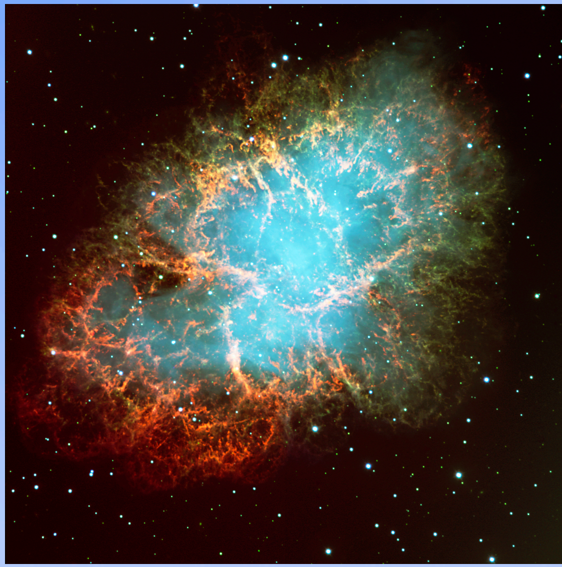
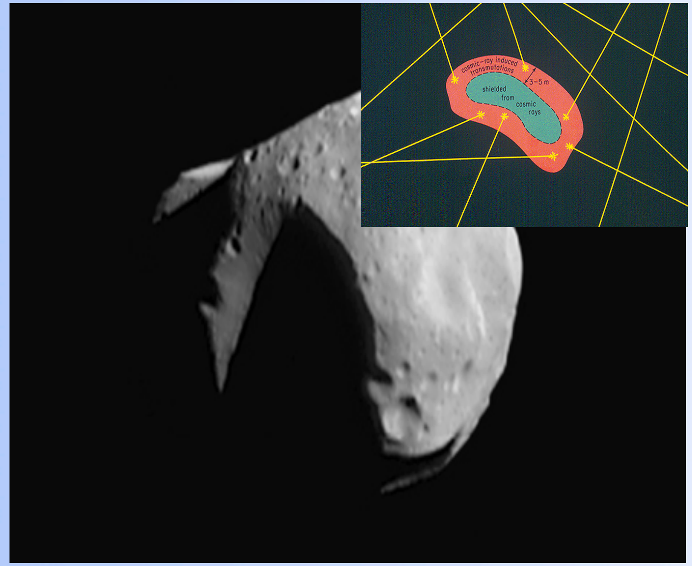
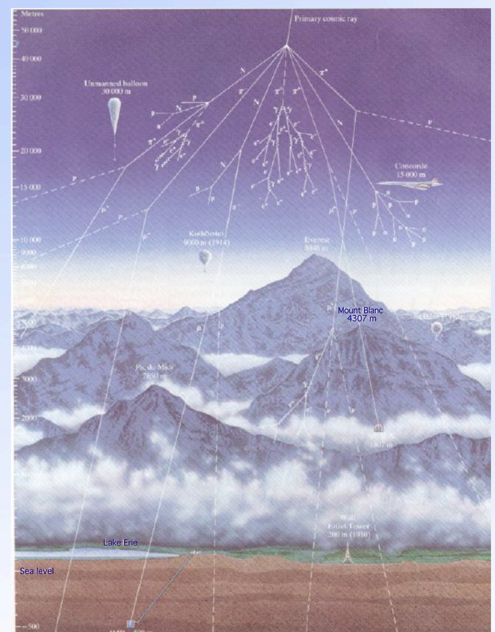



cosmic-ray induced transmutations
3–5 m
shielded from cosmic rays

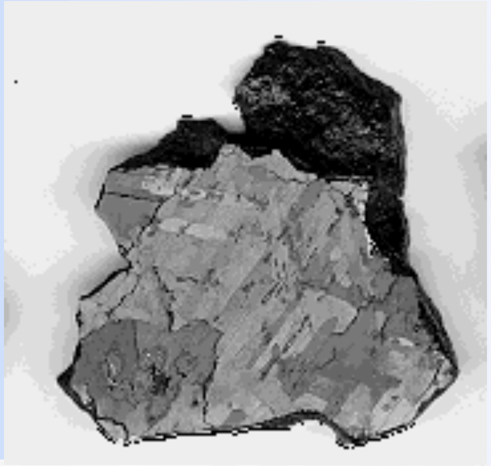

Metres
50 000
40 000
30 000
20 000
15 000
10 000
Primary cosmic ray
Unmanned balloon
30 000 m
Concorde
15 000 m
Mount Blanc
4307 m
Lake Erie
Sea level

Brief history of cosmogenic nuclides

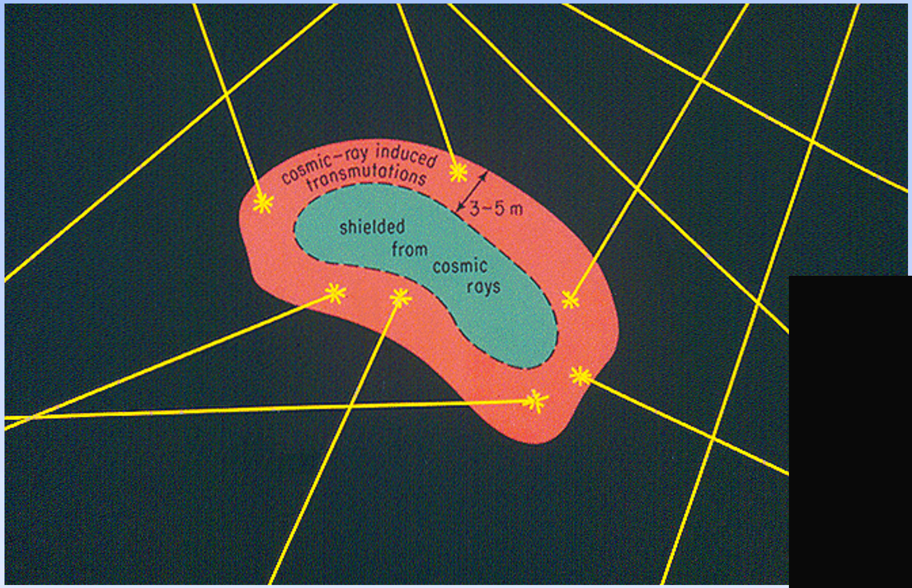
- 1911 - First cosmic ray measurements: Hess
- 1927 - Cosmic rays contained charged particles: Skobeltzyn
- 1937 - Discovery of ^{14}C at Berkeley: Ruben and Kamen
- 1939 - Prediction of $^{14}N(n,p)\ ^{14}C$ reactions in the atmosphere: Korff and Danforth
- 1947 - Prediction of ^{3}He production in iron meteorites: Baur
- 1949 - First measurement of natural ^{14}C: Chicago group
- 1951 - Publication of first ^{14}C dates: Arnold and Libby

Brief history of cosmogenic nuclides

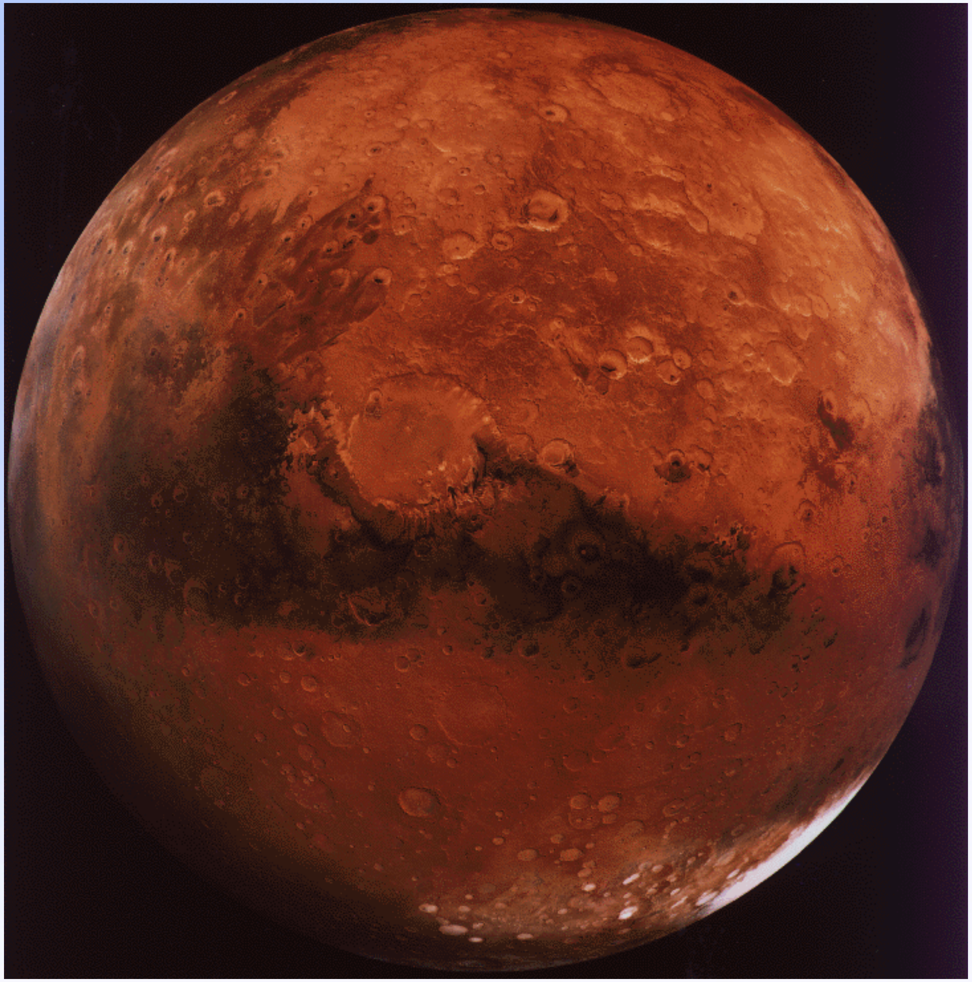
- 1952 - Detection of cosmic-ray-produced ^{3}He in iron meteorites: Paneth, Reasbeck, and Mayne
- Cosmogenic nuclides have been used to study the exposure history of the Canyon Diablo iron meteorite
- Berringer crater is the site of the early terrestrial cosmogenic nuclide calibrations



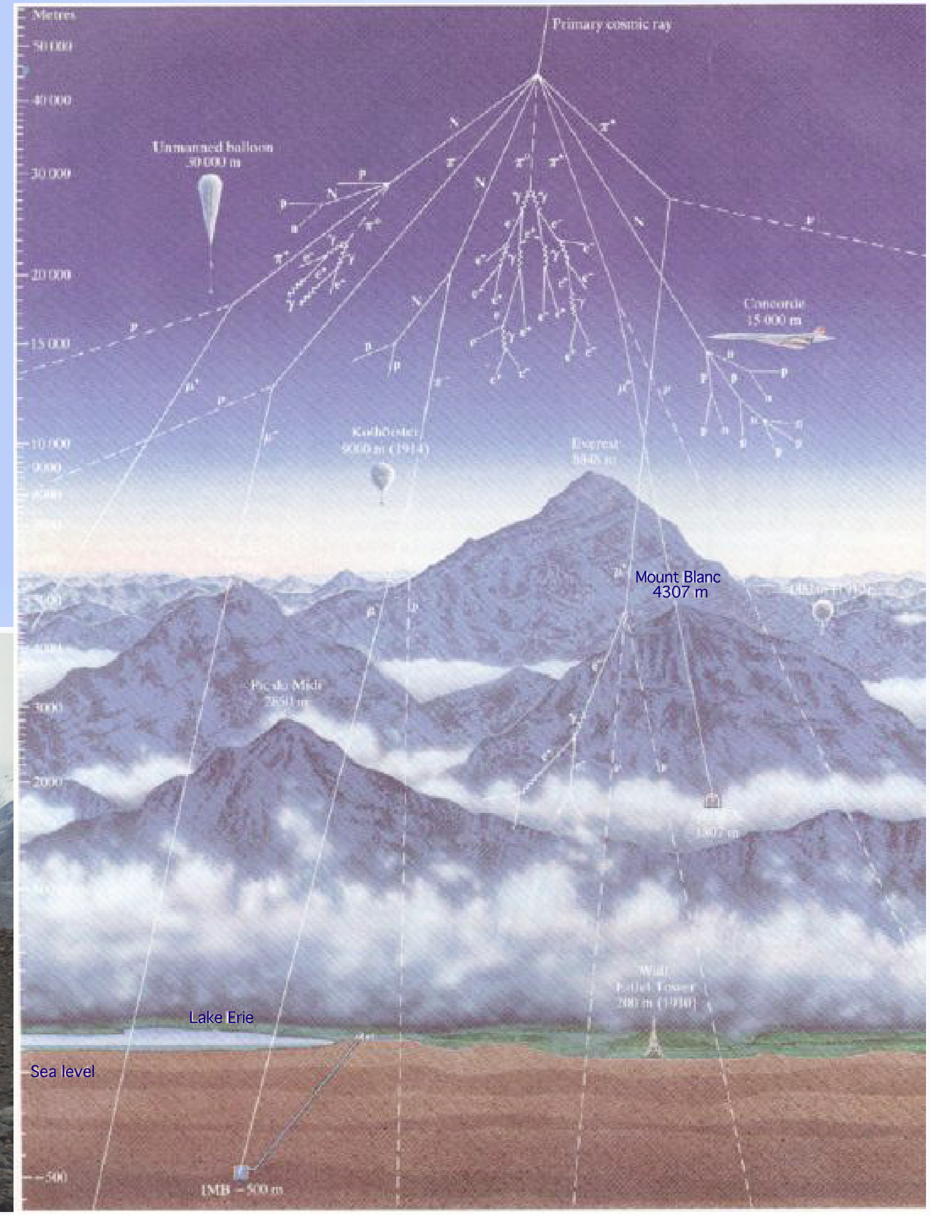
Cosmic rays produce a variety of nuclides in the solar system - meteorites



