Cosmogenic exposure dating of glacial (and other) landforms – potentials and problems

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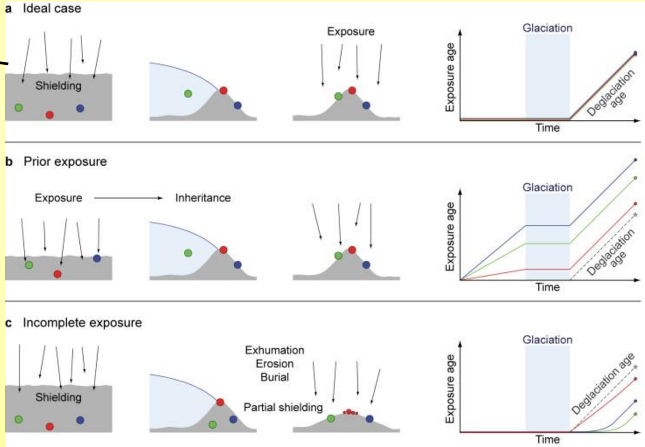
Outline

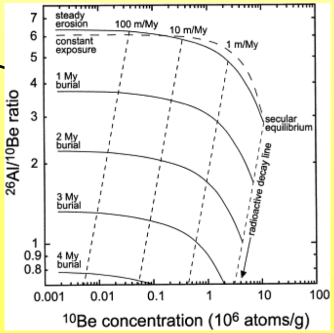
Basics of cosmogenic dating

Glacial exposure dating and geological uncertainties

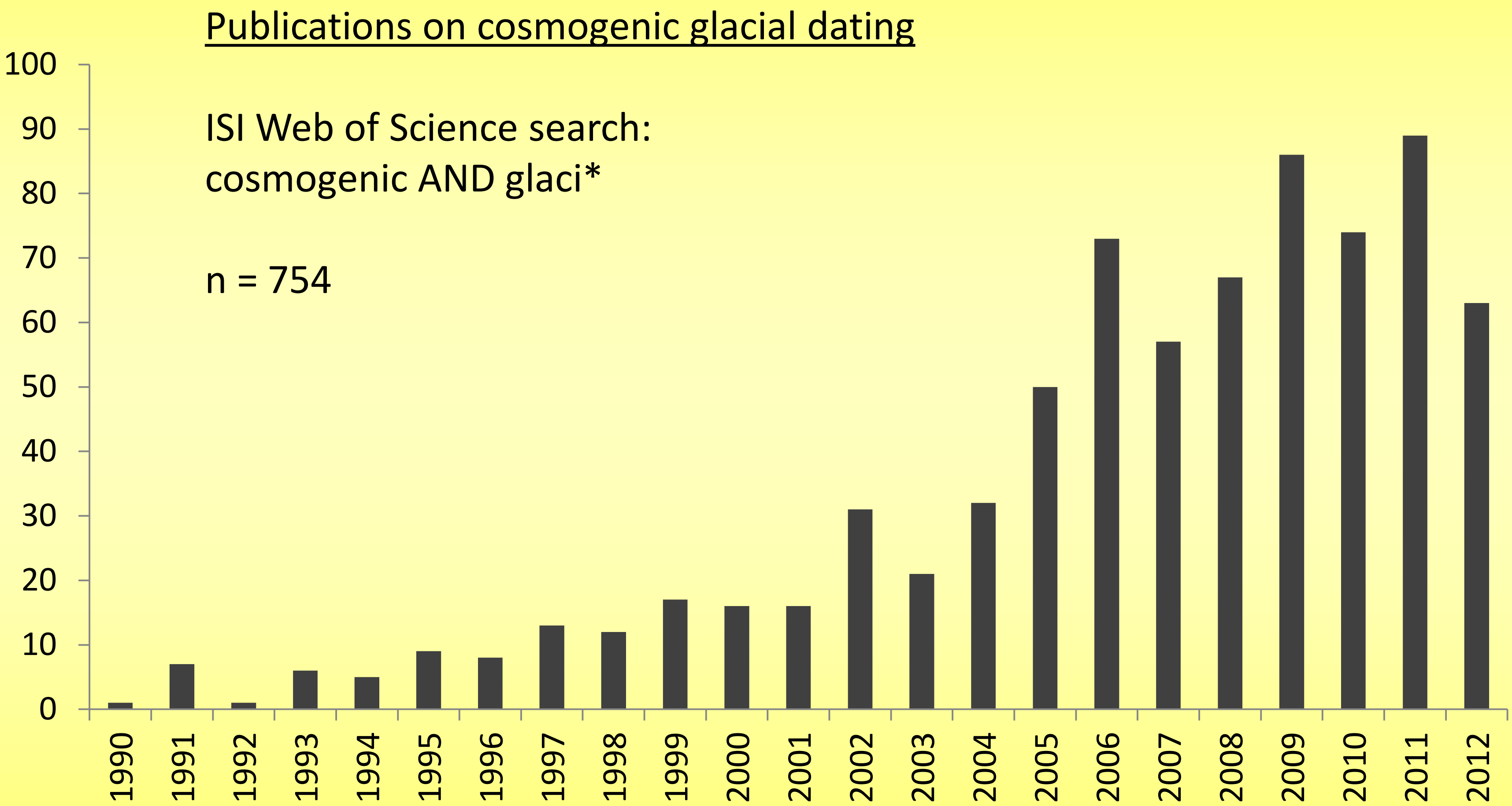


Other cosmogenic nuclide techniques

- **Burial dating**
- **Erosion rate quantification**



History


Publications on cosmogenic glacial dating
ISI Web of Science search:
cosmogenic AND glaci*
n = 754
100
90
80
70
60
50
40
30
20
10
0
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1993
1994
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2008
2009
2010
2011
2012

Basics

Earth is constantly bombarded by cosmic rays

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Interaction in the atmosphere and production of secondary cosmic rays

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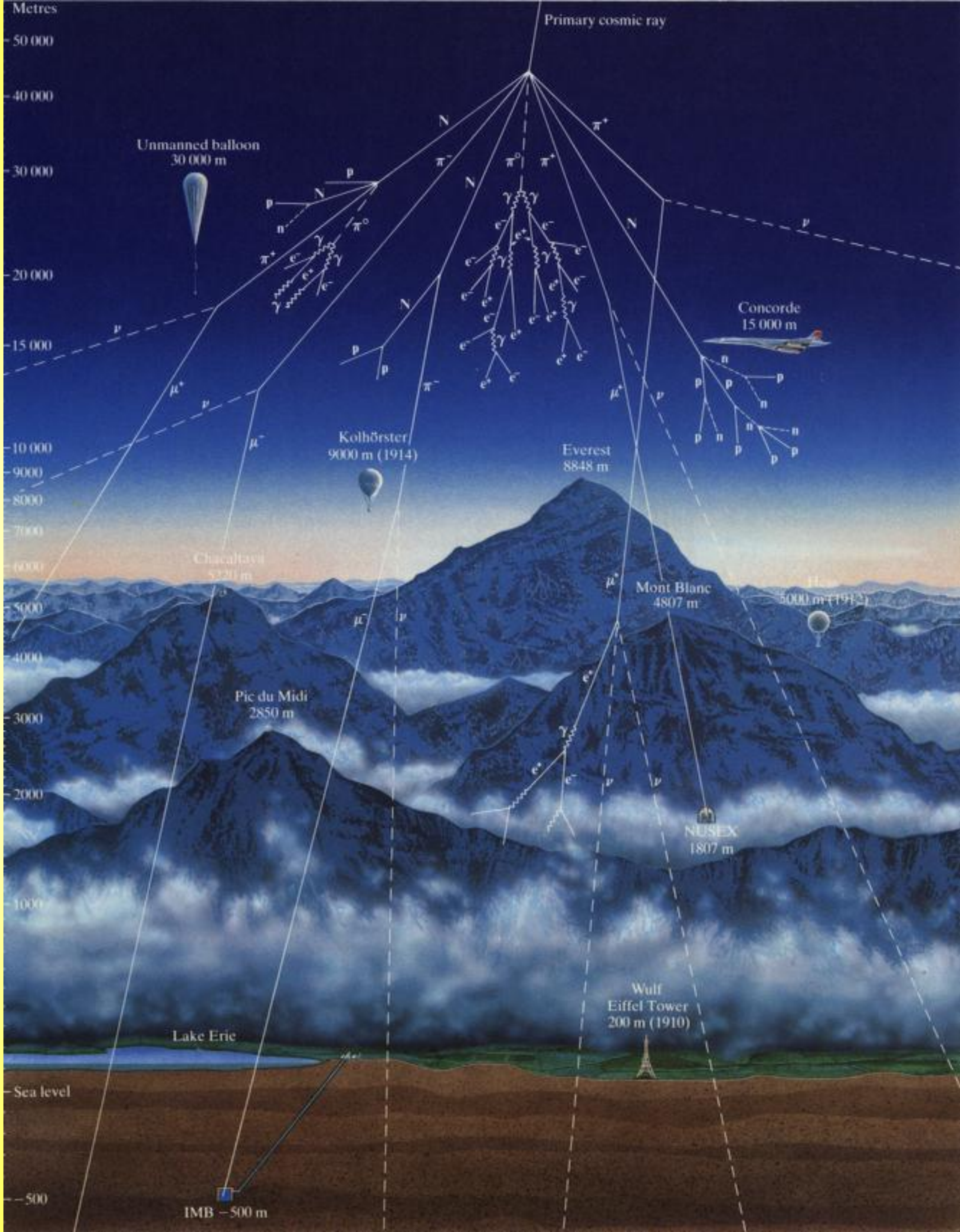
Production of specific cosmogenic nuclides in the earth surface



Cosmogenic nuclides produced in the earth surface when exposed to cosmic rays

Isotope	Half-life (years)	Target mineral
^{10}Be	1 387 000	Quartz
^{26}Al	705 000	Quartz
^{36}Cl	301 000	Several rock types
^{14}C	5 730	Quartz
^{21}Ne	Stable	Quartz, Olivine, Pyroxene
^{3}He	Stable	Olivine, Pyroxene

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Most commonly used isotope for dating studies: **^{10}Be**

Cosmogenic isotope surface production

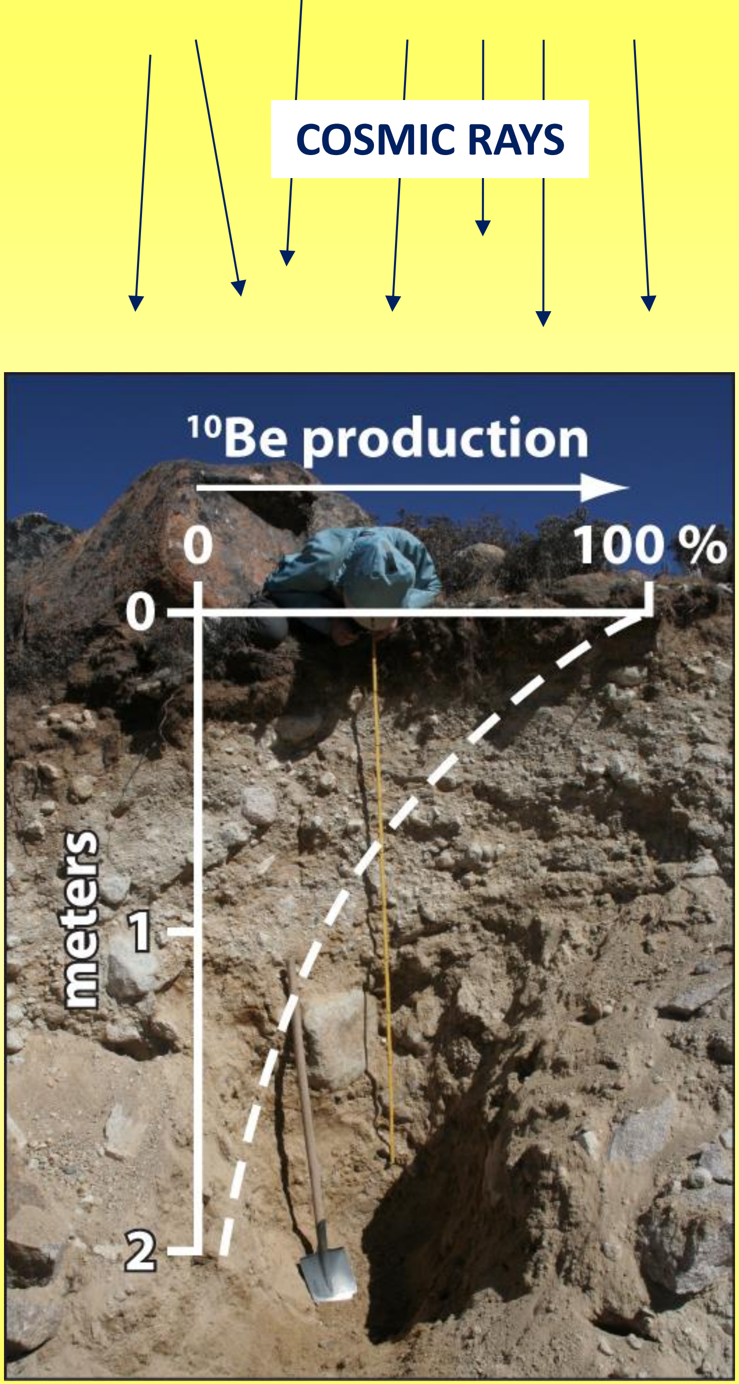
Cosmic rays

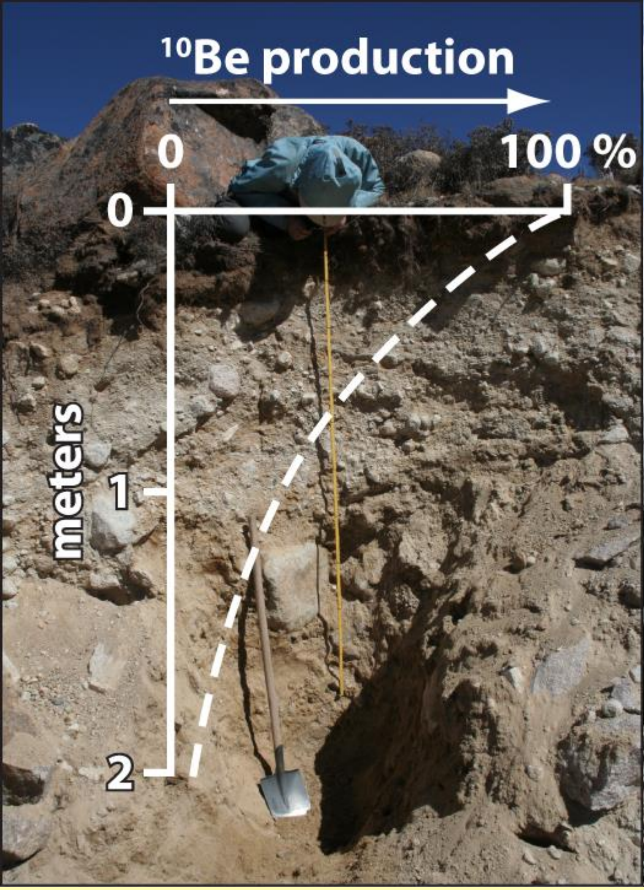
Production of ^{10}Be in quartz

The production rate decrease exponentially with depth below the surface

At depths of 2-3 m or more is the production rate very low

Important for surface exposure dating





At depths of 2-3 m or more is the production rate very low

Important for surface exposure dating

Glaciers erode!

