^{60}Fe and ^{244}Pu deposited on Earth constrain the r-process yields of recent nearby supernovae

Wallner et al. (2021)

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The origin of nuclides heavier than iron

- Nuclear processes involving the successive captures of neutrons
  - Slowly by steady stellar fusion
  - Rapid neutron capture process (r-process)—— all actinide(锕) elements, include Pu
    - sites? yields ?
    - short but intense flux of neutrons
    - explosive stellar environments: supernovae (SNe) or neutron-star mergers (NSMs)
    - scattered through the interstellar medium (ISM) and could be deposited on Earth

^{60}Fe and ^{244}Pu(钚) on Earth

- ^{60}Fe
  - Half-life ($t_{1/2}$) = 2.6 Myr
  - Produced in massive stars and ejected in SN explosions.
  - Earth's initial abundance of the ^{60}Fe has decayed to extinction over the 4.6 Gyr since the Solar System's (SS) formation.

- ^{244}Pu
  - Half life ($t_{1/2}$) = 80.6 Myr
  - SNe may enrich the local ISM with actinides, such as ^{244}Pu
  - It can also be contributed by older r-process events

Searched for extraterrestrial ^{60}Fe and ^{244}Pu

- Deep-sea sample on Earth—a ferromanganese (FeMn) crust (Crust-3)
  - 115-cm^2 area and ~25-mm thickness
- ^{60}Fe
  - ~1-cm^2 area is subdivided into 24 layers, each ~1-mm thick, corresponding to a time resolution of ~0.4 Myr per layer
- ^{244}Pu
  - remaining part of Crust-3 (114-cm^2 area) is split into three thick, horizontal layers

million years ago (Ma)

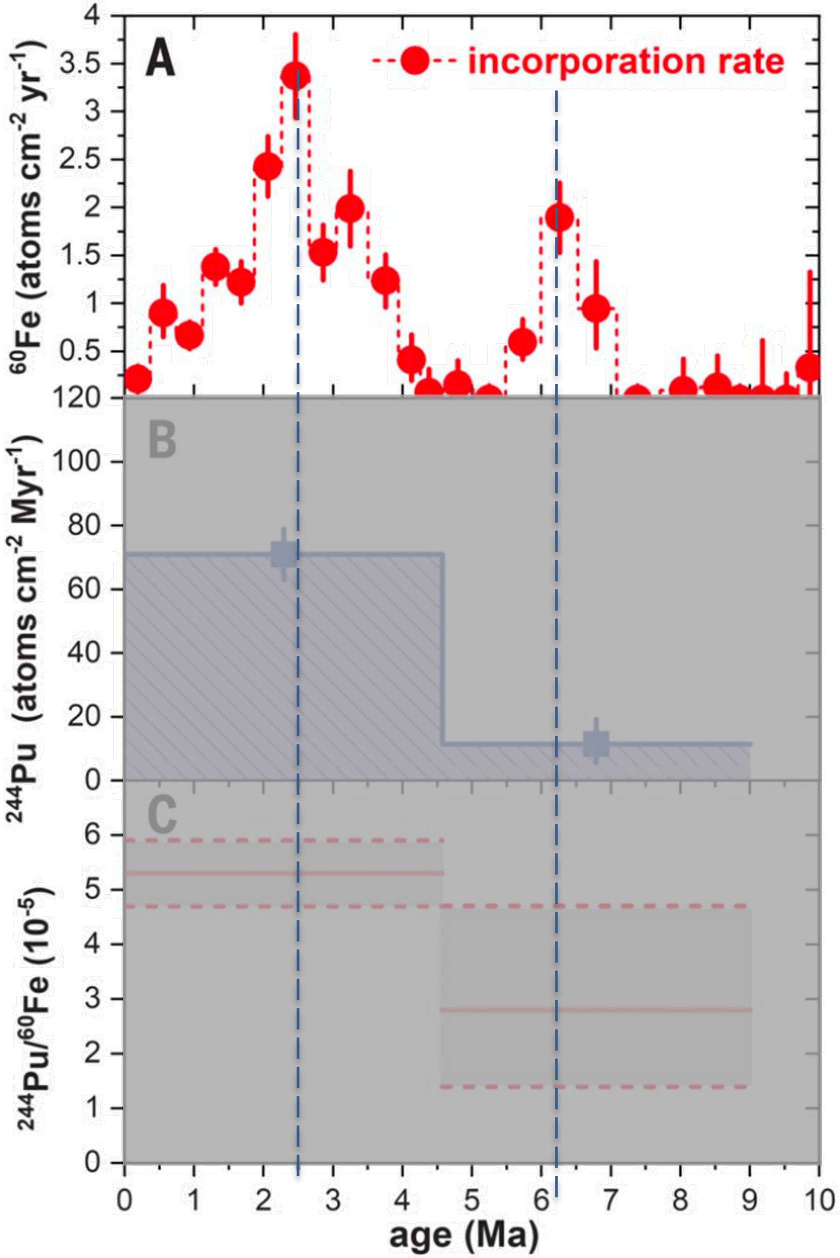
	depth/mm	time/Ma	mass/g
3/A	0 ~ 3	0 ~ 1.3	~20
3/B	3 ~10	1.3 ~ 4.6	179
3/C	10 ~ 20	4.6 ~ 9.0	208