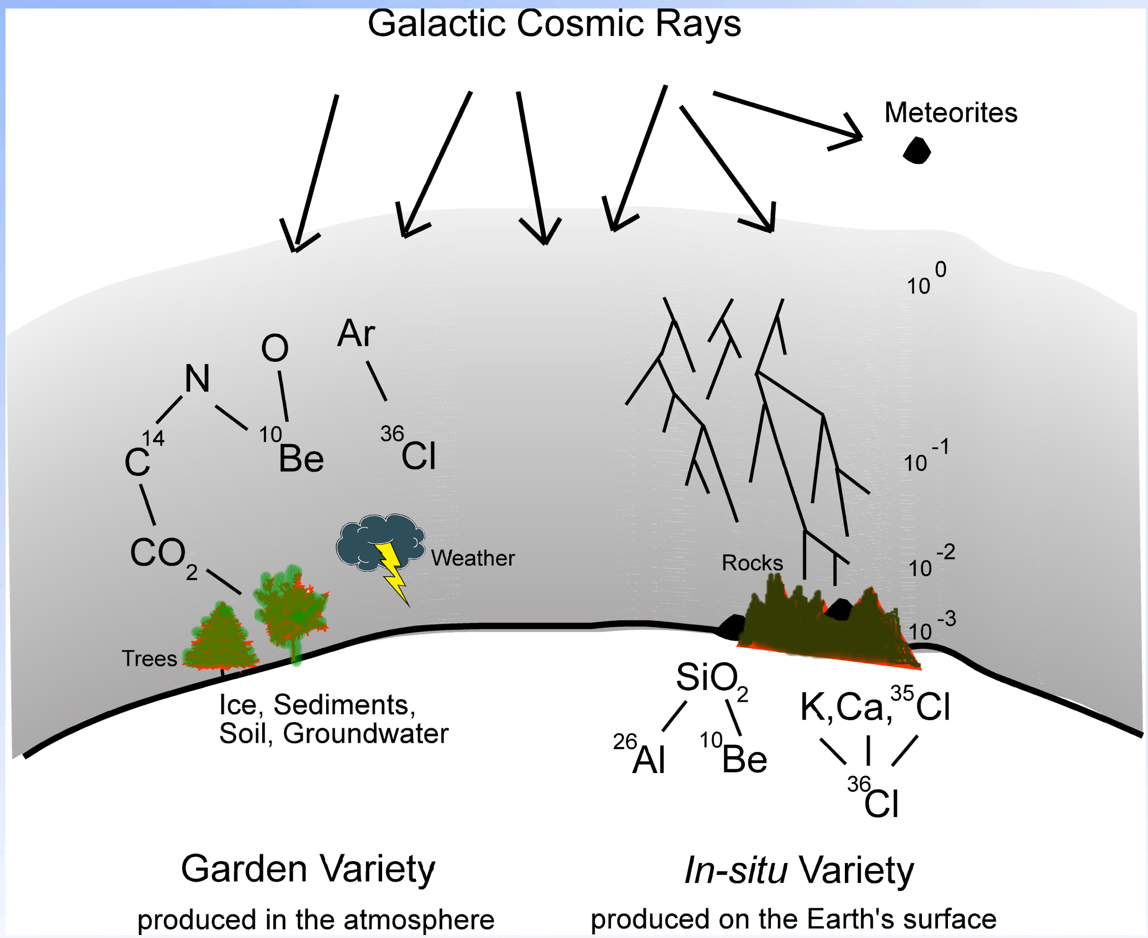
Cosmogenic nuclides - planetary surfaces



Cosmic rays produce a variety of nuclides on the Earth's surface



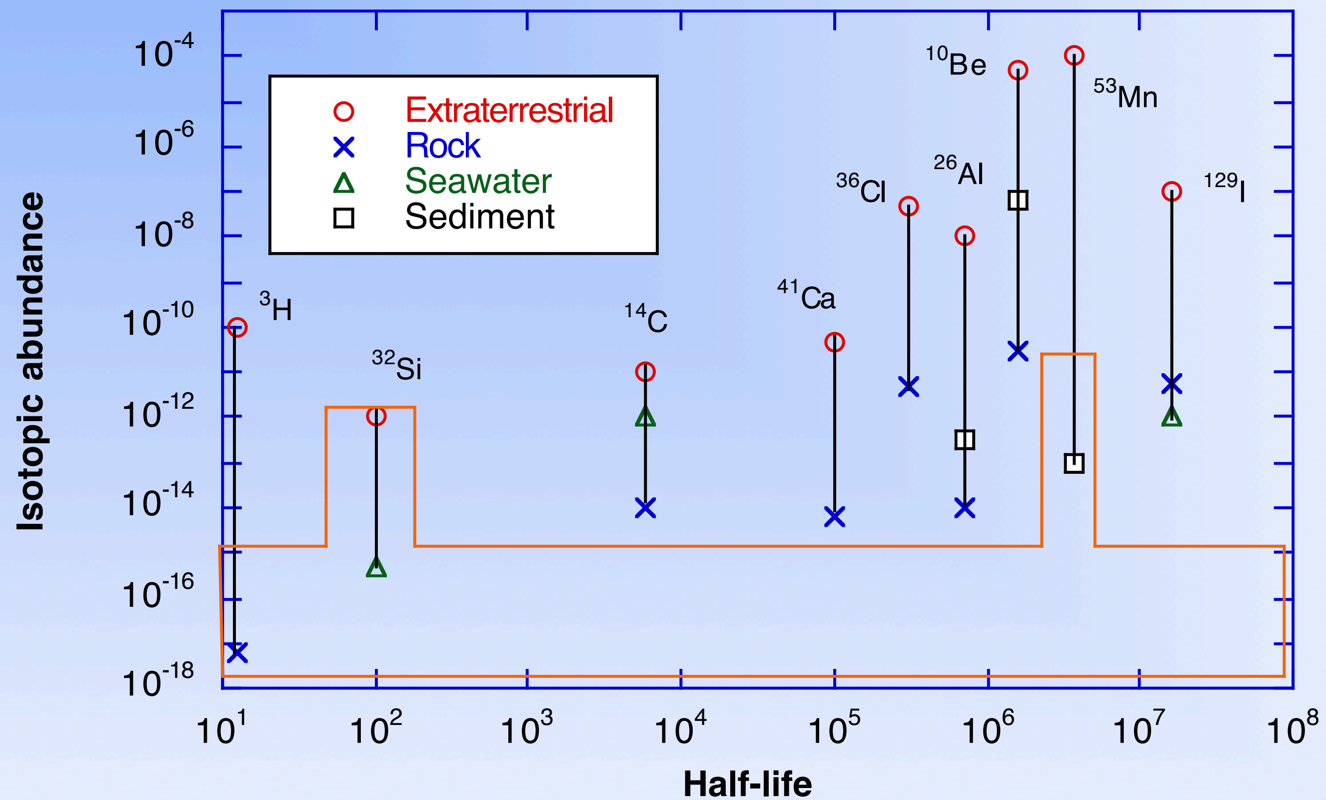
Production of terrestrial cosmogenic nuclides

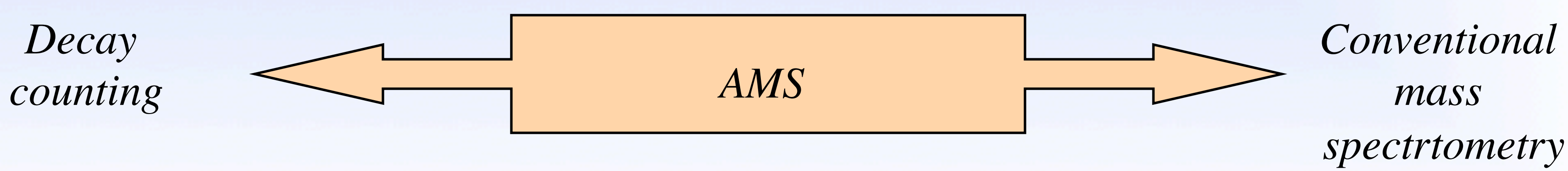


Cosmogenic Nuclides

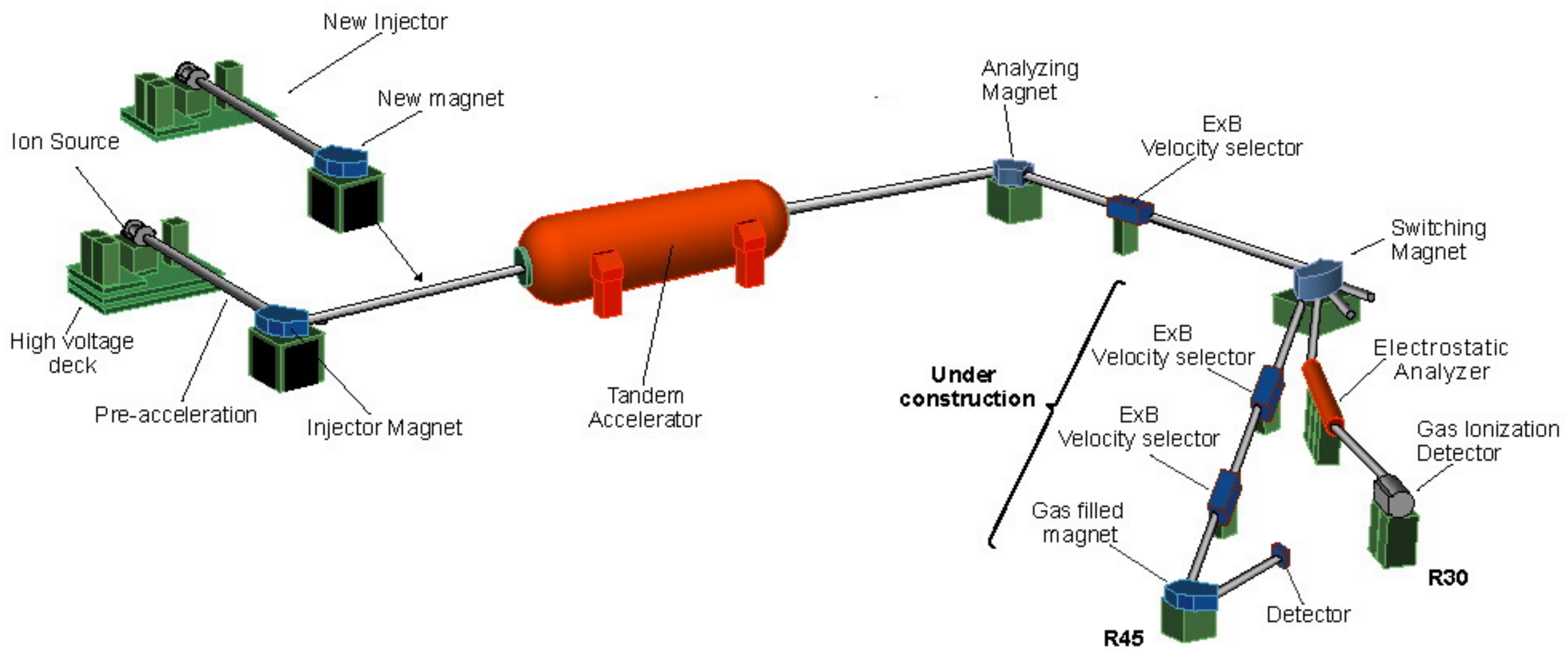
Nuclide	Half-life (yr)	Main Targets
^{3}H	12.3	All elements
^{3}He	Stable	All elements
^{10}Be	1.5×10^{6}	C, O
^{14}C	5730	O
^{21}Ne, ^{22}Ne	Stable	Mg, Al, Si
^{26}Al	7.1×10^{5}	Si, Al
^{36}Cl	3.0×10^{5}	Ca, K, Fe, Cl
^{36}Ar, ^{38}Ar	Stable	Fe, Ca, Cl
^{41}Ca	1.0×10^{5}	Ca, Fe
^{53}Mn	3.7×10^{6}	Fe
^{59}Ni	7.6×10^{4}	Ni
^{81}Kr	2.3×10^{5}	Rb, Sr, Zr
^{129}I	1.6×10^{7}	Te, Ba, La

