

A global compilation of glacial ^{10}Be and ^{26}Al exposure age data

Jakob Heyman

Beryllium-10 Dating of the Duration and Retreat of the Last Pinedale Glacial Sequence

J. C. Gosse,* J. Klein, E. B. Evenson, B. Lawn, R. Middleton

Accurate terrestrial glacial chronologies are needed for comparison with the marine record to establish the dynamics of global climate change during transitions from glacial to interglacial regimes. Cosmogenic beryllium-10 measurements in the Wind River Range indicate by 21,71 recessive rapid an 12,100 :

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 94, NO. B12, PAGES 17,907-47.

Cosmic Ray Production Rates of ^{10}Be and ^{26}Al

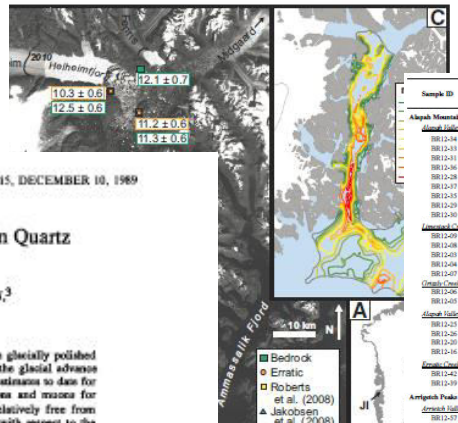
JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 94, NO. B12, PAGES 17,907-17,915, DECEMBER 10, 1989

Cosmic Ray Production Rates of ^{10}Be and ^{26}Al in Quartz
From Glacially Polished Rocks

K. NISHIZUMI,¹ E. L. WINTERER,² C. P. KOHL,¹ J. KLEIN,³

R. MIDDLETON,³ D. LAL,² AND J. R. ARNOLD¹

We have studied the concentrations of ^{10}Be and ^{26}Al in quartz crystals extracted from glacially polished granitic surfaces from the Sierra Nevada range. These surfaces were identified with the glacial advances during the Tigua period ~11,000 years ago. Our measurements yield the most accurate estimates to date for the absolute production rates of these nuclides in SiO_2 due to cosmic ray nucleons and muons for geomagnetic latitudes 43.8° – 44.6°N and altitudes 2.1 – 3.6 km. The estimates are relatively free from



Sample name	Quartz dissolved (g)	⁹⁰ Be spike (mg)	¹⁰ Be (10 ⁴ at g ⁻¹)	Al ^a (μg g ⁻¹)	²⁶ Al (10 ⁴ at g ⁻¹)	²⁶ Al/ ¹⁰ Be	¹⁰ Be apparent exposure age (ka)	²⁶ Be exposure age (ka) (corrected for cosmic ray effects)					
Murchison syncline area													
Wargentin-1	50.7	0.3	16.6±1.1	140.0	112.5±10.1	7.4±0.8	28.5±1.9	(3.1)					
Wargentin-2	50.3	0.3	50.6±2.9	76.0	403.5±18.6	8.7±0.6	86.5±5.3	(9.2)					
Wargentin-3	51.5	0.3	23.1±1.6	72.0	158.6±9.4	8.1±0.8	37.7±2.9	(4.3)					
Wargentin-4	51.7	0.3	18.0±1.0	61.0	160.5±8.7	9.0±0.8	32.1±1.9	(3.3)					
Flora-1	56.7	0.3	8.3±0.6	n.a.	36.9±9.9	11.2±1.4	15.0±1.0	(1.7)					
Flora-2	51.8	0.3	62.3±3.0	n.a.	n.a.	111.4±5.8	11.2	1160±60 (1.6)					
Cidun-1	51.6	0.3	45.9±2.8	n.a.	n.a.	74.5±4.6	(7.0)	77±4±4 (8.1)					
Cidun-2	51.6	0.3	21.6±1.2	122.0	196.2±12.9	9.0±0.9	37.2±2.1	(3.8)					
Prins Ocean Landrope													
Sno-1	54.3	0.2	68.9±4.1	43.0	558.3±34.6	8.9±0.8	118.0±7.3	(12.5)					
Sno-2	51.2	0.3	17.4±0.8	89.0	132.6±9.2	8.3±0.7	34.7±1.7	(3.5)					
Sno-3	50.6	0.3	2.0±0.2	n.a.	3.7±0.4	(0.5)	3.7±0.4	(0.5)					
Sno-5	45.8	0.3	33.6±1.4	84.0	189.2±9.6	5.8±0.4	62.1±2.7	(5.9)					
Meijend-1	52.3	0.3	6.6±0.5	79.0	47.9±4.7	8.0±1.1	13.1±1.0	(1.5)					
Meijend-3	53.4	0.3	6.4±1.1	206.0	40.3±1.6	6.9±1.6	12.7±1.1	(2.4)					
Meijend-4	52.5	0.3	49.4±3.3	391.0	362.6±23.5	5.7±0.5	115.6±9.9	(11.5)					
Abi-2	56.7	0.3	63.5±3.8	144.0	460.1±22.1	7.7±0.6	90.9±6.7	(11.1)					
Brim-2	37.3	0.3	40.2±2.0	101.0	294.9±17.4	8.0±0.6	65.8±3.5	(6.6)					
Brailes-1	51.7	0.3	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.					
Brailes-2	52.7	0.3	12.4±1.8	82.0	148.6±9.1	13.1±2.0	23.8±3.3	(2.9)					
Brailes-3	52.7	0.3	12.0±0.9	121.0	87.7±8.3	8.0±1.0	25.0±1.9	(3.8)					
Other sites													
BO0807	1414	4.0	2.0	0.97	45.04	0.71	5.97E-4	1.12E-4	2.24E-05	4.6E-05	157±50	0.3	BO0400
BO7962	1362	2.0	2.0	0.97	43.03	0.71	5.65E-3	1.12E-4	2.24E-05	4.10E-05	15±6±7	0.3	BO0409
BO1104	1191	0.5	2.0	0.91	30.09	0.71	3.22E-3	6.42E-5	1.90E-05	3.80E-05	16±0±7	0.3	BO0404

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Intro Data References Production Calculator

A global compilation of glacial ^{10}Be and ^{26}Al data

These pages host a global compilation of published ^{10}Be and ^{26}Al data from glacial samples, with the goal of providing easy access to data enabling recalculation of exposure ages and cosmogenic data meta-analysis. Data has been compiled from published sources and additional data sources (data directly from the authors, data from another paper,

expage.github.io

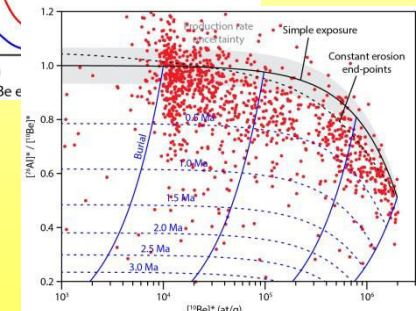
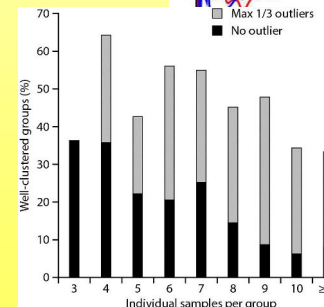
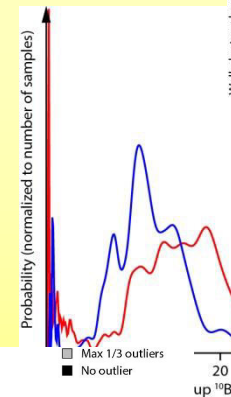
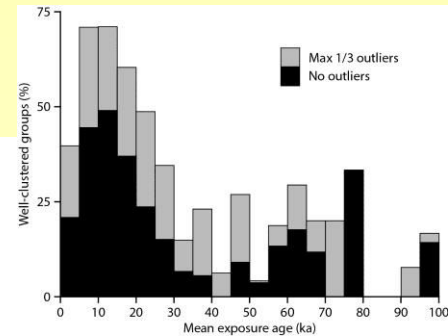
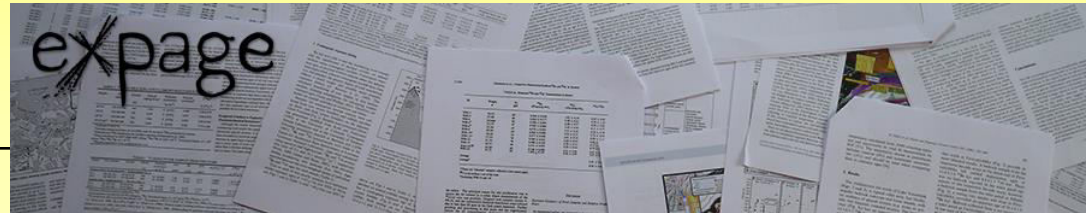
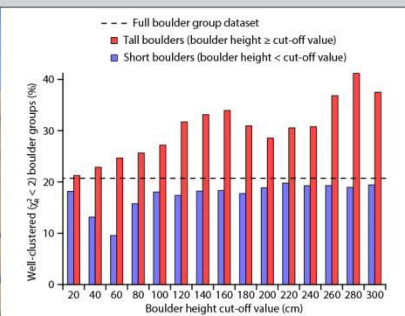
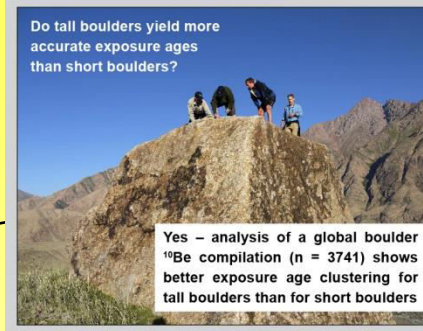
Outline

Motivation

The compilation

Analysis

- Scatter / clustering
- Well-clustered ages
- ^{26}Al / ^{10}Be burial dating
- How many samples to collect?