Results of ^{60}Fe

- Background of $^{60}Fe/Fe = (3 \pm 1) \times 10^{-17}$
- Maxima at 2.5 and 6.3 Ma

- The ^{60}Fe incorporation：
  - 2.5 Ma：$(6.10 \pm 0.31) \times 10^{6}$ atoms cm^{-2}
  - 6.3 Ma：$(1.77 \pm 0.25) \times 10^{6}$ atoms cm^{-2}
- Consistent with previous reports：
  - 2.5 Ma：$(5.9 \pm 0.8) \times 10^{6}$ atoms cm^{-2}
  - 6.3 Ma：$(3.5 \pm 1.4) \times 10^{6}$ atoms cm^{-2}

- Incorporation efficiency for ^{60}Fe into Crust-3 is 17%

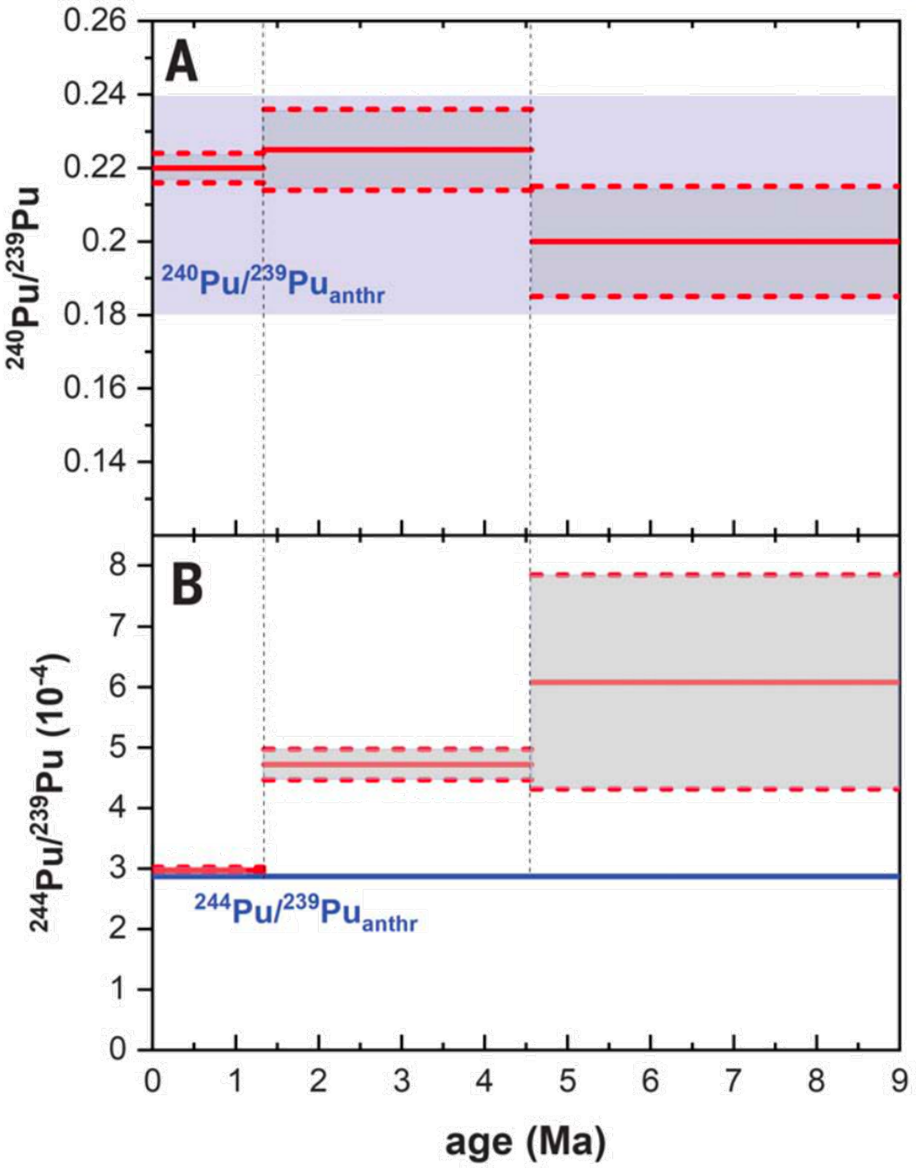


Results of ^{244}Pu

- An anthropogenic Pu signal in the top layer of Crust-3, consistent with the nuclear weapons fallout