Radio-isotope abundance ratios





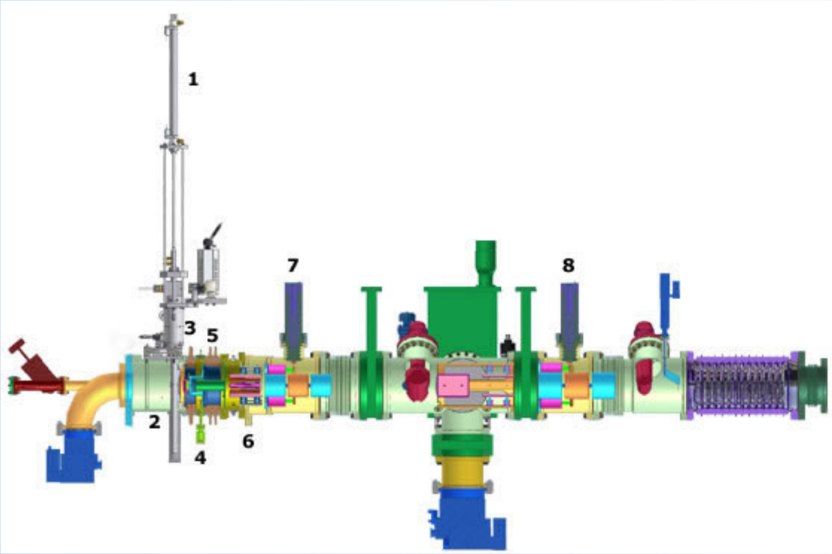
AMS at Purdue

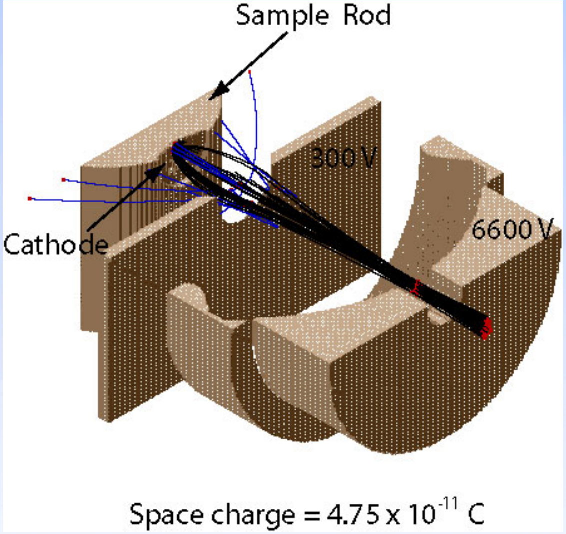


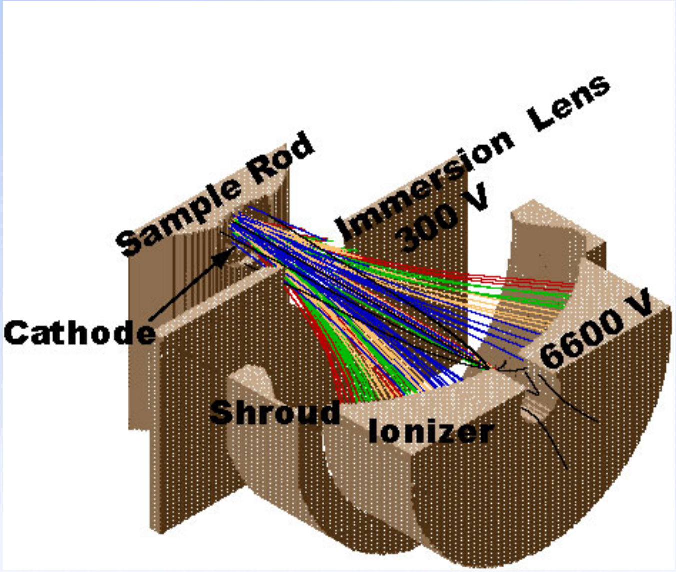
How does AMS differ from conventional MS?

- High abundance sensitivity
  - Multiple stages of momentum, velocity, and electrostatic analysis
- Molecular species generally eliminated *via* stripping
  - ^{14}C: $^{12}C^{1}H_2^{+q}$, $^{12}C^{16}O^{+2q}$
  - ^{36}Cl: $^{1}H^{35}Cl$
- Particle energies allow *dE*/*dx* techniques to be utilized
  - ^{10}B is separated from ^{10}Be by an absorbing foil
  - ^{36}S is distinguished from ^{36}Cl by *dE*/*dx* in the detector

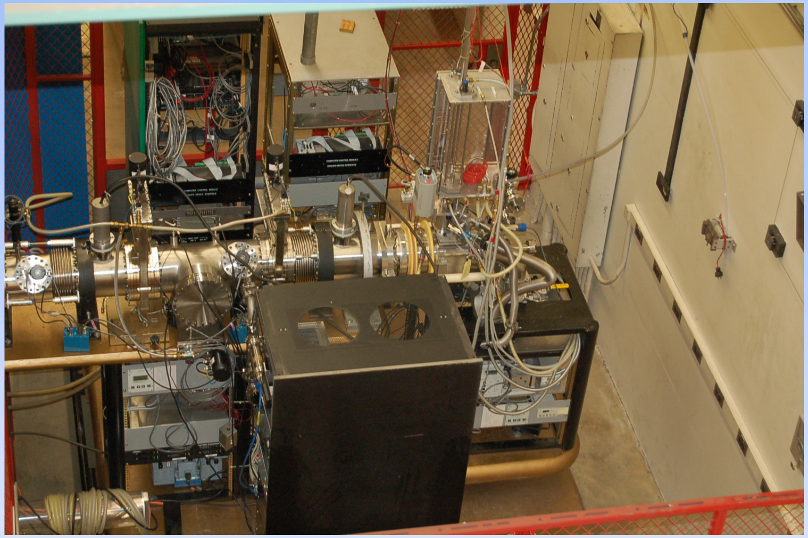
AMS requires the production of a negative ion