Motivation 1

Enable easy recalculation of glacial exposure ages

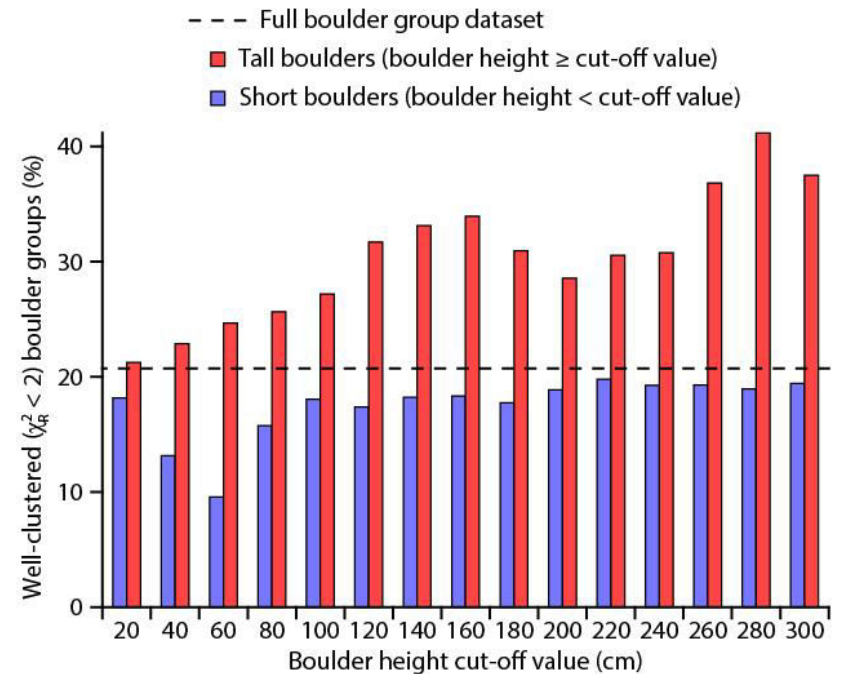
Publication	Sample-type	Surface-ID	Group-ID	Sample	Lat (DD)	Long (DD)	Elev (masl)	Thickn (cm)	Density (g/cm3)	Shield	10Be-conc (at/g)	10Be-unc (at/g)				
10Be-std	26Al-conc (at/g)	26Al-unc (at/g)	26Al-std	Sampl-year		Publ-10-age (yr)	Publ-10-unc (yr)	Publ-26-age (yr)	Publ-26-unc (yr)	10Be-age (yr)	10-ext-unc (yr)	10-int-unc (yr)				
26Al-age (yr)	26-ext-unc (yr)	26-int-unc (yr)	Extra-publ													
Heyman et al. (2011)	pebbles	Heym2011-1	Heym2011-A	TB-05-051	34.108167	97.645933	4780	2	2.7	1	2863124	73331	KNSTD	0	0	0
2005	30361	2677	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Heyman et al. (2011)	boulder	Heym2011-2	Heym2011-B	TB-05-018	34.268533	97.858433	4716	1	2.7	1	4581447	117445	KNSTD	0	0	0
2005	46517	4119	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Heyman et al. (2011)	boulder	Heym2011-3	Heym2011-B	TB-05-019	34.268817	97.865417	4683	1	2.7	1	8701361	222951	KNSTD	0	0	0
2005	92334	8271	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Heyman et al. (2011)	boulder	Heym2011-4	Heym2011-C	TB-05-048	33.989310	97.449230	4576	1	2.7	1	1095381	61254	KNSTD	0	0	0
2005	13559	1369	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Heyman et al. (2011)	boulder	Heym2011-5	Heym2011-C	TB-05-049	33.986667	97.449050	4573	1	2.7	1	926127	26858	KNSTD	0	0	0
2005	11495	1021	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Heyman et al. (2011)	boulder	Heym2011-6	Heym2011-C	TB-05-050	33.986183	97.448350	4576	1	2.7	1	1520856	60700	KNSTD	0	0	0
2005	18459	1719	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Heyman et al. (2011)	pebbles	Heym2011-7	Heym2011-C	TB-07-29	33.987889	97.448472	4574	2	2.7	1	4734112	118571	07KNSTD	0	0	0
2007	59242	5252	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Heyman et al. (2011)	boulder	Heym2011-8	Heym2011-D	TB-06-01	34.599056	97.984639	4259	5	2.7	1	3290490	119237	07KNSTD	0	0	0
2006	47302	4365	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Heyman et al. (2011)	boulder	Heym2011-9	Heym2011-D	TB-06-02	34.596500	97.986861	4264	5	2.7	1	4126823	111897	07KNSTD	0	0	0
2006	60660	5418	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Heyman et al. (2011)	boulder	Heym2011-10	Heym2011-D	TB-06-37	34.599222	97.994611	4256	3	2.7	1	2353618	97376	07KNSTD	0	0	0
2006	34795	3277	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Heyman et al. (2011)	boulder	Heym2011-11	Heym2011-D	TB-07-125	34.604917	98.015056	4248	5	2.7	1	4020038	143384	07KNSTD	0	0	0
2007	59514	5495	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Heyman et al. (2011)	pebbles	Heym2011-12	Heym2011-D	TB-07-12	34.596139	97.986250	4266	2	2.7	1	2082644	90767	07KNSTD	0	0	0
2007	30781	2927	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Heyman et al. (2011)	boulder	Heym2011-13	Heym2011-E	TB-06-16	34.526389	97.987194	4332	4	2.7	1	2917059	61565	07KNSTD	0	0	0
2006	40691	3548	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Heyman et al. (2011)	boulder	Heym2011-14	Heym2011-E	TB-06-17	34.525778	97.987528	4332	4	2.7	1	3688936	138929	07KNSTD	0	0	0
2006	51136	4753	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Heyman et al. (2011)	pebbles	Heym2011-15	Heym2011-E	TB-07-13	34.526139	97.986944	4331	2	2.7	1	2471948	115493	07KNSTD	0	0	0
2007	34964	3381	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Heyman et al. (2011)	boulder	Heym2011-16	Heym2011-F	TB-06-05	33.991861	97.430472	4593	4	2.7	1	2698316	123372	07KNSTD	0	0	0
2006	34743	3342	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Heyman et al. (2011)	boulder	Heym2011-17	Heym2011-F	TB-06-07	33.989556	97.429667	4590	5	2.7	1	1294833	47593	07KNSTD	0	0	0
2006	17887	1642	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Heyman et al. (2011)	pebbles	Heym2011-18	Heym2011-F	TB-07-30	33.991917	97.430500	4589	2	2.7	1	5649820	230123	07KNSTD	0	0	0
2007	69949	6626	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Heyman et al. (2011)	boulder	Heym2011-19	Heym2011-G	TB-06-46	34.153528	98.019028	4573	3	2.7	1	3387206	77434	07KNSTD	0	0	0
2006	41823	3666	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Heyman et al. (2011)	boulder	Heym2011-20	Heym2011-G	TB-06-47	34.155389	98.020194	4583	4	2.7	1	3982840	105727	07KNSTD	0	0	0
2006	49049	4359	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Heyman et al. (2011)	boulder	Heym2011-21	Heym2011-G	TB-06-48	34.156972	98.020333	4592	3	2.7	1	6421993	185987	07KNSTD	0	0	0
2006	79903	7219	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Heyman et al. (2011)	boulder	Heym2011-22	Heym2011-H	TB-06-31	34.511556	97.740750	4456	4	2.7	1	3509687	69298	07KNSTD	0	0	0
2006	45540	3961	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Heyman et al. (2011)	boulder	Heym2011-23	Heym2011-H	TB-06-32	34.513444	97.740722	4451	4	2.7	1	7095024	233596	07KNSTD	0	0	0
2006	94727	8724	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Motivation 2

Enable meta-analysis using a comprehensive dataset

Do tall boulders yield more accurate exposure ages than short boulders?

Yes – analysis of a global boulder ^{10}Be compilation (n = 3741) shows better exposure age clustering for tall boulders than for short boulders



Compilation work

- **Searching** (Journals, Google Scholar, reference lists...)
- **Copy-paste, copy-paste, copy-paste...**
- **Correcting mistakes**
- **Emails**
- **Assumptions**
- **Recalculation**

Abramowski et al. (2006)
Latitudes and longitudes based on map figures and Google Earth.
Sample density assumed to be 2.65 g/cm³.
10Be standard assumed to be S555.
Sampling year assumed to be 2002 (based on Abramowski 2004).

Ackert et al. (2007)
Sample density assumed to be 2.65 g/cm³.
10Be concentration derived from Ackert et al. (2011).
10Be standard traced via CRONUS calculator to 07KNSTD.
Sampling year based on sample names.

DATA COMMENTS

Included data

1. Primary publication
2. Sample type
3. Surface ID
4. Group ID
5. Sample name
6. Latitude
7. Longitude
8. Elevation
9. Sample thickness
10. Sample density
11. Shielding
12. ¹⁰Be concentration
13. ¹⁰Be uncertainty
14. ¹⁰Be standard
15. ²⁶Al concentration
16. ²⁶Al uncertainty
17. ²⁶Al standard
18. Sampling year
19. Publ ¹⁰Be exp age
20. Publ ¹⁰Be exp age unc
21. Publ ²⁶Al exp age
22. Publ ²⁶Al exp age unc
23. Recalc ¹⁰Be exp age
24. ¹⁰Be external unc
25. ¹⁰Be internal unc
26. Recalc ²⁶Al exp age
27. ²⁶Al external unc
28. ²⁶Al internal unc
29. Extra publication

For recalculation

Recalculated ages

Recalculation

^{10}Be - ^{26}Al exposure age calculator



For calculating an exposure age when erosion rate is known independently.