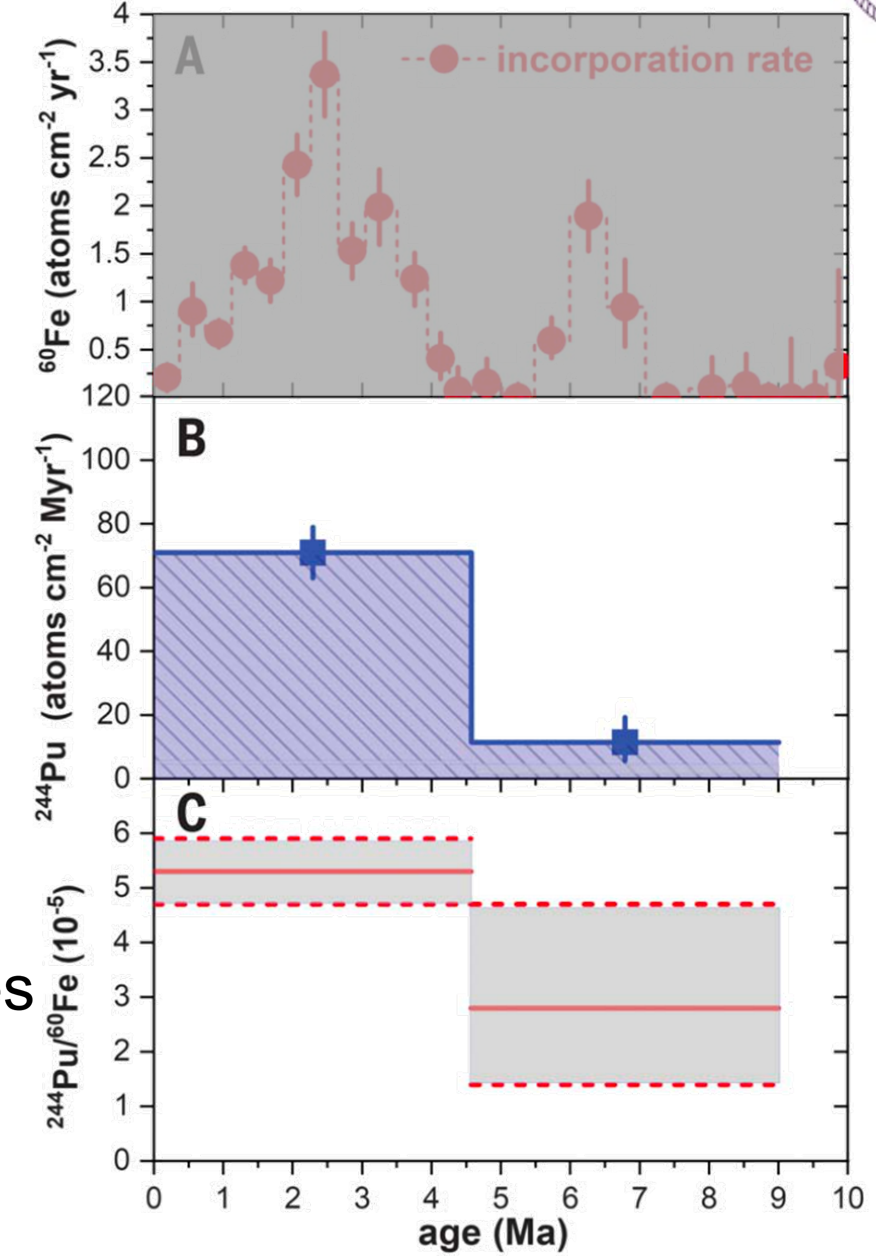
- ^{239}Pu, ^{240}Pu, and ^{244}Pu in all three layers
- ^{241}Pu ($t_{1/2}$ = 13.2 yr) in the first two layers.

- The $^{240}Pu/^{239}Pu$ and $^{241}Pu/^{239}Pu$ ratios are constant
- The $^{244}Pu/^{239}Pu$ ratio shows an excess over anthropogenic levels