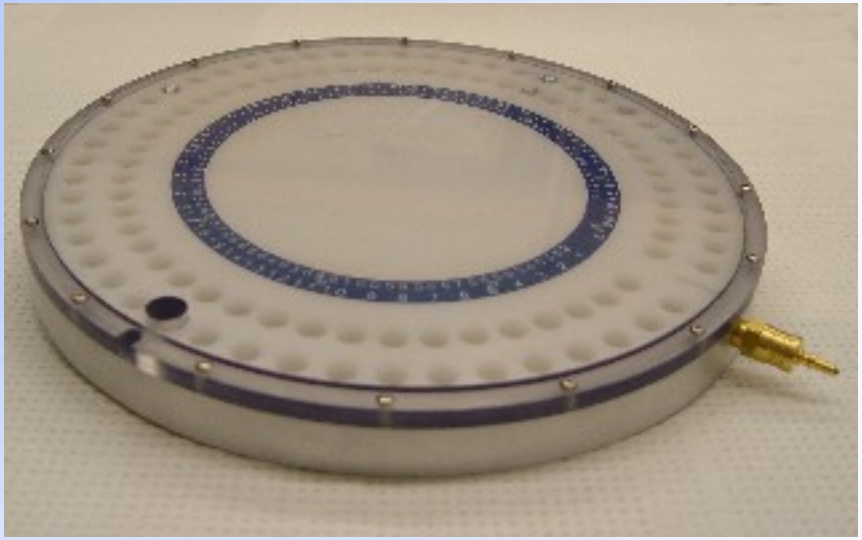




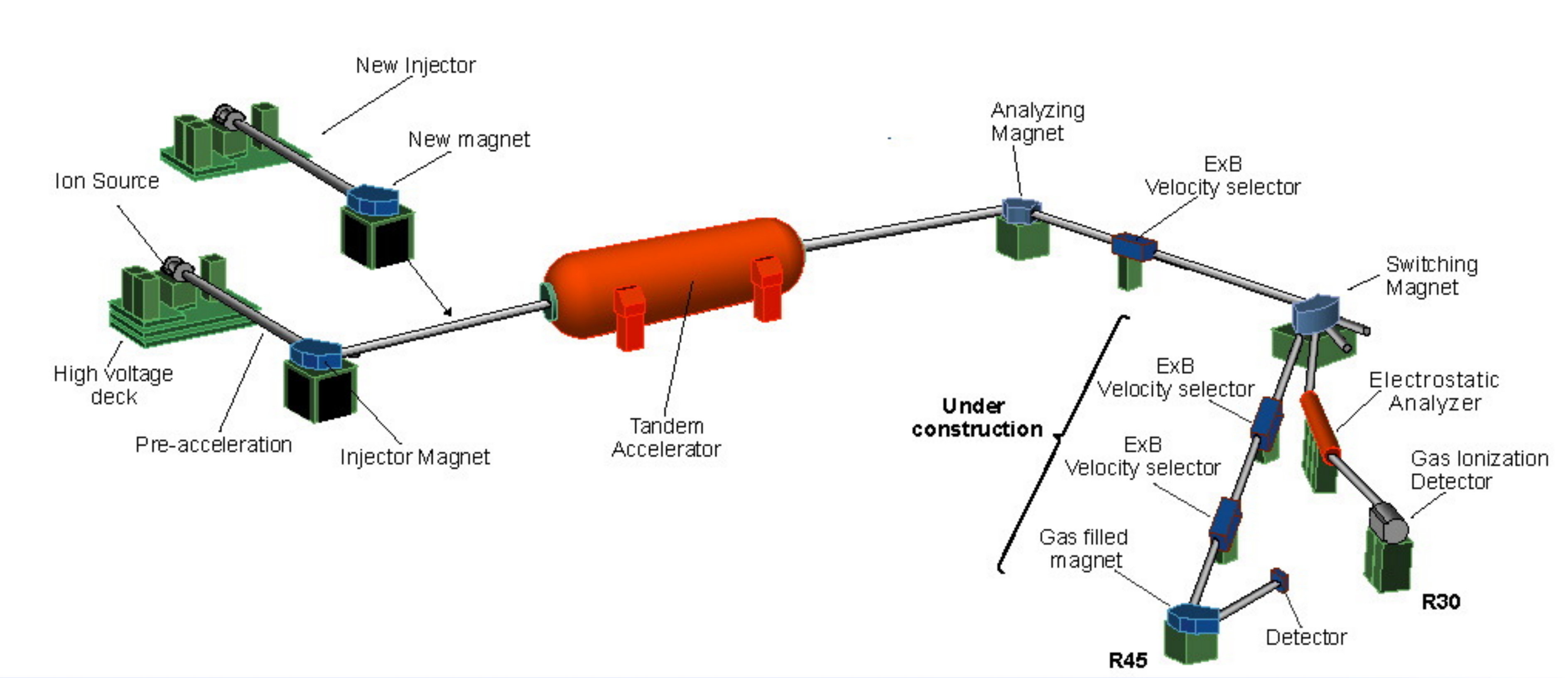


Negative ion production enables the measurement of ^{14}C and ^{26}Al

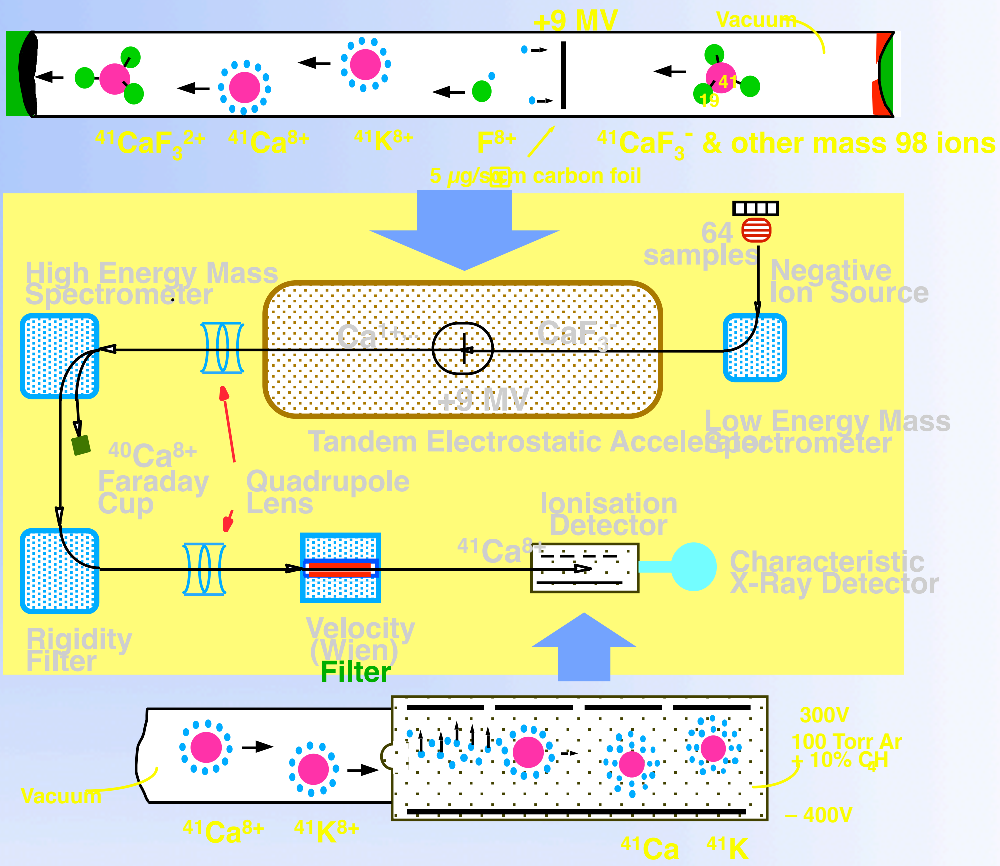




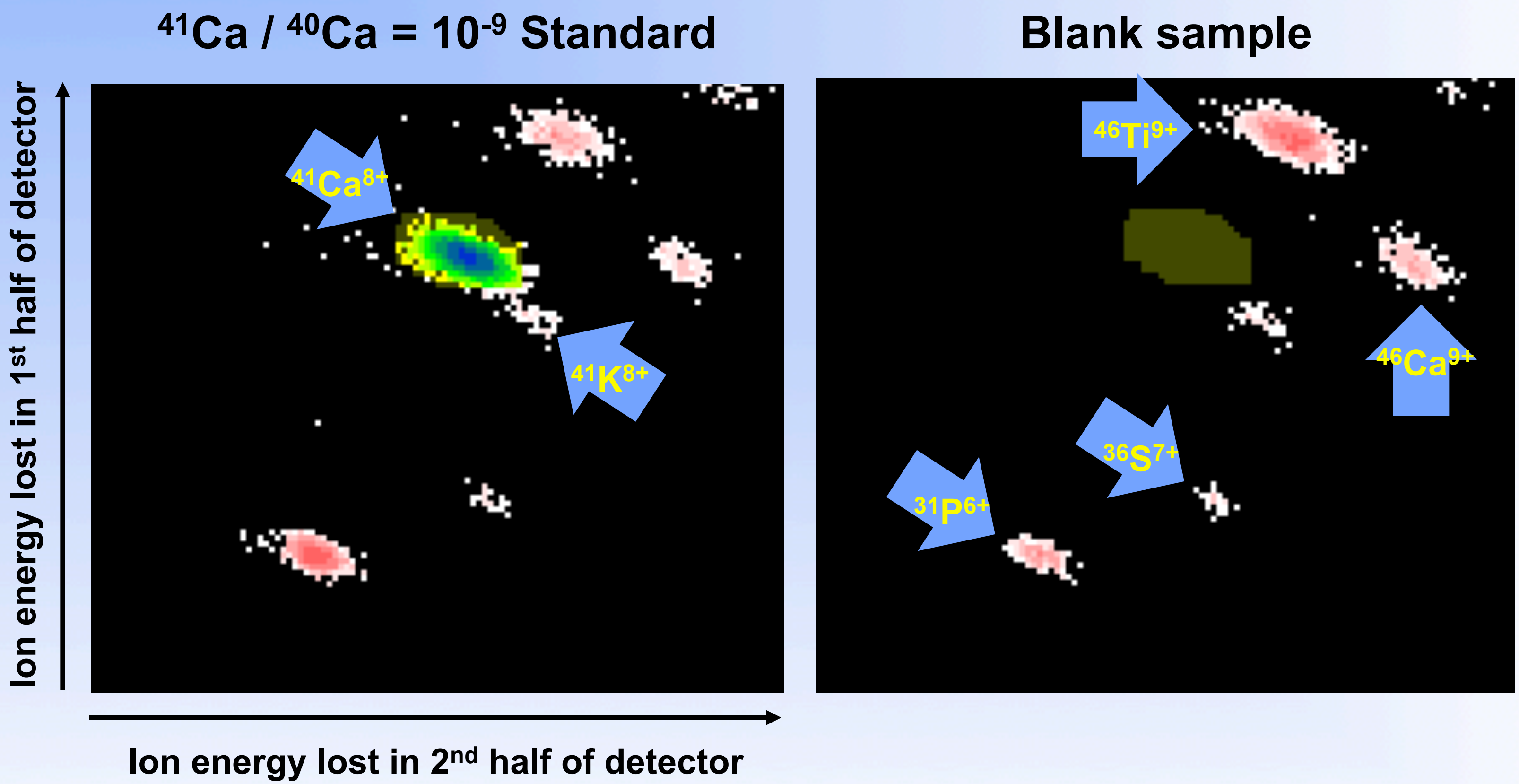
AMS at Purdue



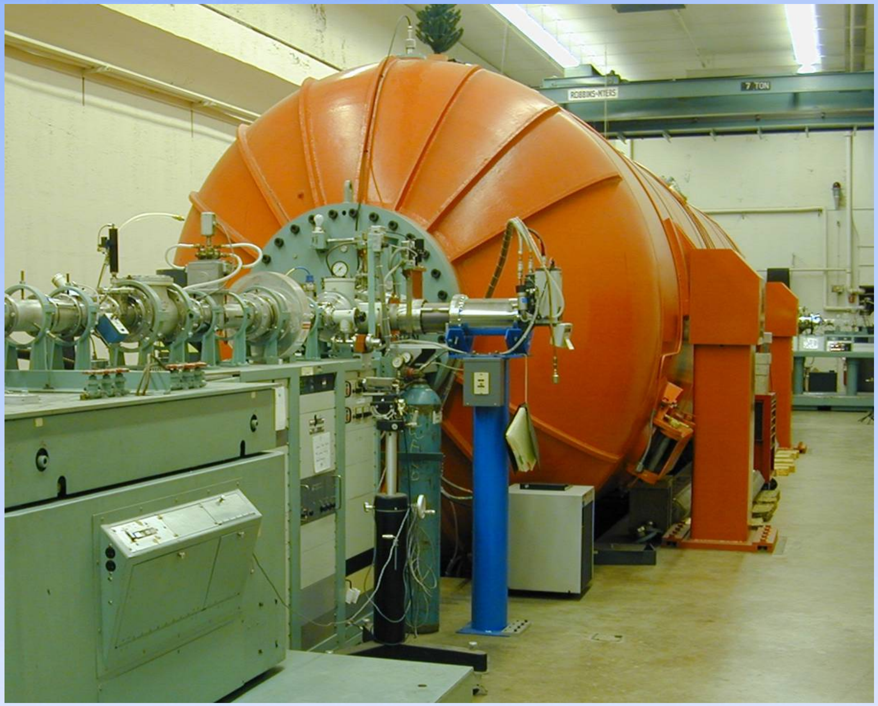
The stripper at the accelerator terminal suppresses molecular interferences



$^{41}CaF_3^-$ MeV 76 MeV $^{41}Ca^{8+}$ energy loss spectra



The Purdue Rare Isotope Measurement Laboratory (PRIME Lab)



- Purdue University is home of the only university-based accelerator-mass-spectrometry (AMS) multi-isotope facility in the United States
- PRIME Lab has facilities support from the NSF geosciences program and facilities upgrade funds from NASA

Measurements performed at PRIME Lab enable Purdue research endeavors and research activities from numerous research groups outside Purdue University

Research areas enabled by AMS

The ability to measure cosmogenic or tracer radionuclides has opened new fields of research

- Traditional Geoscience
  - Extraterrestrial studies
  - Landscape evolution
  - Atmospheric sciences
  - Hydrologic science
- Environmental Science
  - Radionuclide migration
  - Transport and fate of toxins
- Archaeology
- Biomedical Science

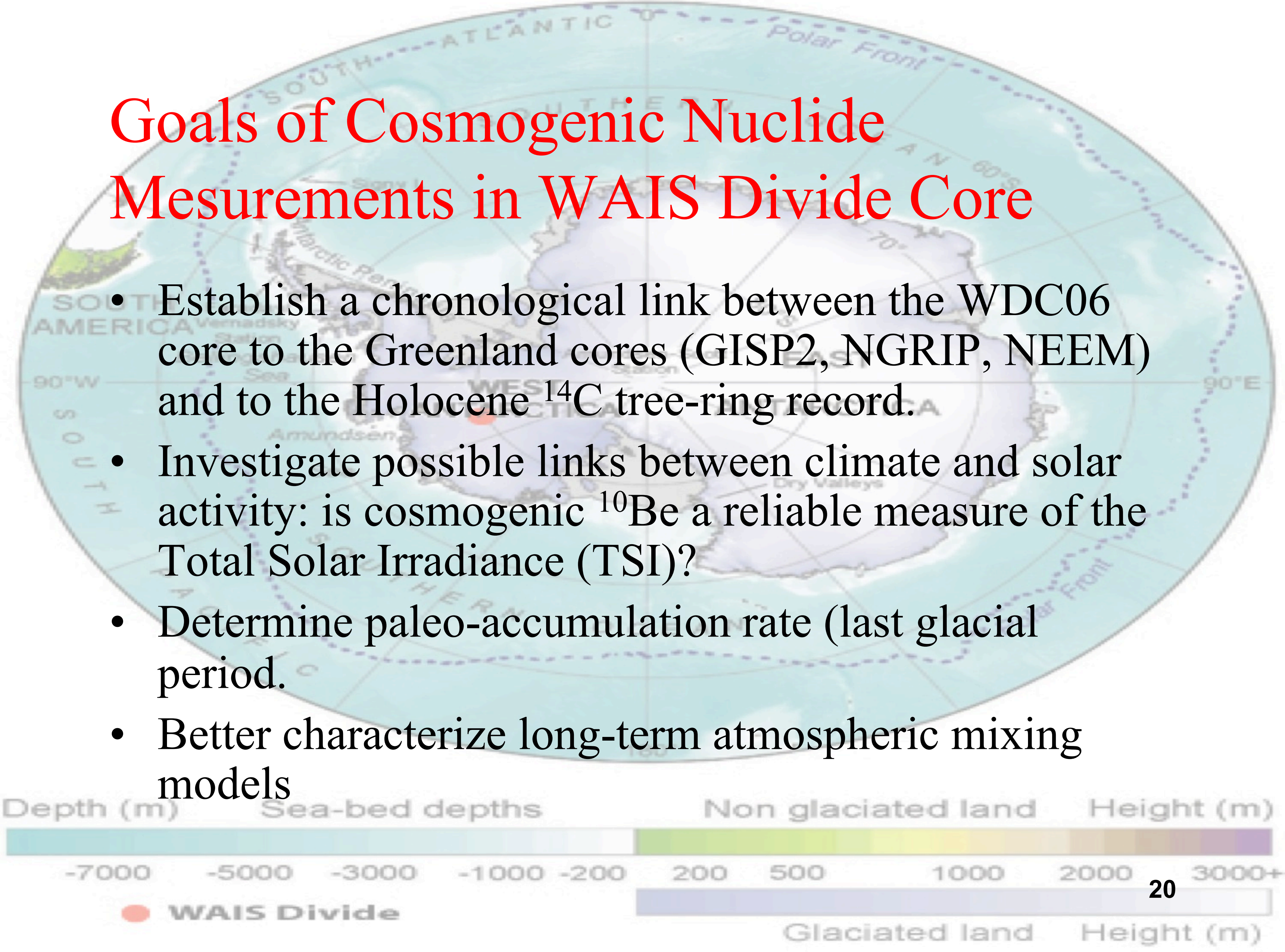
The list of applications is long and growing

Cosmogenic nuclides - present and future

- Cosmogenic nuclides have been used extensively to determine exposure age histories for extra-terrestrial materials
- A relatively new application is terrestrial exposure age dating
  - Many studies have amply demonstrated desirability of this method
  - Nevertheless, there are numerous complications in this application
- Previous experience with extraterrestrial material points the way to advances possible in the terrestrial setting

Goals of Cosmogenic Nuclide Mesurements in WAIS Divide Core

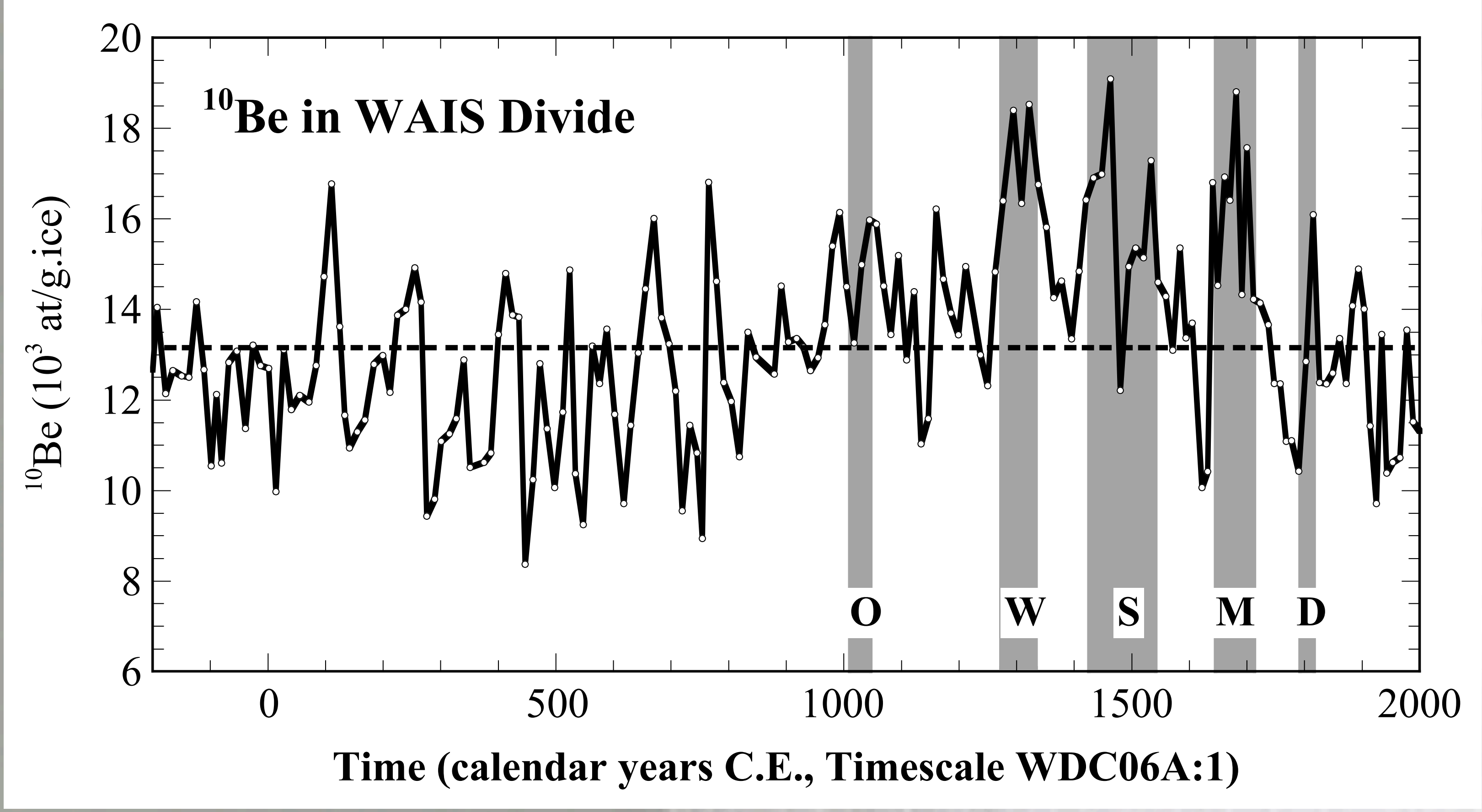
- Establish a chronological link between the WDC06 core to the Greenland cores (GISP2, NGRIP, NEEM) and to the Holocene ^{14}C tree-ring record.
- Investigate possible links between climate and solar activity: is cosmogenic ^{10}Be a reliable measure of the Total Solar Irradiance (TSI)?
- Determine paleo-accumulation rate (last glacial period.
- Better characterize long-term atmospheric mixing models