↓

^{10}Be produced in the surface is removed

At the time of deglaciation (T = 0) the ^{10}Be concentration is zero

As time passes after deglaciation the sample will be exposed to cosmic ray bombardment and the ^{10}Be concentration will increase

$$T = \ln(1 - N\lambda / P) / -\lambda$$

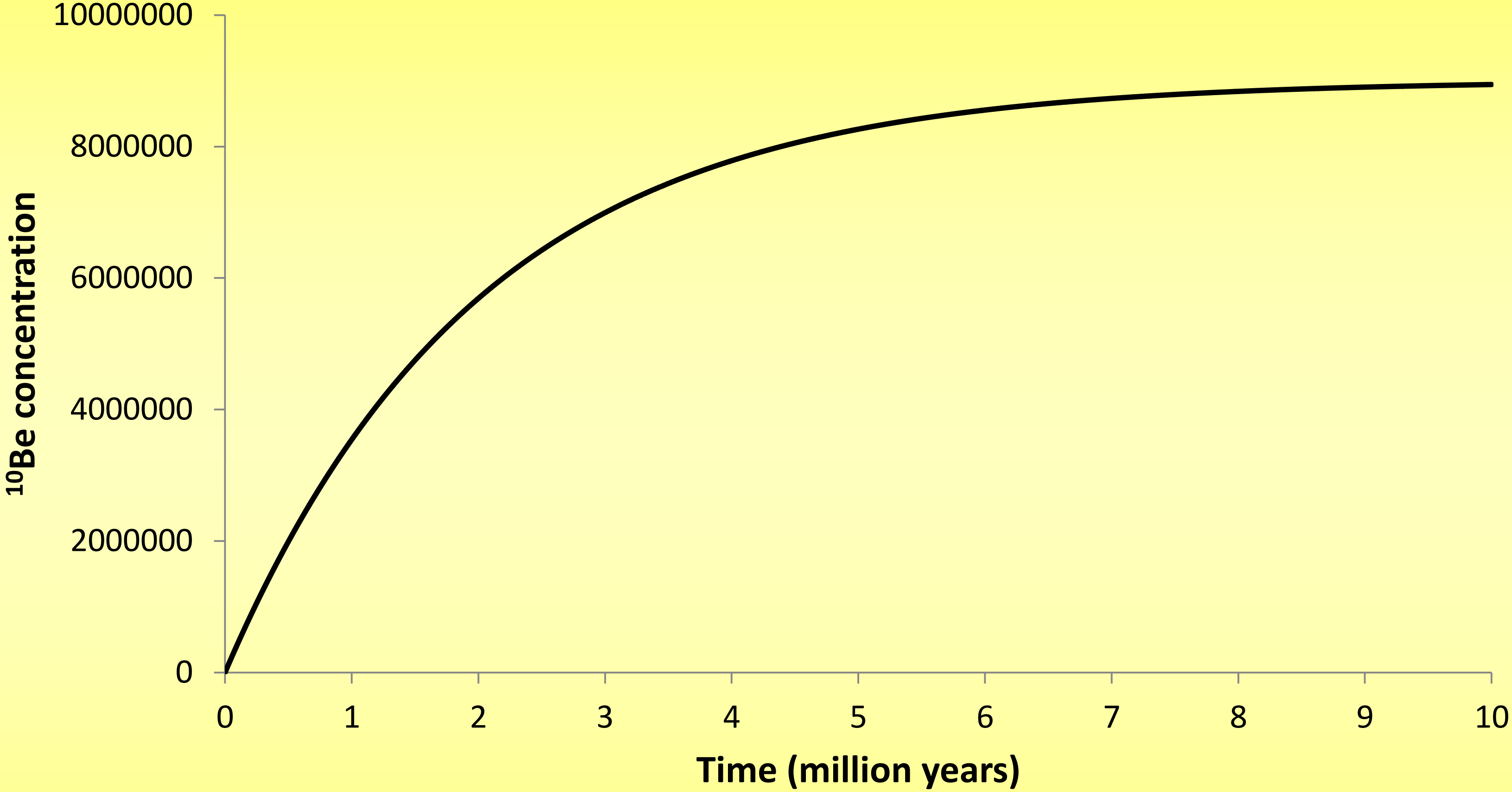
T = Time (age)

$\boxed{N = {}^{10}Be\ \text{concentration}}$

λ = decay constant
$-\ln 0.5 / 1\,387\,000$

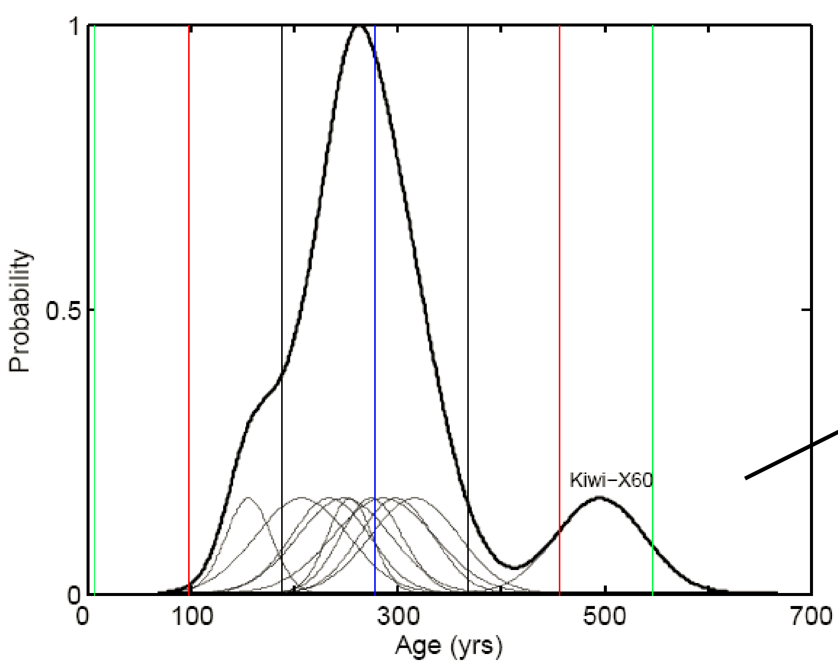
P = production rate

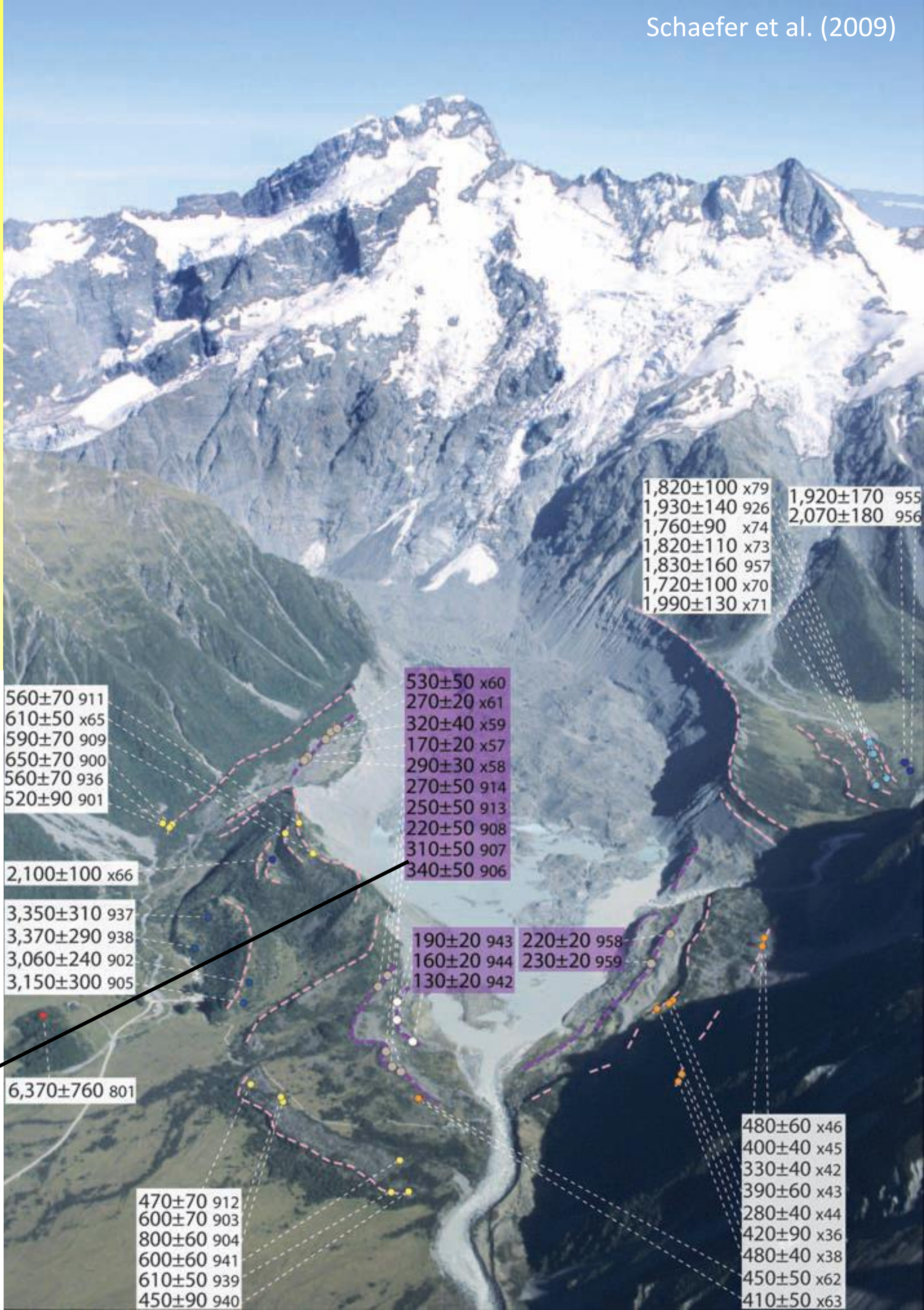
Buildup of ^{10}Be



In theory, dating of several million years old events is possible

Also, high measurement precision has enabled dating of very young surfaces

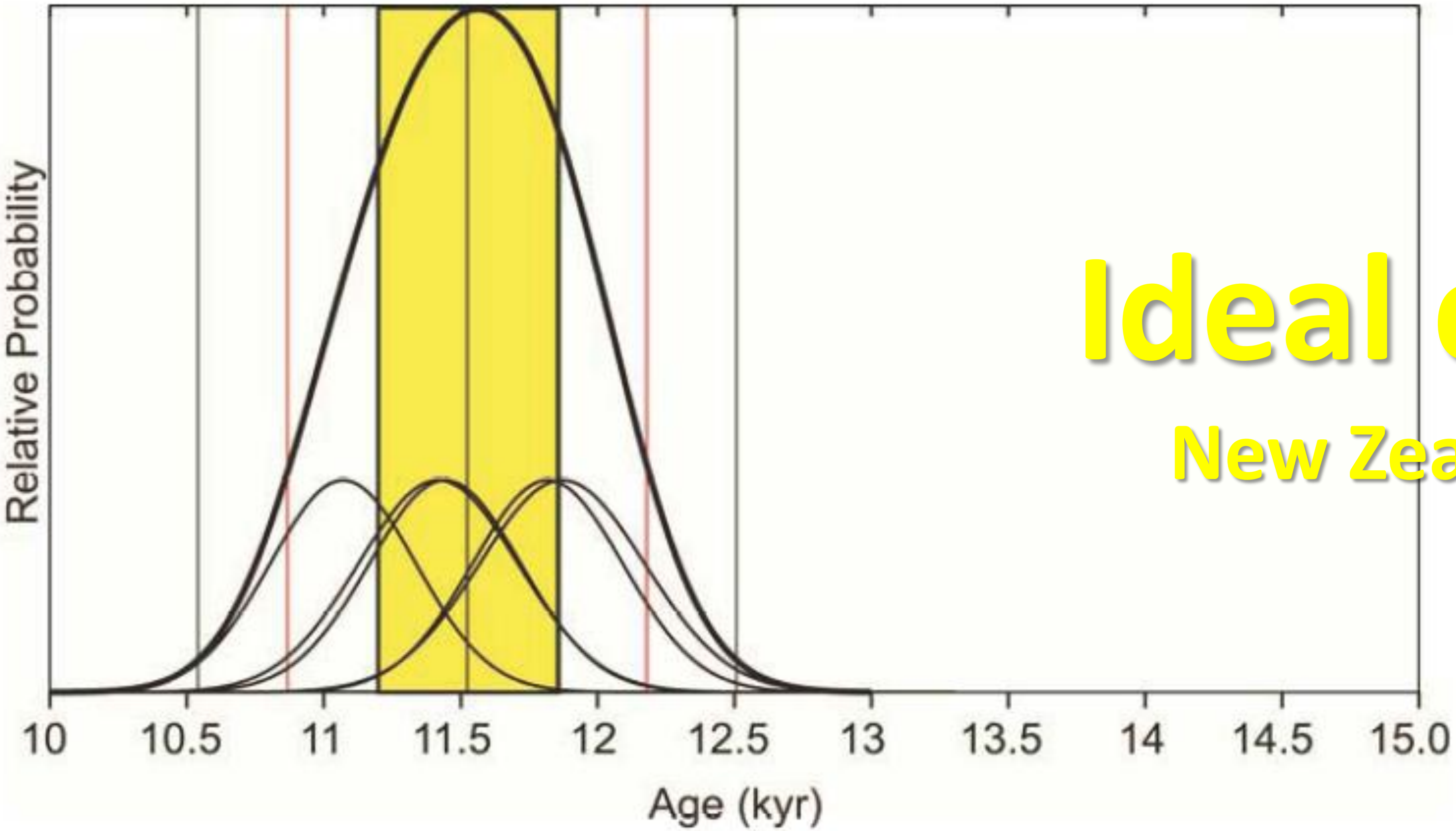




Ideal case

New Zealand

From Kaplan et al. (2010)



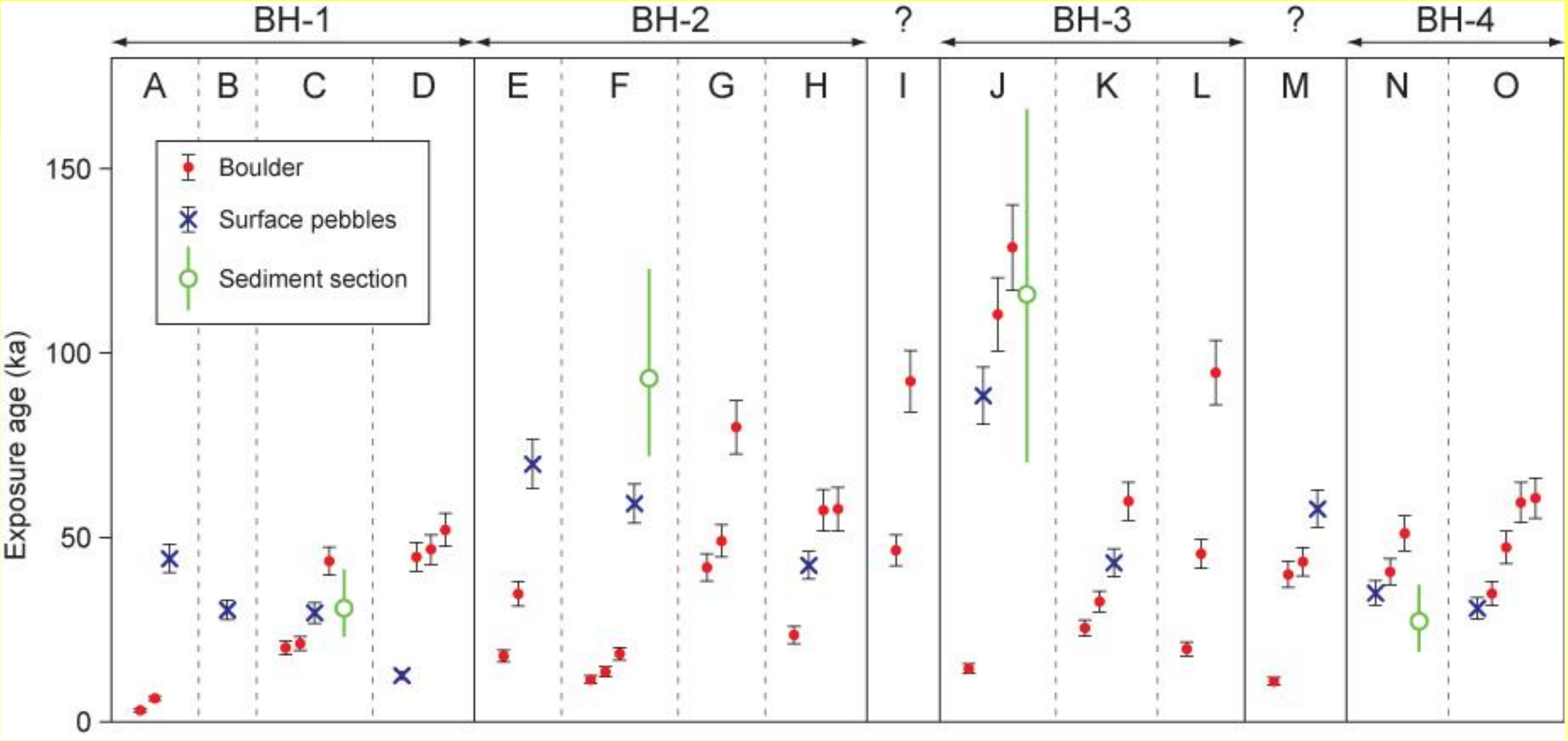
Ideal case

New Zealand

Statistics:
Arithmetic mean/1 sigma uncertainty: 11,500±330 yrs
Including production rate uncertainty: 11,500±420 yrs

Weighted mean/weighted uncertainty: 11,500±130 yrs
Peak age: 11,600 yrs
Median/Interquartile Range: 11,400±500 yrs
Reduced χ^2: 1.4

From Kaplan et al. (2010)