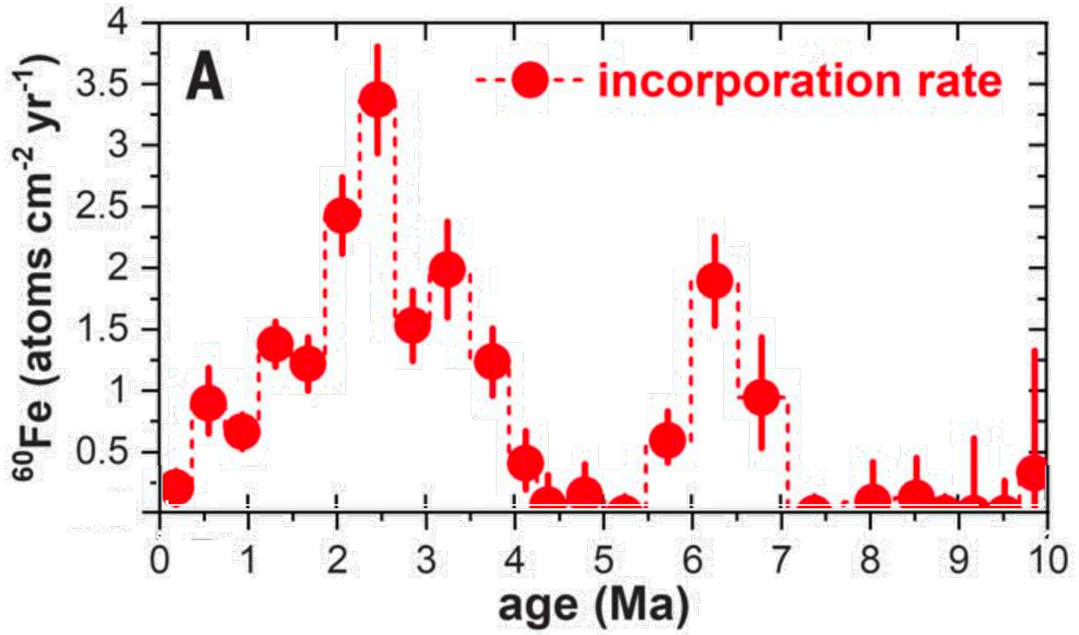


Results of ^{244}Pu

- The averaged extraterrestrial ^{244}Pu incorporation rate：
  - 0 to 4.6 Ma：(71 ± 8) atoms cm^{-2} Myr^{-1}
  - 4.6 to 9 Ma：($11.5^{+7.8}_{-5.8}$) atoms cm^{-2} Myr^{-1}
- Consistent with previous 2σ limits of <188 (0.5 ~5 Ma) and <66 atoms cm^{-2} Myr^{-1}(5~12 Ma)
- Atom ratio of $^{244}Pu/^{60}Fe$,
  - 0 ~ 4.6 Ma, (5.3 ± 0.7) × 10^{-5}
