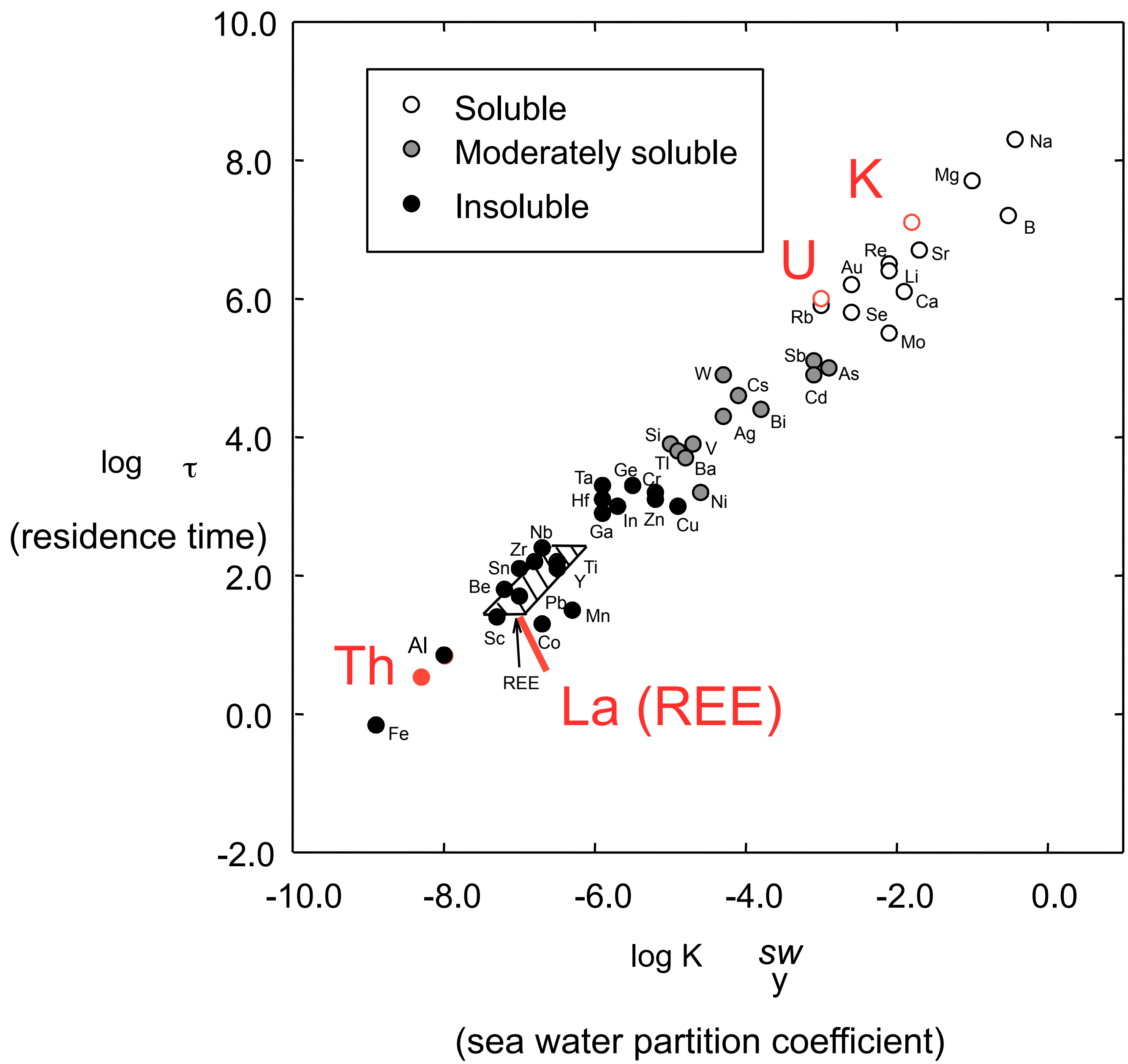
Mancos Shale, Utah, photo USGS

Goldschmidt's idea


Greenland Photo: Steve Jurvetson

- Glaciers pulverize rocks as they move
- Deposits less susceptible to modification by weathering or sorting
- Continental ice sheets sample large areas
- Sample fine-grained glacial deposits to determine composition of average UCC

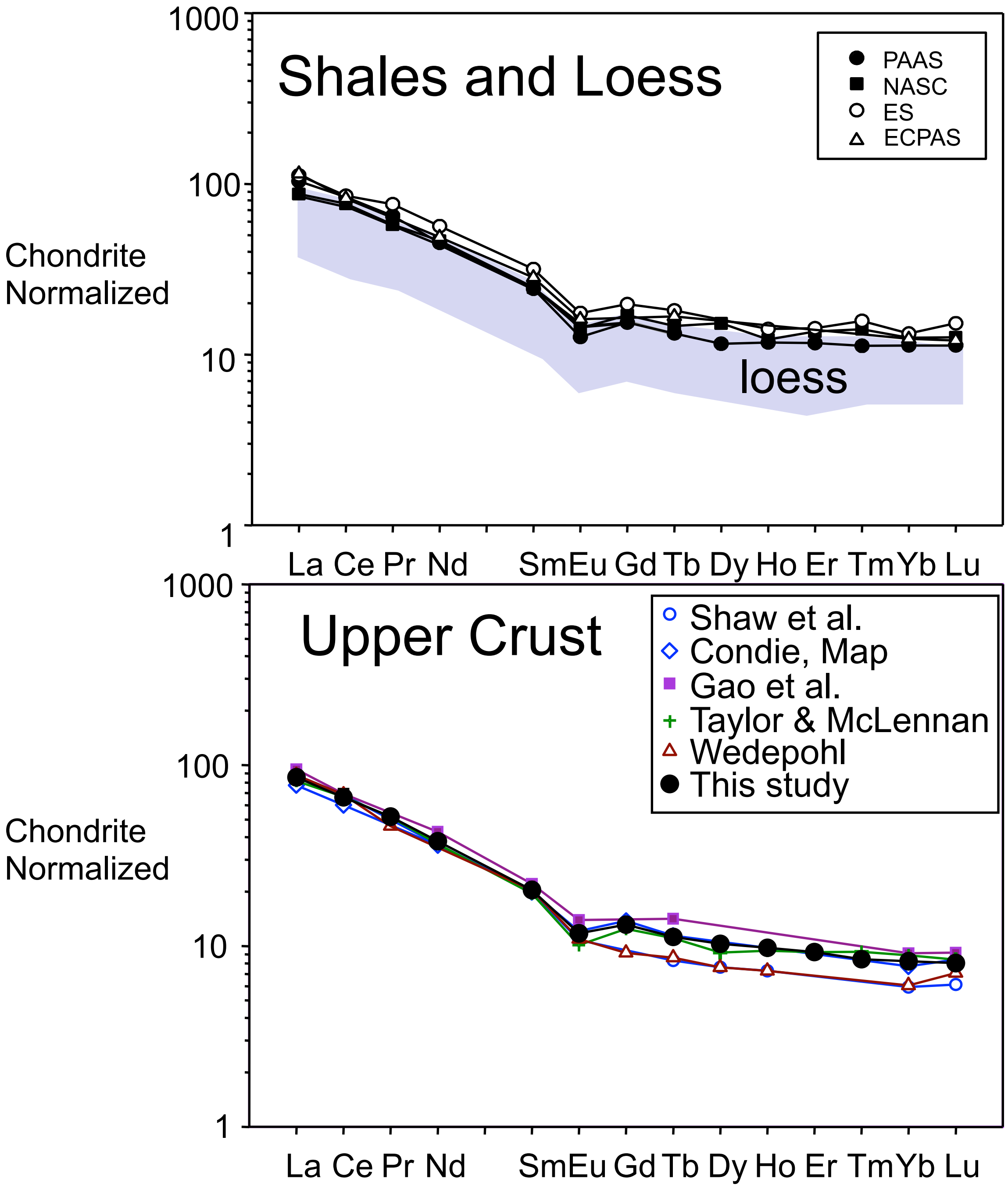

Glacial outwash, PA



<u>Insoluble elements</u>:

Transferred from source of weathering to sediments

Taylor & McLennan, 1985

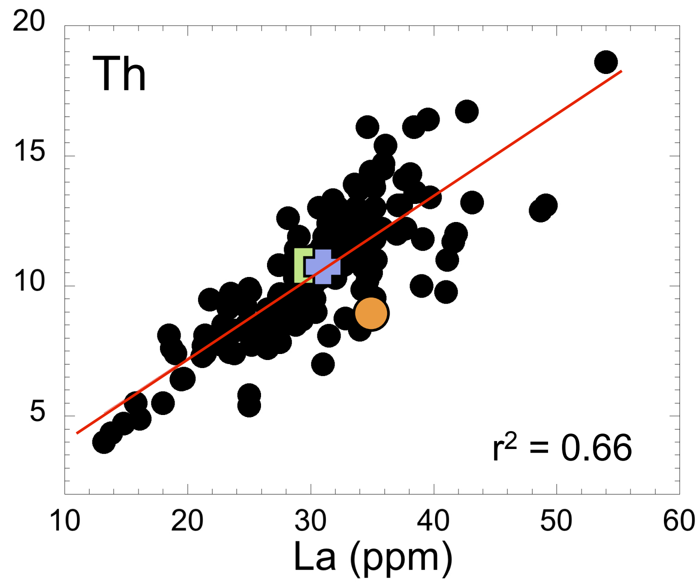


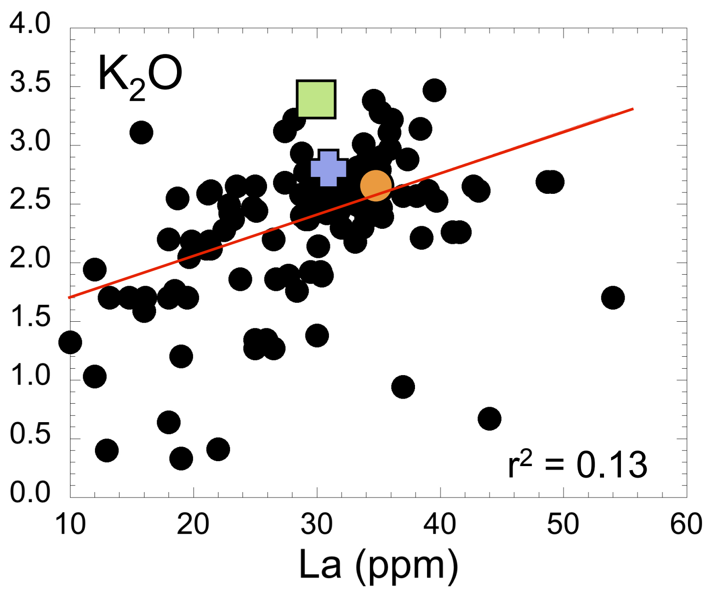
Rare earth element concentrations of upper crust are well constrained