Multiple sample form, Version 2.2, March, 2009. Written by Greg Balco, balco@bgc.org

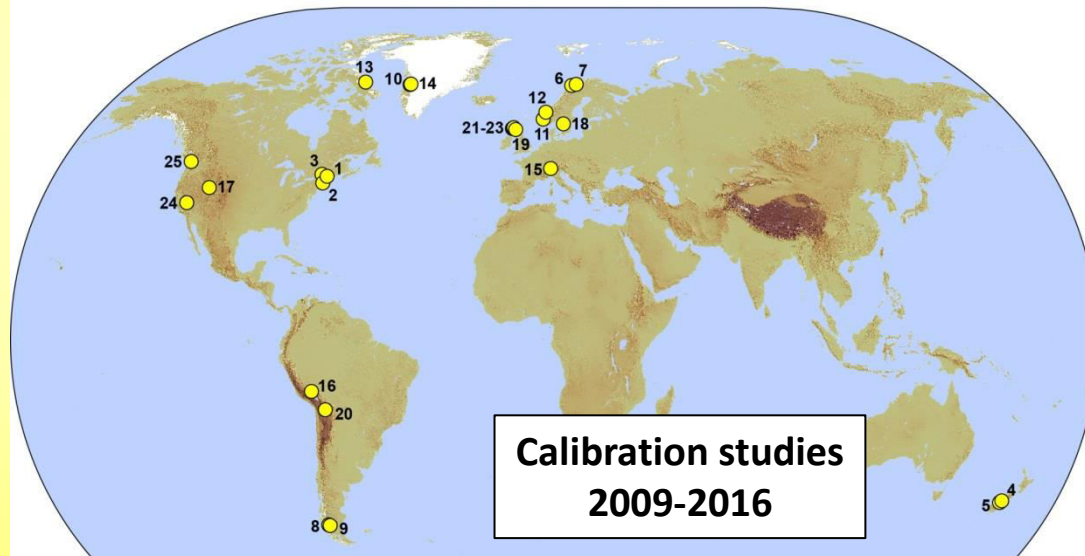
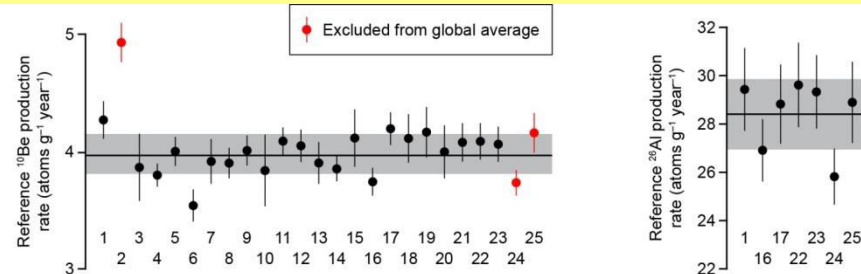
[Calculators home](#)
[Erosion rates](#)
[Documentation](#)

Use a test sample
for demonstration
purposes --

Enter data block here See below for formatting instructions

TB-06-02	34.596500	97.986961
4126823	111897	0702020 0
TB-06-37	34.599222	97.994611
2353618	97376	0702020 0
TB-07-125	34.604917	98.015056
4020038	143384	0702020 0

Balco et al. (2008)



**Calibration studies
2009-2016**

expage.github.io/calculator

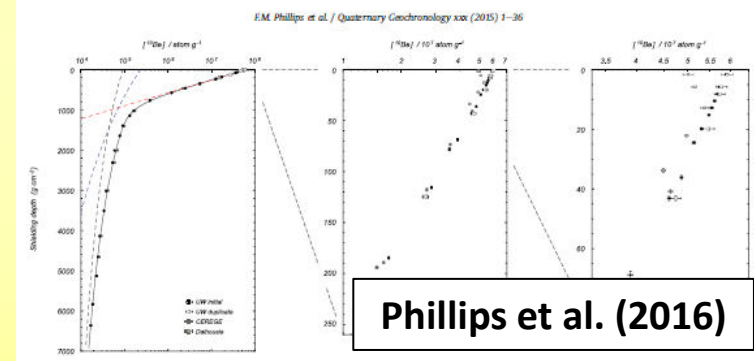


Scaling *in situ* cosmogenic nuclide production rates using analytical approximations to atmospheric cosmic-ray fluxes

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^a Department of Earth, Atmospheric, and Planetary Sciences and Department of Physics
^b Research Group for Radiation Protection, Division of Environment and Radiation Safety
Japan Atomic Energy Agency, Tokai, Naka, Ibaraki 319-1195, Japan
^c Institut für Geologie und Mineralogie, Universität zu Köln, Greifstrasse 4, Gebäude

Lifton et al. (2014)



Phillips et al. (2016)

Table 4

The table used for the interpolation of attenuation lengths based on the given atmospheric depth (top row, in units of g/cm^2) and cutoff rigidity (first column, in units of GV). Values based on those obtained using the spreadsheet that accompanied [Sato et al. \(2008\)](#), but include the additional 11.1% correction discussed in the text.

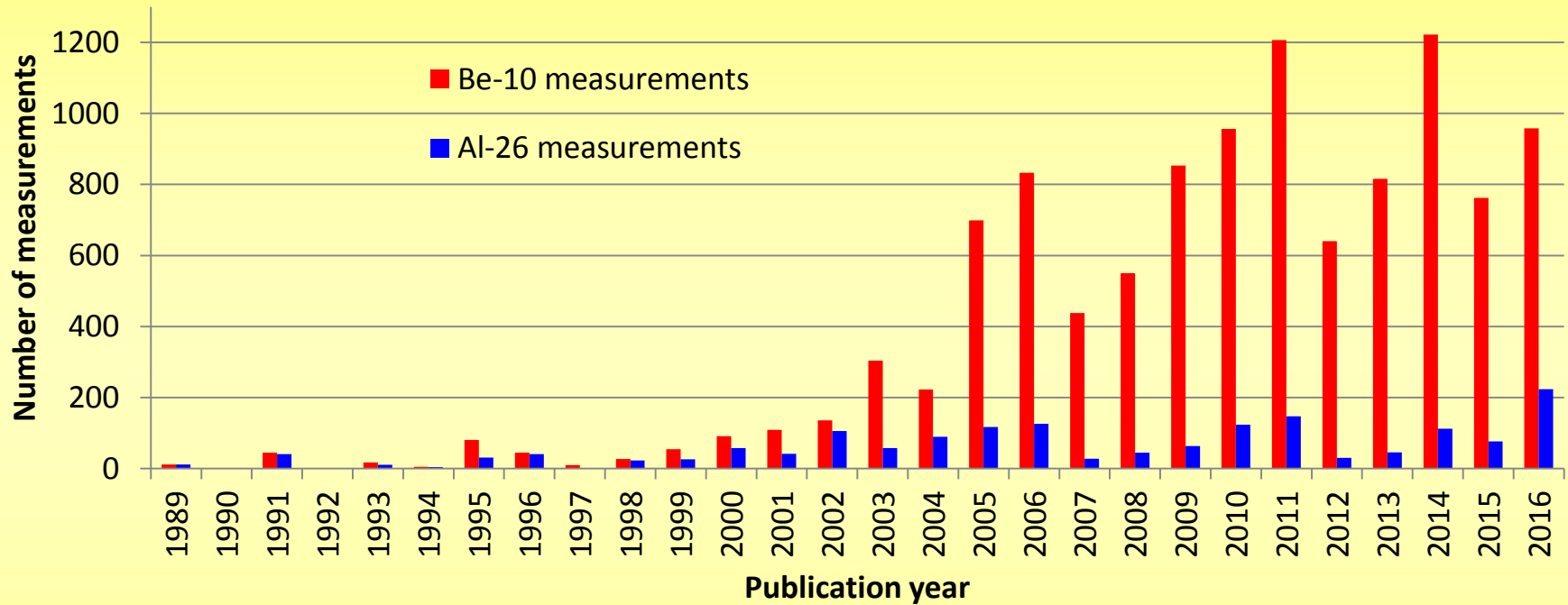
Depth/Cut. Rig.	1100	1000	900	800	700	600	500	400
0	151	152	153	154	155	158	163	172
4	152	152	154	156	159	164	171	185
8	156	159	161	164	168	175	185	204
12	162	165	168	171	176	184	196	218
16	168	170						
20	169	171						

Marrero et al. (2016)