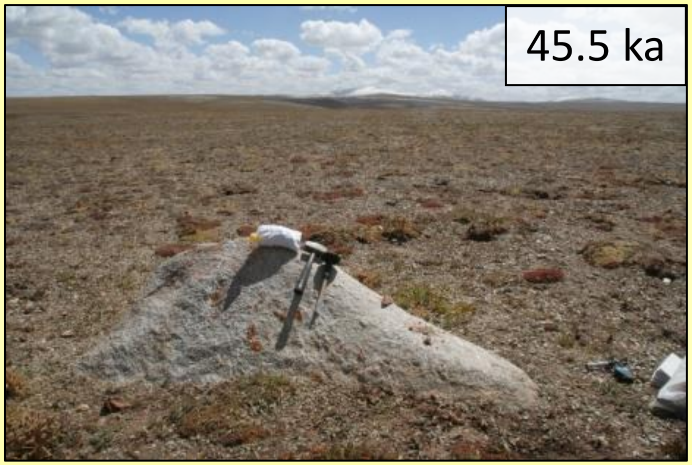
Non-ideal case

Tibetan Plateau

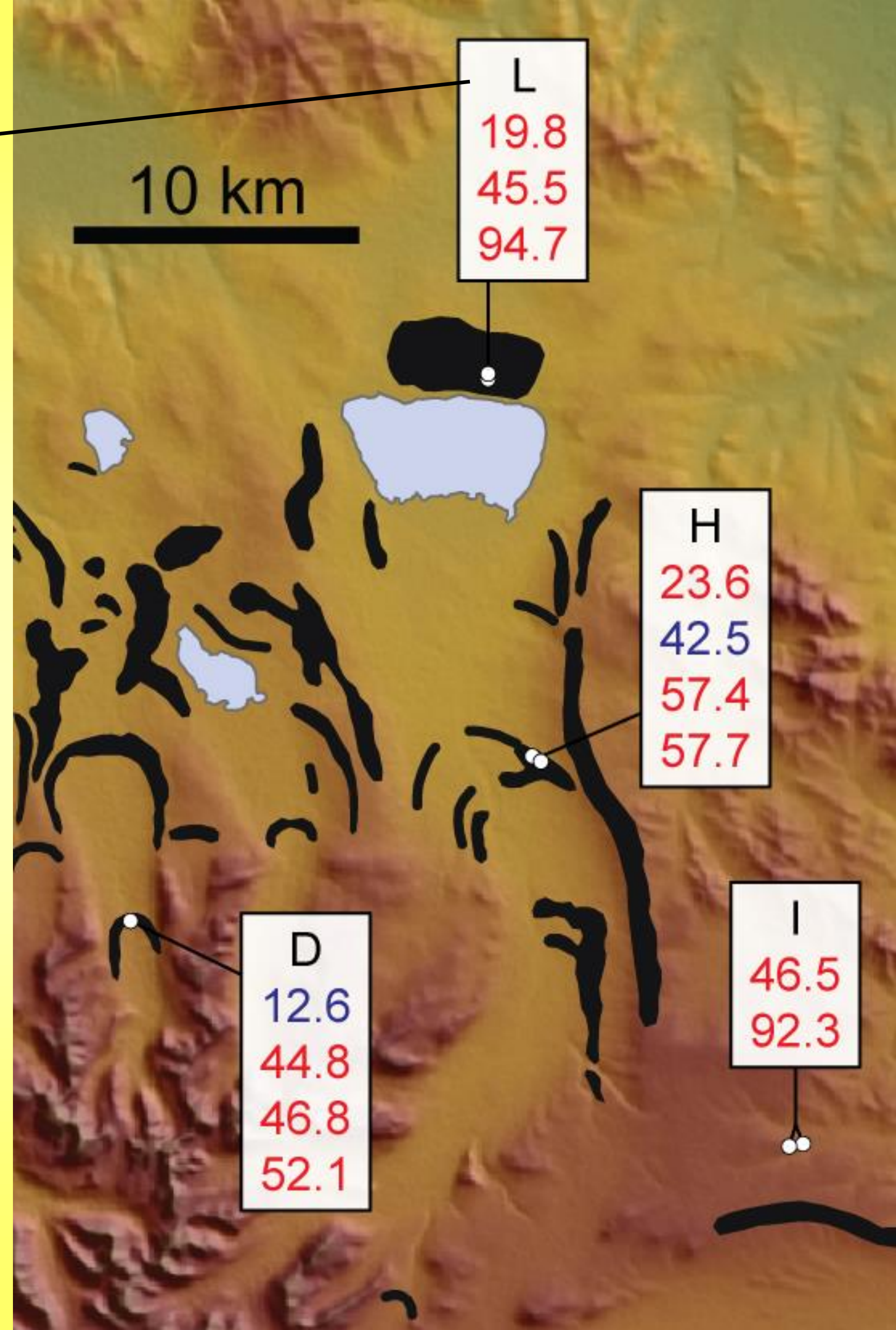
From Heyman et al. (2011)

Correct age ???

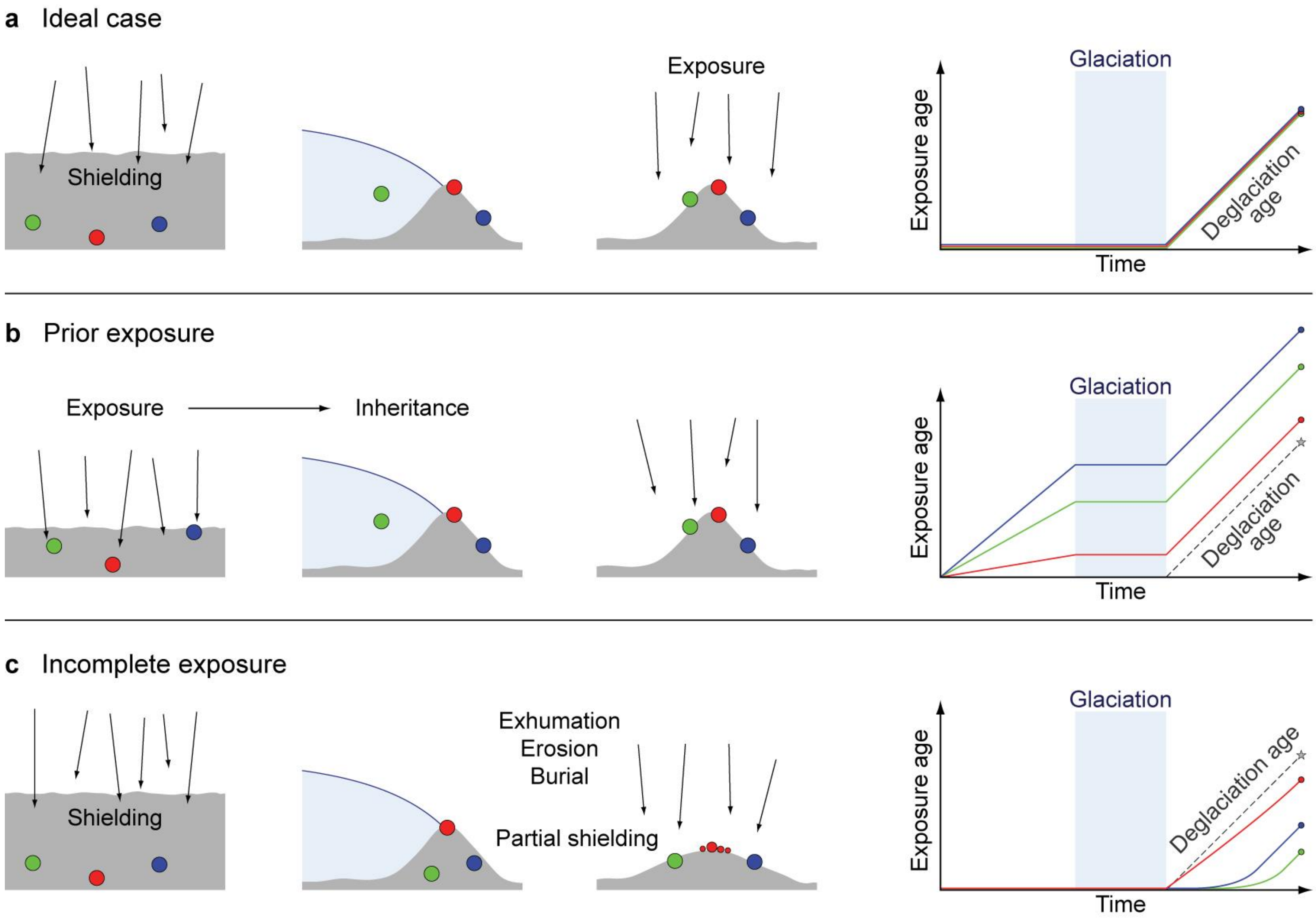

94.7 ka


45.5 ka

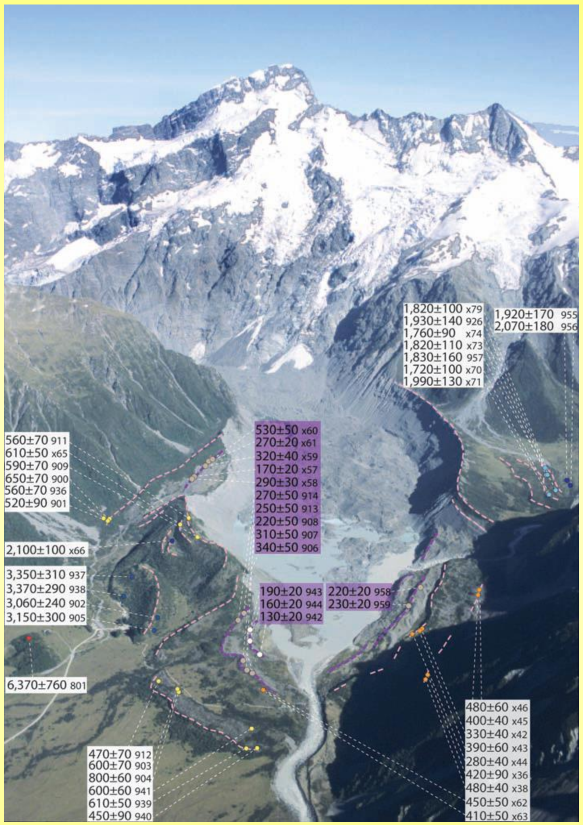

19.8 ka


10 km
L
19.8
45.5
94.7
H
23.6
42.5
57.4
57.7
D
12.6
44.8
46.8
52.1
I
46.5
92.3

Glacial exposure dating – problems

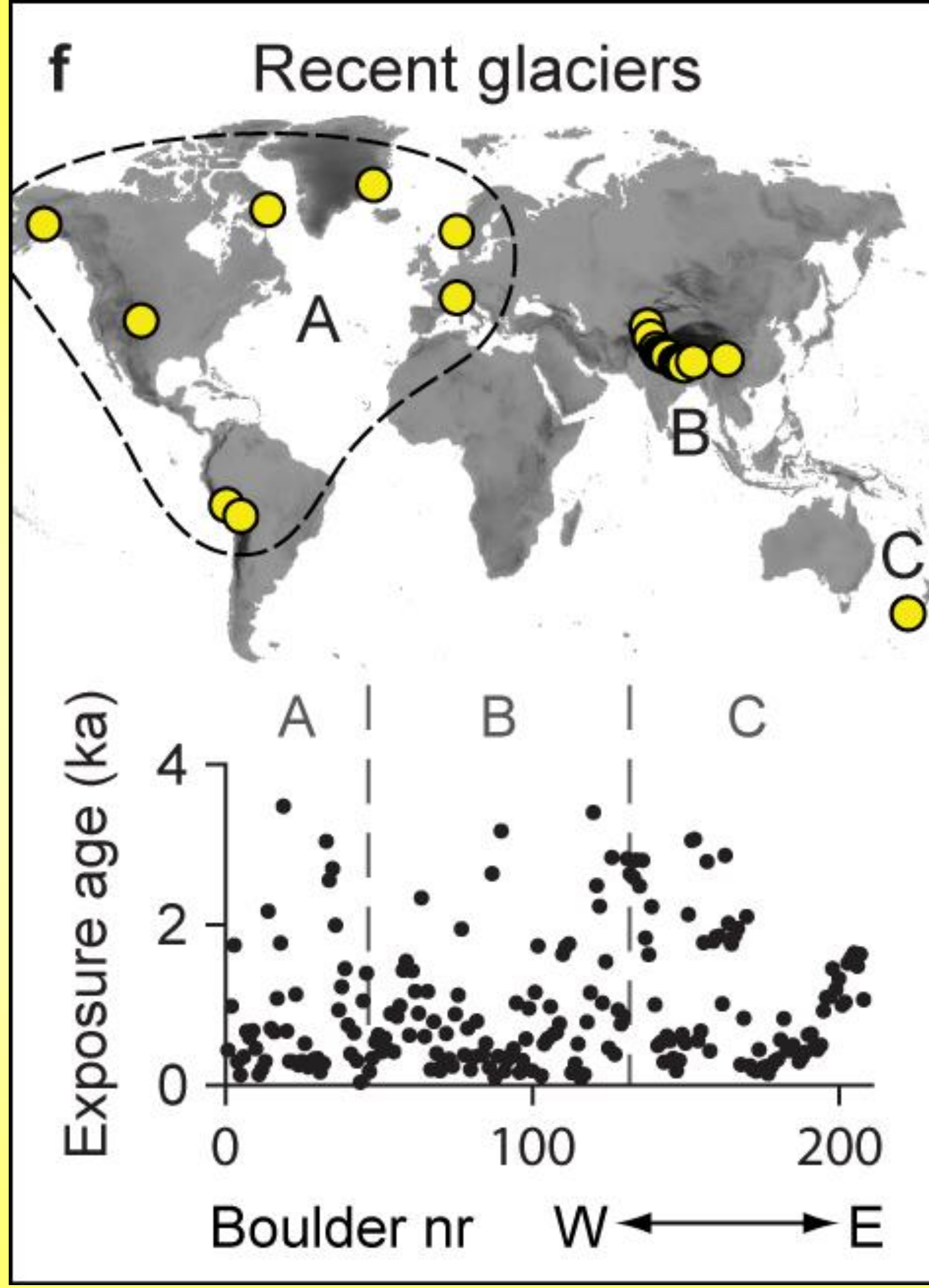


How common is prior exposure?
- in young boulders?



All boulders < 4 ka exposure age

No large prior exposure!



Heyman et al. (2011)

How common is prior exposure?

In boulders from the last deglaciation?