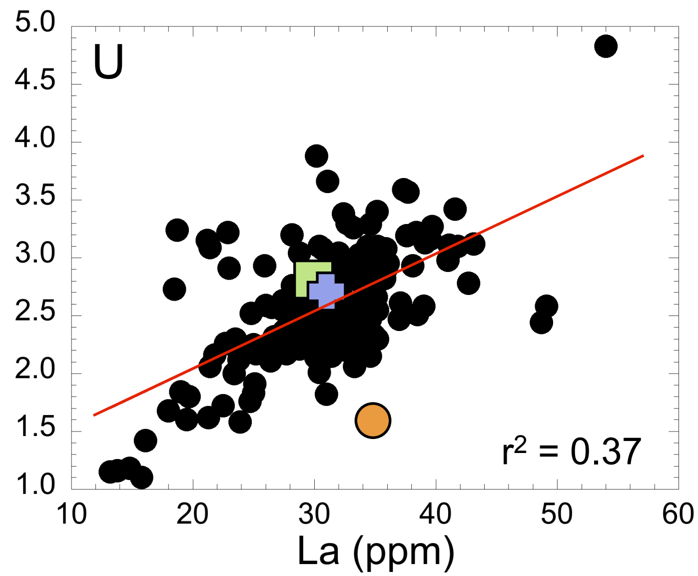
Rudnick & Gao, 2003

Concentrations linked to LREE

Loess data







Upper crustal Estimates

- Rudnick & Gao, 2003
- Taylor & McLennan, 1985
- Gao et al., 1998

First-order Observations

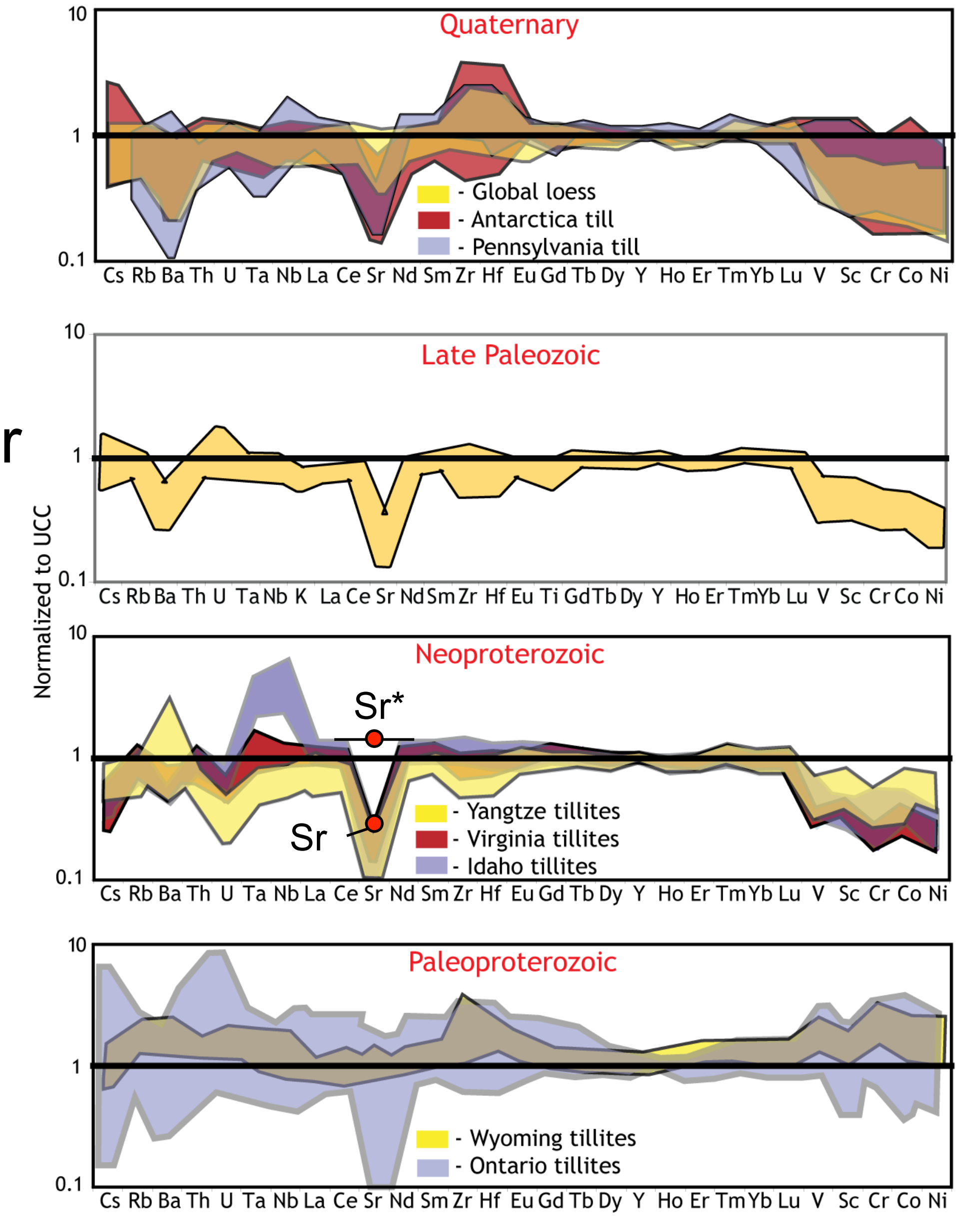
Less scatter on diagrams

Regional differences easier to see

Persistent depletions in Sr (except for WY tillites)

Temporal changes (e.g., transition metals)