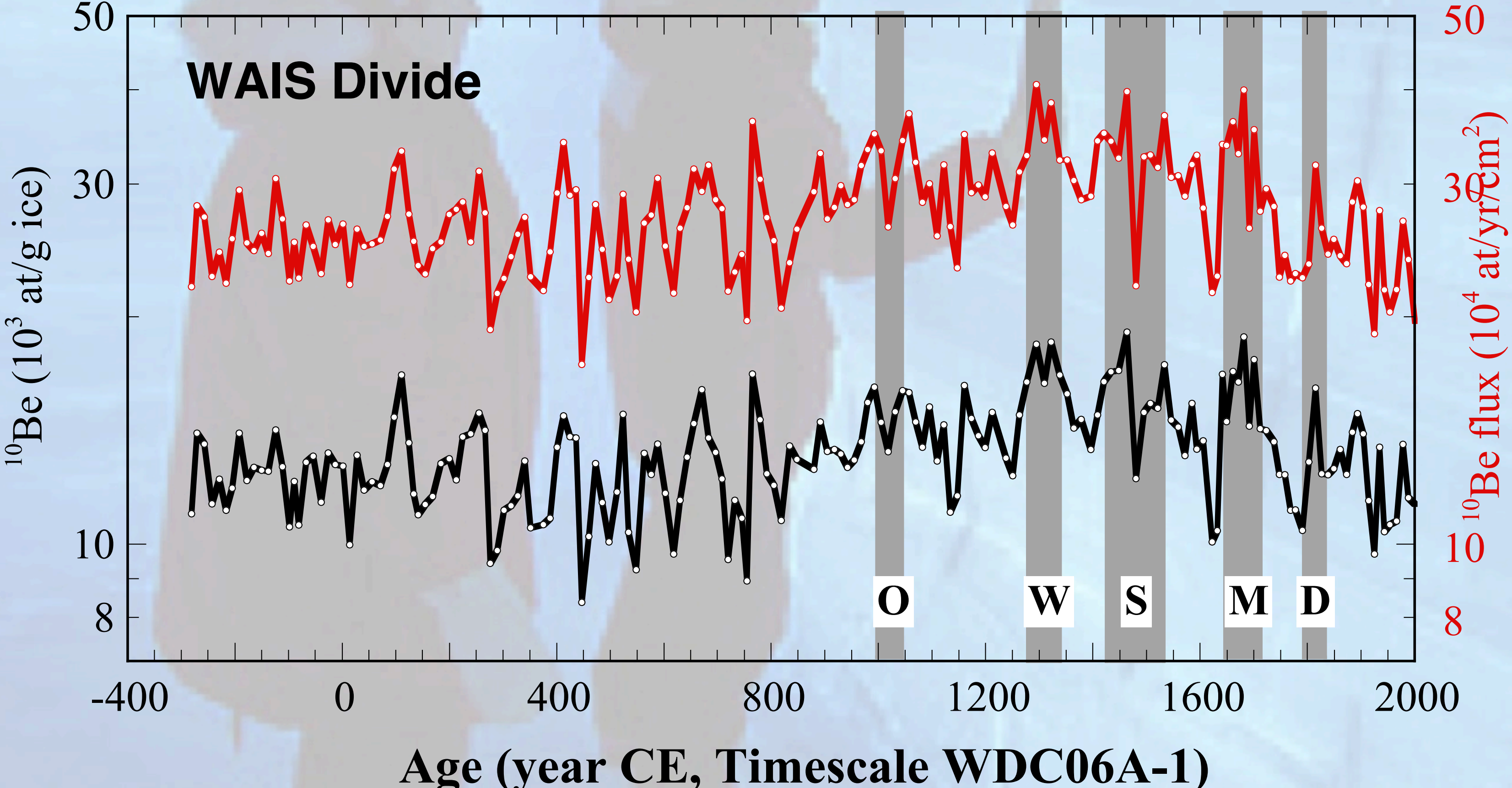
WAIS Divide ice core

- Low-resolution core (0-560m)
  - Waste samples of 1-2 kg were collected from the continuous ice core melter at the Desert Research Institute (DRI)
  - A typical ^{10}Be sample represents ~3 m of ice core and 12 years of snow accumulation
  - Two samples were combined for ^{36}Cl analysis
    - We assumed an average Cl of 43±10 ppb (which is 5-10% of total Cl)
- High resolution core (0-114m)
  - We are measuring ^{10}Be from annual layers
  - Each sample is 100-300 g of ice

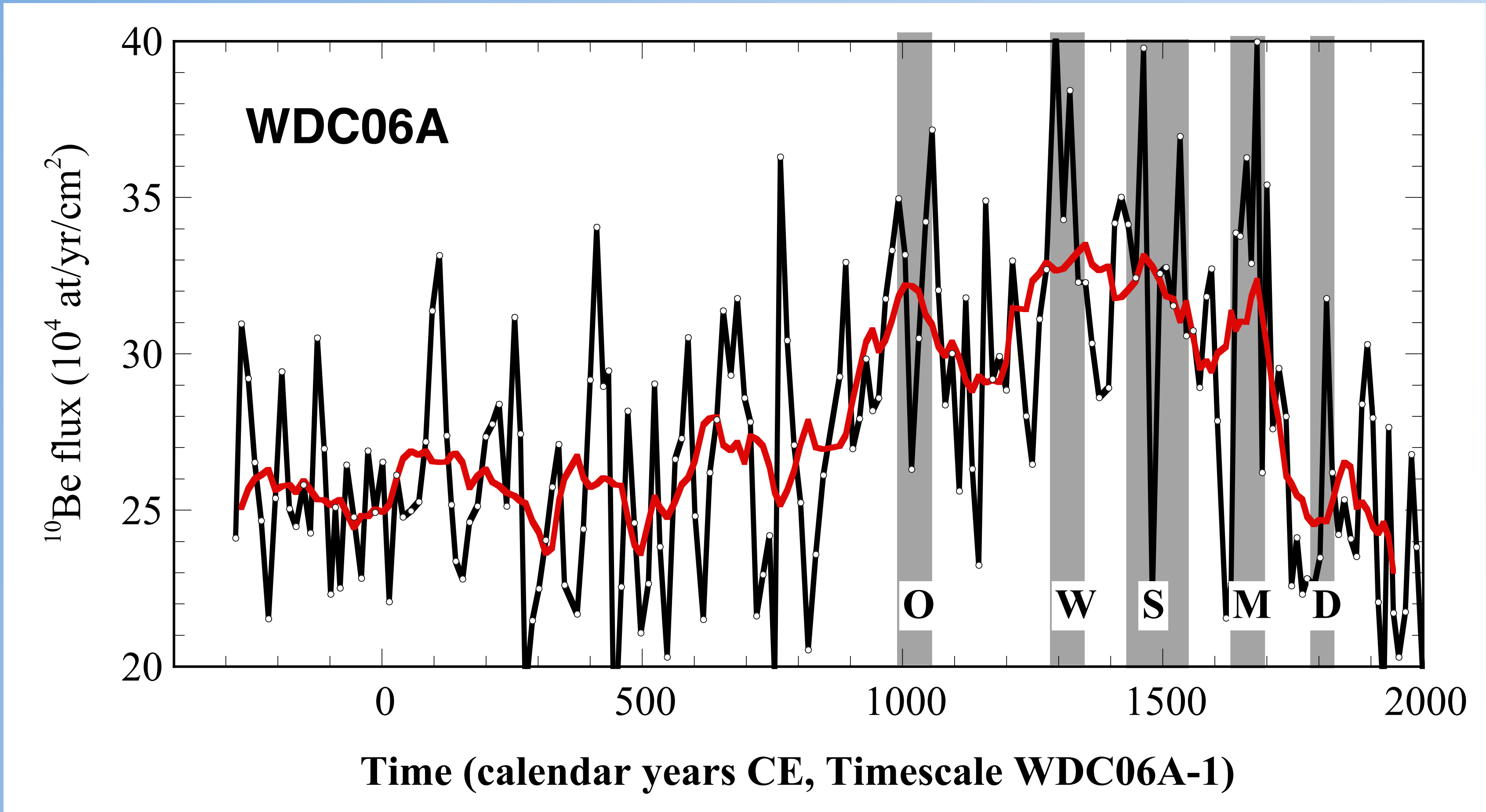
^{10}Be concentration in WDC06A



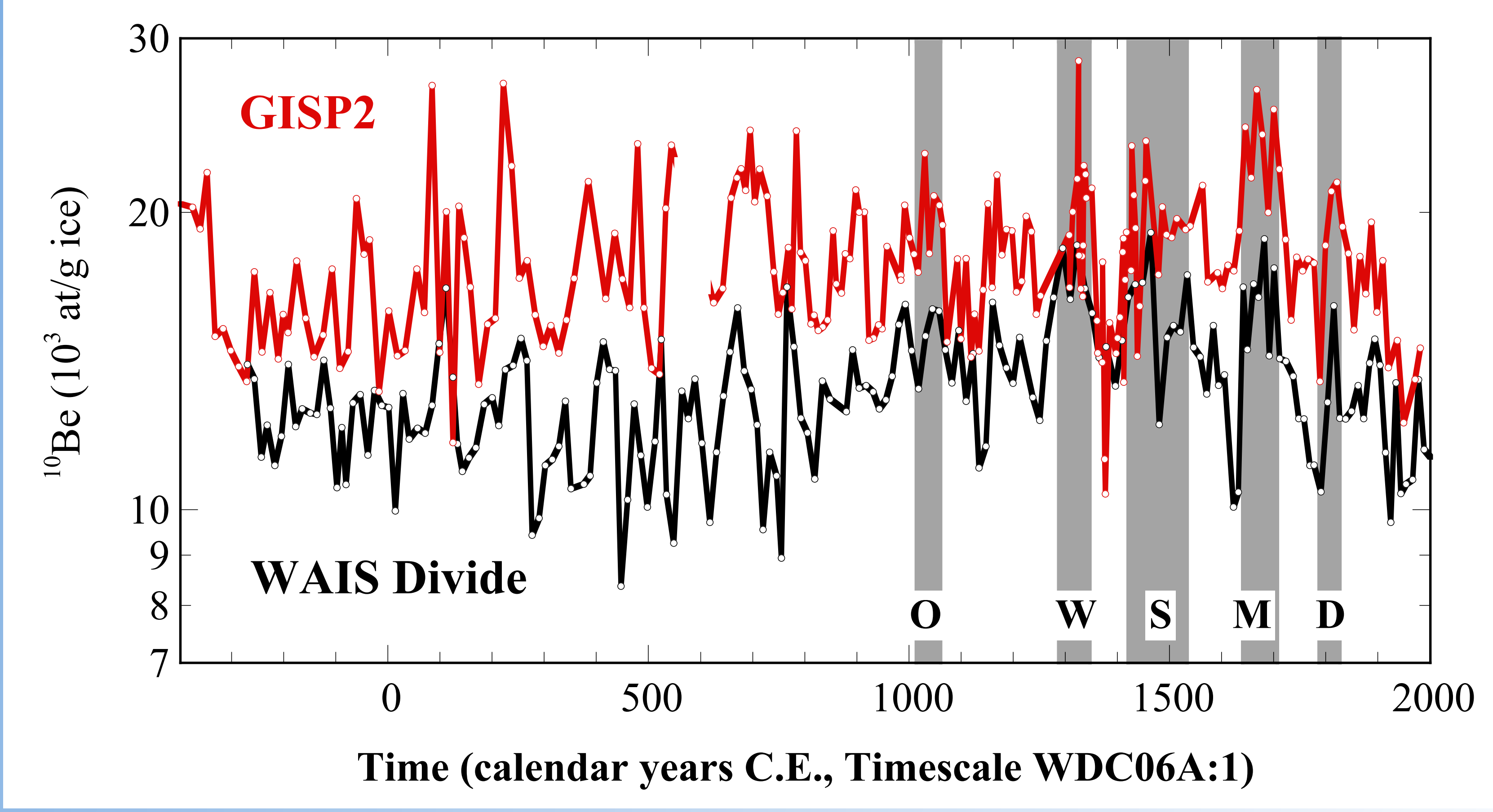
^{10}Be flux = ^{10}Be * SAR (cm weq/yr)