  - 4.6 ~ 9 Ma, ($2.8^{+1.9}_{-1.4}$) × 10^{-5}
- Consistent with each other within the uncertainties



Potential explanation for peaks in ^{60}Fe profile



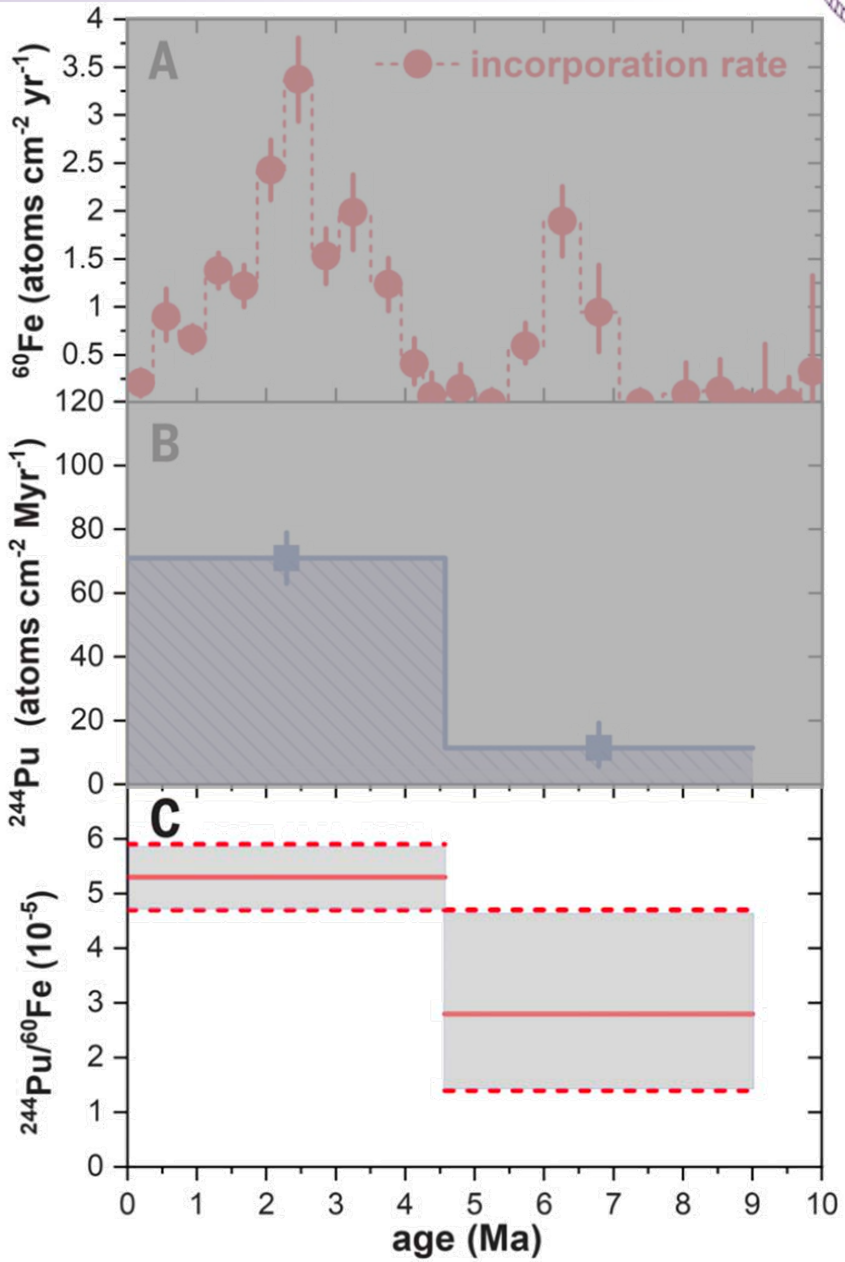
- 3 to 4× higher ^{60}Fe influx for the younger time period:
  - a SN at about half the distance
  - a more massive star, more ^{60}Fe,
  - more than one SN explosion
  - different ISM conditions