$$Sr/Sr^* = \frac{Sr/Sr_{UCC}}{\sqrt{(Ce_{UCC} * Nd_{UCC})}}$$

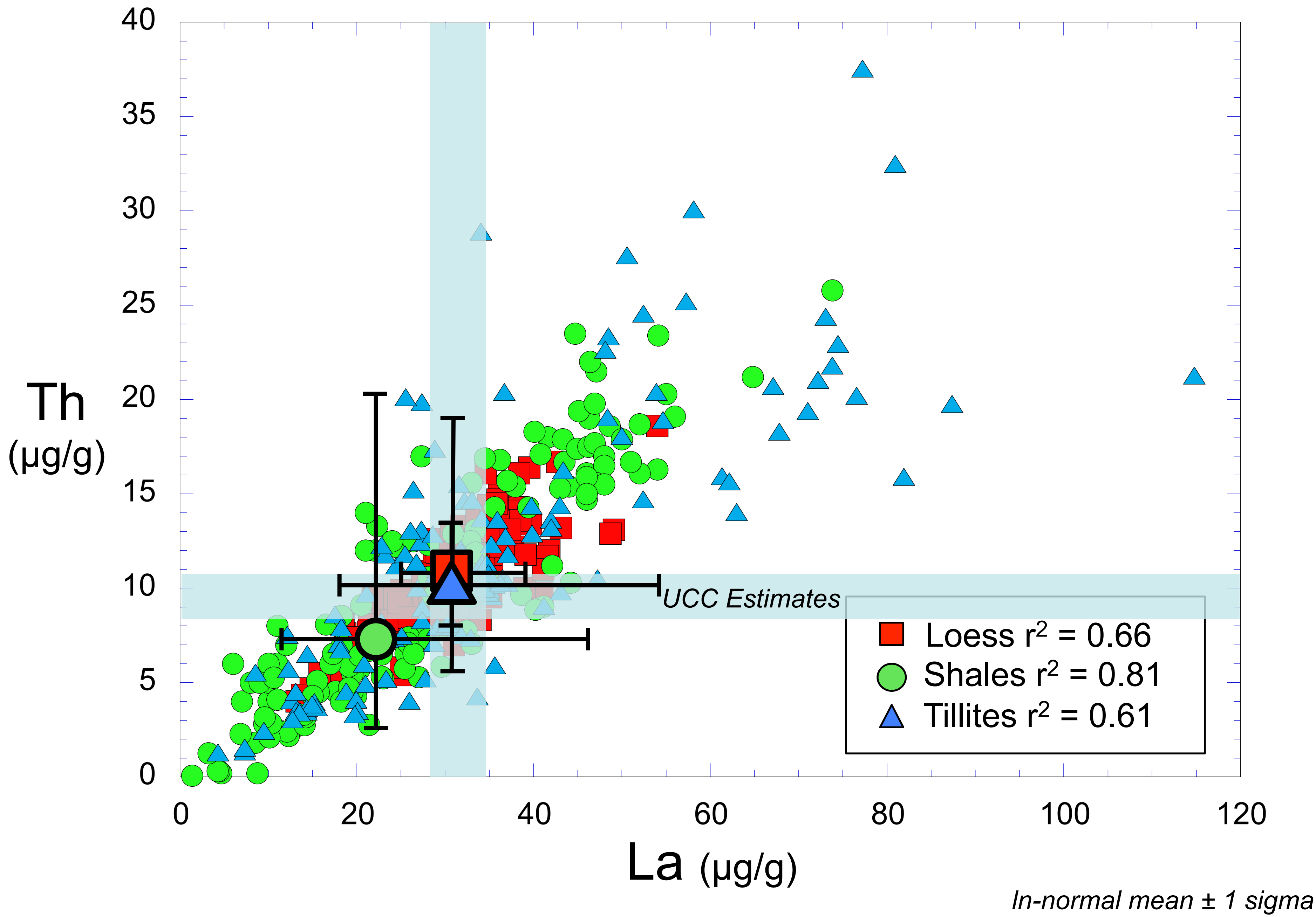


UCC estimates

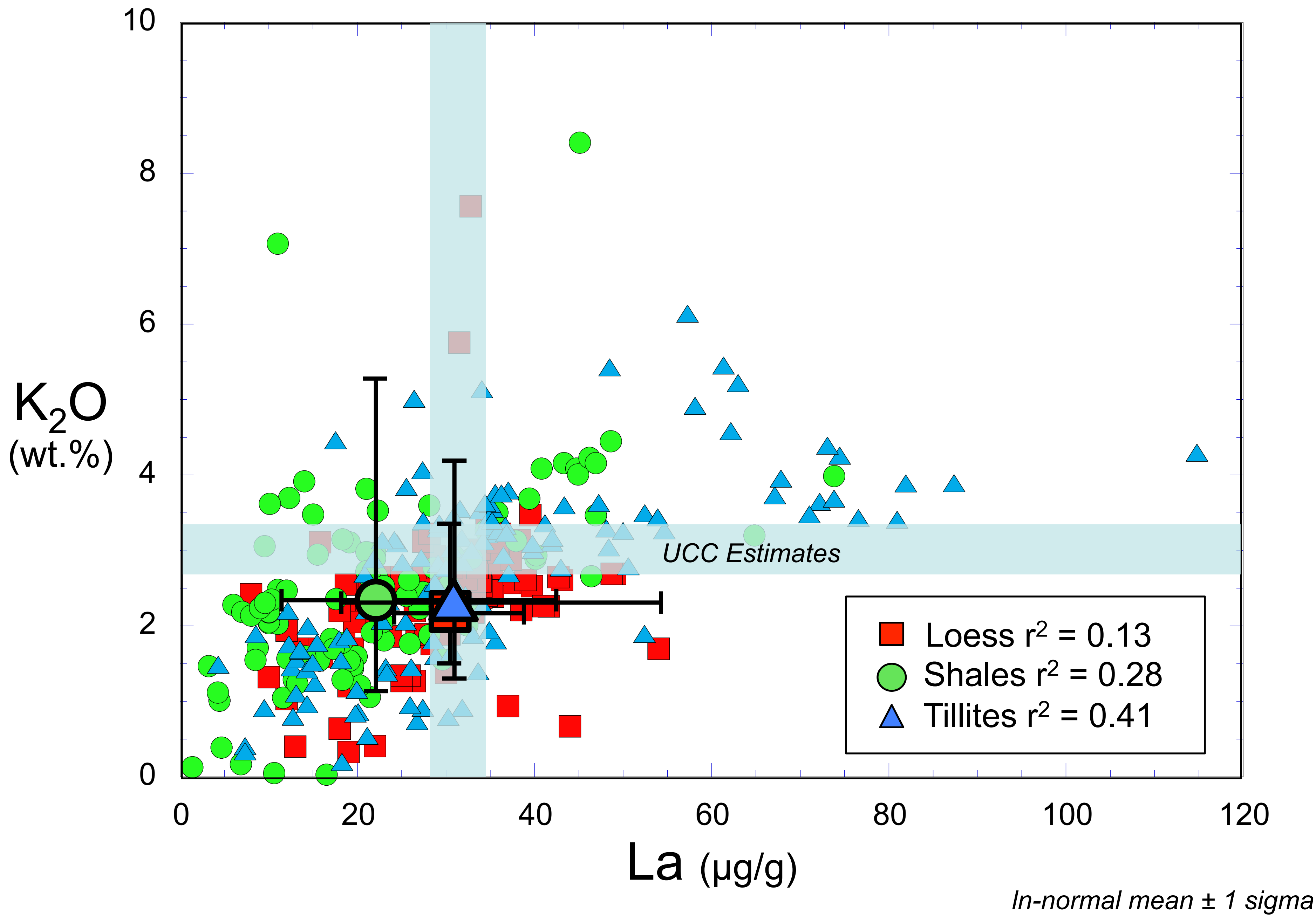
	K_2O (%)	Th µg/g	U µg/g
Eade & Fahrig, '73	2.9	10.8	1.5
Shaw et al., '67, '76	3.2	10.3	2.5
Condie, '93	2.8	8.6	2.2
Gao et al., '98	2.7	9.0	1.6
Taylor & McLennan	3.4	10.7	2.8
Rudnick & Gao '03	2.8	10.5	2.7

25% variation

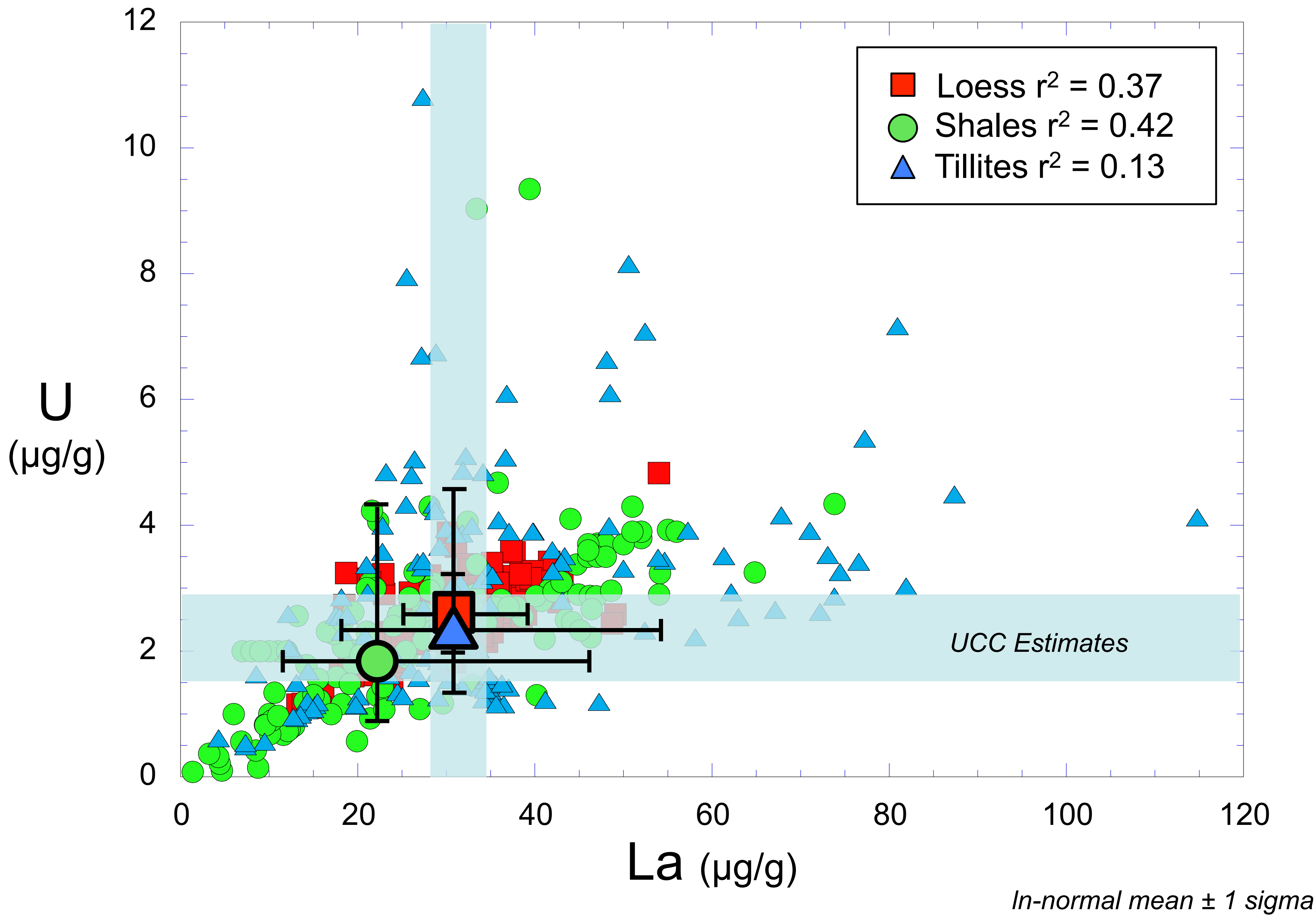
~90% variation

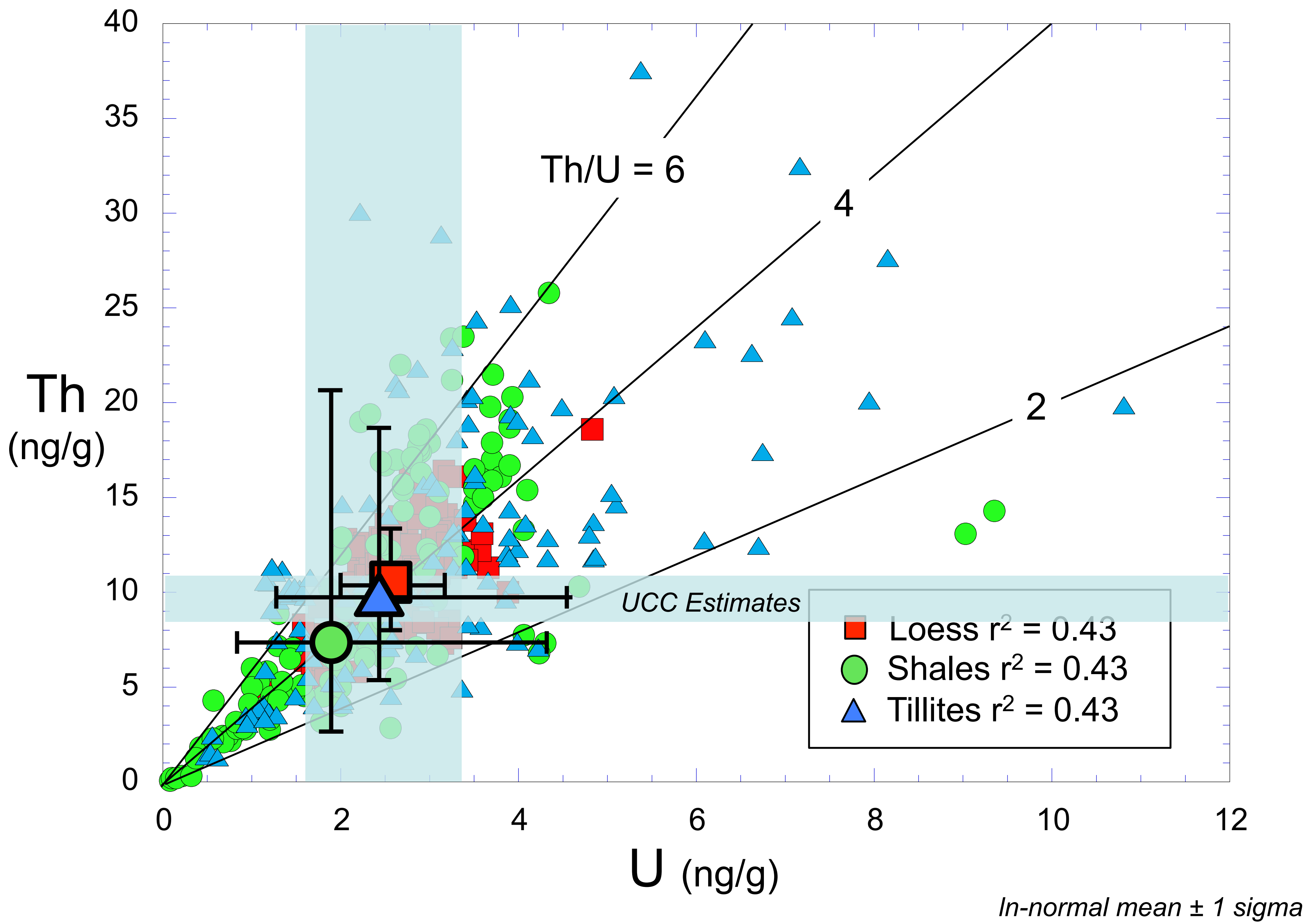


Th
(µg/g)
La (µg/g)
0
5
10
15
20
25
30
35
40
0
20
40
60
80
100
120
UCC Estimates
Loess r2 = 0.66
Shales r2 = 0.81
Tillites r2 = 0.61
ln-normal mean ± 1 sigma