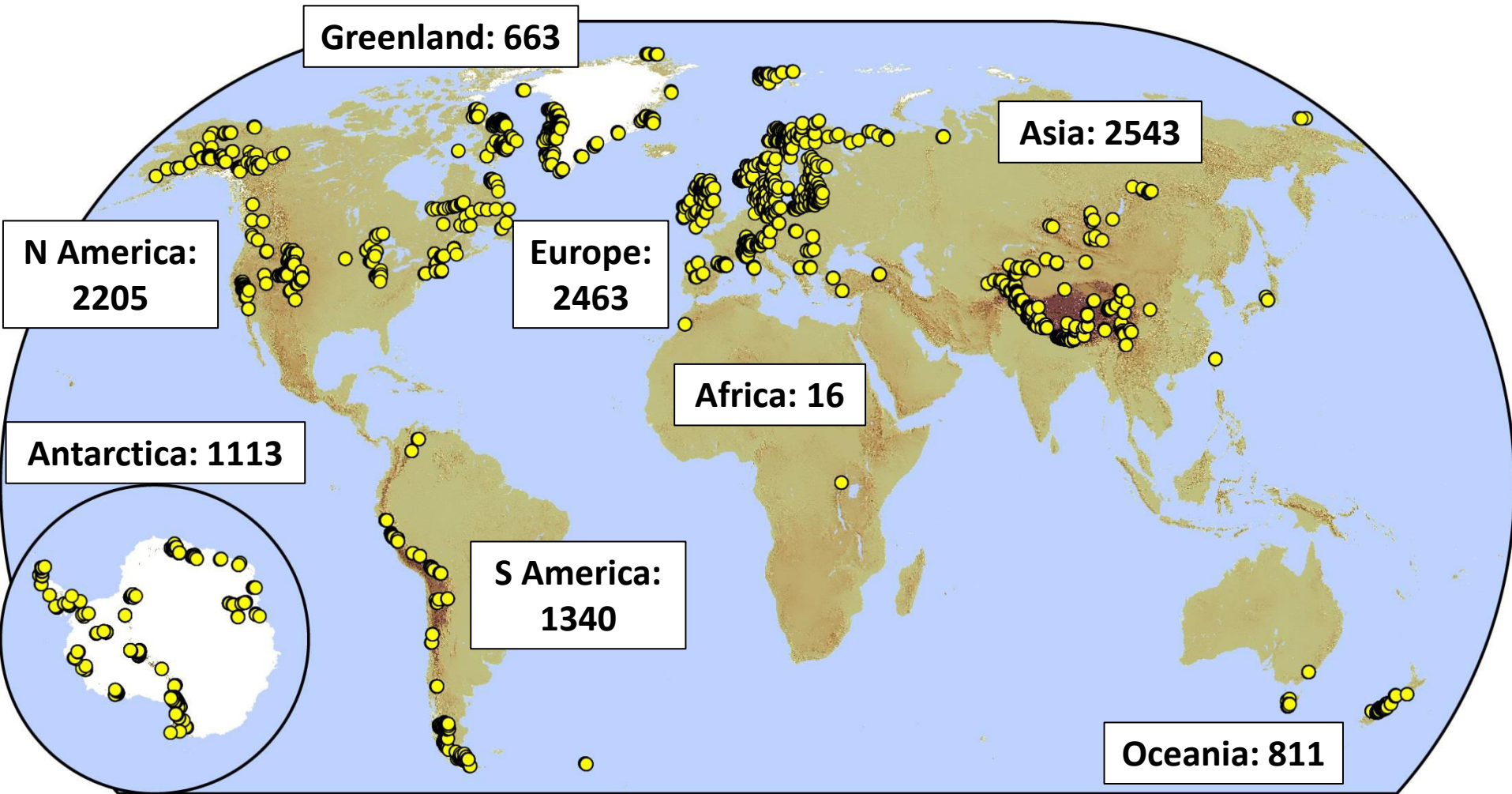
Data from 527 primary publications

^{10}Be : **11 093** measurements

^{26}Al : **1 683** measurements



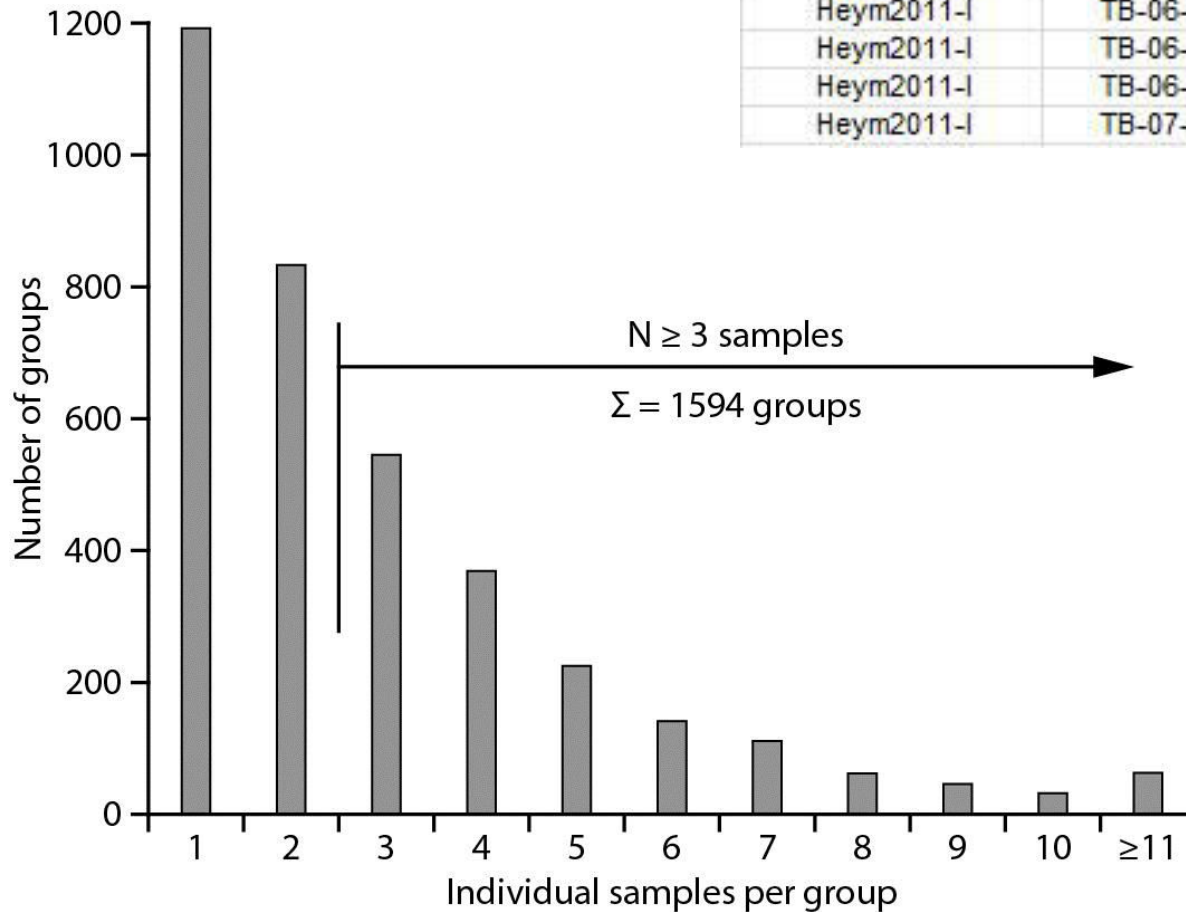
Spatial distribution



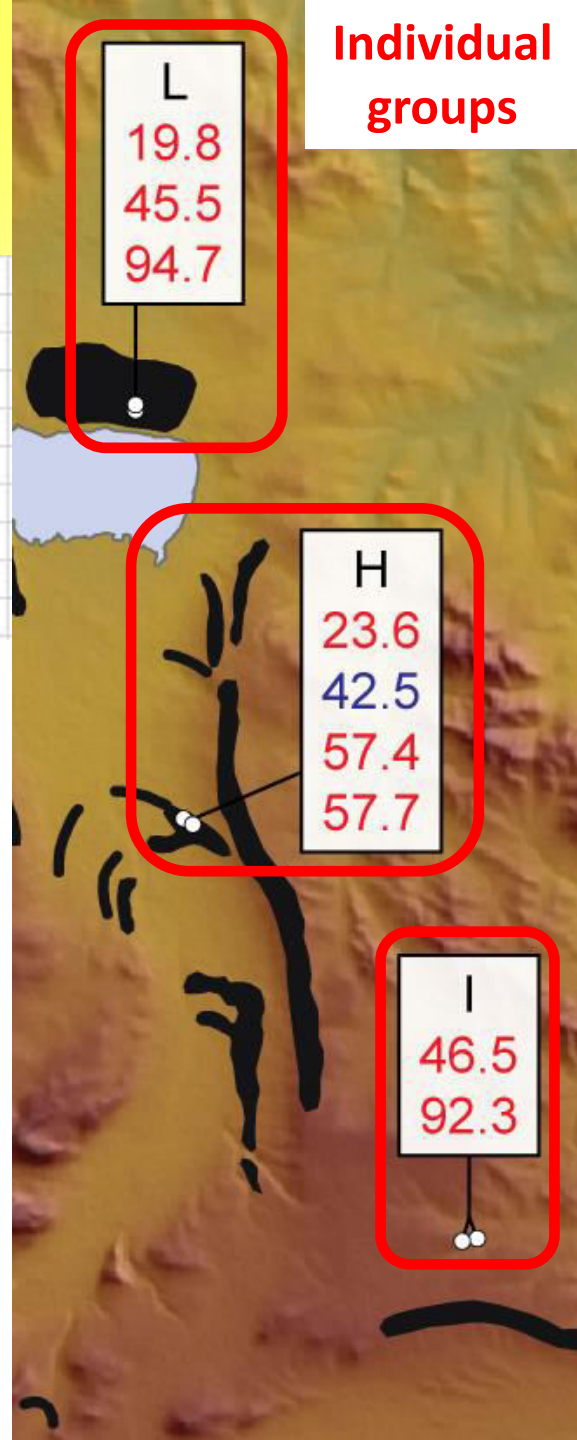
All samples ordered in groups

One group = one deglaciation age

Heym2011-G	TB-06-46
Heym2011-G	TB-06-47
Heym2011-G	TB-06-48
Heym2011-H	TB-06-31
Heym2011-H	TB-06-32
Heym2011-H	TB-06-33
Heym2011-I	TB-06-25
Heym2011-I	TB-06-26
Heym2011-I	TB-06-27
Heym2011-I	TB-07-90



Individual groups

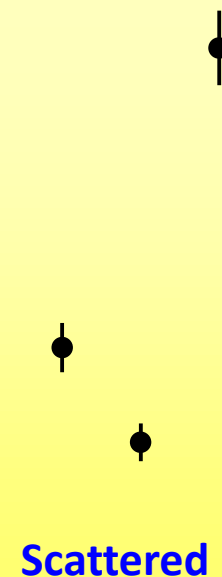
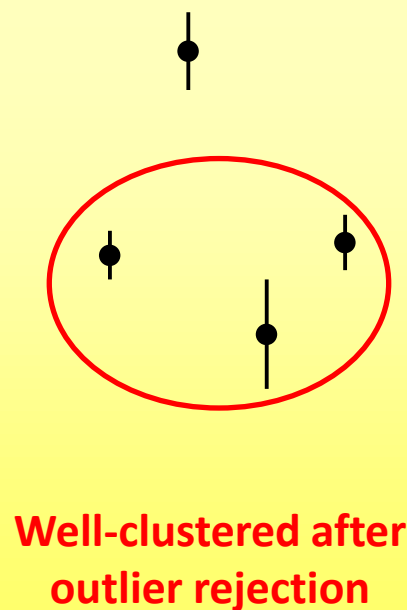
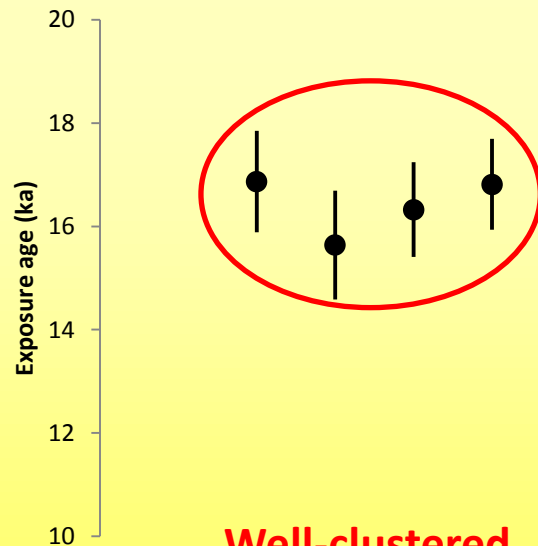