- Two to four SN events at distances of 50 to 100 pc.
  - Two SNe, with a ^{60}Fe-yield of 2×10^{-5} $M_\odot$ each, would enrich the ISM within a volume of 75 pc radius to $\lesssim 10^{-11}$ atoms cm^{-3}；Galaxy-averaged concentration of ^{60}Fe： ~4×10^{-12} atoms cm^{-3}
  - Probability of dust formation and SS penetration for SN-produced ^{60}Fe： ~3 to 6% in mass, close to the measured fraction

The origin of extraterrestrial ^{244}Pu

- The extraterrestrial ^{244}Pu, deposited concomitantly with SN-produced ^{60}Fe, shows an approximately constant $^{244}Pu/^{60}Fe$ ratio of (3 to 5) × 10^{-5}
- The ratio is lower than expected from SNe——contribution from other sources

- Depending on the rate of actinide production, older ^{244}Pu could be present in the ISM in
  1. a steady-state concentration ×
  2. as the remaining fraction of an earlier rare event (NSMs, collapsars, or magneto-rotational SNe)



Take home message

1. Confirm an influx of interstellar material into the inner SS through two or more local and transient SN events over the last ~10 Myr

2. SN actinide yields seem insufficient to account for the overall abundance of r-process nuclides in the Galaxy

Questions & comments

- How to calculate the $^{244}Pu/^{60}Fe$ ratio?
  subtracting the anthropogenic ^{244}Pu fraction and blank background; considering the decay and incorporation efficiency

- How does the ^{244}Pu from older events reach the earth?
  It was incorporated into dust that survived the LB formation (>10 to 15 Ma) and was swept up by the more recent SN ejecta, together with freshly produced ^{60}Fe

- The expected $^{244}Pu/^{60}Fe$ ratio from SNe models may have large uncertainties. The conclusion about the origin of ^{244}Pu is not so convincing (considering the steady ratio at different time)

Thanks!