Deglaciation reconstructions based on ^{14}C dates

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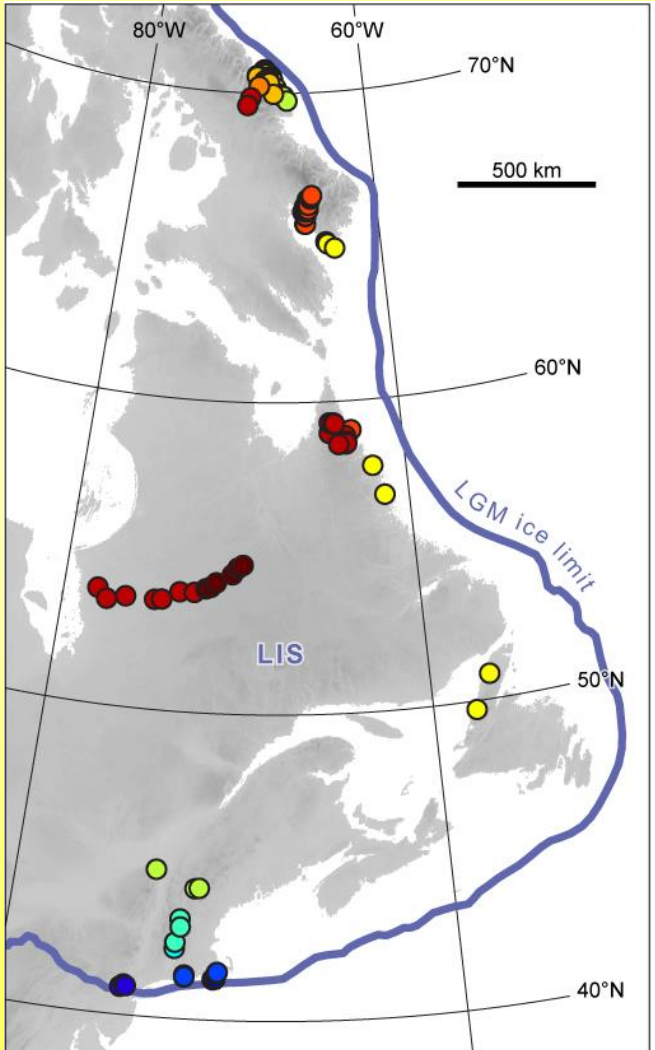
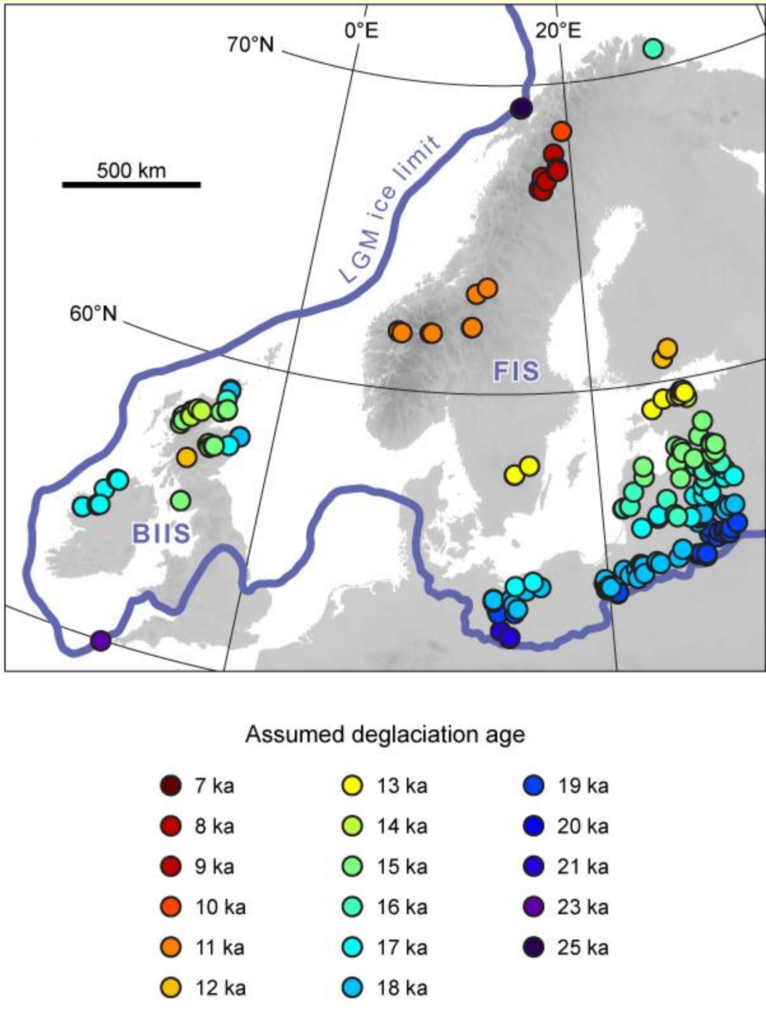
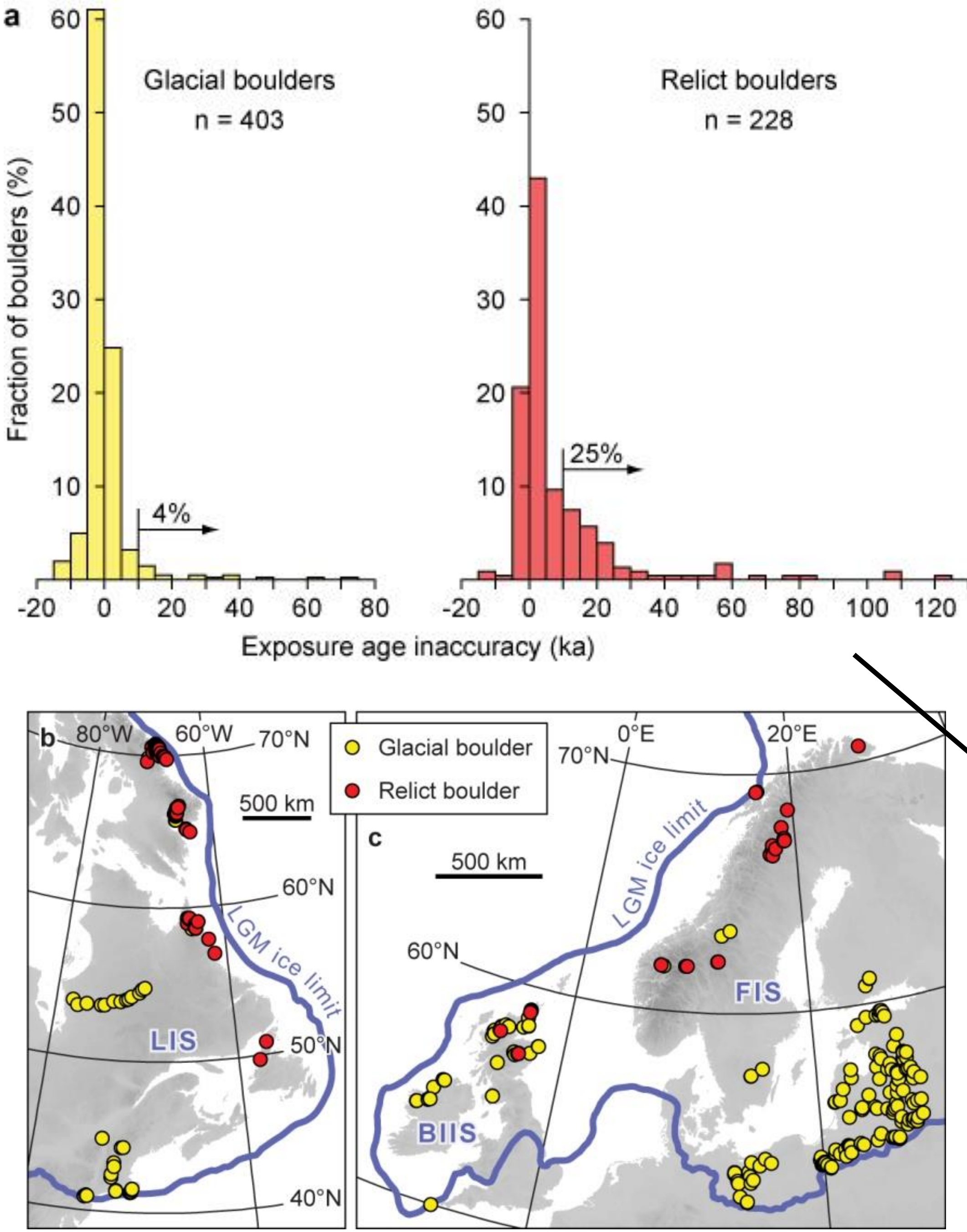
Independent deglaciation ages for comparison with exposure ages

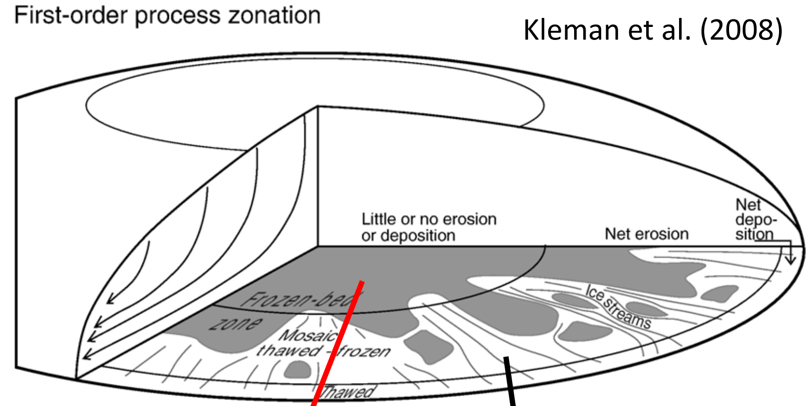
LIS: Kleman et al. (2010) / Dyke et al. (2003)



BIIS/FIS: Gyllencreutz et al. (2007)







Kleman et al. (2008)

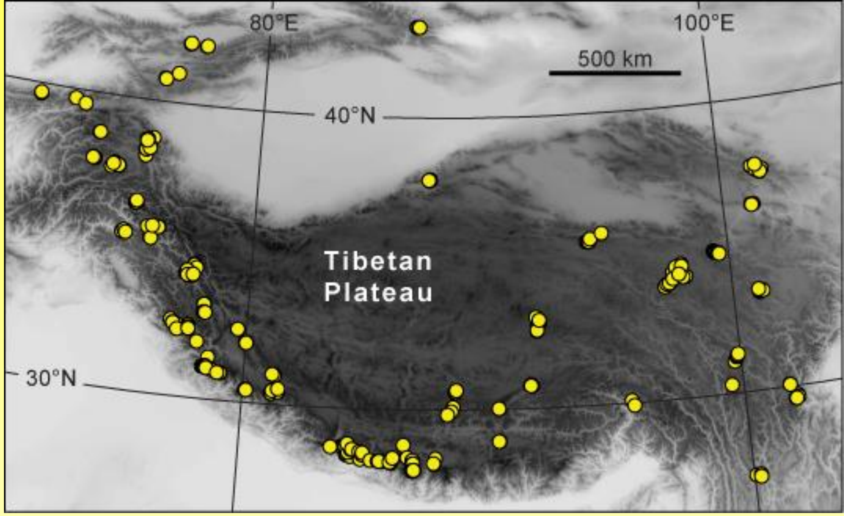
Relict boulders preserved under non-erosive ice

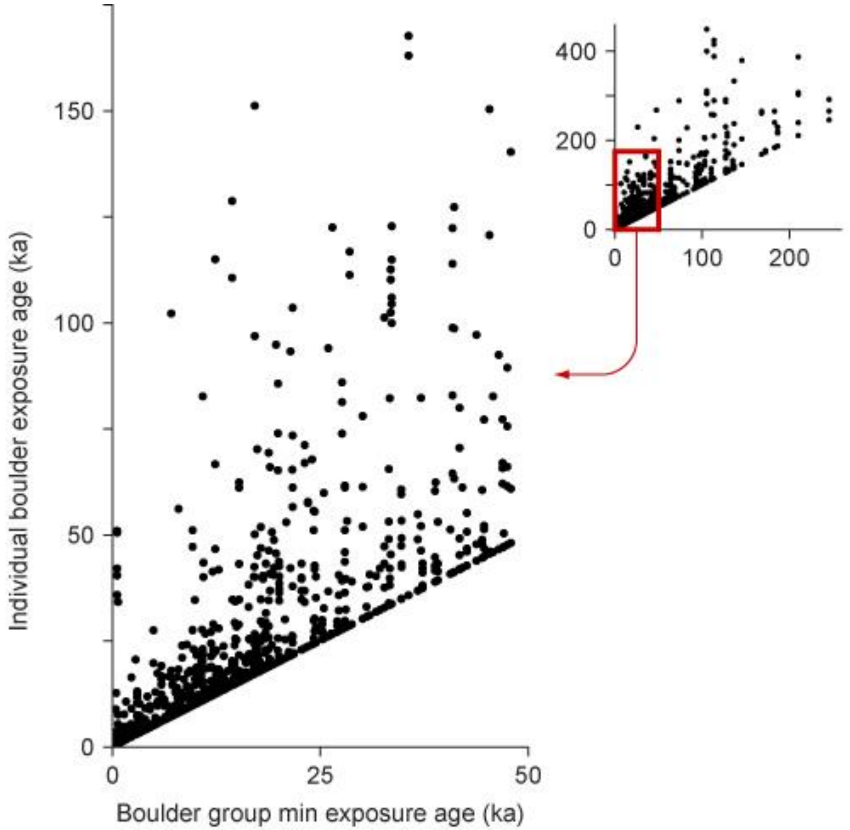
Glacial boulders from glacially modified landscapes

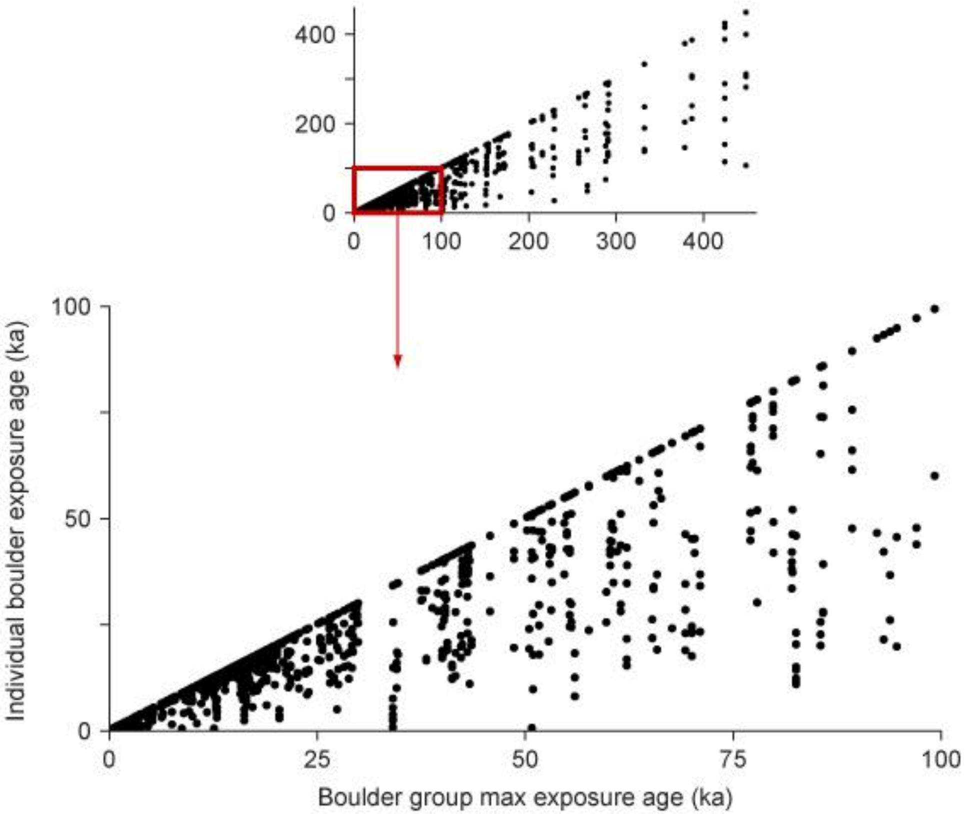
More common than in young boulders but still limited

Exposure age scatter in boulders from the Tibetan Plateau

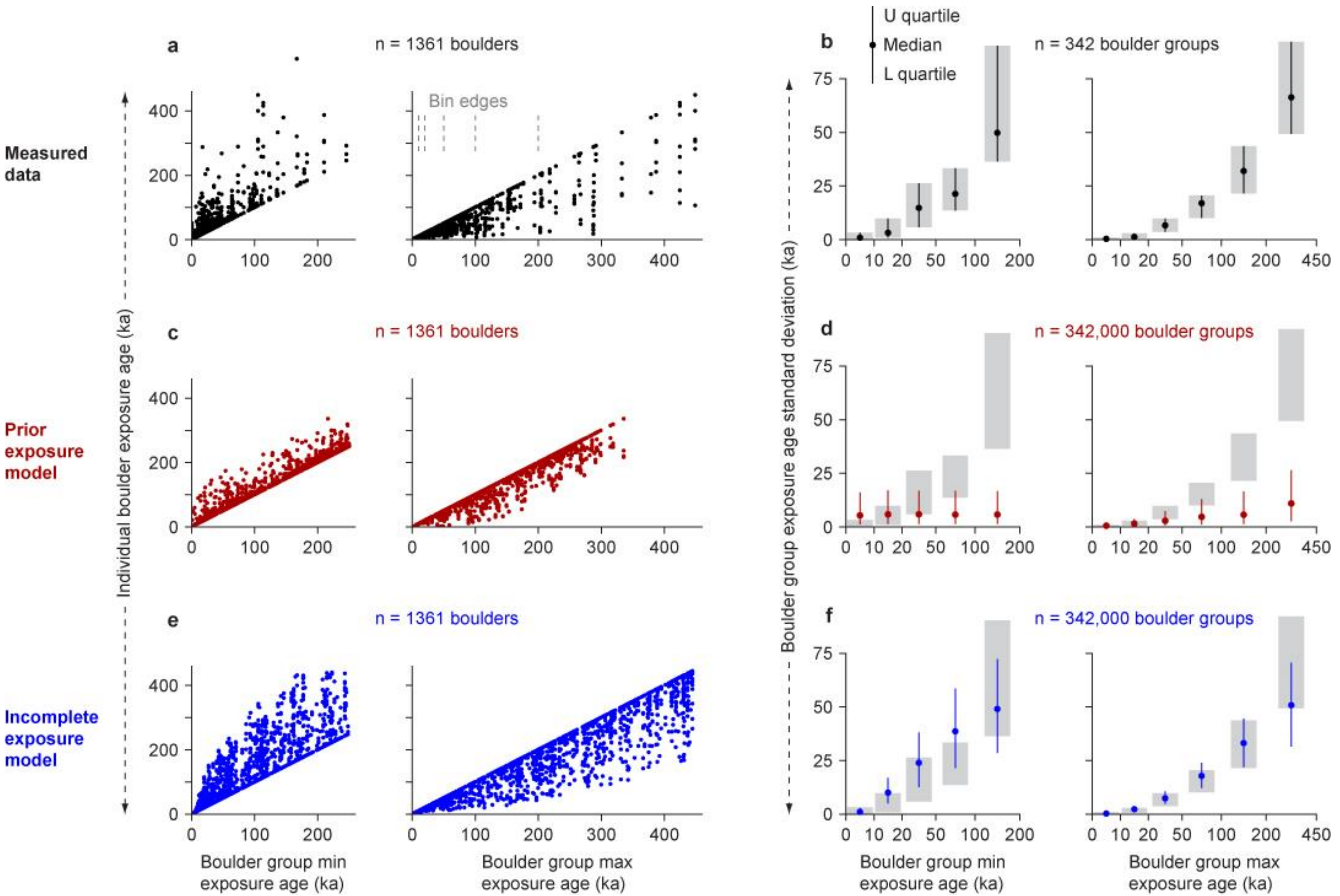
Caused by prior exposure or incomplete exposure?