Group exposure age clustering

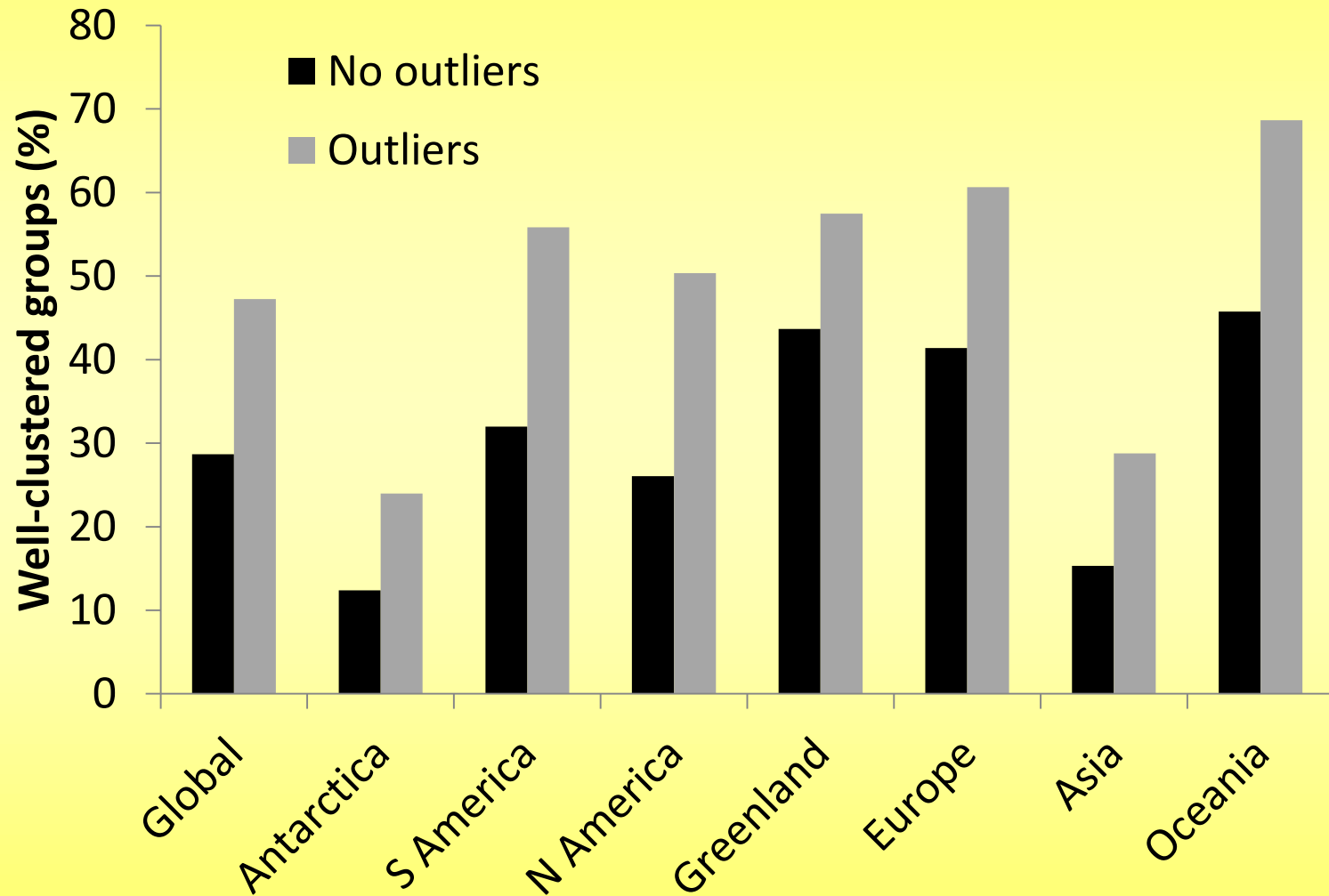
Scattered: Chi-square analysis P-value < 0.05

Well-clustered: Chi-square analysis P-value > 0.05

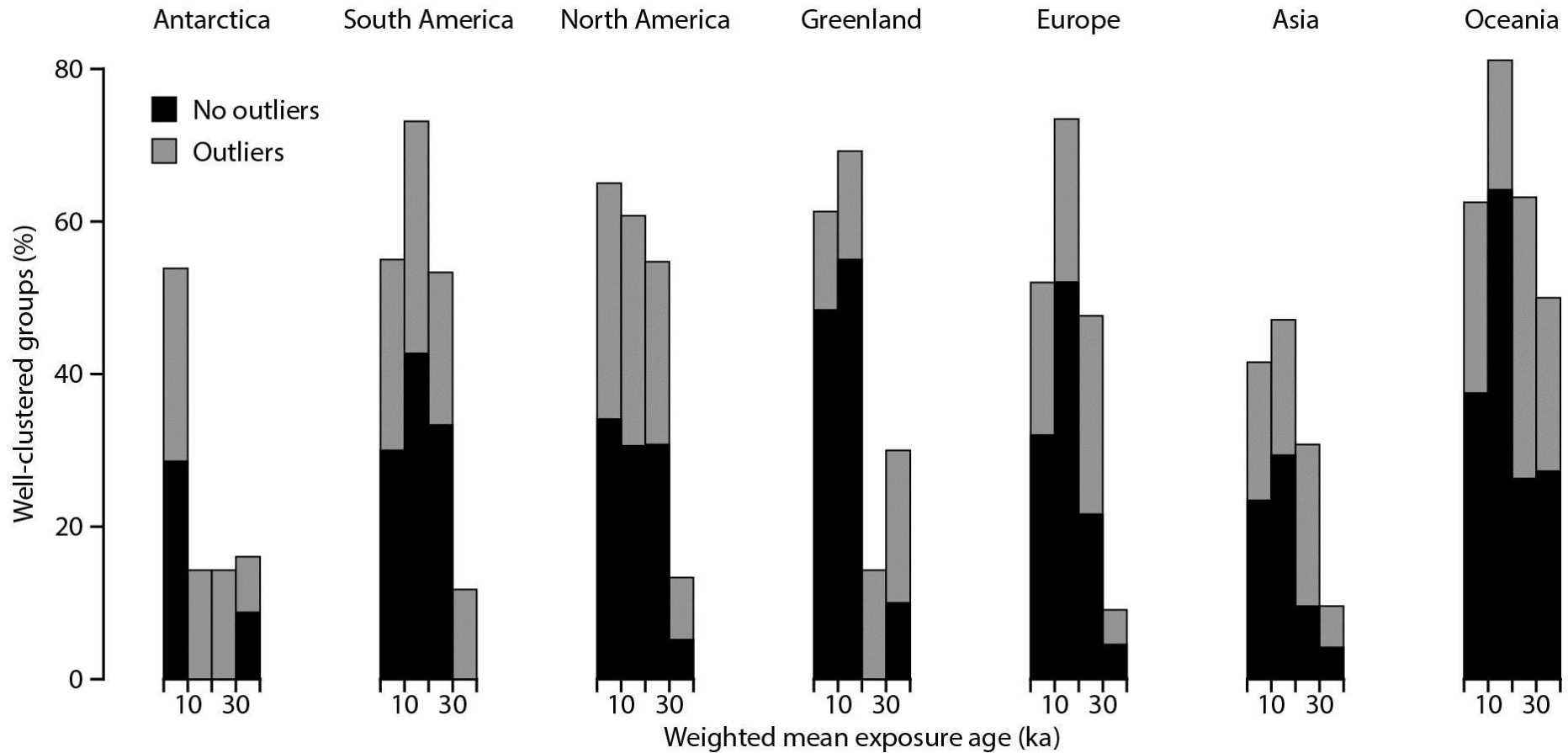
Outlier rejection: max 1/3 still requiring at least 3 samples