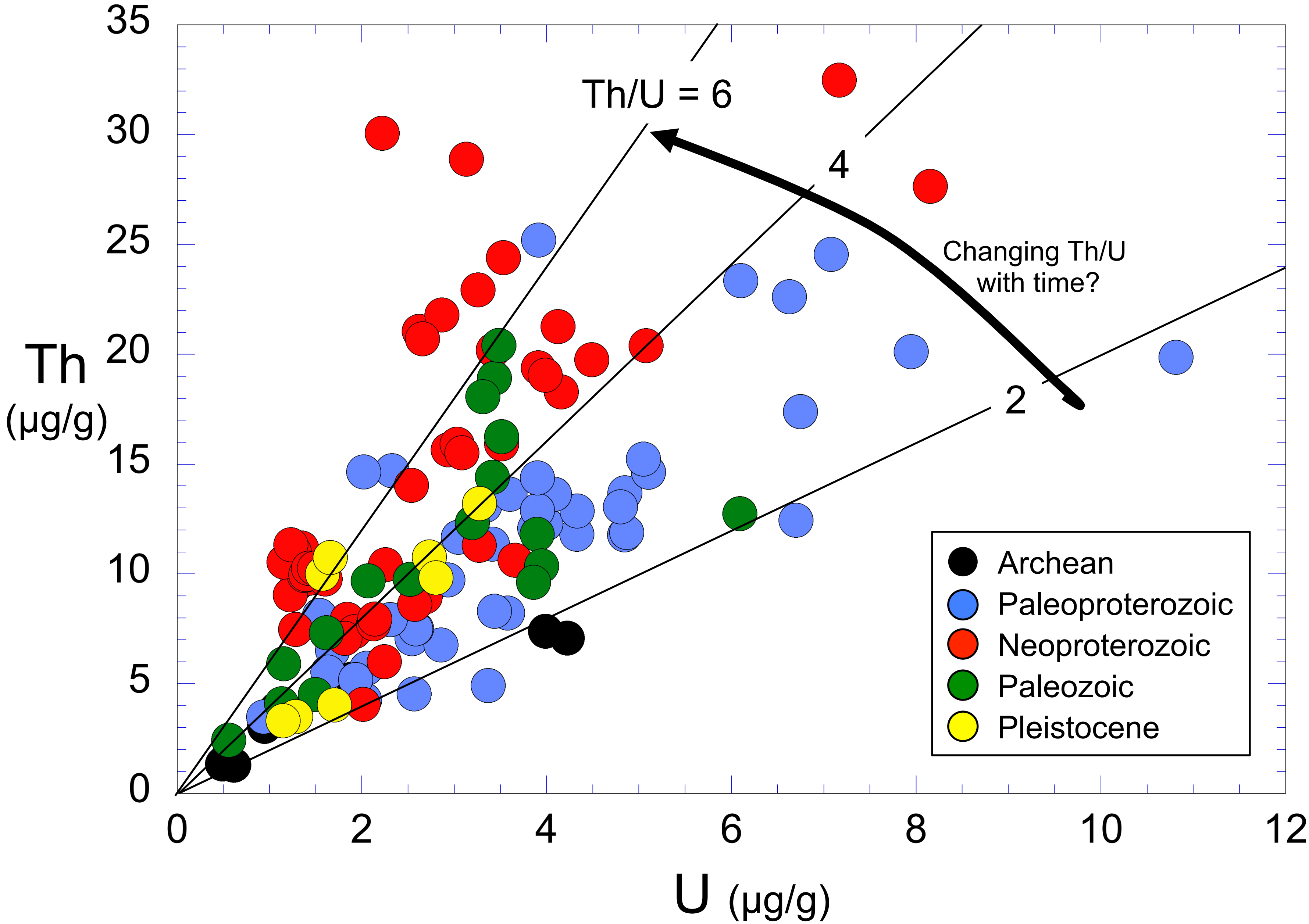


K$_2$O
(wt.%)
10
8
6
4
2
0
0
20
40
60
80
100
120
La (µg/g)
UCC Estimates
Loess r^2 = 0.13
Shales r^2 = 0.28
Tillites r^2 = 0.41
ln-normal mean ± 1 sigma


Loess r² = 0.37
Shales r² = 0.42
Tillites r² = 0.13
UCC Estimates
U
(μg/g)
La (μg/g)
0
2
4
6
8
10
12
0
20
40
60
80
100
120
ln-normal mean ± 1 sigma

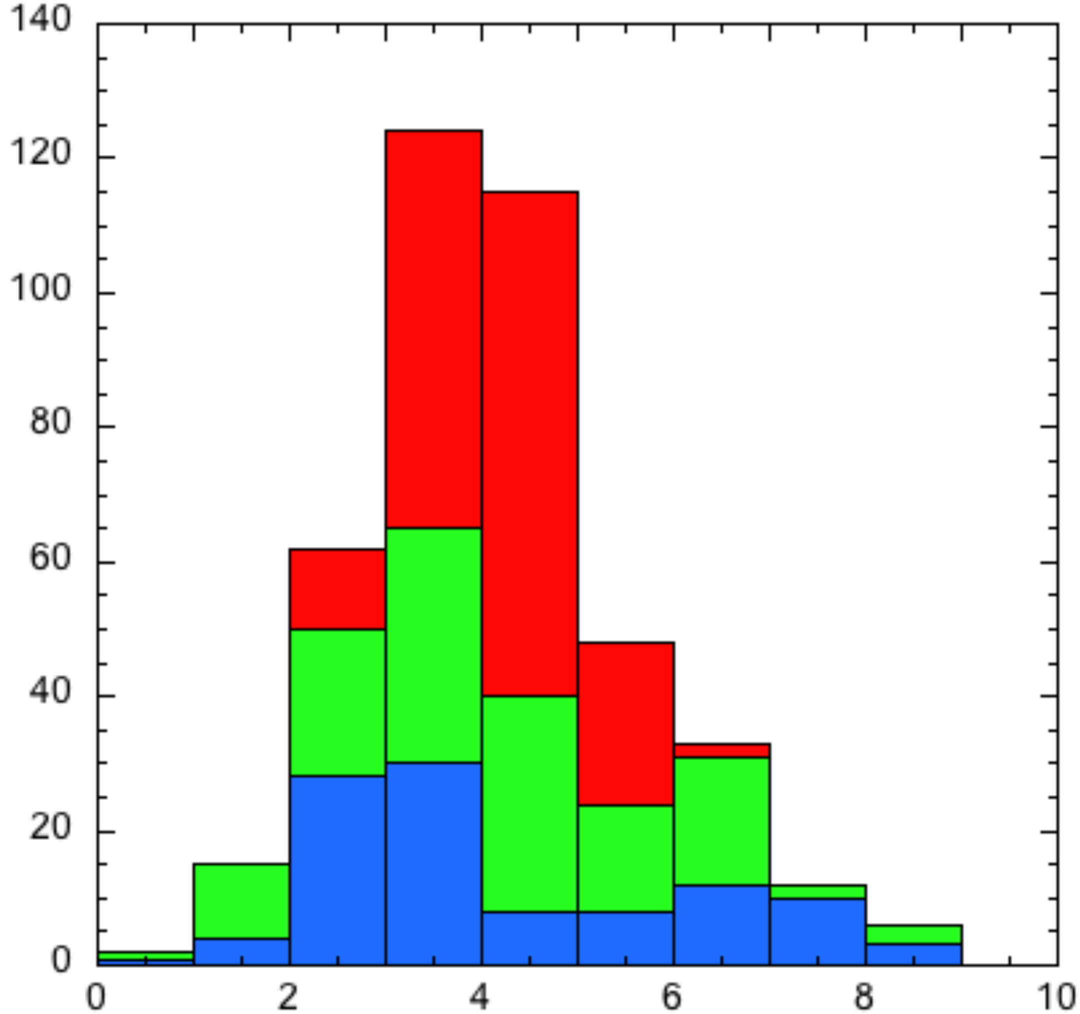


Th
(ng/g)
40
35
30
25
20
15
10
5
0
0
2
4
6
8
10
12
U (ng/g)
Th/U = 6
4
2
UCC Estimates
Loess r² = 0.43
Shales r² = 0.43
Tillites r² = 0.43
ln-normal mean ± 1 sigma



Th
(µg/g)
U (µg/g)
Th/U = 6
4
2
Changing Th/U
with time?
Archean
Paleoproterozoic
Neoproterozoic
Paleozoic
Pleistocene
0
5
10
15
20
25
30
35
0
2
4
6
8
10
12

Th/U ratio of the UCC



	Loess	Shales	Tillites
Mean	4.2	4.1	4.4
Median	4.1	4.1	3.7
Ln Mean	4.1	3.8	4.0
n	172	125	135

All samples converge on Th/U ratio of 4.0 ± 0.2

The UCC contains much of the K, Th and U in the continental crust

	K	Th	U
UCC	2.32%	10.5 µg/g	2.7 µg/g
UCC mass*	15.6	70.7	18.2
Bulk crust mass*	31.4	115.8	27
% in UCC	50%	61%	67%

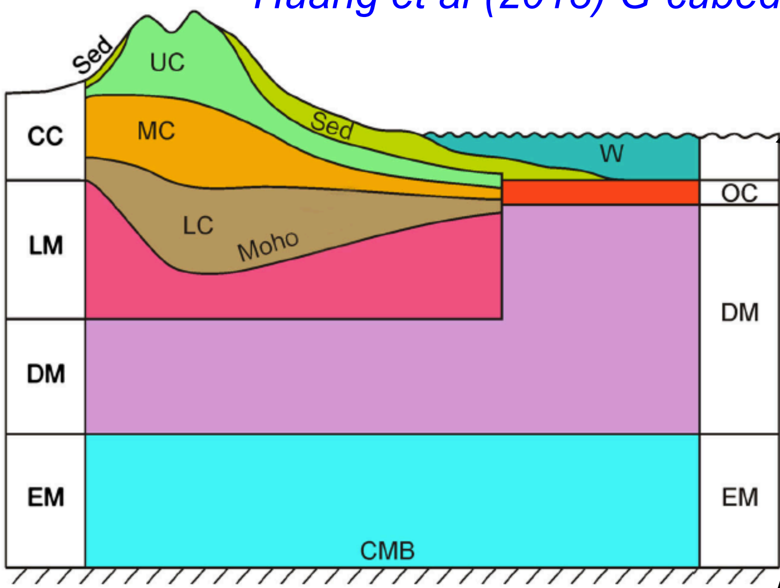
** x 10^{19} kg for K, x 10^{15} kg for Th & U*