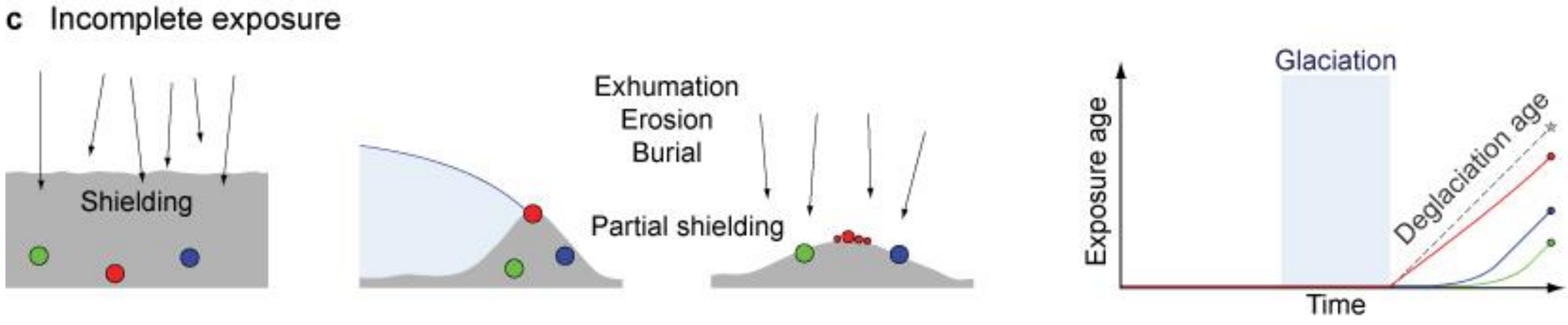


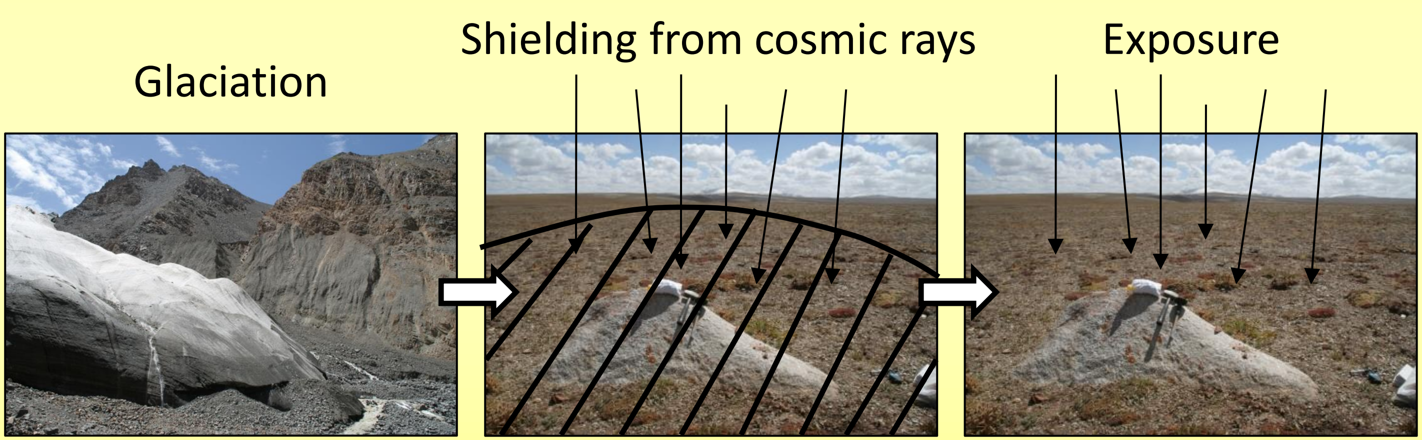


Exposure age modeling (Monte Carlo model)



Incomplete exposure is typically more important than prior exposure





Minimum age

However, prior exposure (inheritance) does happen every now and then and cannot be ignored

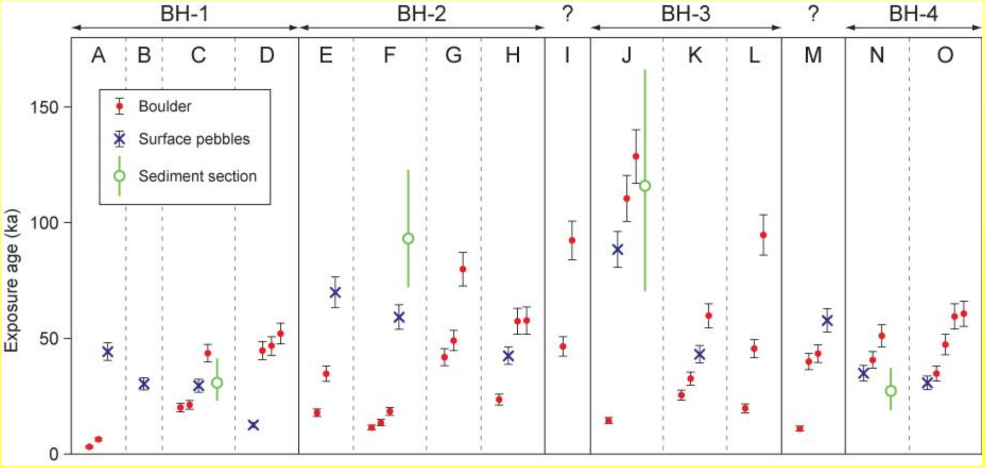
Reduced chi-square statistics:

Test if exposure age scatter can be explained by analytical uncertainty

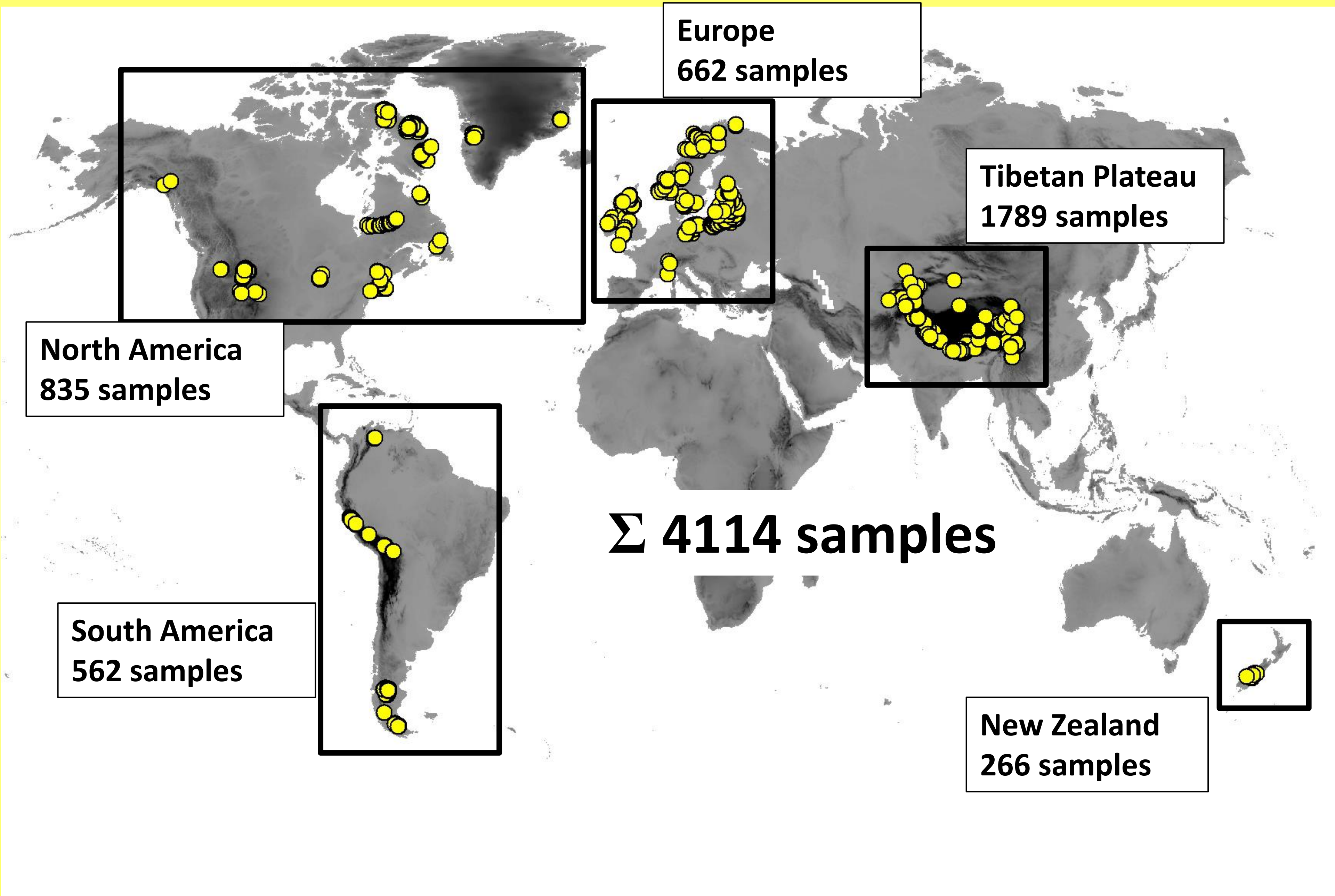
$$\chi_R^2 = \frac{1}{n-1}\sum_{i=1}^{n}\left[\frac{t_i - \bar{t}_i}{\sigma t_i}\right]^2$$

Reduced χ^2 value around 1 indicates that the entire exposure age scatter can be explained by the analytical uncertainty

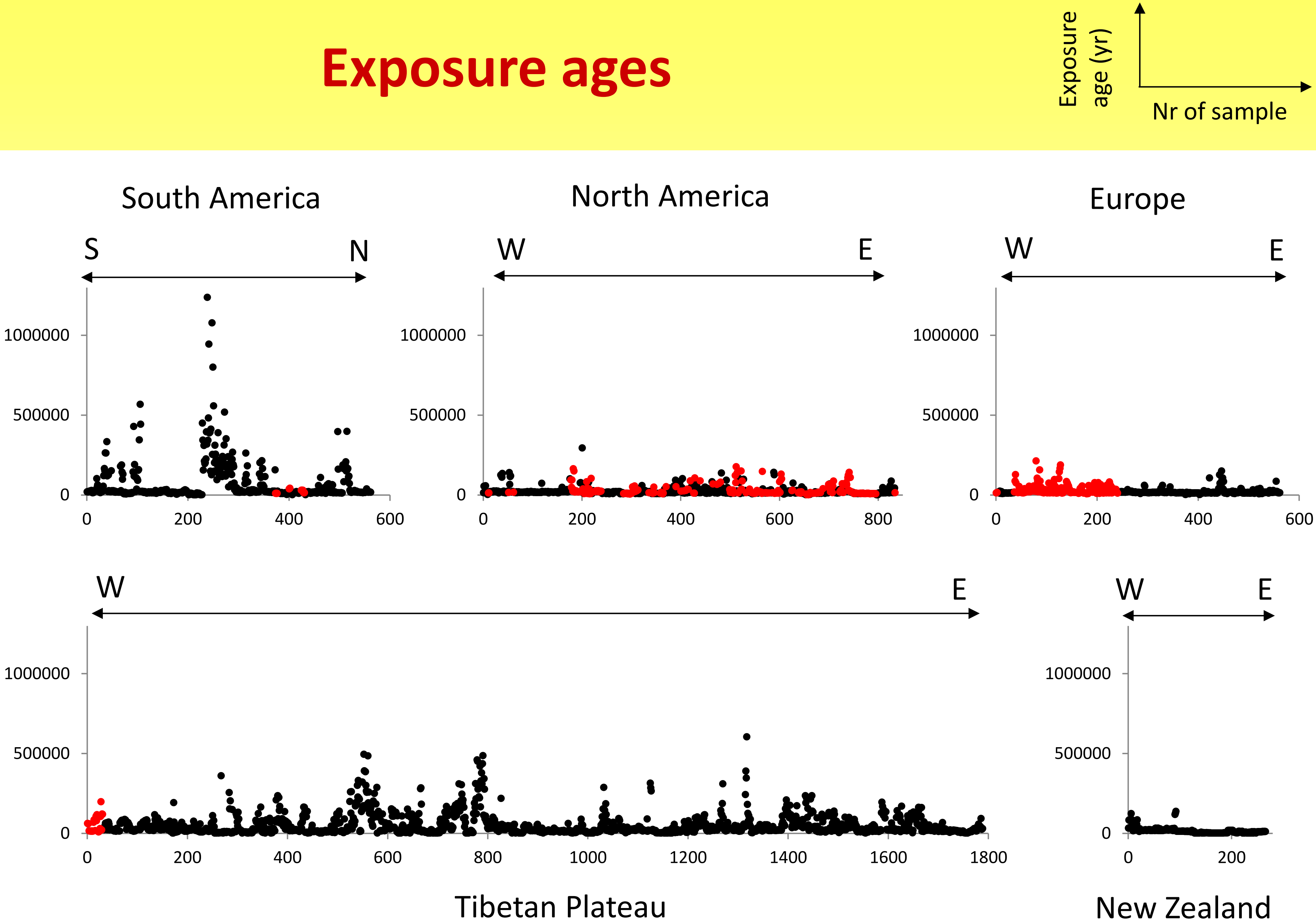
Reduced χ^2 value >2 → Geomorphological factors…



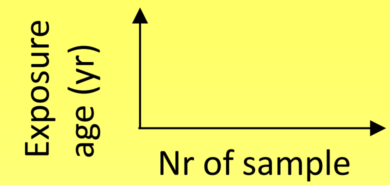
(Global) glacial ^{10}Be exposure age compilation