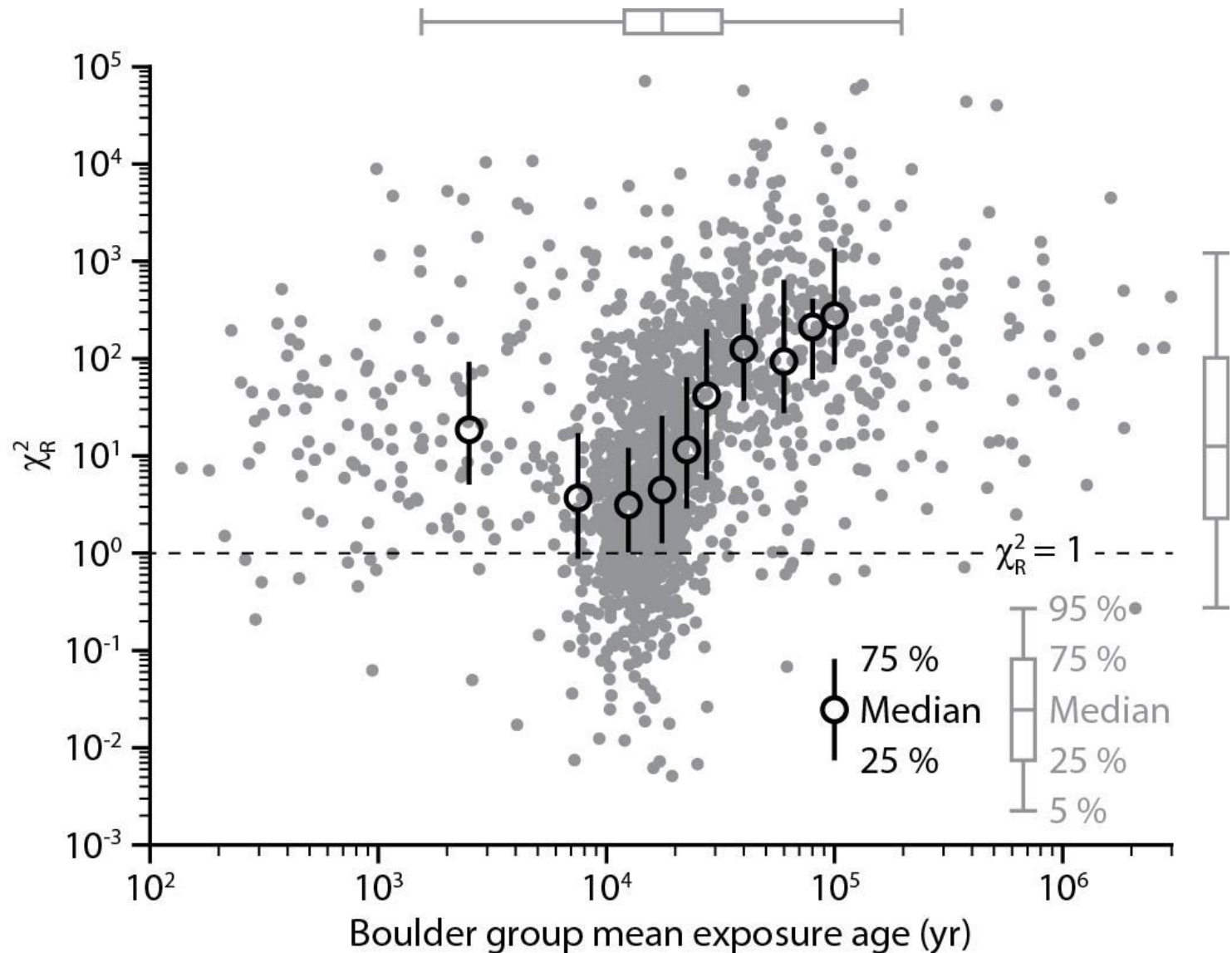
How common is well-clustered data?