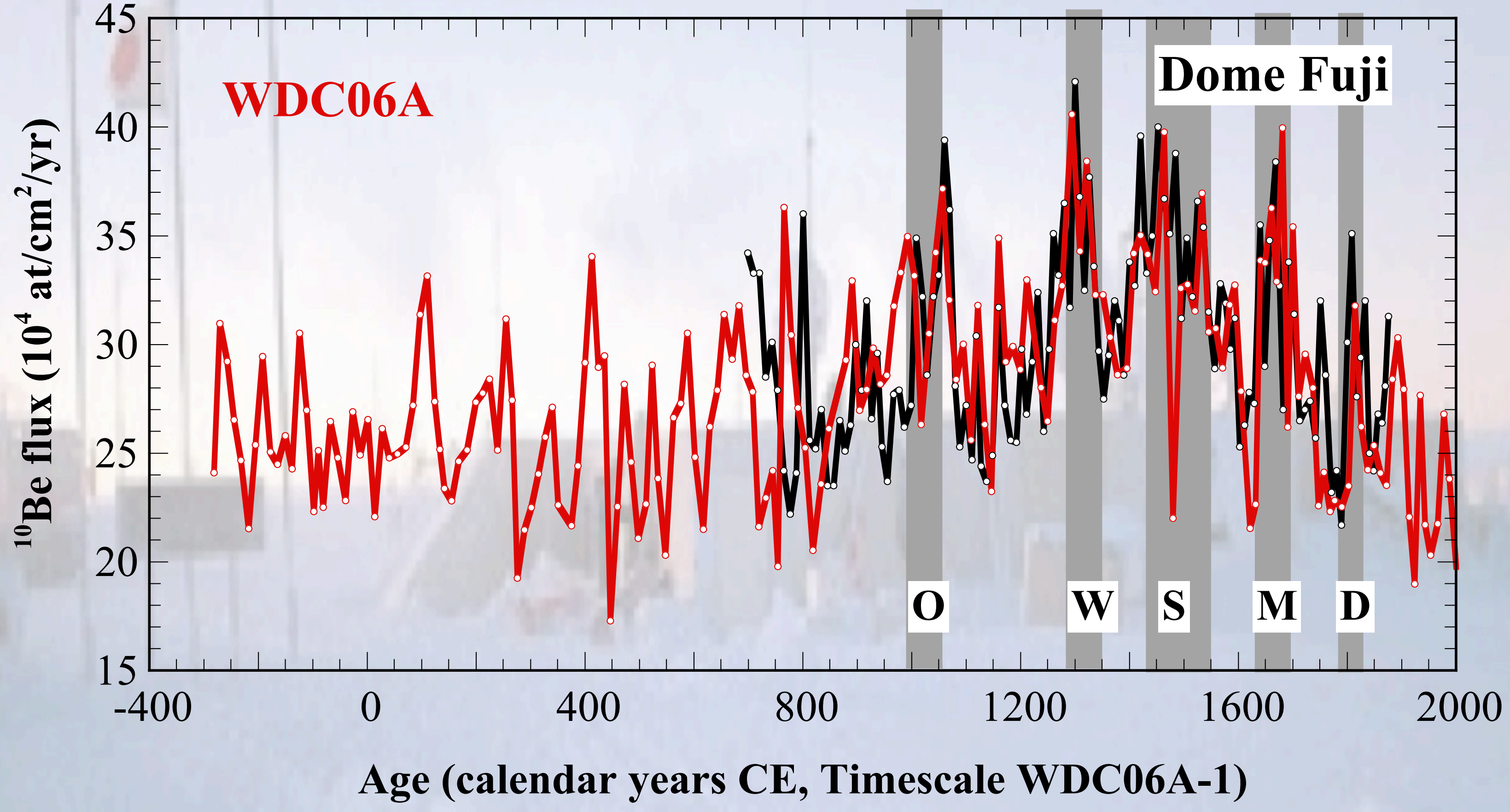
Variations in ^{10}Be on 10 and 100 year timescales