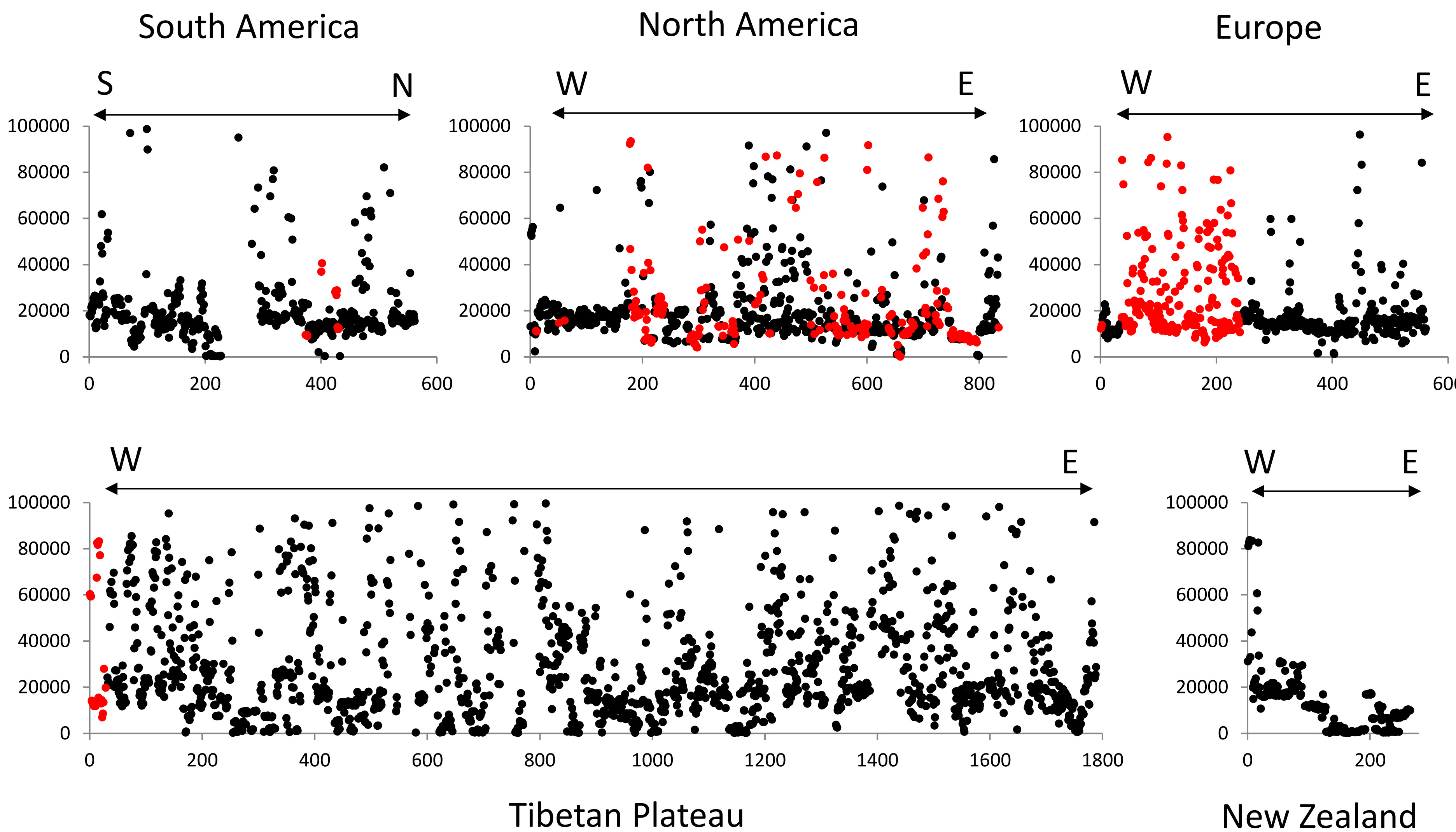


Exposure ages

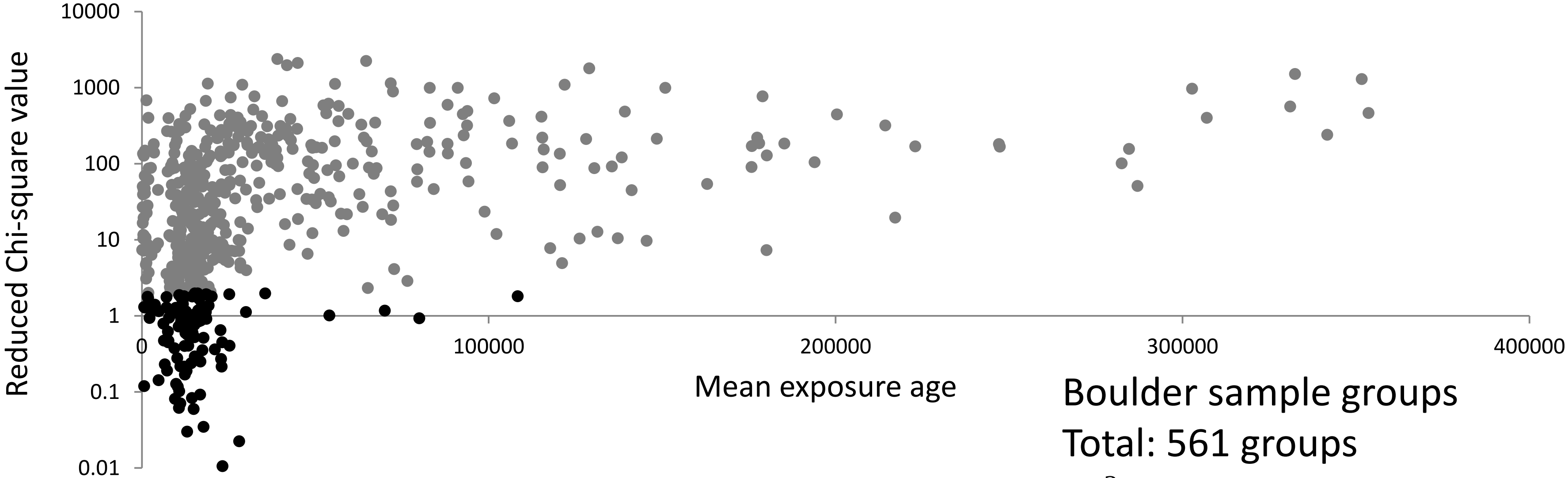


Exposure ages

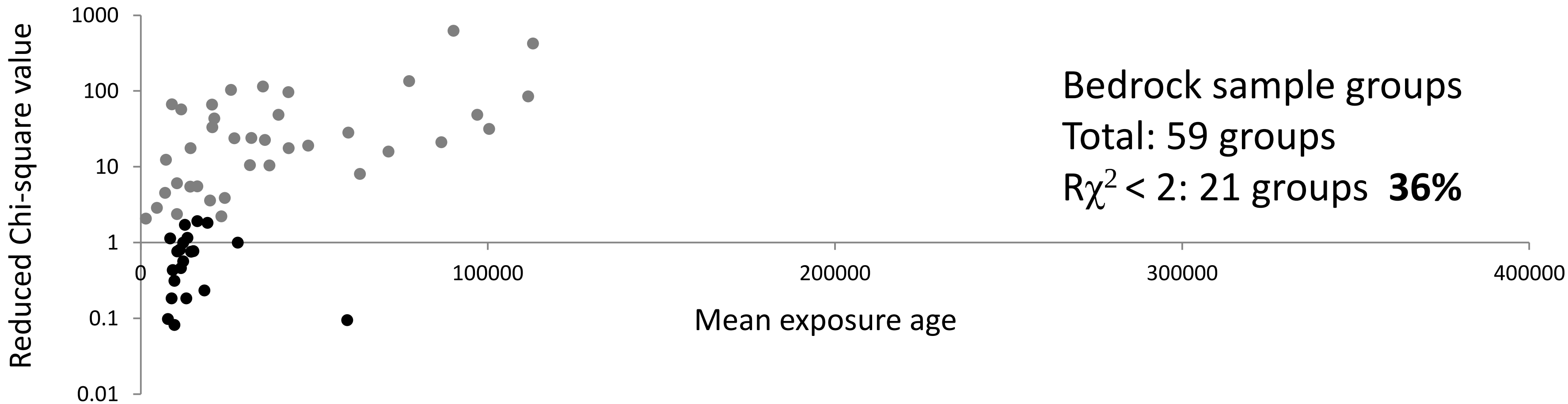




Reduced chisquare

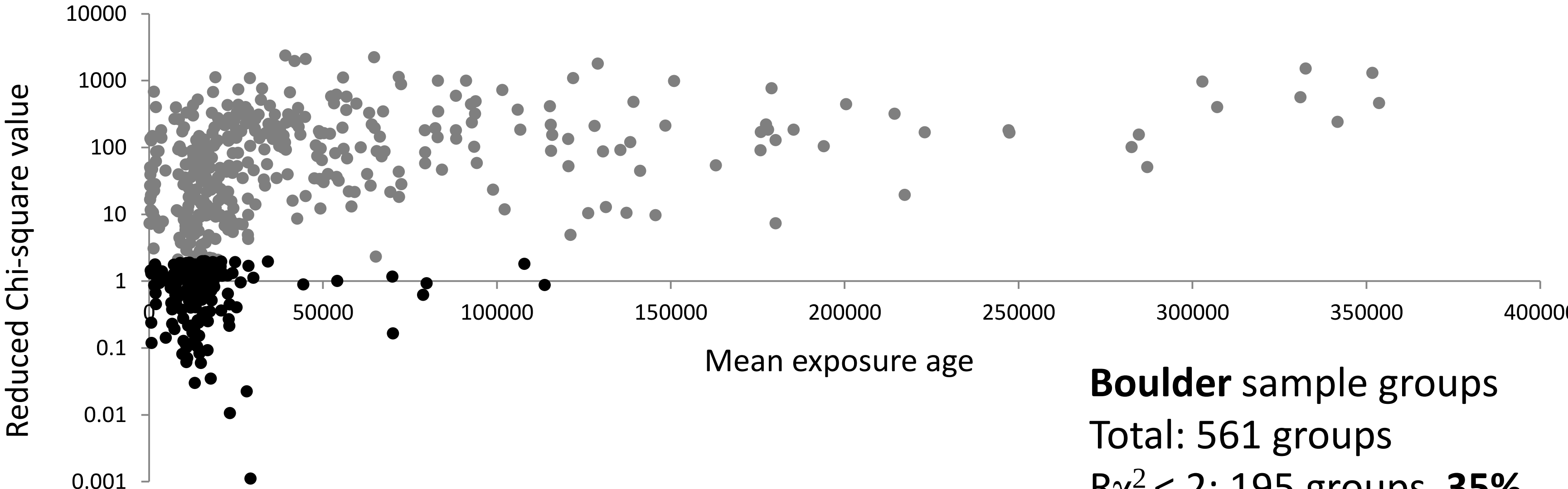


Boulder sample groups
Total: 561 groups
$R\chi^2 < 2$: 111 groups **20%**



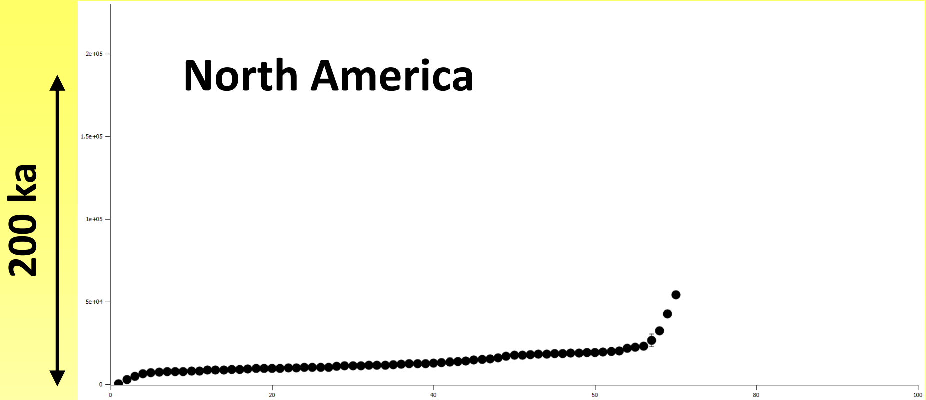
Bedrock sample groups
Total: 59 groups
$R\chi^2 < 2$: 21 groups **36%**

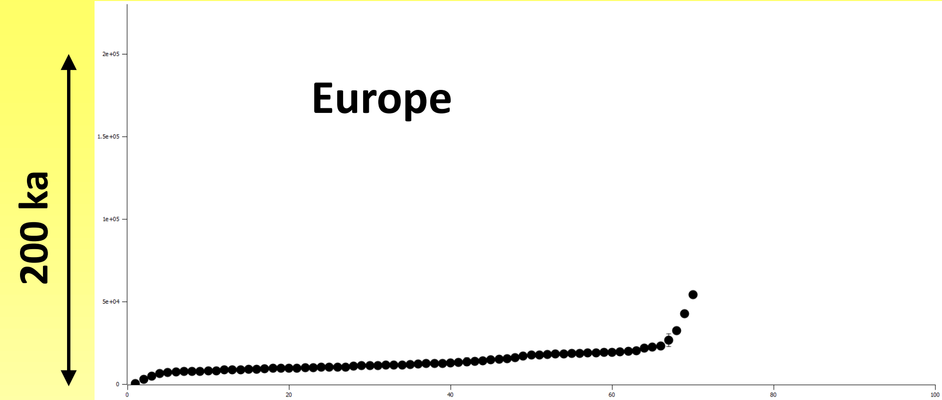
Reduced chisquare

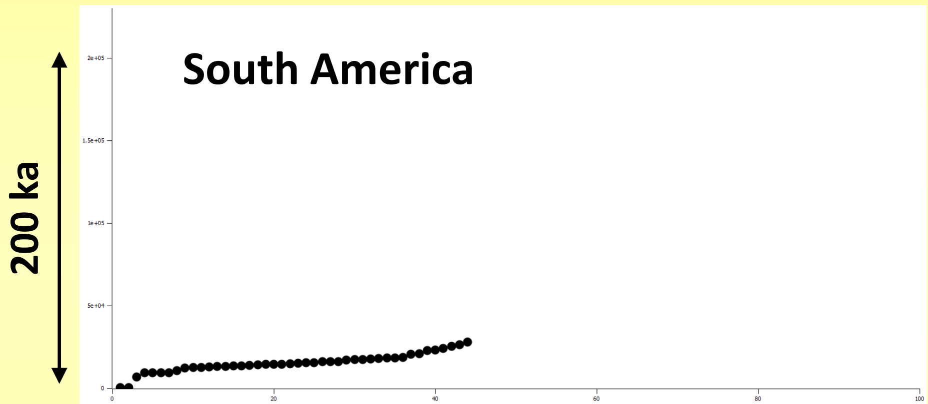


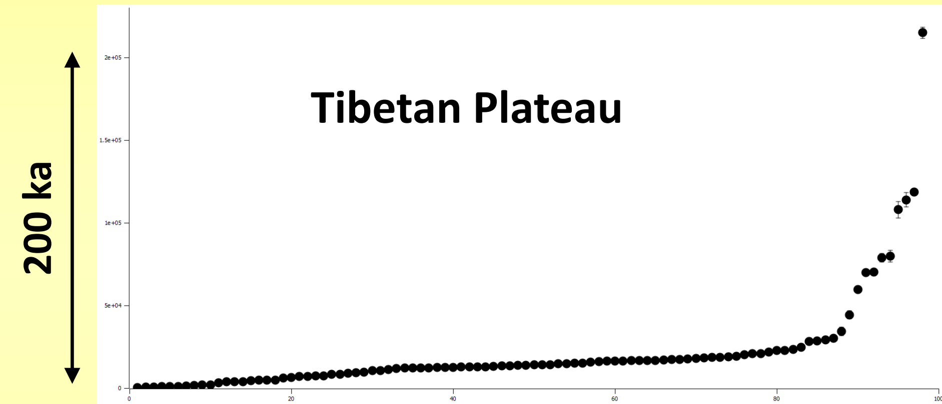
Boulder sample groups
Total: 561 groups
$R\chi^2 < 2$: 195 groups **35%**

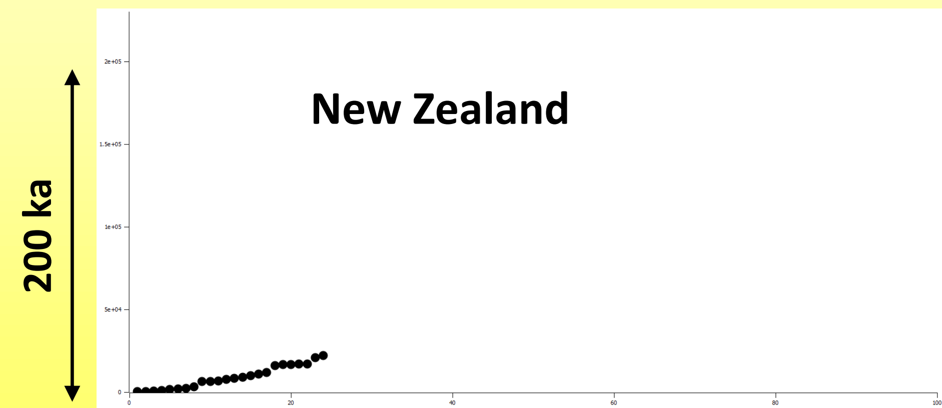
Bedrock sample groups
Total: 59 groups
$R\chi^2 < 2$: 26 groups **44%**