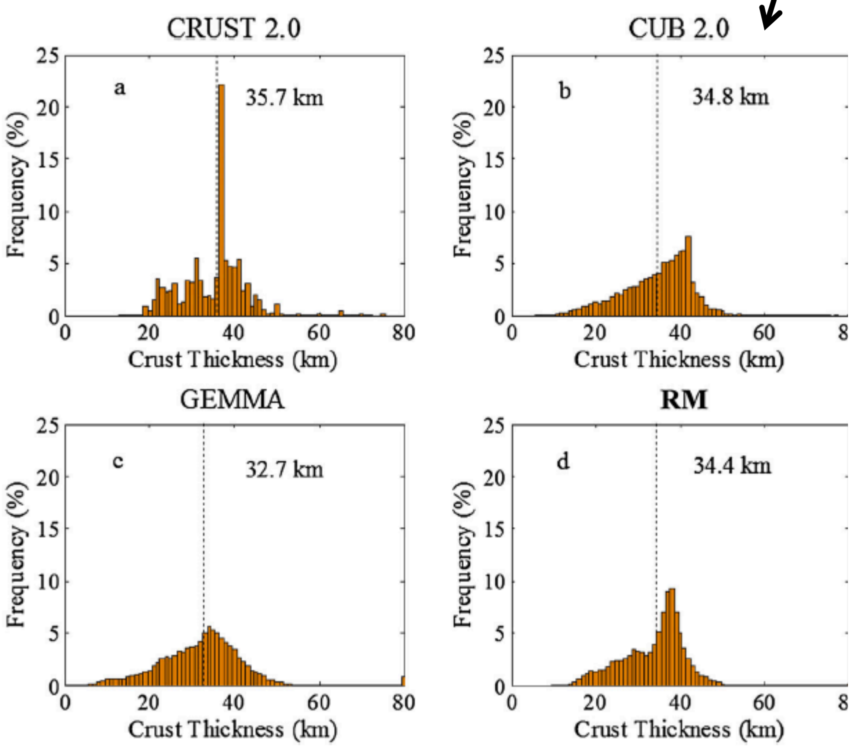
Huang et al., 2013, G-cubed

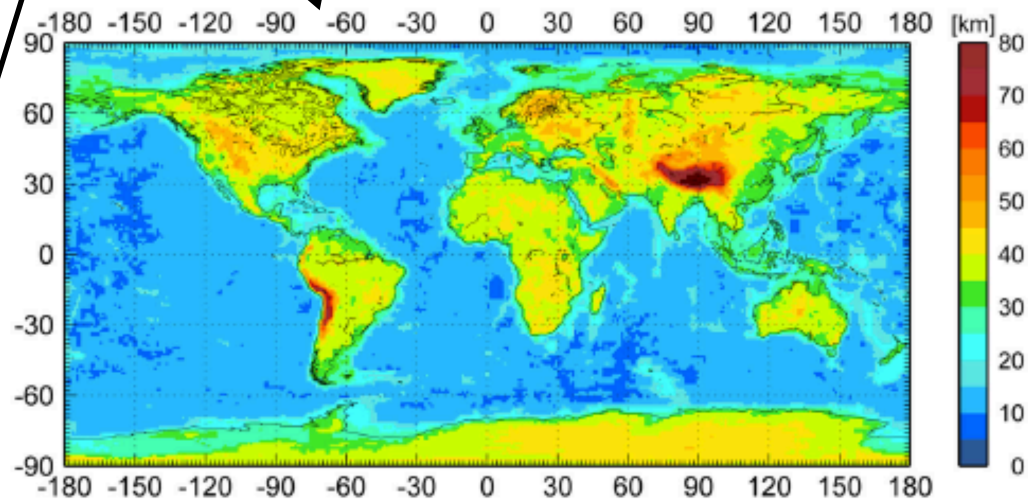
Global Earth Reference Model

- 7 layers for the top 200 km
- Integrate 3 global models for the crust
- New crust model with uncertainties

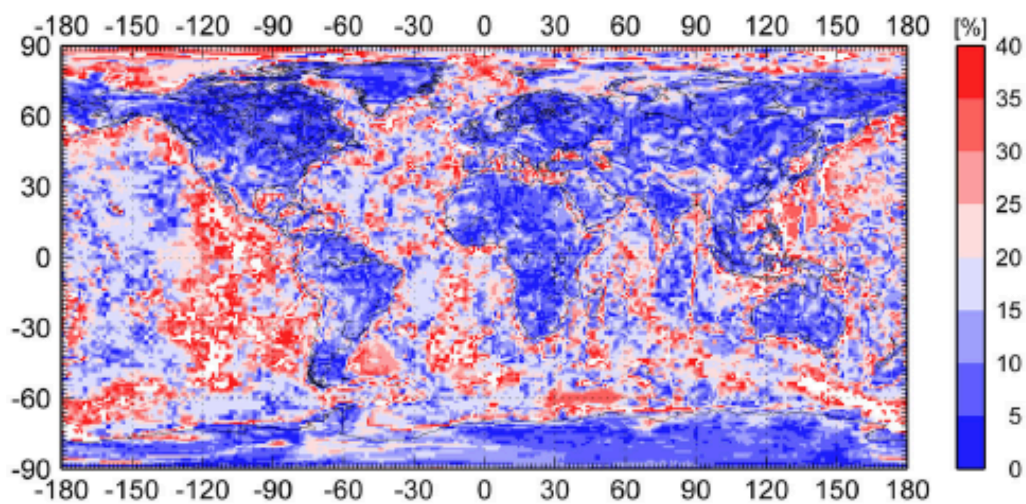
Huang et al (2013) G-cubed





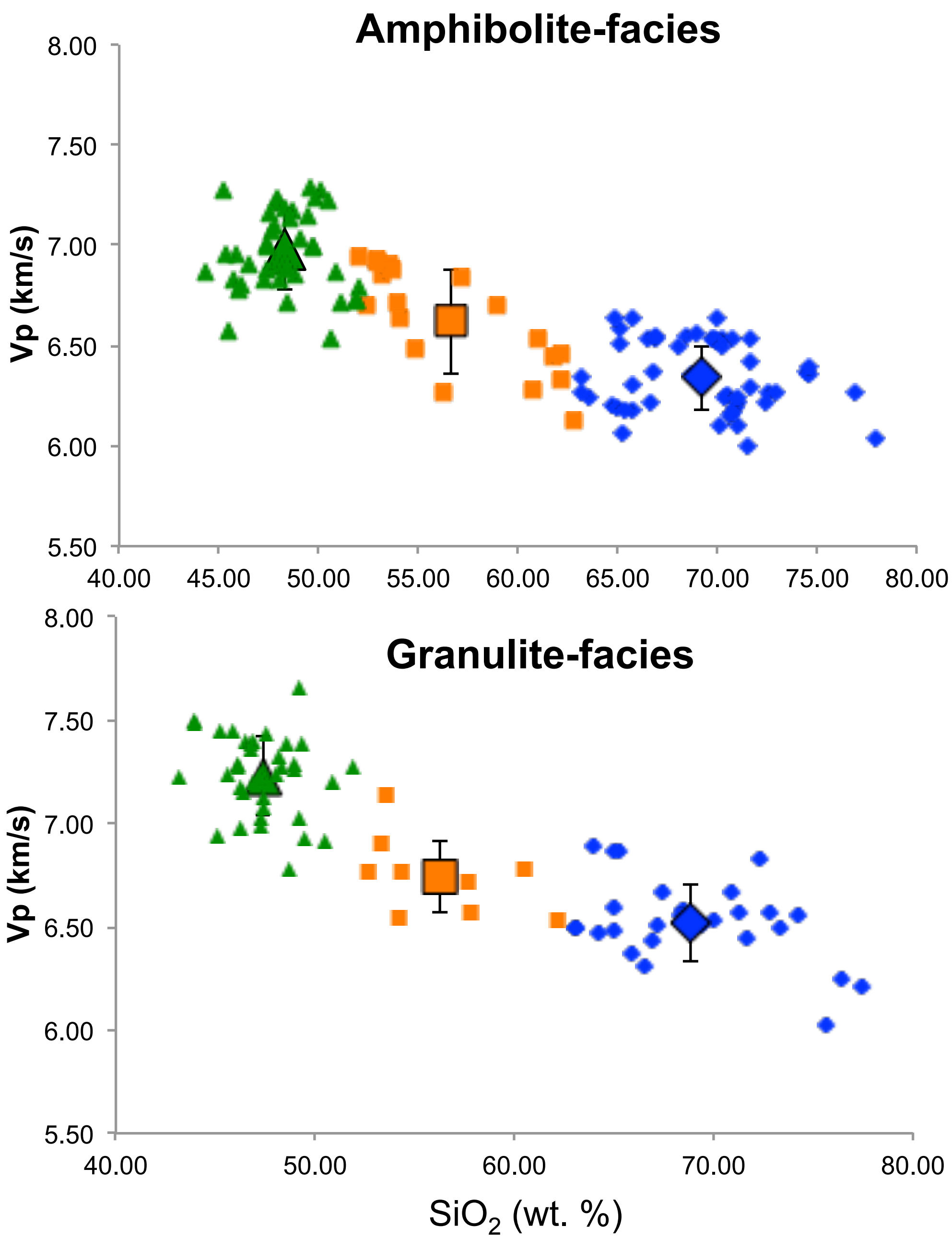


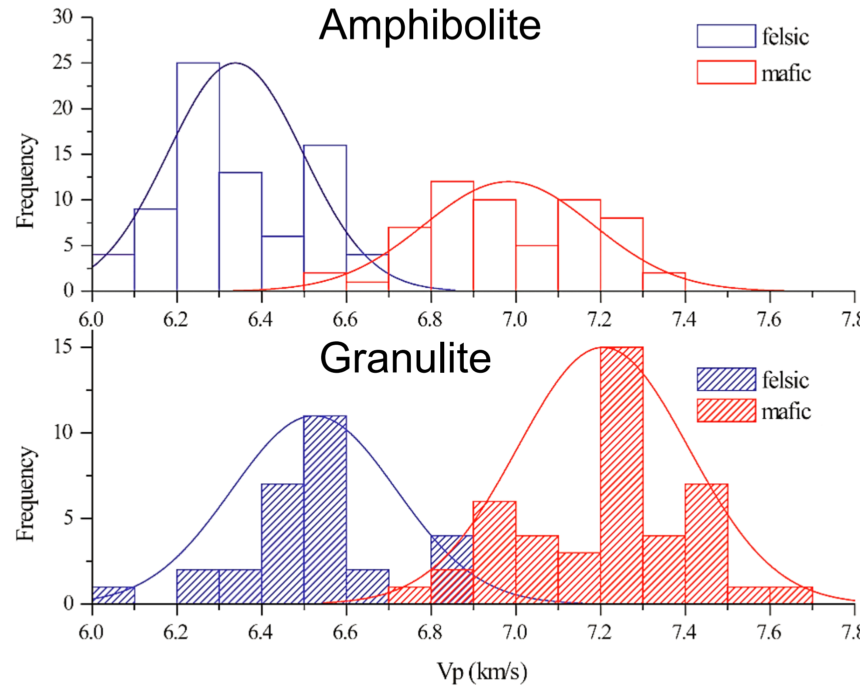
(a)