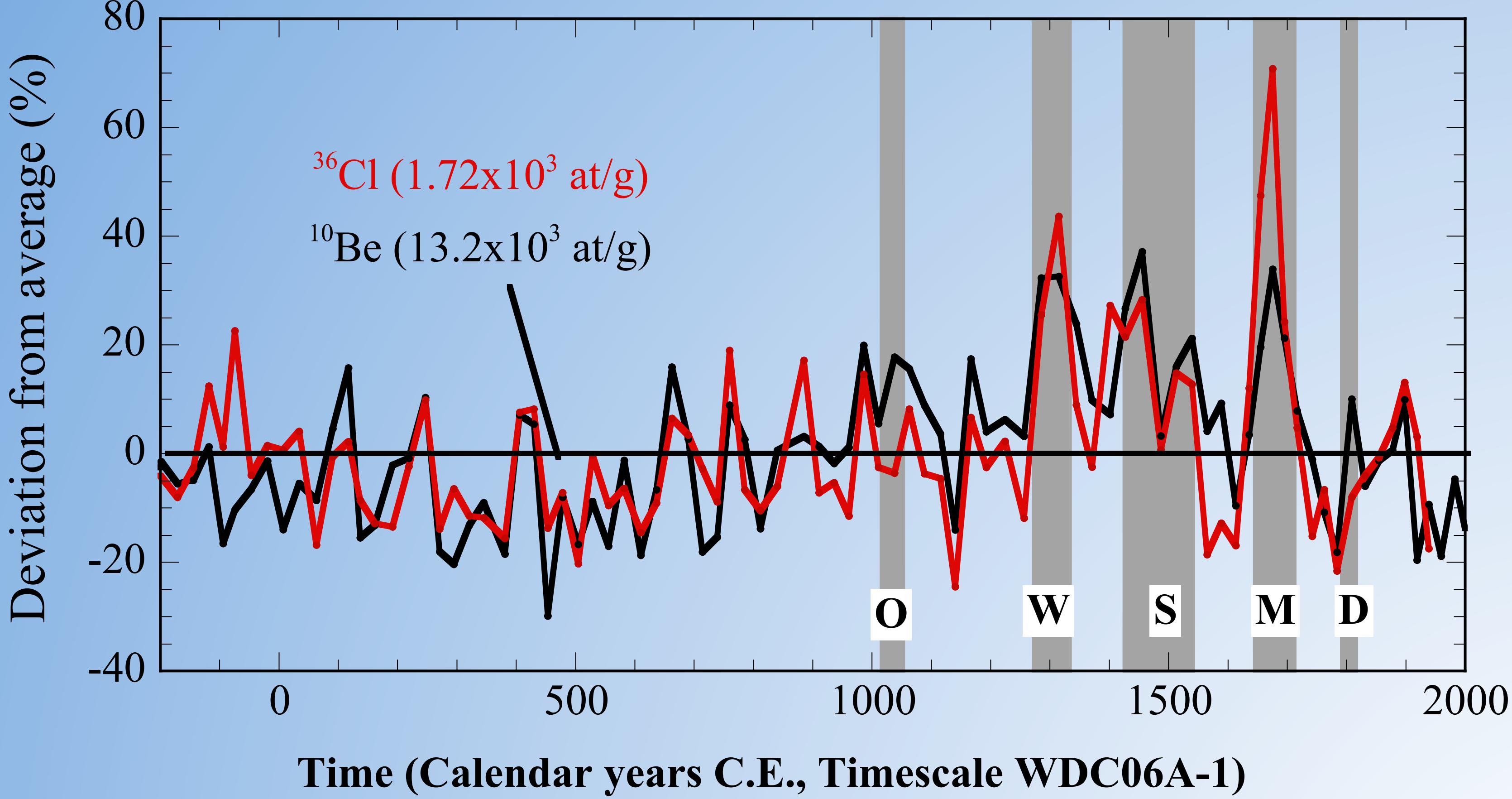
^{10}Be in WDC06A and GISP2 cores



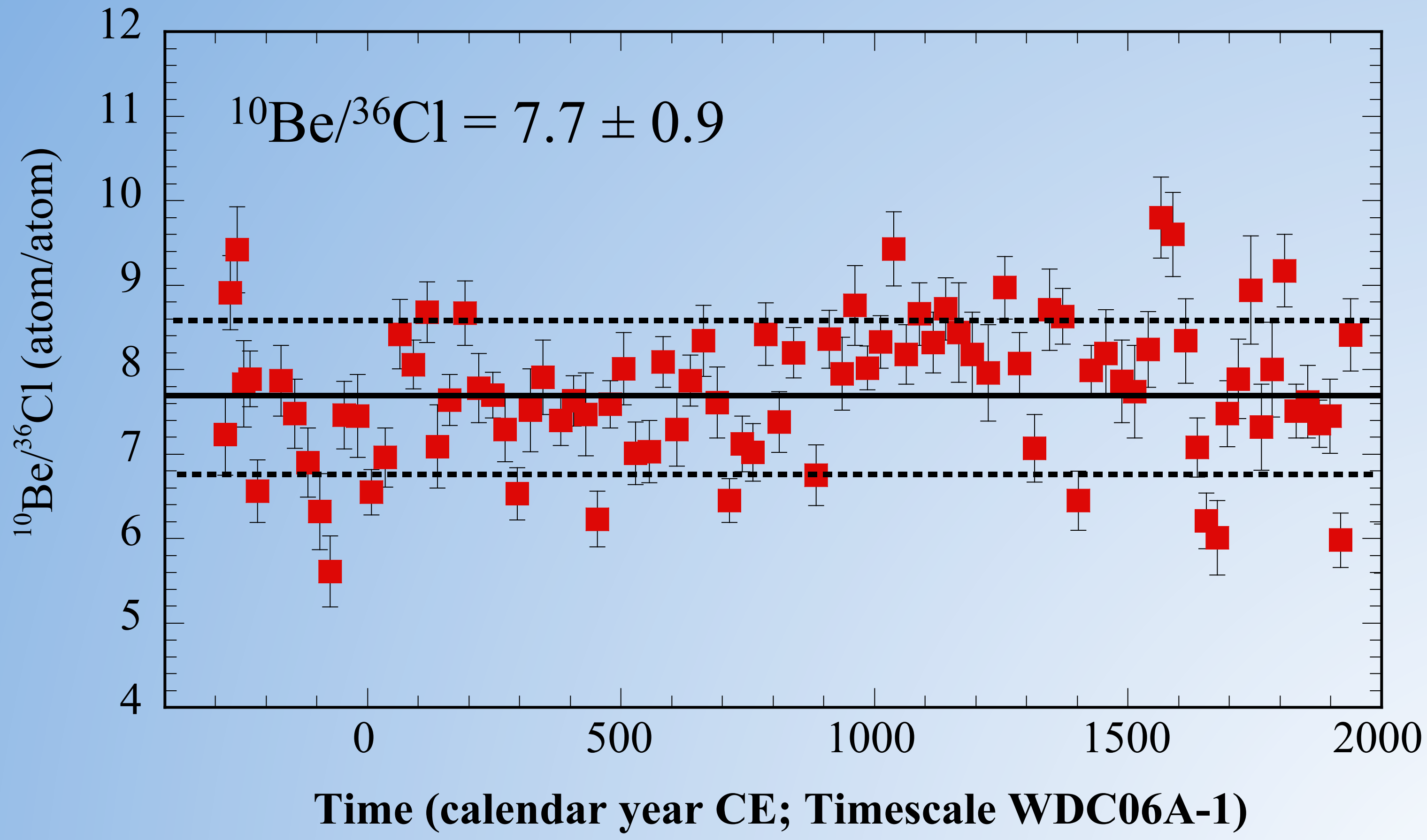
^{10}Be in WDC06A and Dome Fuji



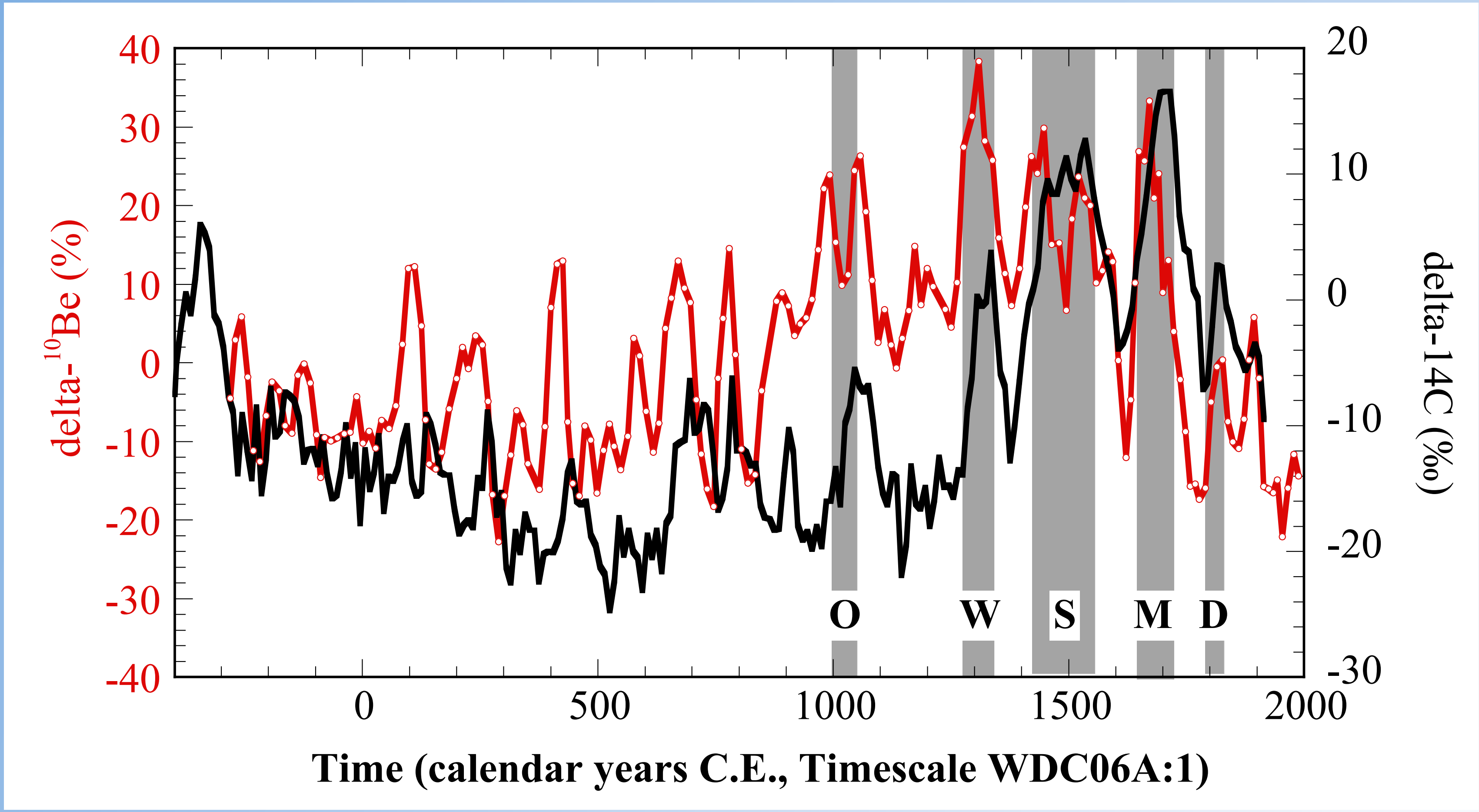
^{10}Be and ^{36}Cl in WDC06A



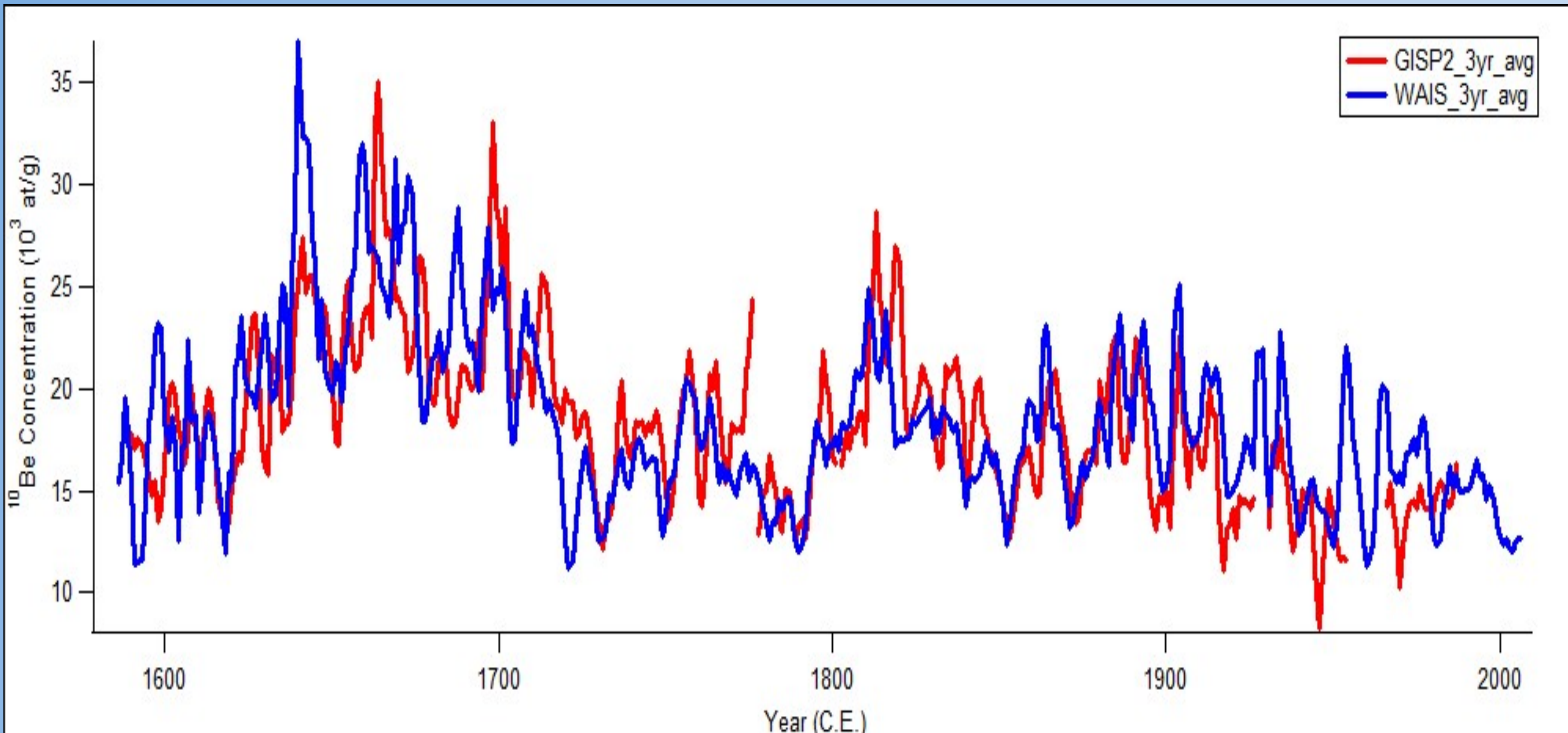
$^{10}Be/^{36}Cl$ in WDC06A



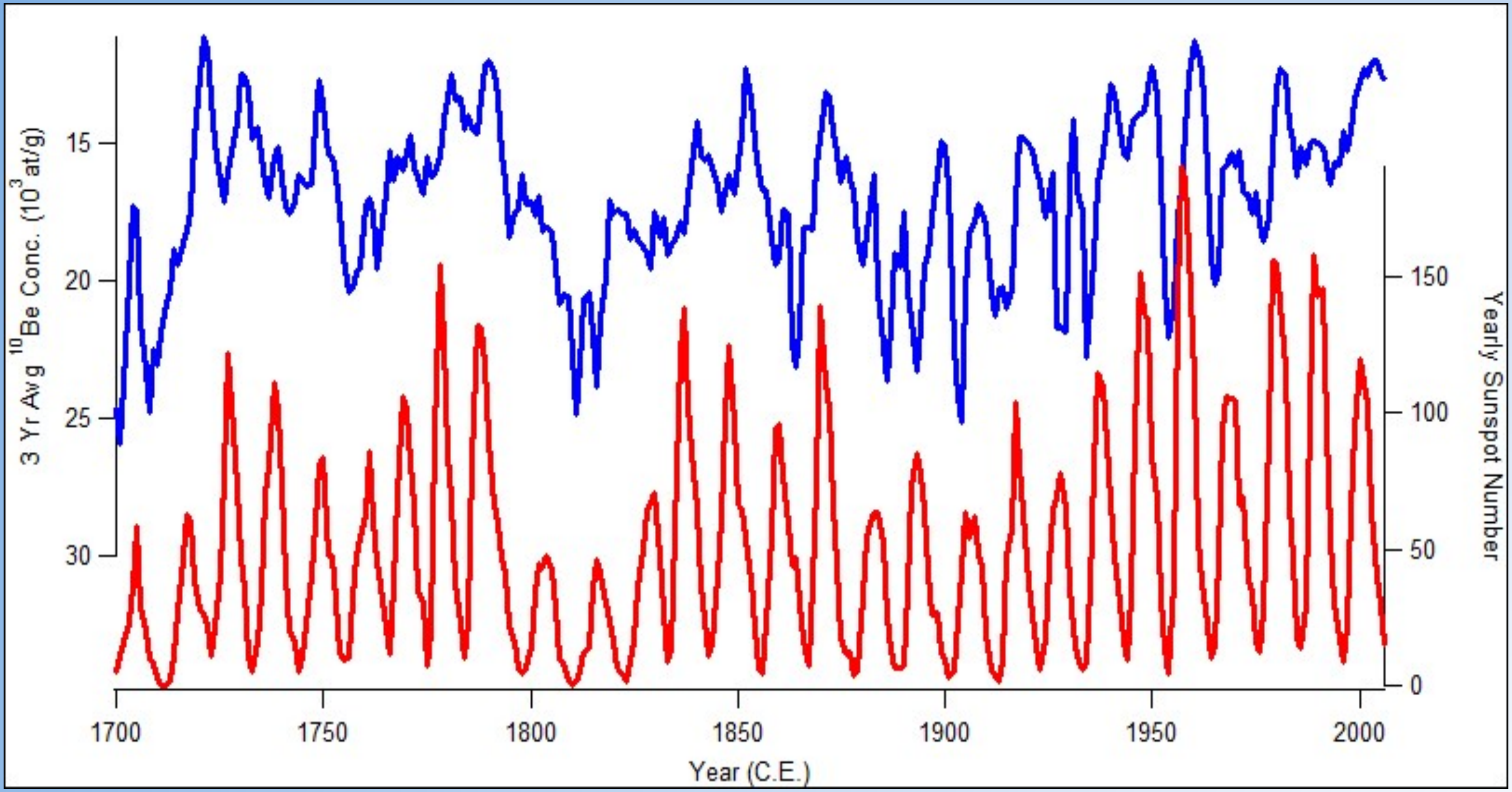
^{10}Be in WDC06A vs. ^{14}C tree-ring record

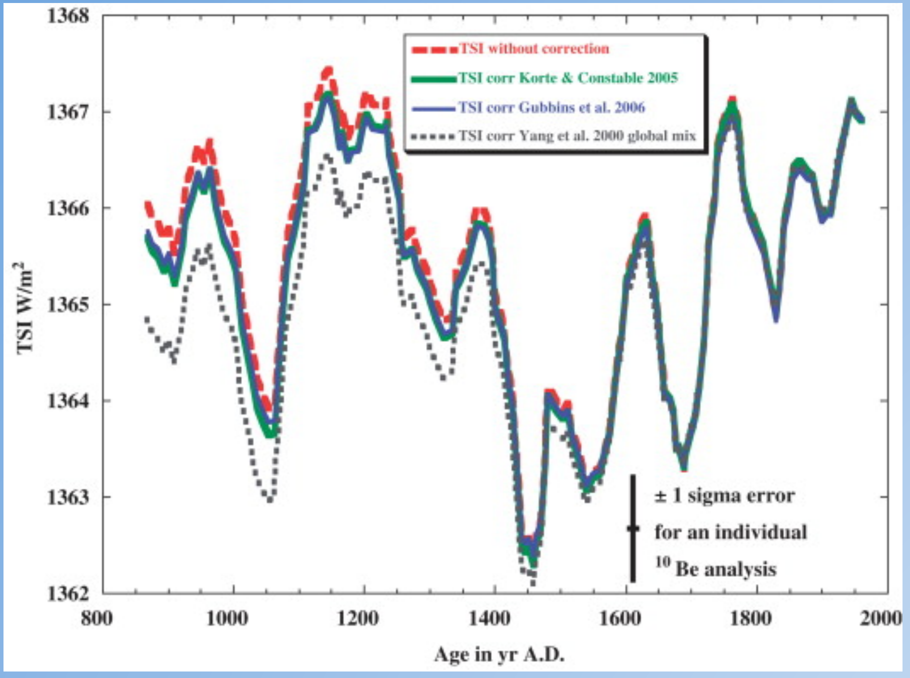


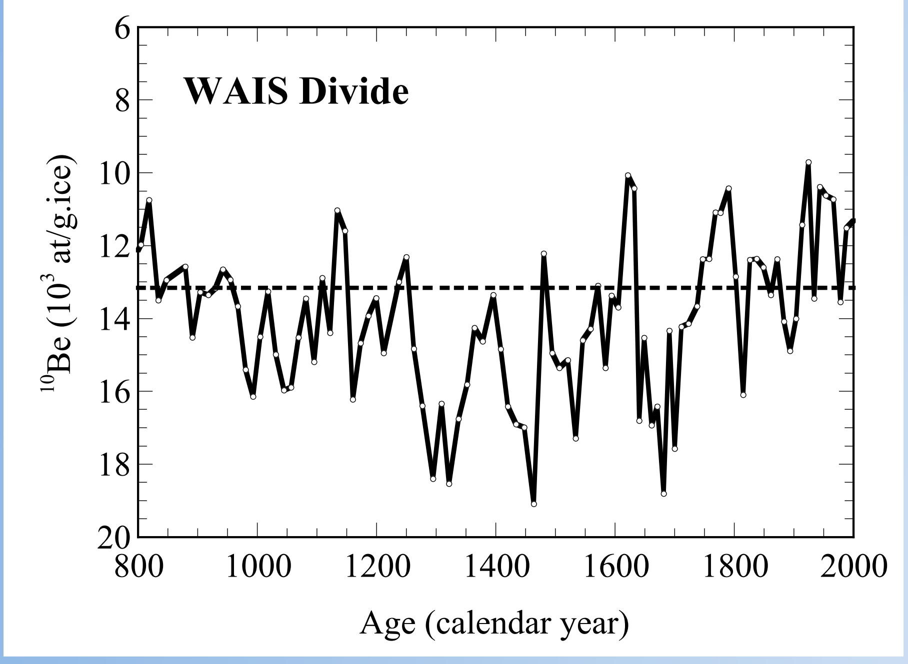
WAIS Divide and GISP2 concentrations – 3 year averages



^{10}Be concentration and sunspot number?