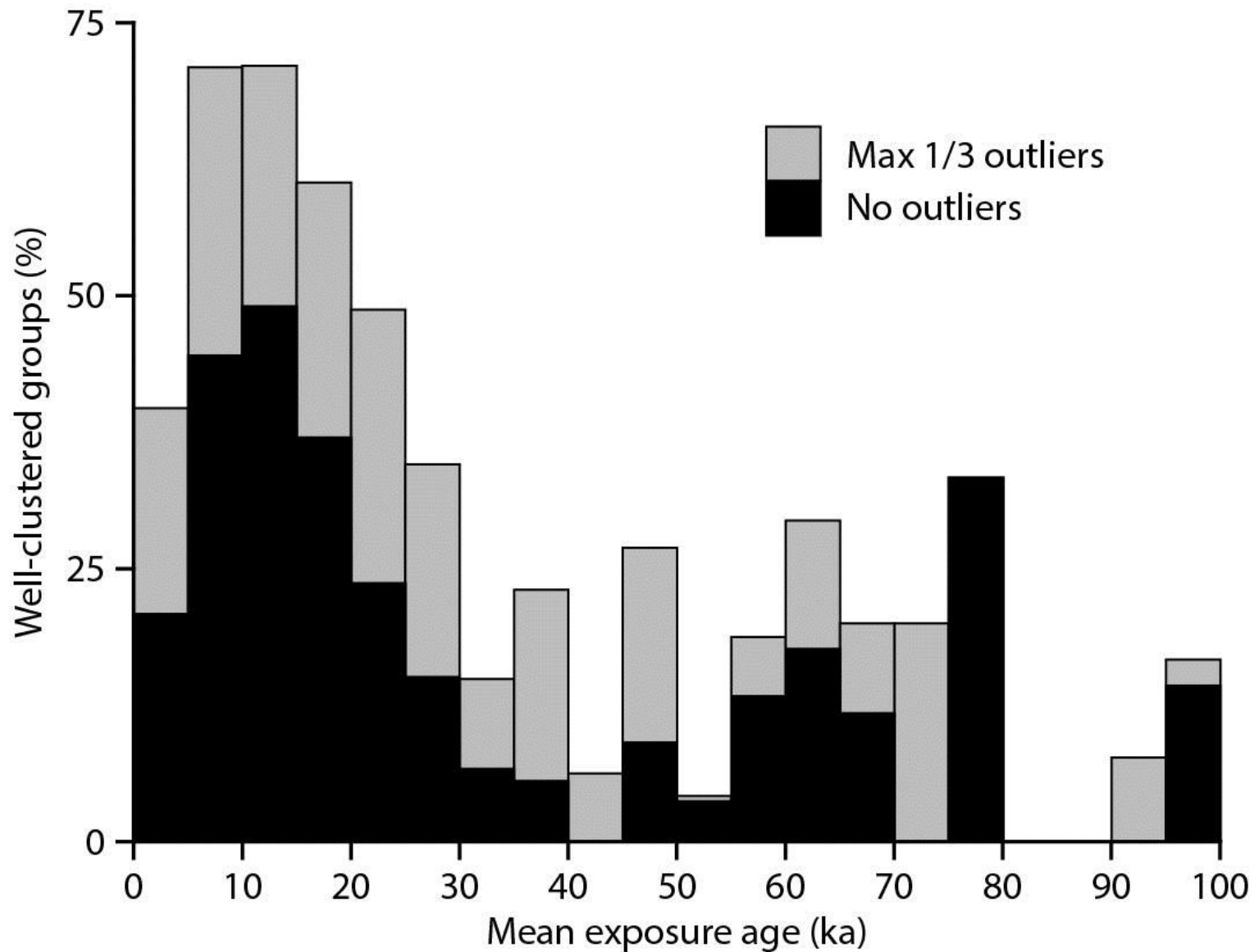
Clustering against mean age



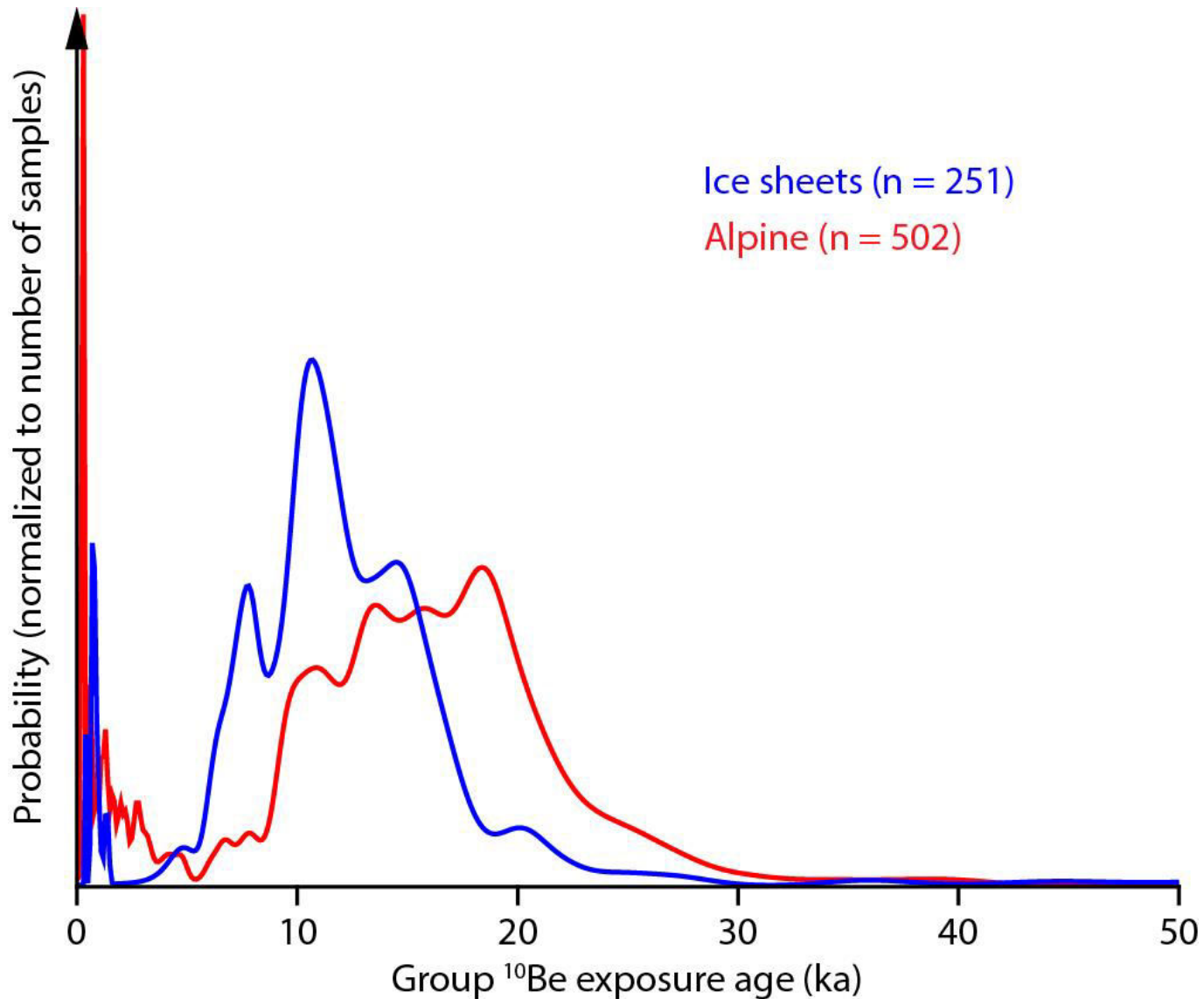
Clustering/scatter against mean age



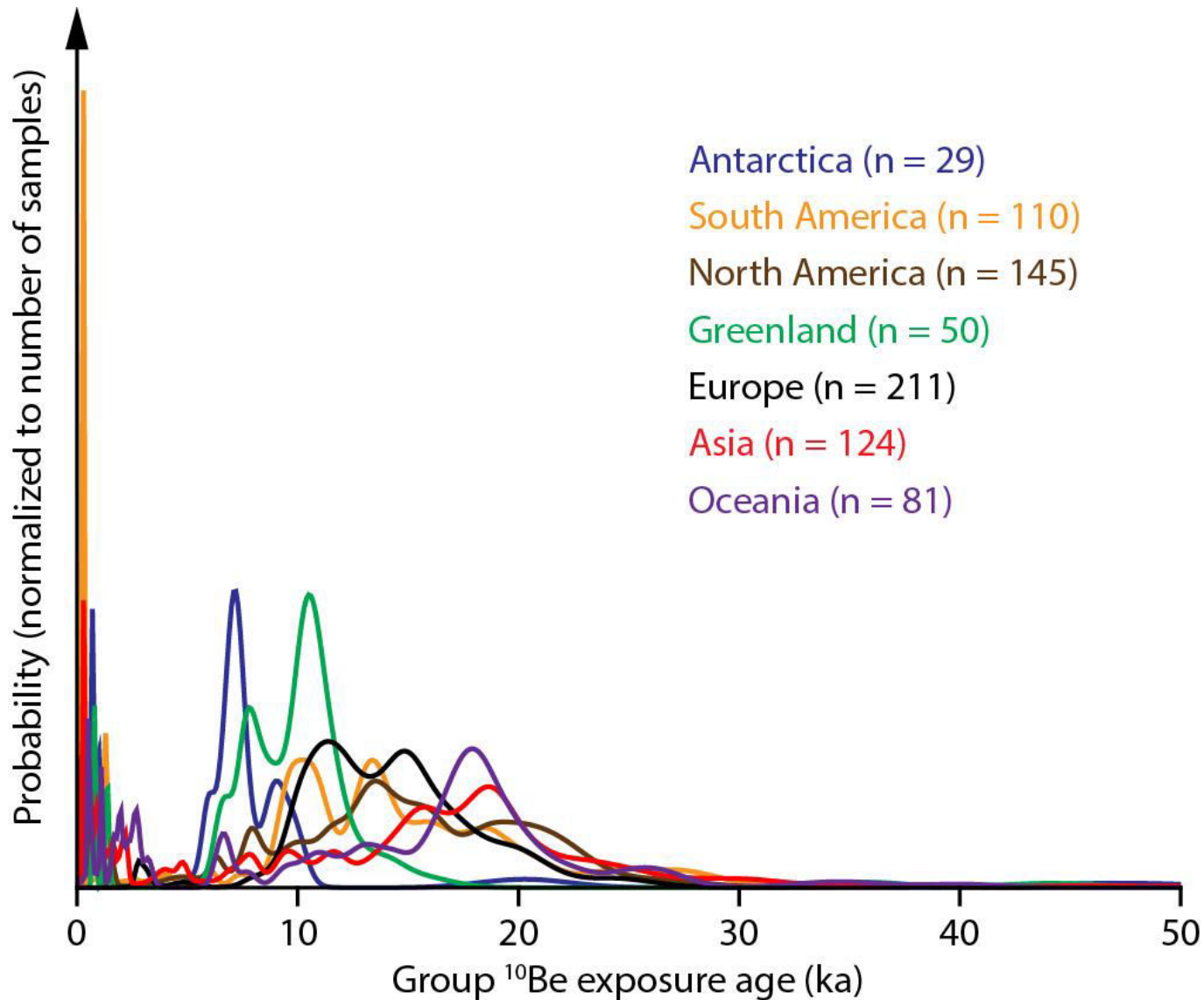
Clustering against mean age



Well-clustered group ages

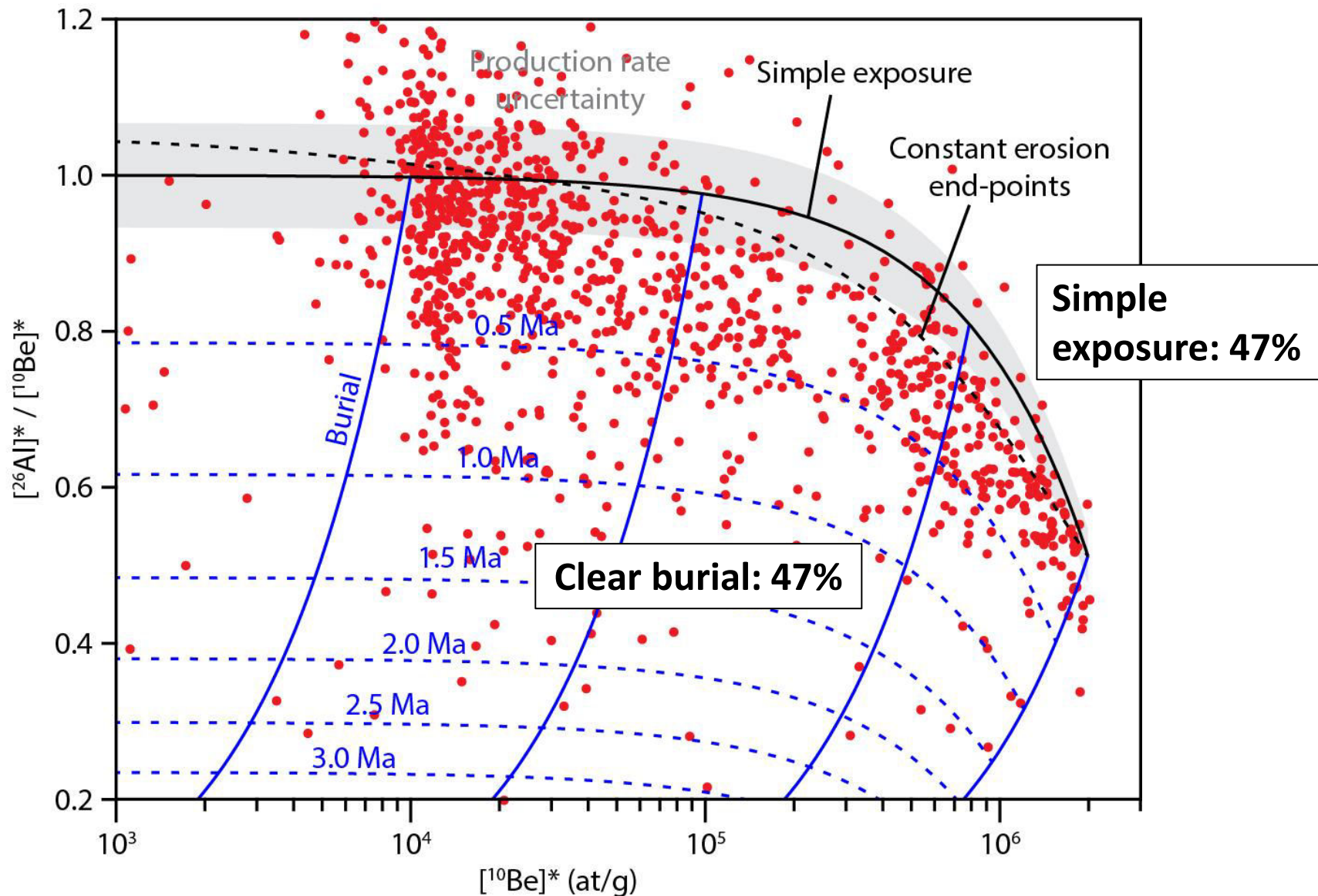


Well-clustered group ages



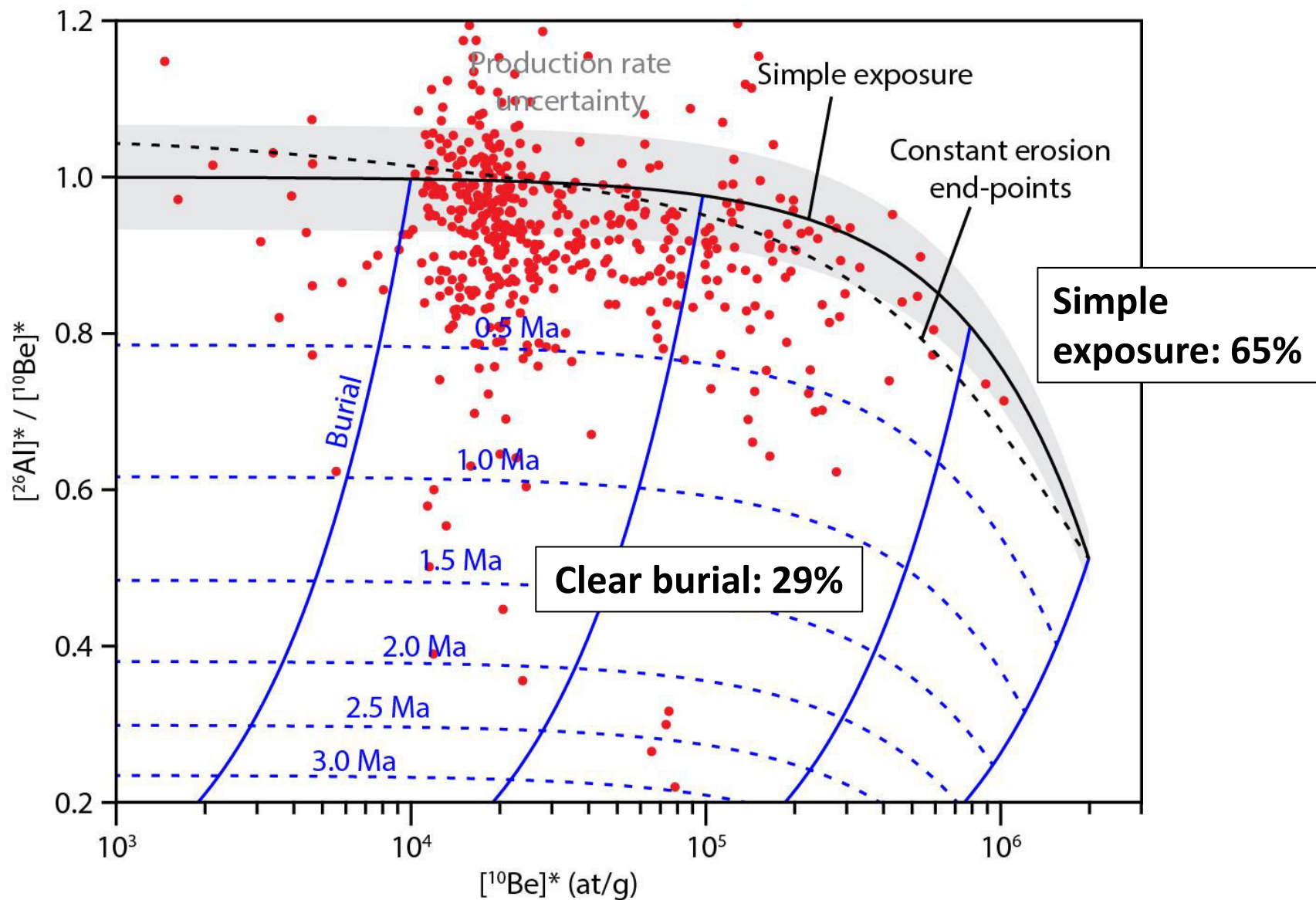
ICE SHEETS

Forbidden zone: 6%

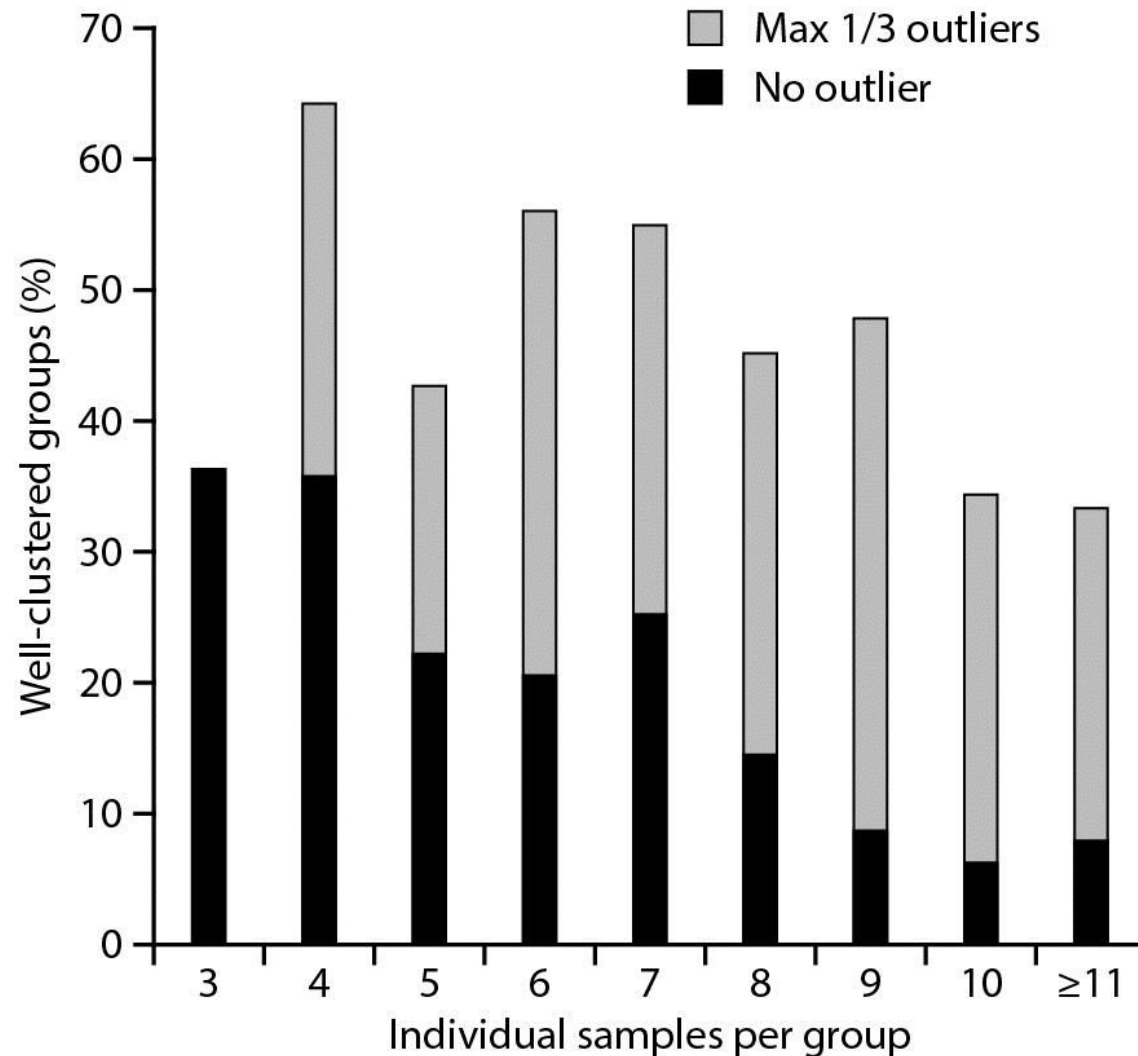


ALPINE

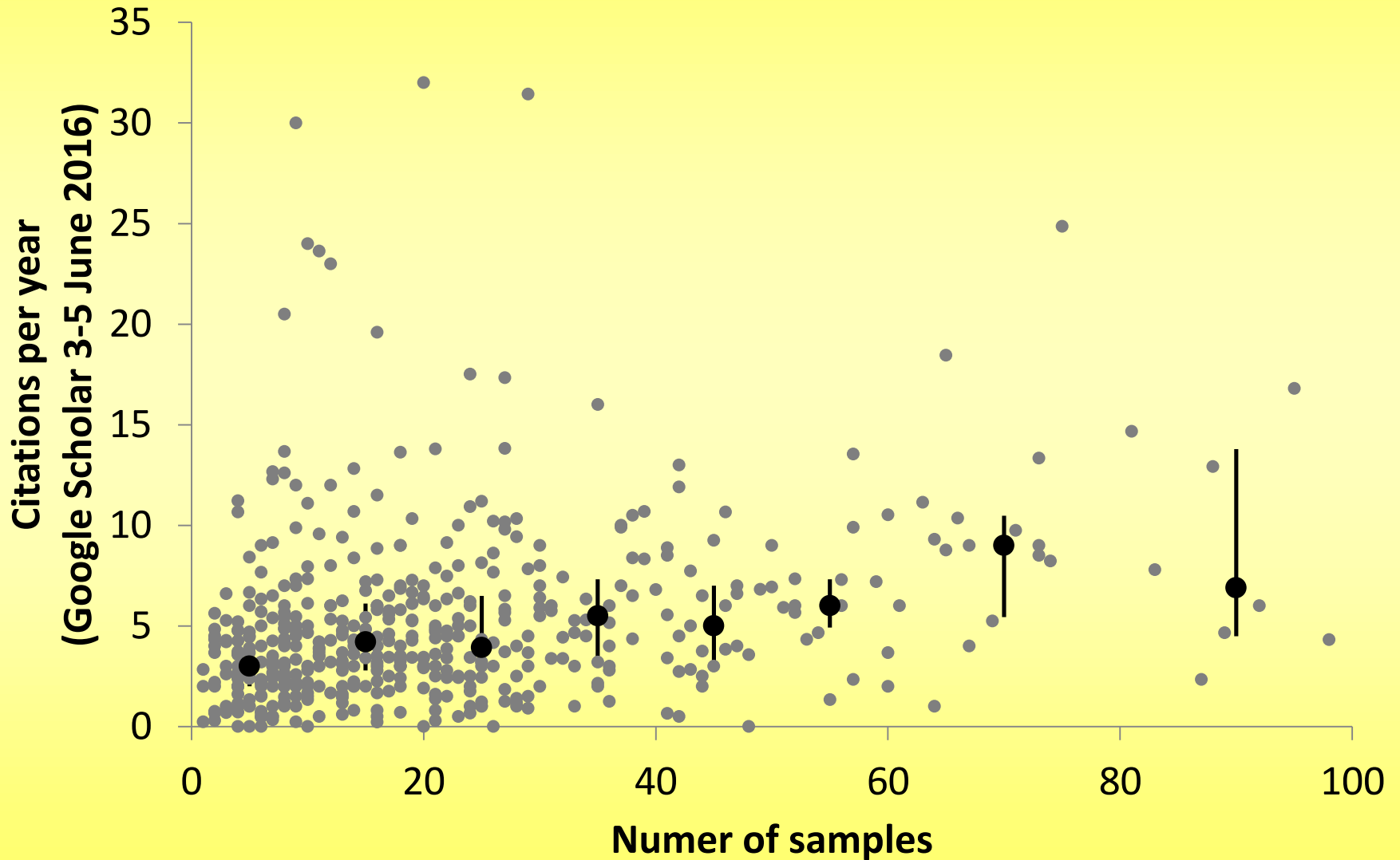
Forbidden zone: 6%



How many samples per site?



How many samples per publication?



A global compilation of glacial ^{10}Be and ^{26}Al data

These pages host a global compilation of published ^{10}Be and ^{26}Al data from glacial samples, with the aim of allowing easy access to data enabling recalculation of exposure ages and cosmogenic data meta-analysis. Data has been compiled from published sources and additional data sources (data directly from the authors, data from another paper, assumptions etc) are recorded.

If you find mistakes in the data or if you have more correct / new data: jakob.heyman@gu.se

Data description

The exposure age data is presented in tab-delimited text files with the following 29 columns:

1. **Publication** – Primary publication presenting the data with enough detail to enable recalculation.
2. **Sample type** – Type of sample such as boulder, bedrock, cobble, pebbles...
3. **Surface ID** – Identifier to keep track of repeat measurements of single samples and closely spaced samples from single surfaces.
4. **Group ID** – Identifier to keep track of groups of samples derived from single sites with one deglaciation age.
5. **Sample name** – From the original publication.
6. **Latitude** – Sample latitude in WGS-84 datum (DD).
7. **Longitude** – Sample longitude in WGS-84 datum (DD).

Thank you!