(b)

Seismic Velocities of Deep Crustal Rocks

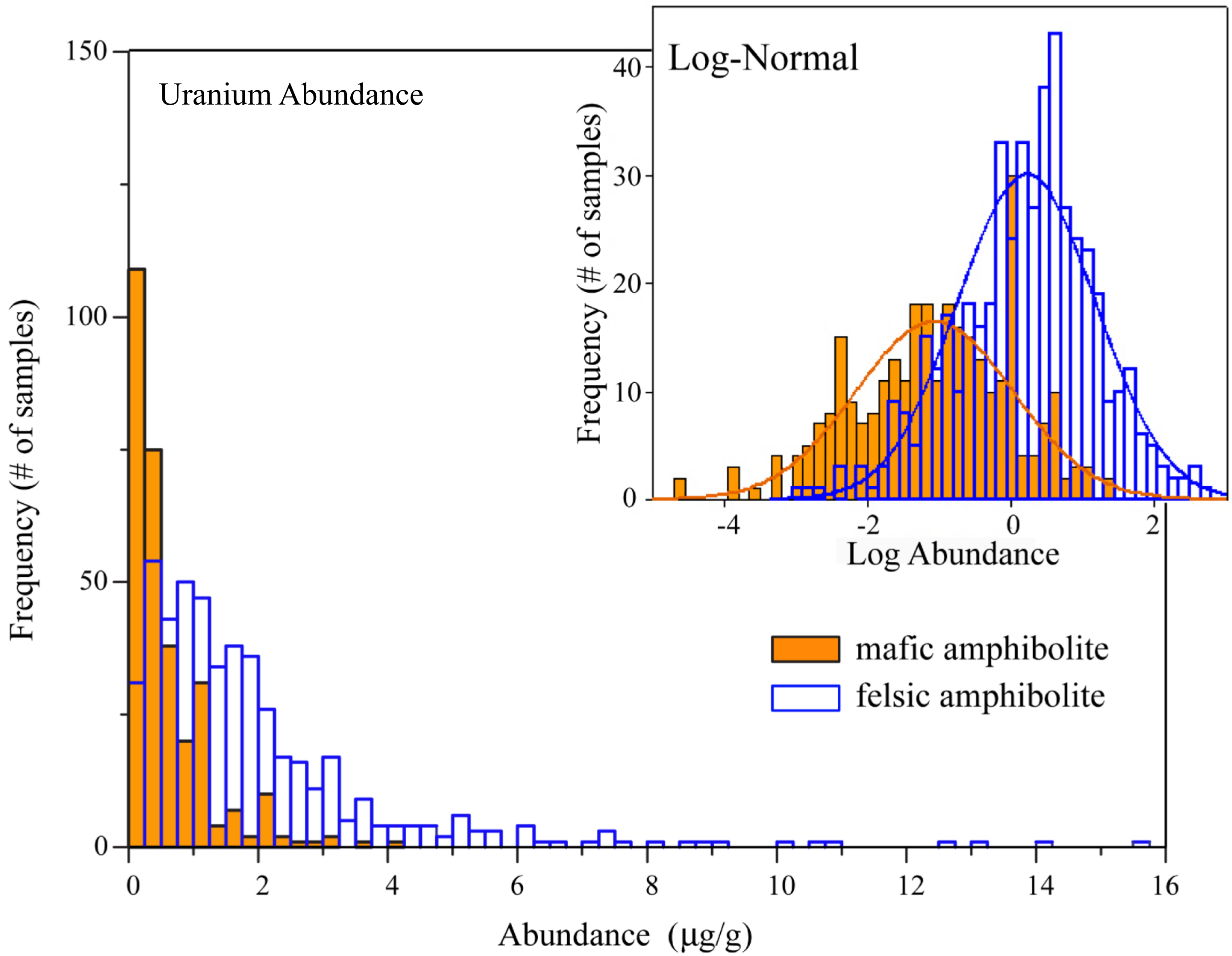




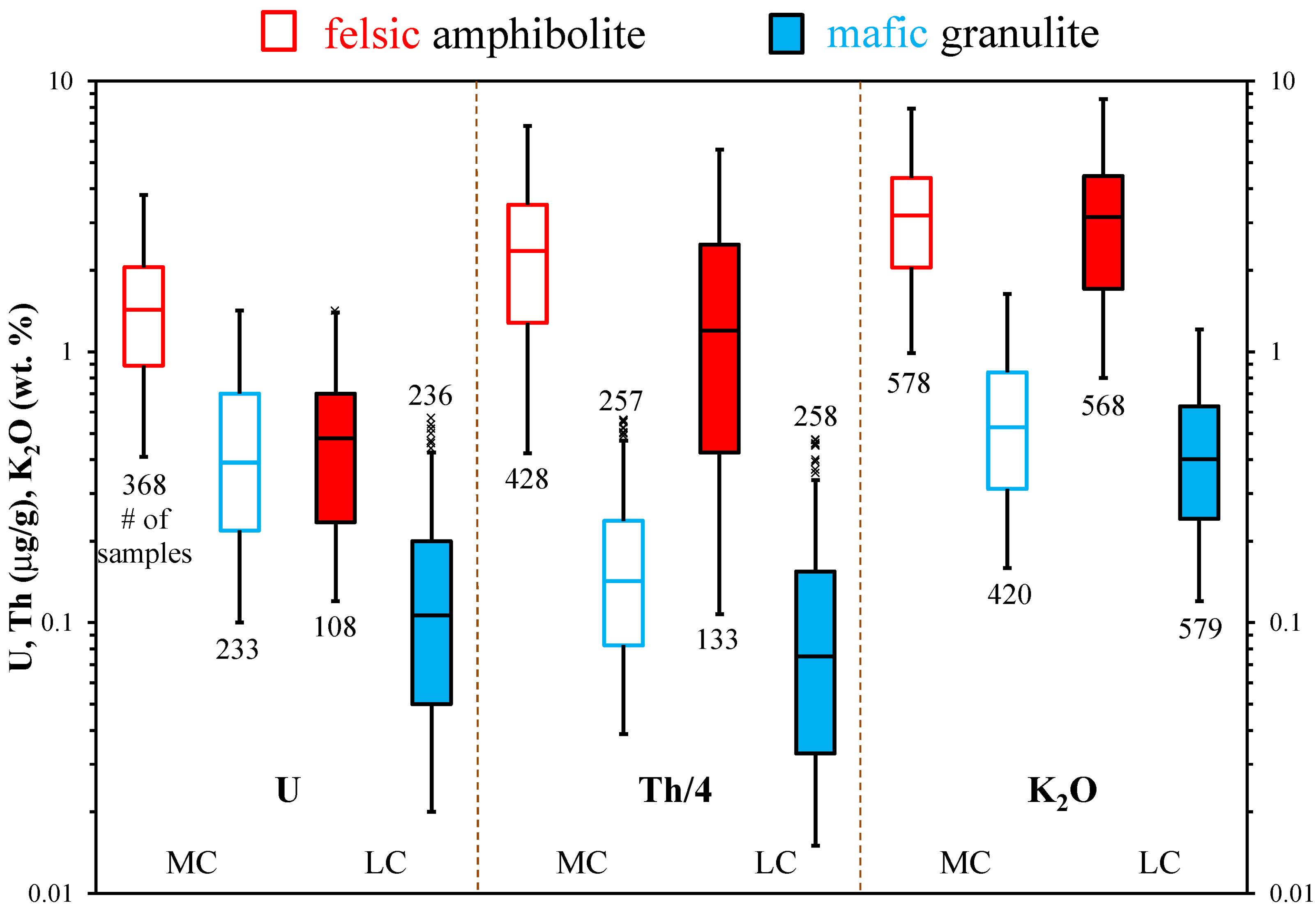
- ✓ Two components mixing in MC and LC: felsic and mafic
- ✓ Distinguishable by Vp (1-sigma)
- ✓ Close to linear relationship (Vp vs. SiO_2)

Composition of *Mafic* & *Felsic* Components

Non-Gaussian distributions



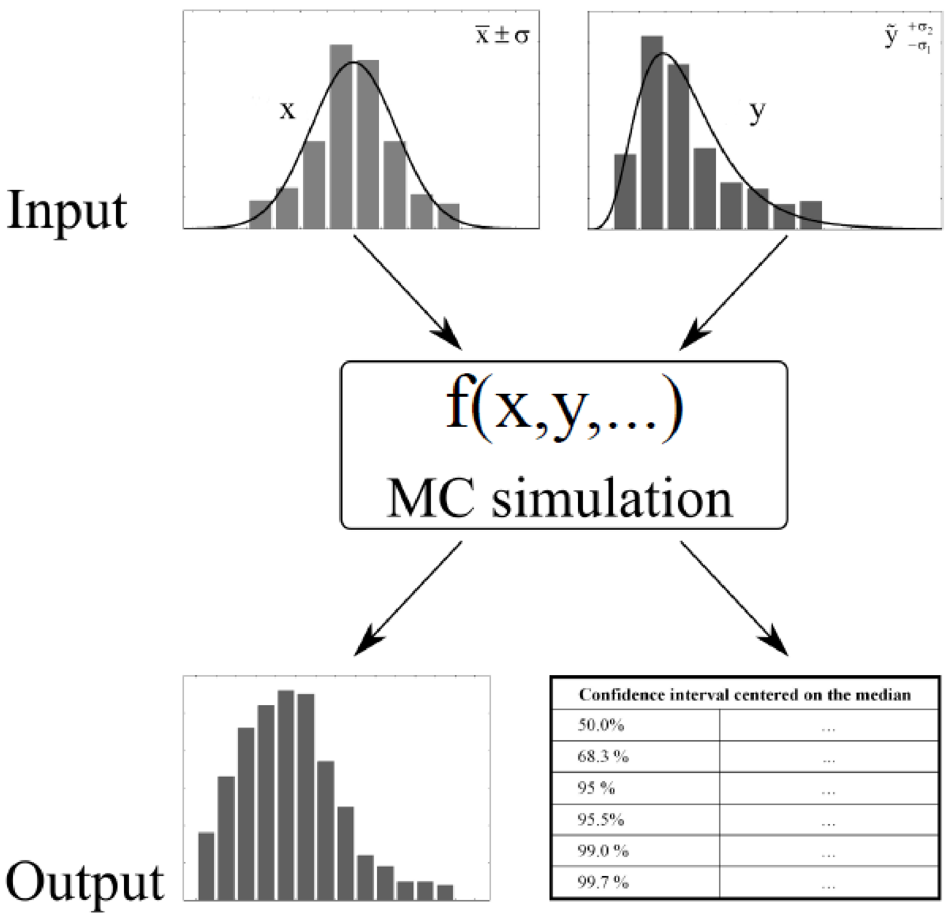
K, Th and U in the middle and lower crust



How to Track Uncertainty?