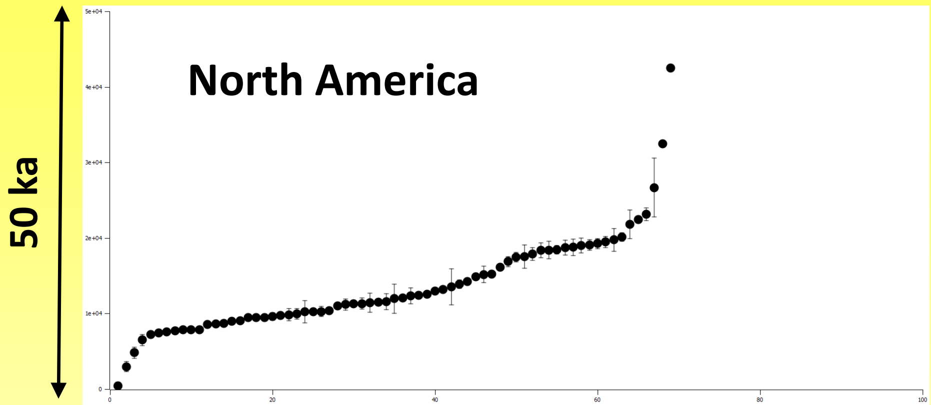


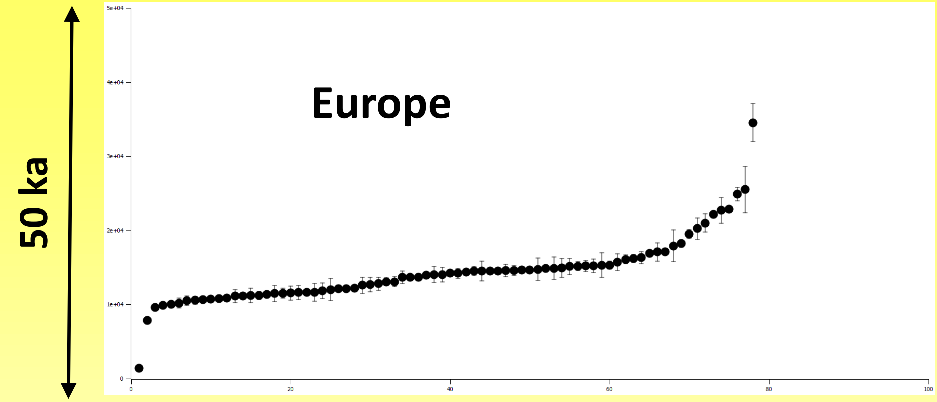


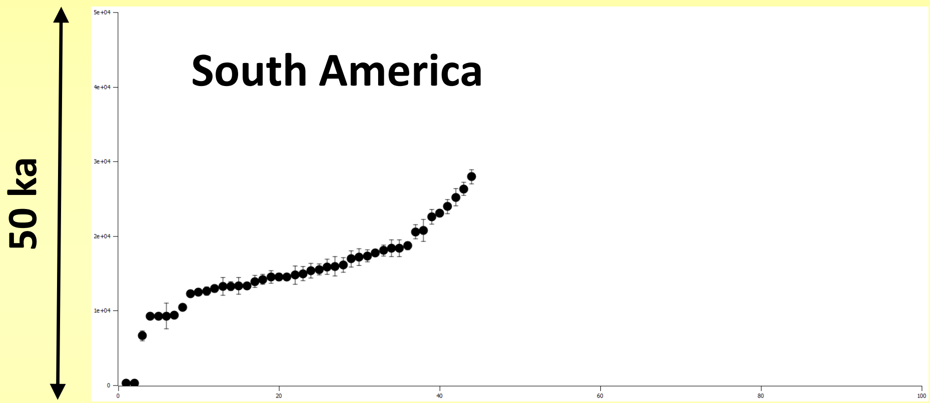


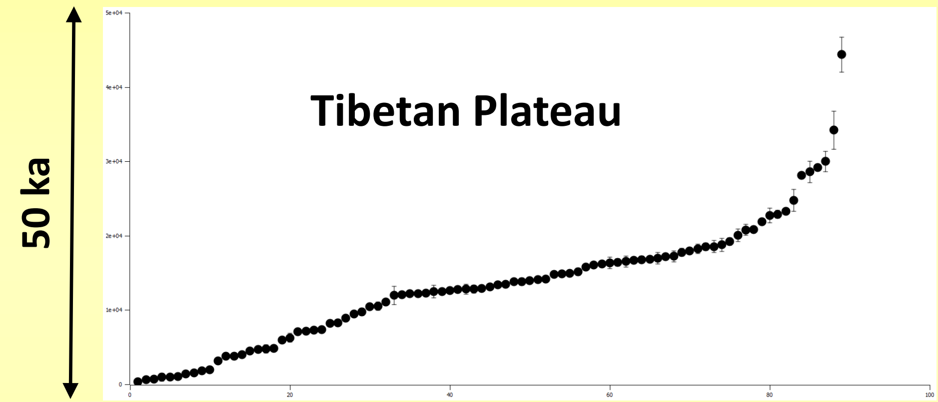


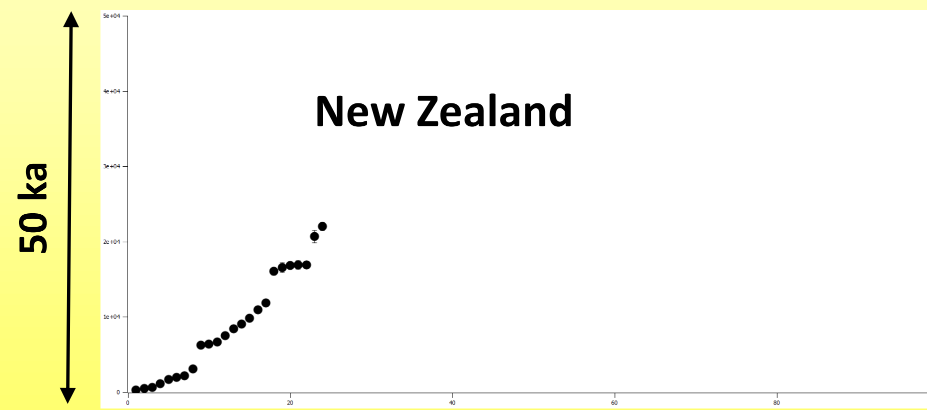
Error weighted mean exposure ages for groups with $R\chi^2 < 2$





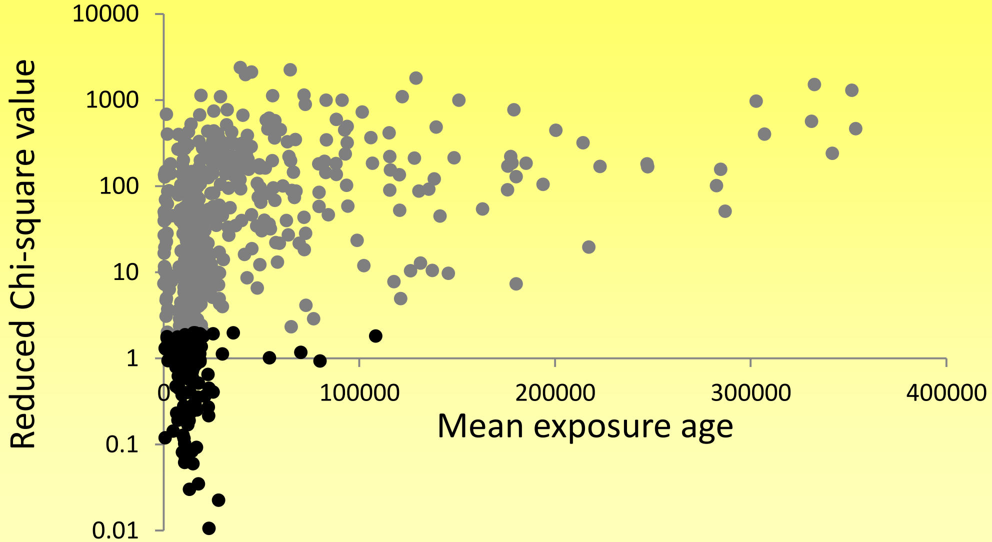




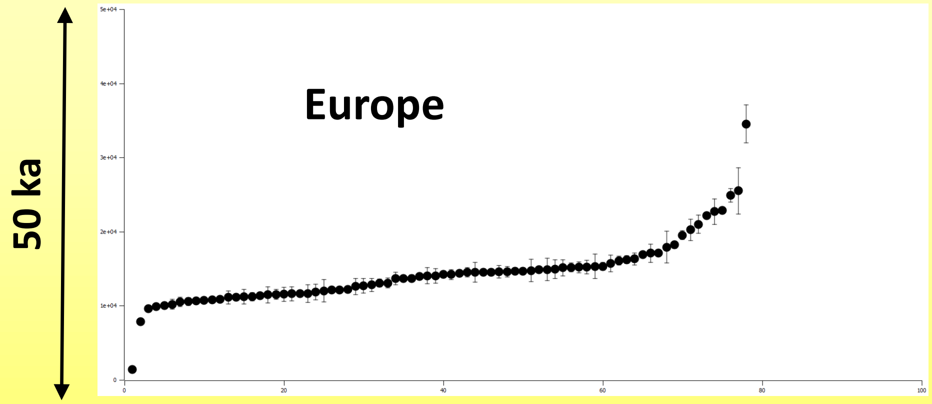


Error weighted mean exposure ages for groups with $R\chi^2 < 2$

Many (perhaps most) glacial exposure ages do not show the deglaciation age



Sample groups with good clustering are mostly from the last major deglaciation



Burial dating with multiple isotopes

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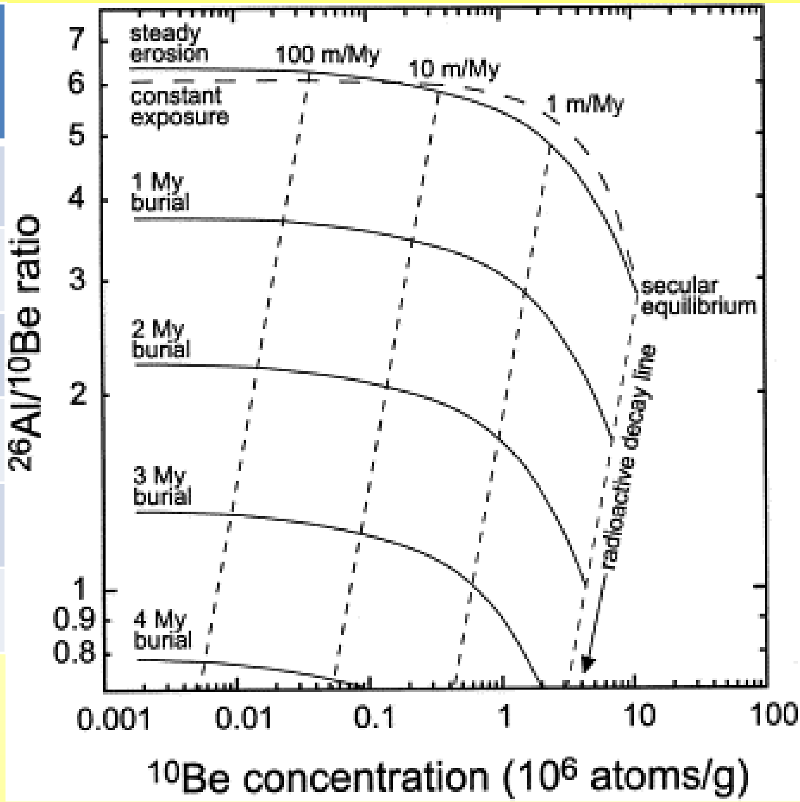
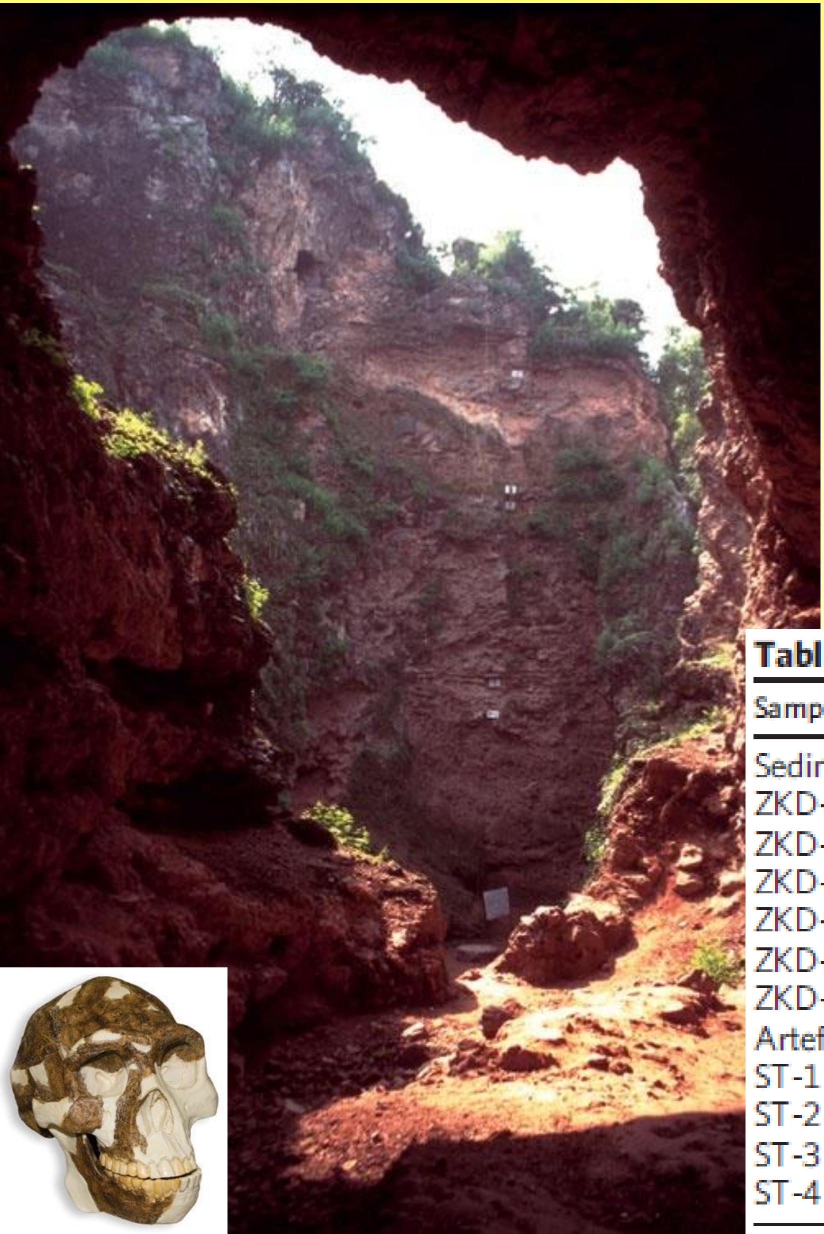


Different half-lives enables quantification of burial time (shielding from cosmic rays)

Burial dating with multiple isotopes



Dating of Peking man

^{10}Be and ^{26}Al concentrations yield burial age of 770 000 ± 80 000 years

Prior estimate: 230 000 – 500 000 years

Shen et al. (2009)

Table 1 | Cosmogenic nuclide concentrations and burial ages

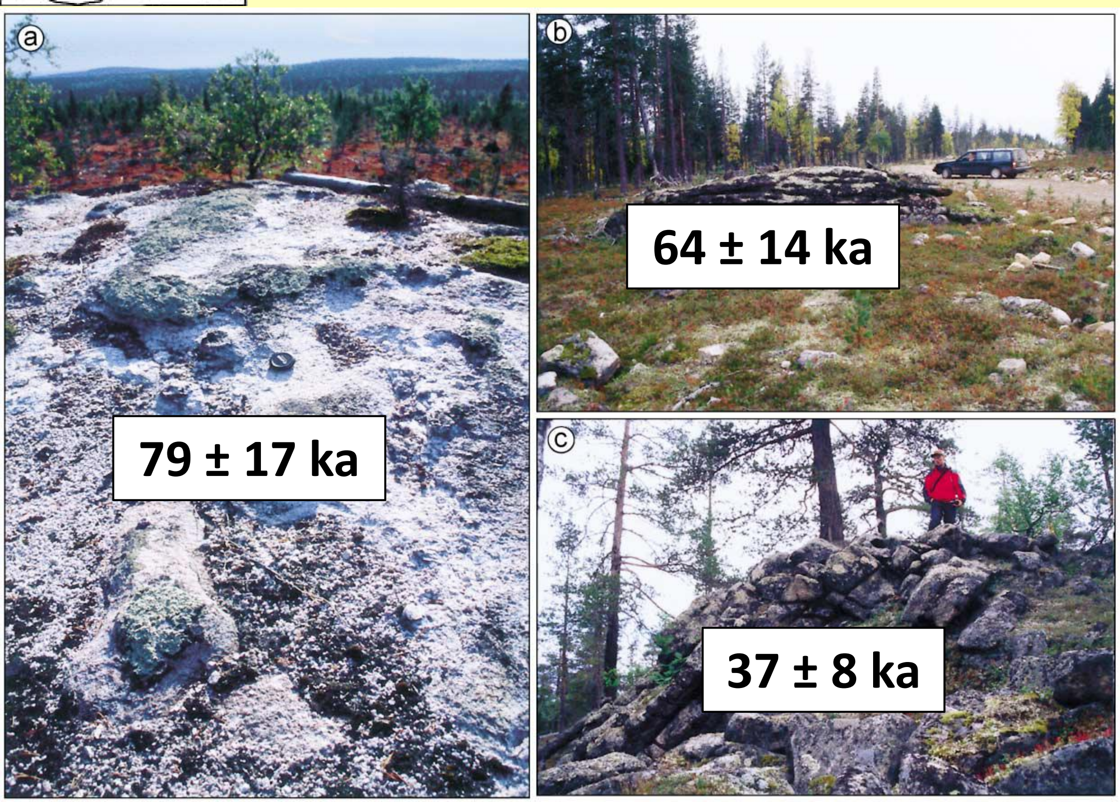
Sample	$[^{26}Al]$ (10^6 at g^{-1})	$[^{10}Be]$ (10^6 at g^{-1})	$^{26}Al/^{10}Be$	Burial age*(Myr)
Sediment				
ZKD-6	0.073 ± 0.018	0.040 ± 0.004	1.82 ± 0.49	2.78 ± 0.51 (0.54)
ZKD-7-2	0.550 ± 0.053	0.132 ± 0.009	4.17 ± 0.49	1.00 ± 0.23 (0.24)†
ZKD-8/9	1.252 ± 0.095	0.273 ± 0.008	4.58 ± 0.38	0.75 ± 0.16 (0.17)†
ZKD-10-2	0.568 ± 0.052	0.120 ± 0.006	4.72 ± 0.50	0.75 ± 0.21 (0.22)†
ZKD-12	0.105 ± 0.030	0.021 ± 0.006	5.10 ± 2.01	0.62 ± 0.74 (0.74)
ZKD-13	0.106 ± 0.028	0.018 ± 0.005	5.89 ± 2.35	0.31 ± 0.74 (0.74)
Artefacts (8/9)				
ST-1	0.199 ± 0.027	0.040 ± 0.002	4.95 ± 0.72	0.67 ± 0.29 (0.29)†
ST-2	0.476 ± 0.037	0.100 ± 0.003	4.77 ± 0.39	0.73 ± 0.17 (0.17)†
ST-3	0.371 ± 0.039	0.122 ± 0.003	3.04 ± 0.33	1.66 ± 0.21 (0.24)
ST-4	0.568 ± 0.083	0.120 ± 0.005	4.72 ± 0.71	0.75 ± 0.29 (0.30)†