Details

Section	Depth (mm)	Time period (Ma)	^{60}Fe detector events	^{60}Fe background events expected	^{60}Fe/Fe (10^{-15})	$^{60}Fe/Fe_{d.c.}$ (10^{-15})	^{60}Fe incorporation (10^6 atoms cm^{-2} per section)	^{60}Fe incorporation rate (atoms cm^{-2} yr^{-1})
I	0 – 9.2	0 – 4.2	379	10	1.10 ± 0.06	1.87 ± 0.12	6.10 ± 0.31	1.46 ± 0.07
II	9.2 – 12	4.2 – 5.5	3	2	0.05 ± 0.03	$0.06^{+0.14}_{-0.06}$	$0.09^{+0.23}_{-0.09}$	$0.07^{+0.16}_{-0.07}$
III	12 – 15	5.5 – 7.0	49	3	0.40 ± 0.06	1.96 ± 0.31	1.77 ± 0.25	1.12 ± 0.16
IV	15 – 24	7.0 – 10.0	4	5	0.02 ± 0.01	<0.05	<0.2	<0.07
Total	0 – 24	0 – 10	435	20	0.56 ± 0.03	0.56 ± 0.03	7.96 ± 0.38	0.79 ± 0.04
Blank	terrestrial Fe	–	2	–	0.03 ± 0.02	–	–	–

Details

Layer	Depth (mm)	Time period (Myr)	$^{60}Fe_{ISM}$ atoms detected	^{60}Fe rate (atom cm^{-2} yr^{-1})	^{60}Fe layer incorporation (10^6 atoms cm^{-2})
Crust-3/A	0 – 3	0 – 1.34	88 ± 9	0.72 ± 0.08	0.97 ± 0.10
Crust-3/B	3 – 10	1.34 – 4.57	282 ± 17	1.61 ± 0.09	5.19 ± 0.31
Crust-3/C	10 – 20	4.57 – 9.0	46 ± 7	0.42 ± 0.04	1.82 ± 0.26
Crust-3$_{0\text{-}4.6}$	**0 – 10**	**0 – 4.57**	**370 ± 19**	**1.35 ± 0.07**	**6.14 ± 0.31**
Crust-3$_{0\text{-}9.0}$	*0 – 20*	*0 – 9.0*	*415 ± 20*	*0.89 ± 0.04*	*7.96 ± 0.38*
blank	–	–	2	–	–

Layer	Time period (Myr)	$^{244}Pu_{ISM}$ atoms detected	^{244}Pu rate (atoms cm^{-2} Myr^{-1})	^{244}Pu layer incorporation (atoms cm^{-2})	$^{244}Pu_{ISM}$ flux at Earth orbit (10^3 atoms cm^{-2} Myr^{-1})	$^{244}Pu_{ISM}$ fluence at Earth orbit 10^3 atoms cm^{-2}	$^{244}Pu/^{60}Fe$ (10^{-6} at/at)
Crust-3/A	0 – 1.34	34 ± 17	38 ± 19	51 ± 26	0.90 ± 0.48	1.2 ± 0.6	52 ± 26
Crust-3/B	1.34 – 4.57	141 ± 19	85 ± 11	274 ± 37	1.99 ± 0.44	6.4 ± 1.4	53 ± 7
Crust-3/C	4.57 – 9.0	$6.3^{+4.3}_{-3.2}$	$11.5^{+7.8}_{-5.8}$	51^{+35}_{-26}	$0.27^{+0.18}_{-0.14}$	$1.2^{+0.8}_{-0.6}$	28^{+19}_{-14}
Crust-3$_{0\text{-}4.6}$	**0 – 4.57**	**175 ± 19**	**71 ± 8**	**325 ± 40**	**1.67 ± 0.35**	**7.7 ± 1.6**	**53 ± 6**
Crust-3$_{0\text{-}9.0}$	*0 – 9.0*	*181 ± 19*	*42 ± 4*	*376 ± 40*	*0.98 ± 0.18*	*8.9 ± 1.8*	*47 ± 5*
Blank	–	1	–	–	–	–	–
Crust-0$_{0.5\text{-}5.0}$	**0.3 – 5.0**	**0**	**<100**	**<420**	**<2.2**	**<10.0**	**<170**
Crust-0$_{0.5\text{-}12}$	*0.3 – 12*	*1*	*<40*	*<440*	*<1*	*<10.0*	–
Crust-0$_{0.5\text{-}25}$	0.3 – 25	2	<30	<700	<0.6	<15.0	–