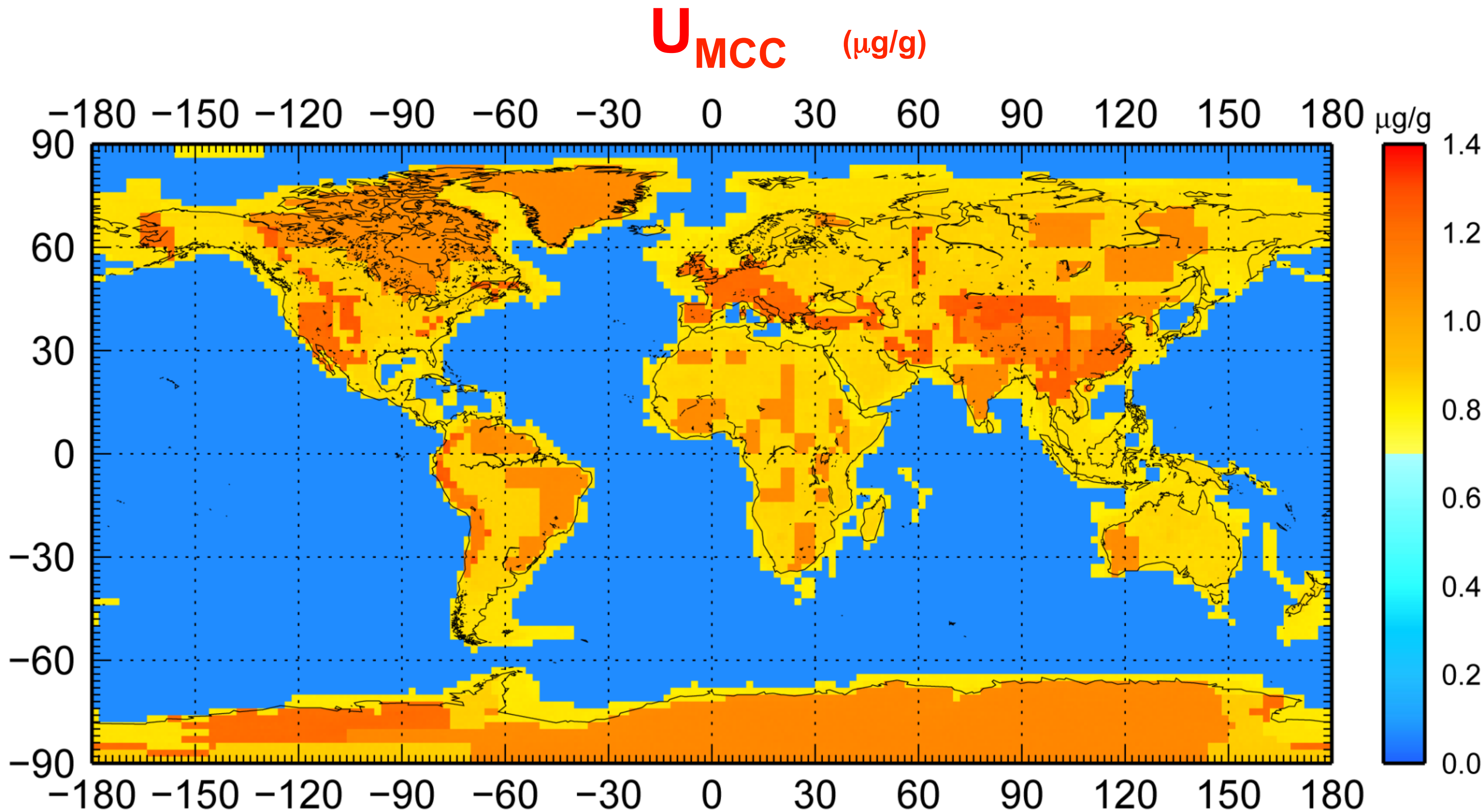
Monte Carlo simulation: highly desired for the propagation of asymmetric uncertainties

Requirement : the PDFs of all inputs are known



- ✓ Generate random samples for inputs, including correlation
- ✓ Calculate output variables
- ✓ Statistical analysis

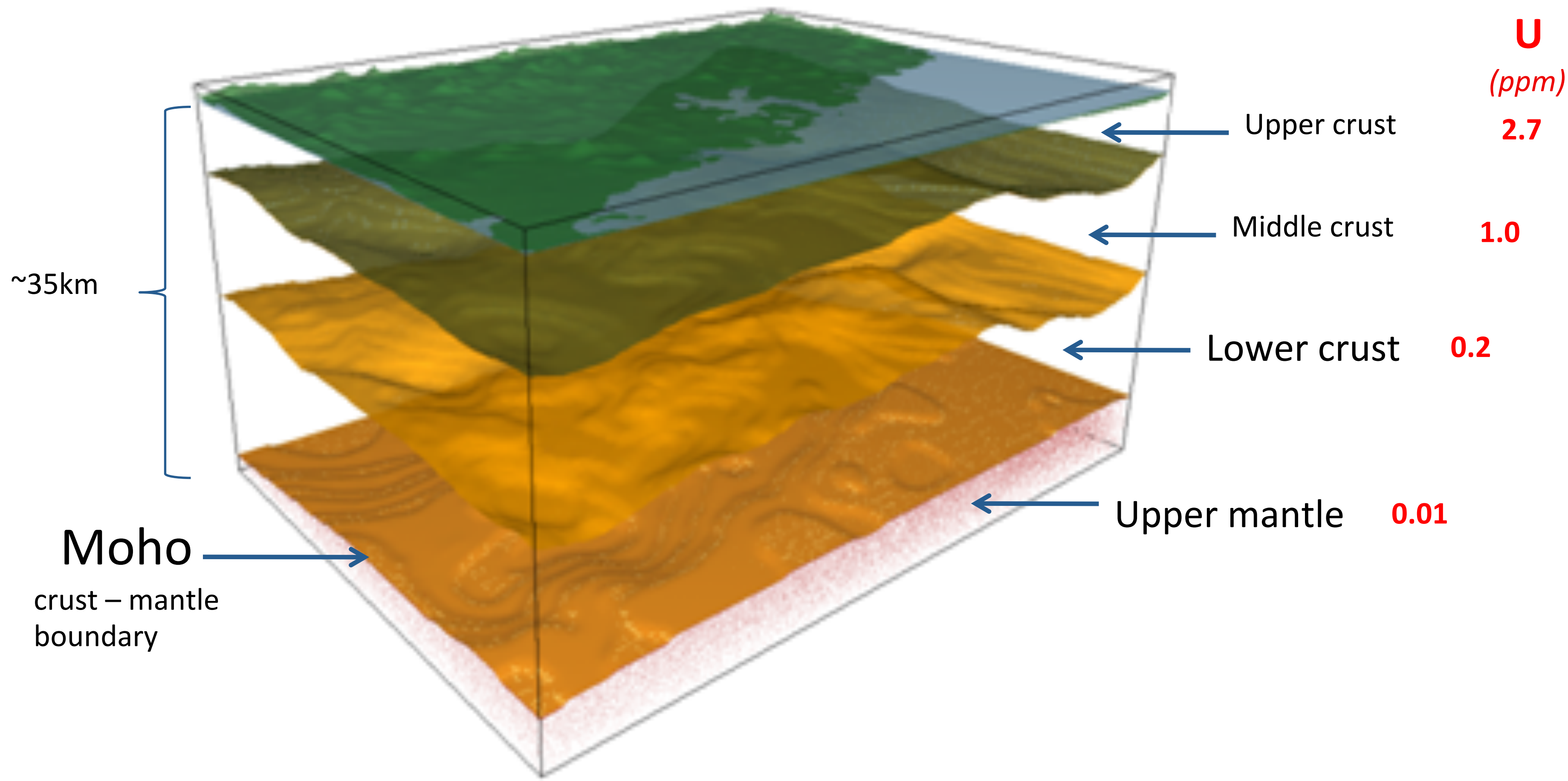
Uranium Abundance in Middle Continental Crust layer