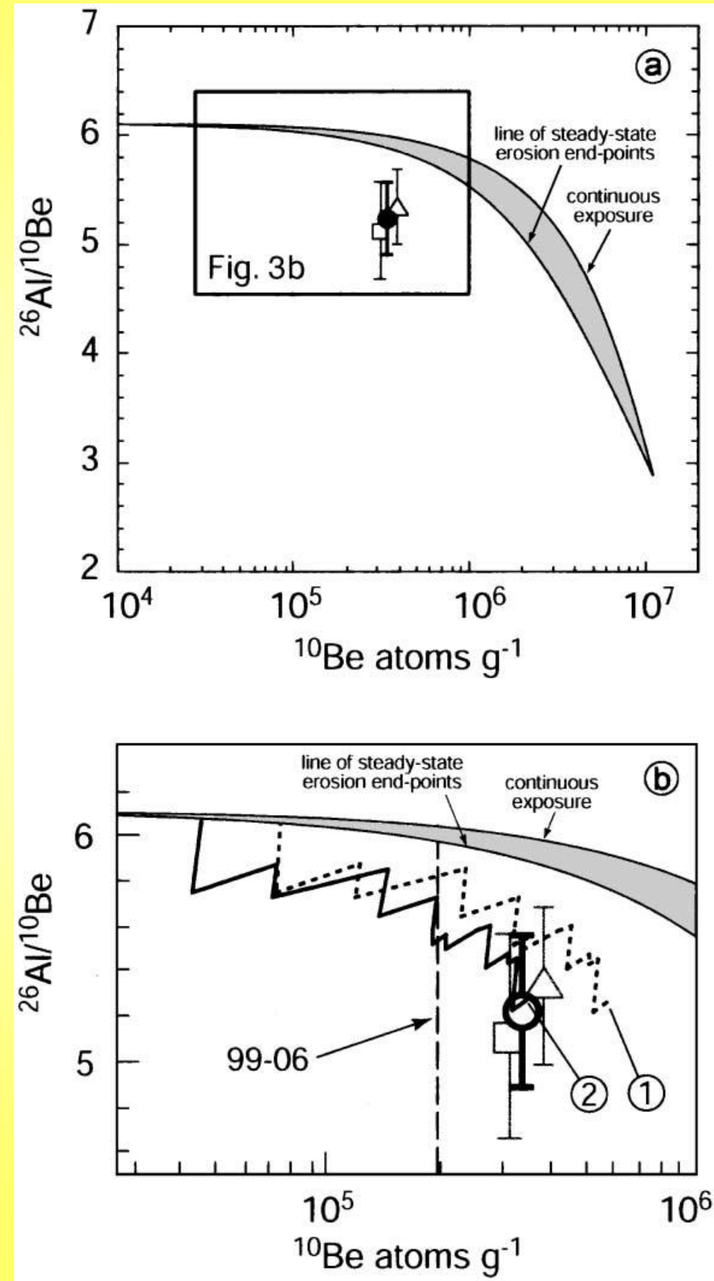
Burial dating with multiple isotopes

Quantification of burial under ice

Stroeven et al. (2002)

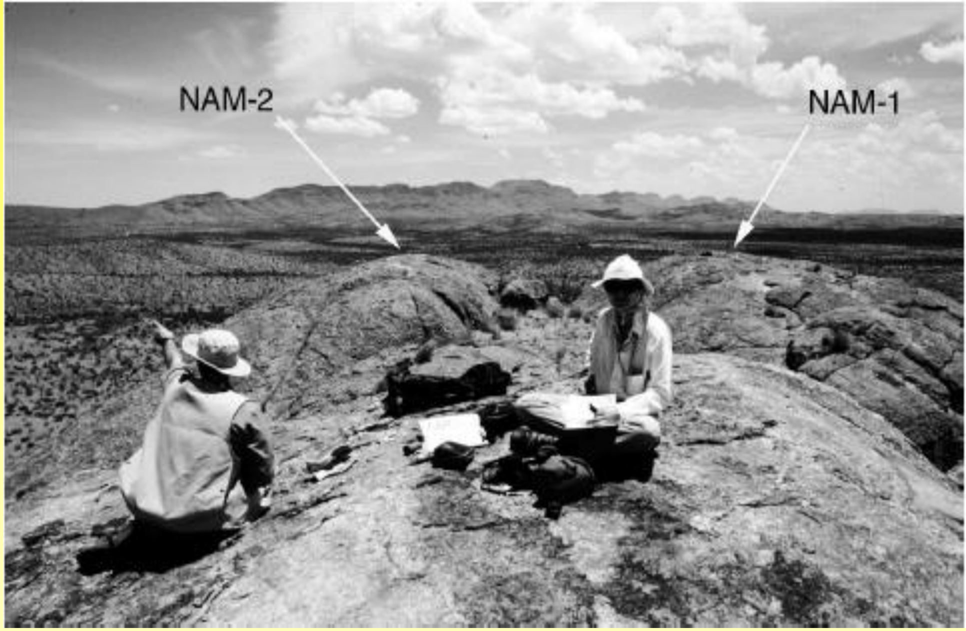
600 000 years burial under ice



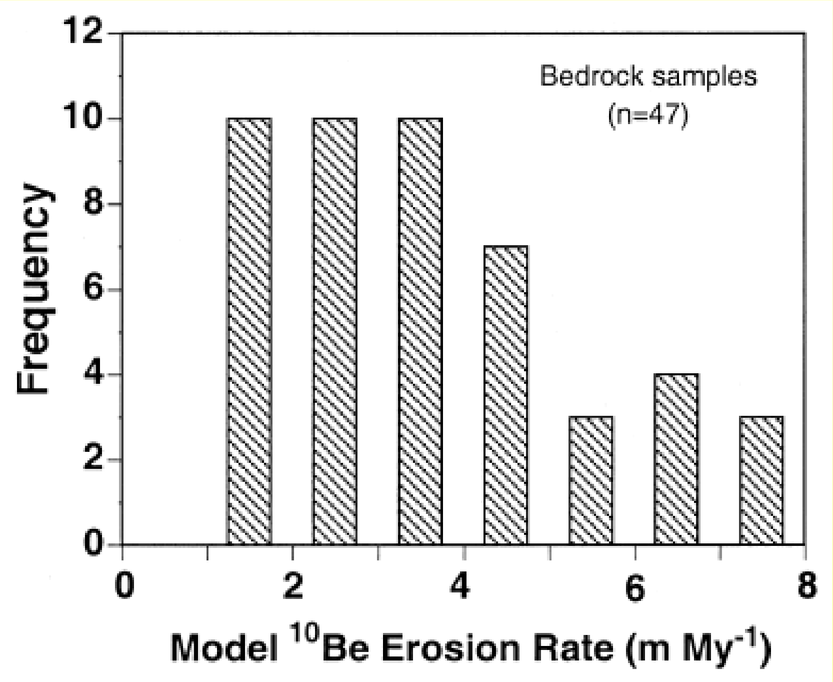


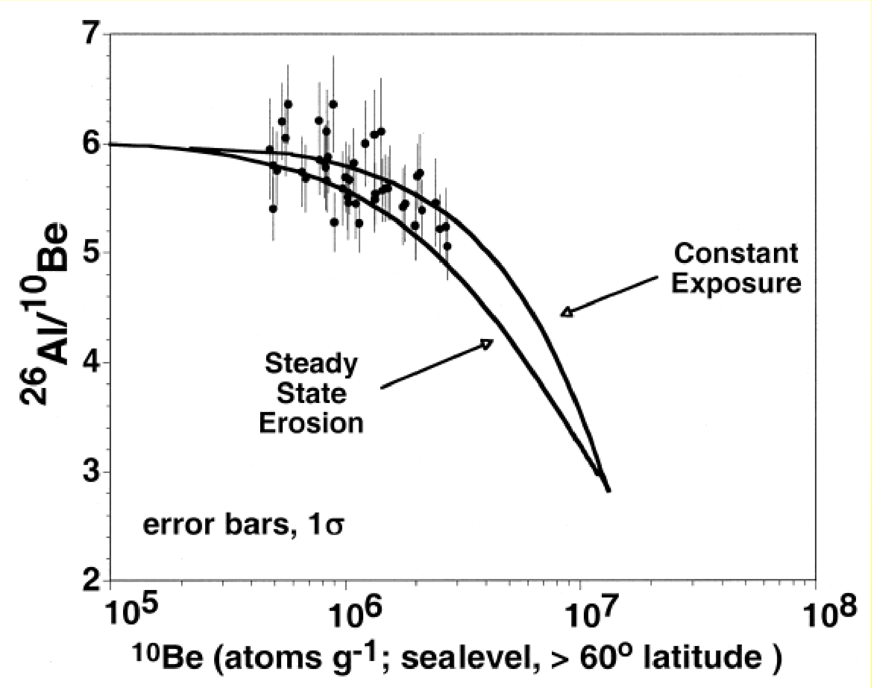
Erosion rate quantification

Bierman and Caffee (2001)
Namib desert



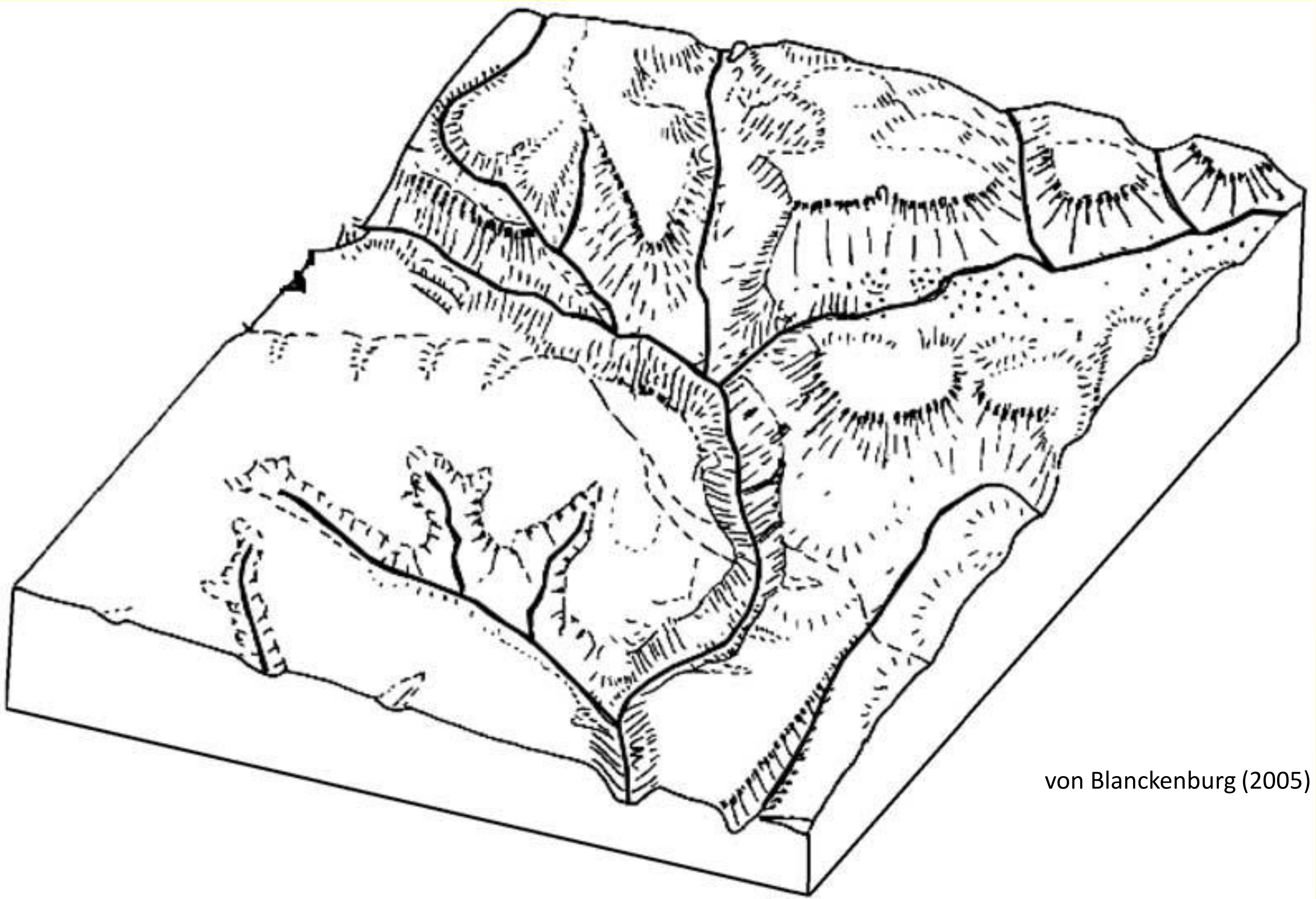
Bedrock samples





Catchment-scale erosion rate quantification

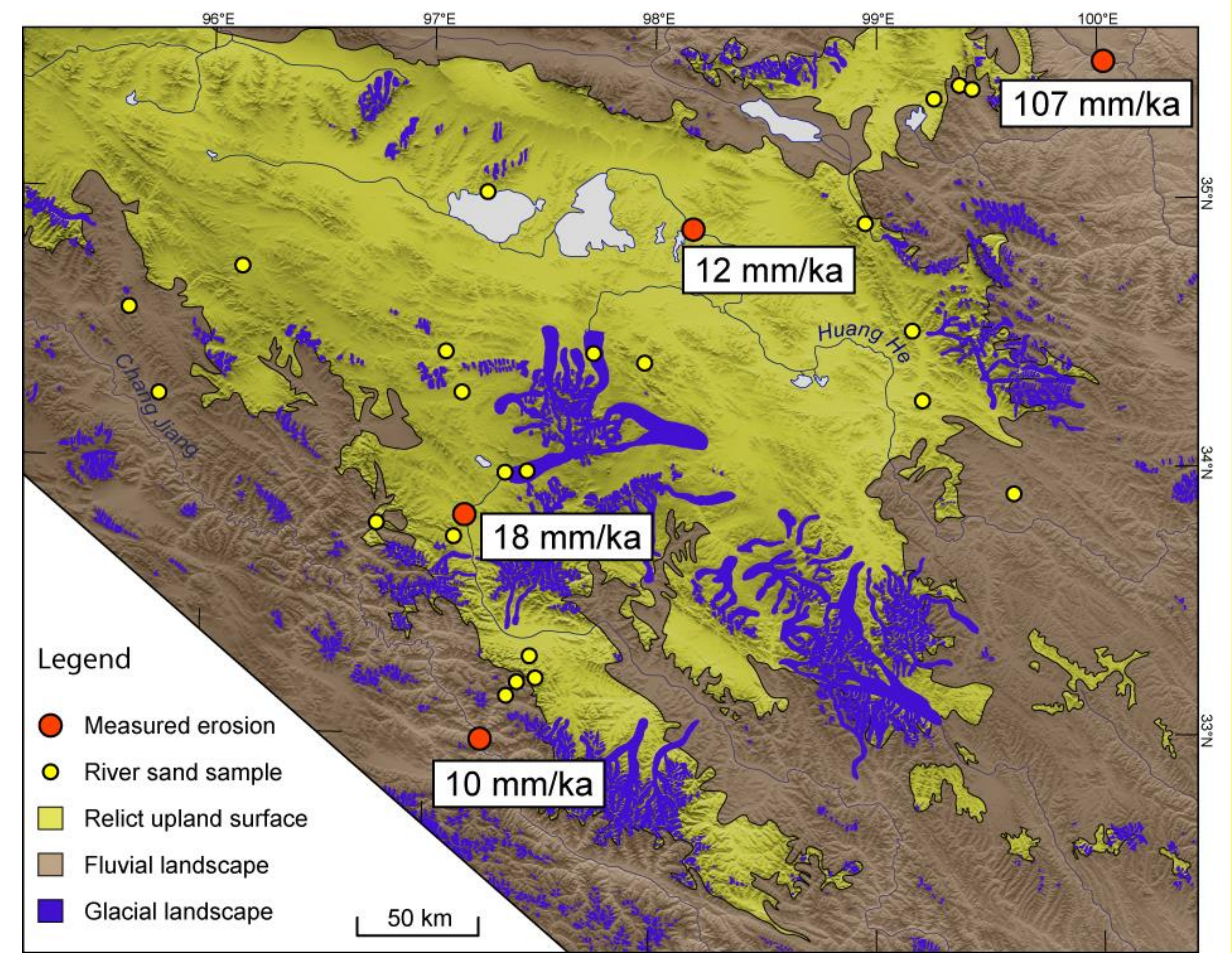
Average catchment-scale erosion rates quantified based on river sediments



von Blanckenburg (2005)

Catchment-scale erosion rate quantification

Catchment-scale erosion rate quantification



Summary

- Cosmogenic dating is easy to apply because rocks (quartz) are everywhere (common)
- It requires much lab work (expensive)
- Cosmogenic dating can give an absolute measurement of exposure to cosmic rays
- To convert exposure to cosmic rays into an age we have to make several crucial assumptions regarding the exposure history

Thank you!