Average middle Cont. Crust U abundance is $0.97^{+0.58}_{-0.36}$ μg/g

Rudnick and Gao (2003) 1.3 μg/g

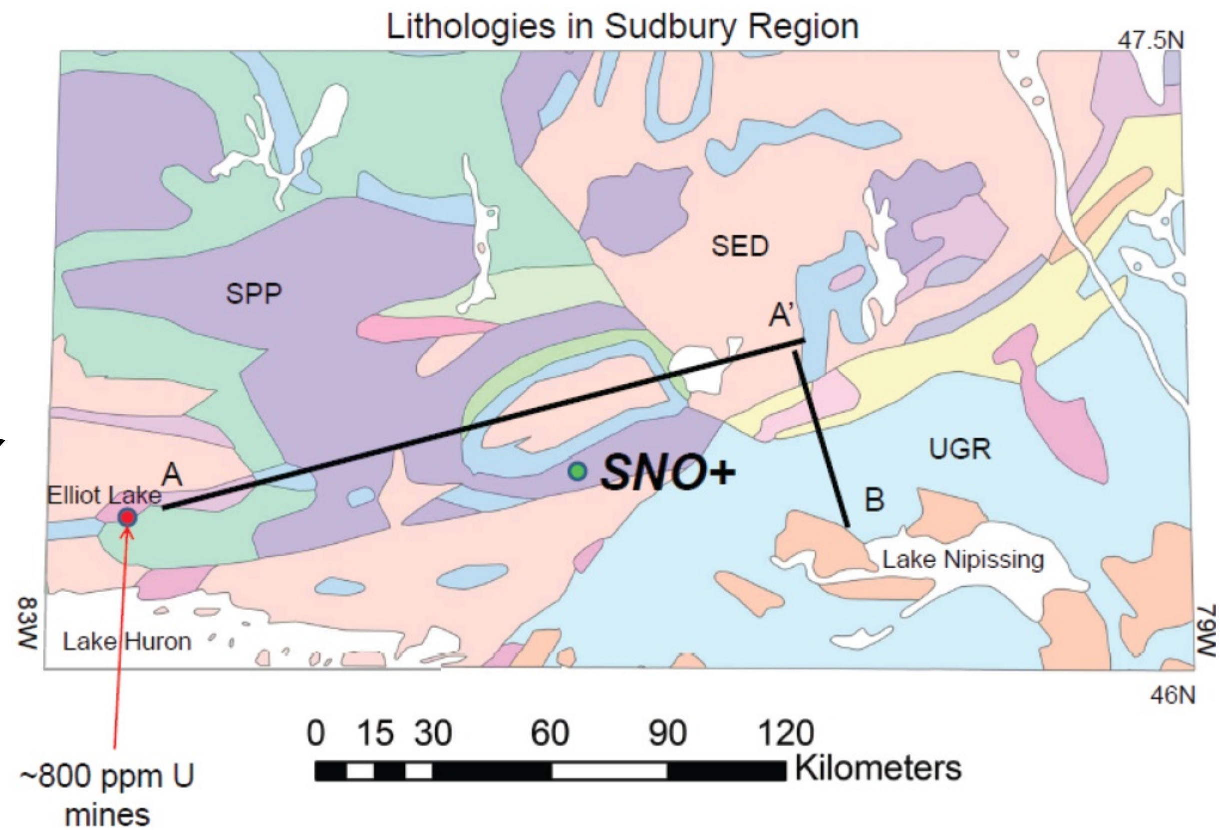
Geological model – Continental Crust



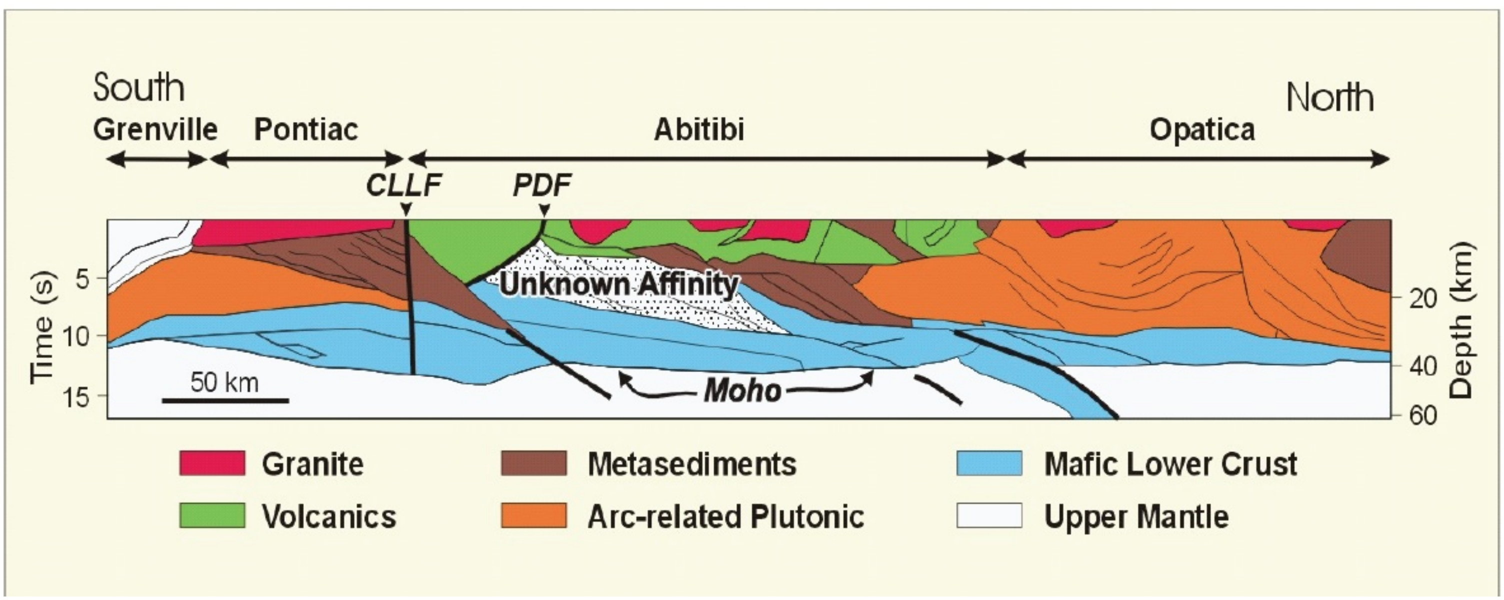
Surfaces of each layer is defined by geophysical data (i.e., gravity and seismic)

Estimating the geoneutrino flux at SNO+

- Geology
- Geophysics



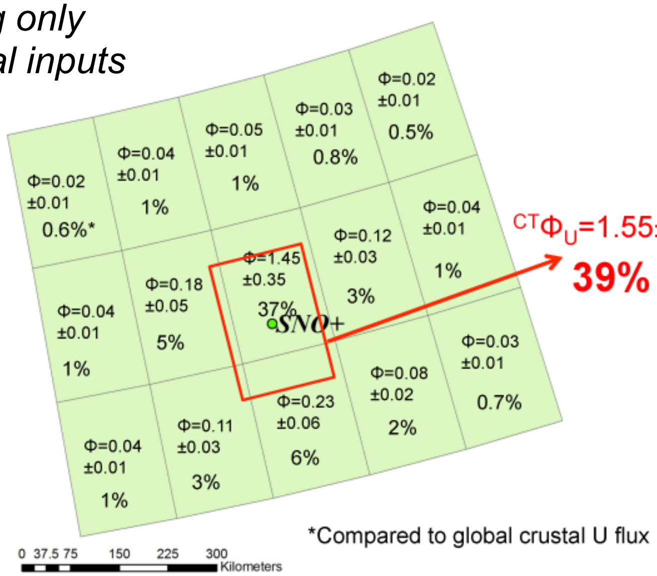
seismic x-section



Global to Regional RRM

Regional Uranium Flux

using only global inputs

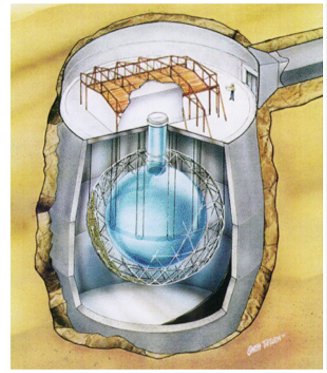


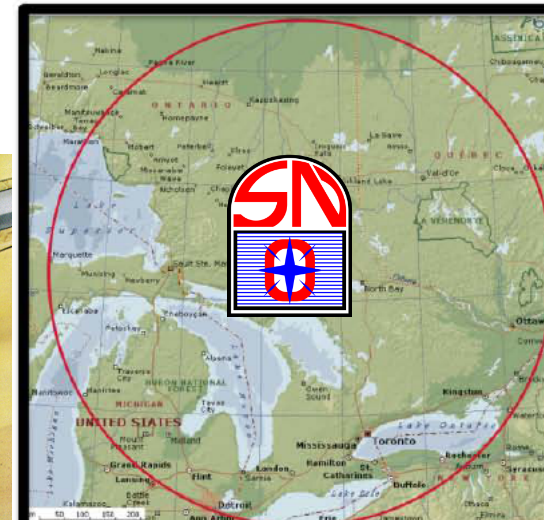
$^{CT}\Phi_U$=1.55±0.37

39%

*Compared to global crustal U flux

SNO+
Sudbury
Canada





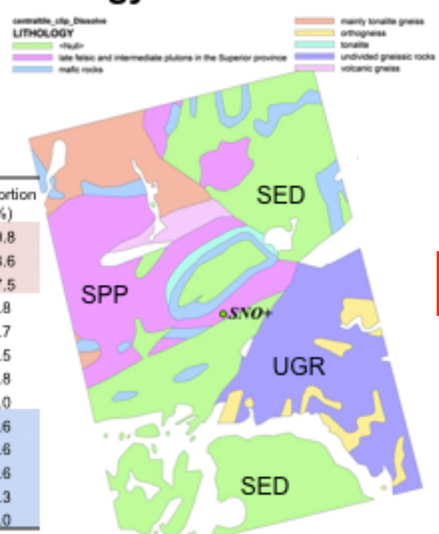
Regional Model: Global vs. Refined*

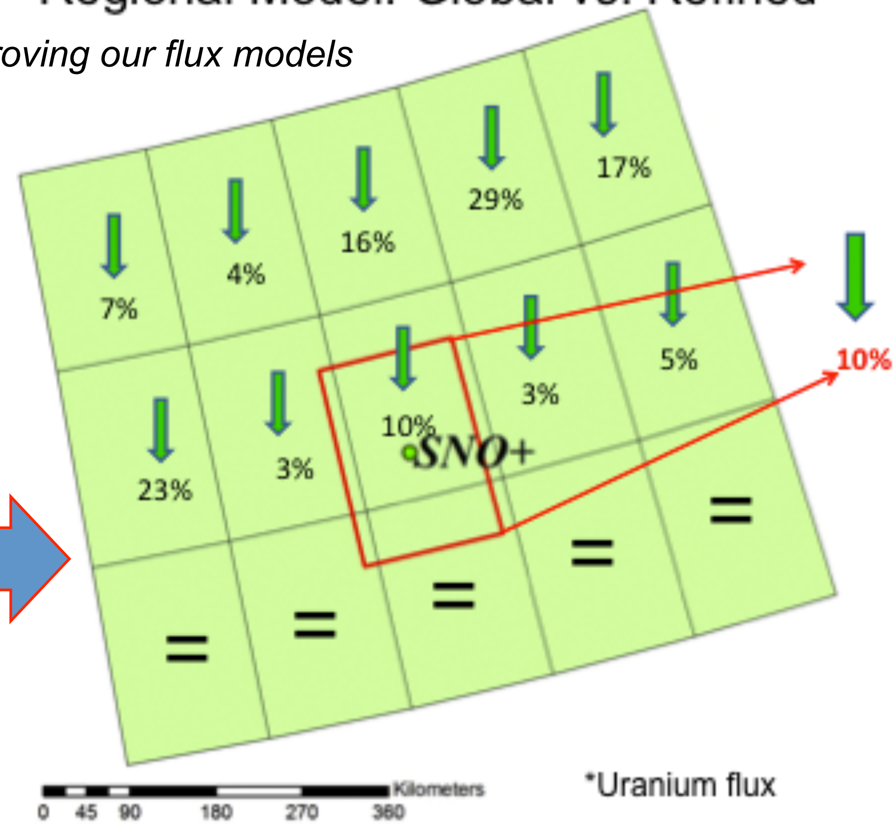
improving our flux models

Central Tile Lithology

adding the regional geology

LITHOLOGY	AREA (10^9 m^2)	Proportion (%)
Sediments (**SED**)	11	40.8
Superior province felsic and intermediate plutons (**SPP**)	5.1	18.6
undivided gneissic rocks (**UGR**)	4.8	17.5
mainly tonalite gneiss	2.1	7.8
mafic rocks	1.8	6.7
orthogneiss	1.0	3.5
volcanic gneiss	0.5	1.8
tonalite	0.3	1.0
felsic rocks	0.2	0.6
gabbro-anorthosite	0.2	0.6
paragneiss	0.2	0.6
undivided granitic rocks	0.09	0.3
undivided volcanic rocks	0.01	0.0





*Uranium flux