TSI vs. ^{10}Be in WAIS Divide

We need to compare the TSI for the last 30 years with the annual ^{10}Be record

Cosmogenic nuclide concentrations: nuclear physics parameters and controlling geologic factors

$$N(z,t) = \left[N(z,0)e^{-\lambda t_e} + \frac{P(t)}{\lambda + \mu\varepsilon} e^{-\mu z}(1 - e^{-(\lambda + \mu\varepsilon)t_e}) \right]$$

$\mu = \rho / \Lambda$

$N(z,0) =$ concentration at depth, z, when $t_e = 0$

$P =$ production rate (latitude and elevation dependent)

$\mu =$ absorption coefficient for cosmic rays

$\Lambda =$ interaction mean free path

$\varepsilon =$ erosion rate

$t_e =$ exposure time

The measured concentration of a cosmic-ray produced radionuclide is controlled by several geologic factors

$$N(z,t) = \left[N(z,0)e^{-\lambda t_e} + \frac{P(t)}{\lambda + \mu\varepsilon} e^{-\mu z}(1 - e^{-(\lambda+\mu\varepsilon)t_e}) \right]$$

Geologic Process	Parameter
Most recent duration of exposure to cosmic rays	t_e
Depth of sample during this exposure	z
Duration of earlier exposure	$N(z,0)$
Erosion rate	ε

Exposure age dating - ideal case

$$N(z,t) = \left[N(z,0)e^{-\lambda t_e} + \frac{P(t)}{\lambda + \mu\varepsilon} e^{-\mu z}(1 - e^{-(\lambda+\mu\varepsilon)t_e}) \right]$$

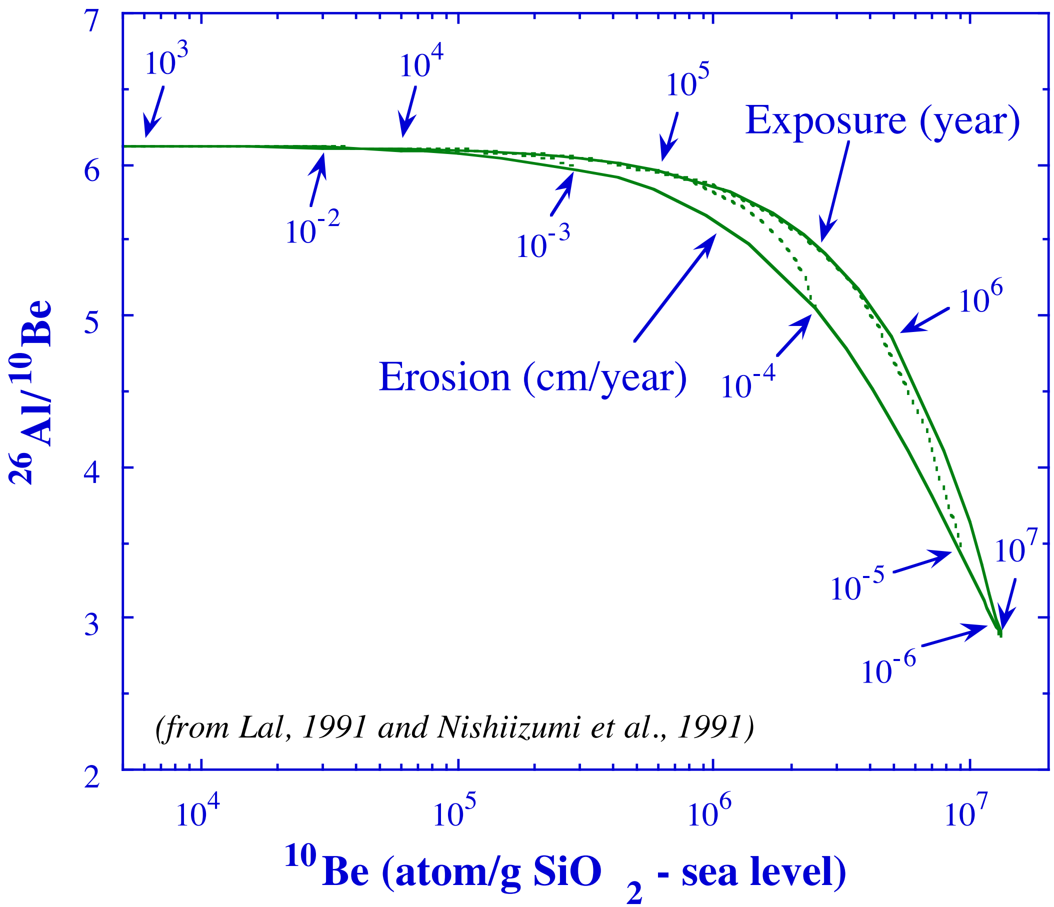
$$N(z,0) = 0$$

$$\varepsilon = 0$$

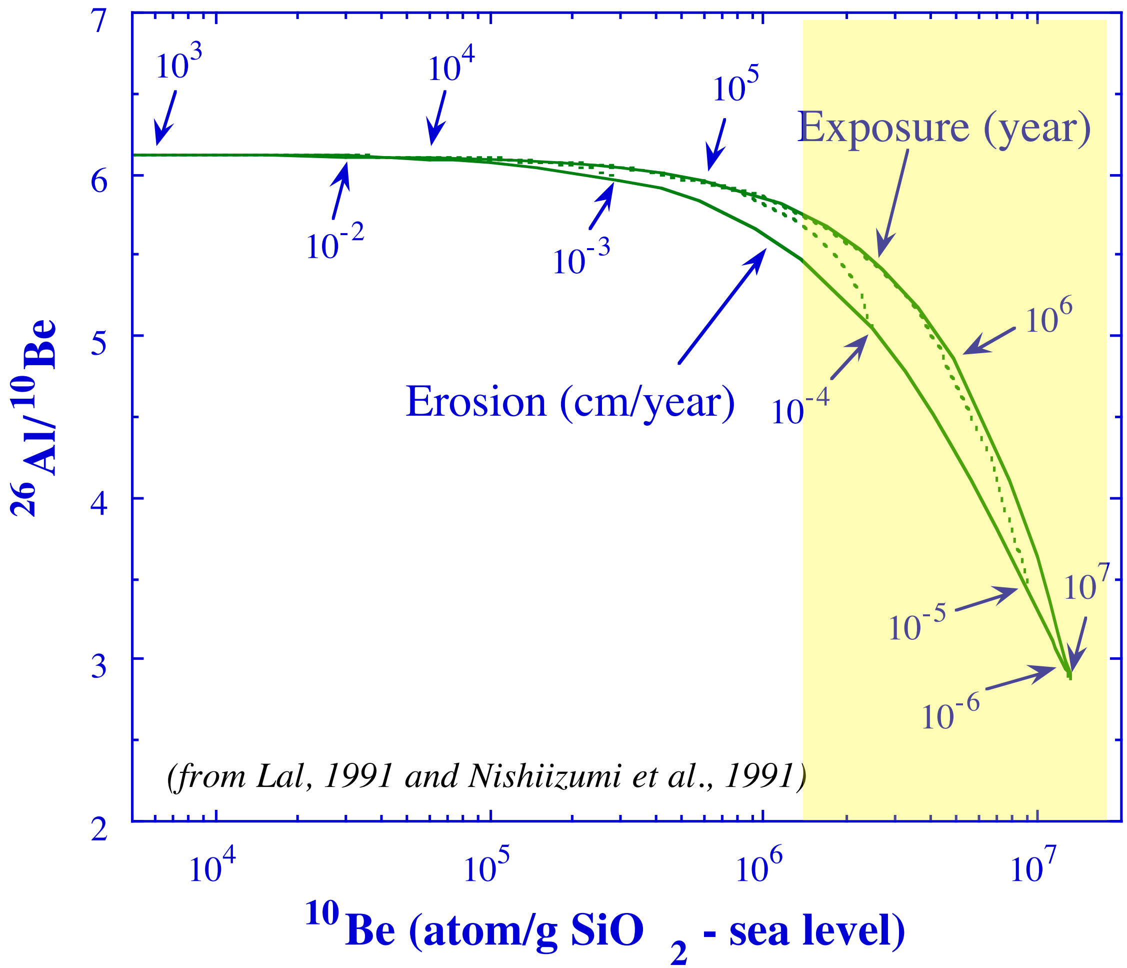
$$z = 0 \text{ or is known}$$

$$N(z,t) = \frac{P(t)}{\lambda}(1 - e^{-\lambda t_e})$$

Systematics of terrestrial production

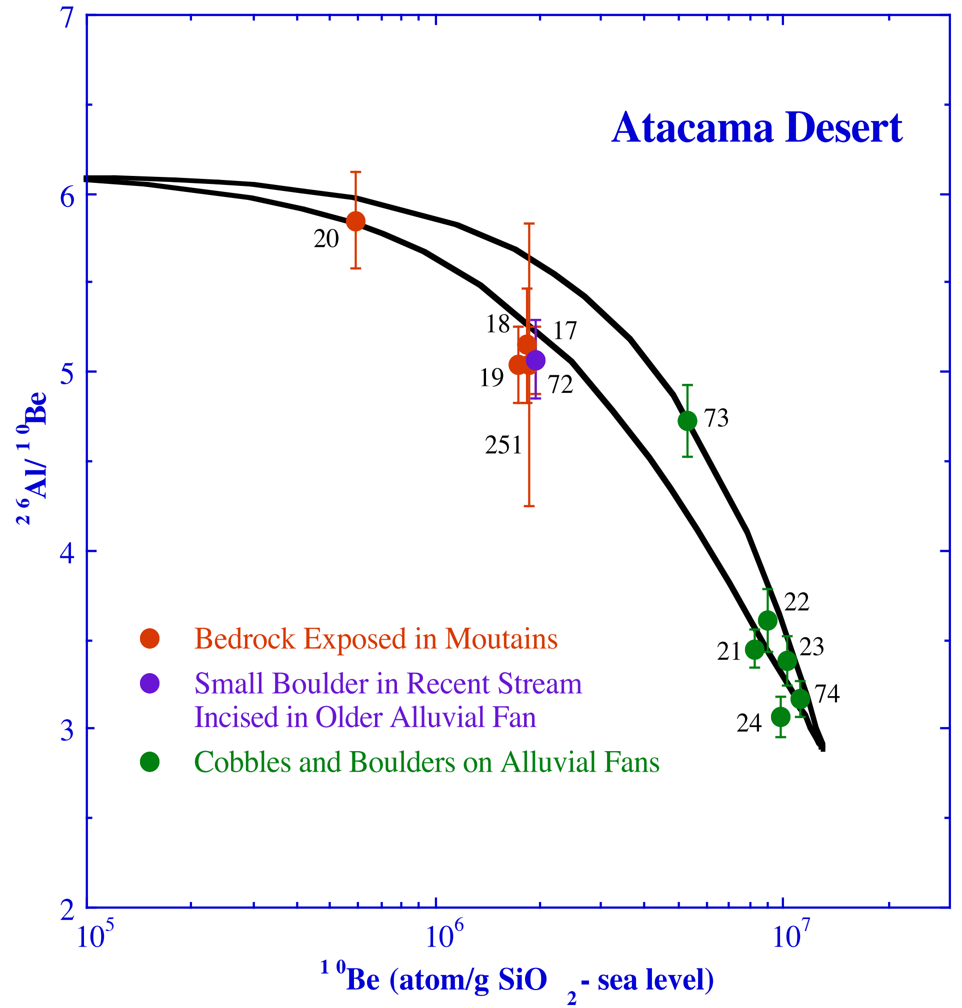


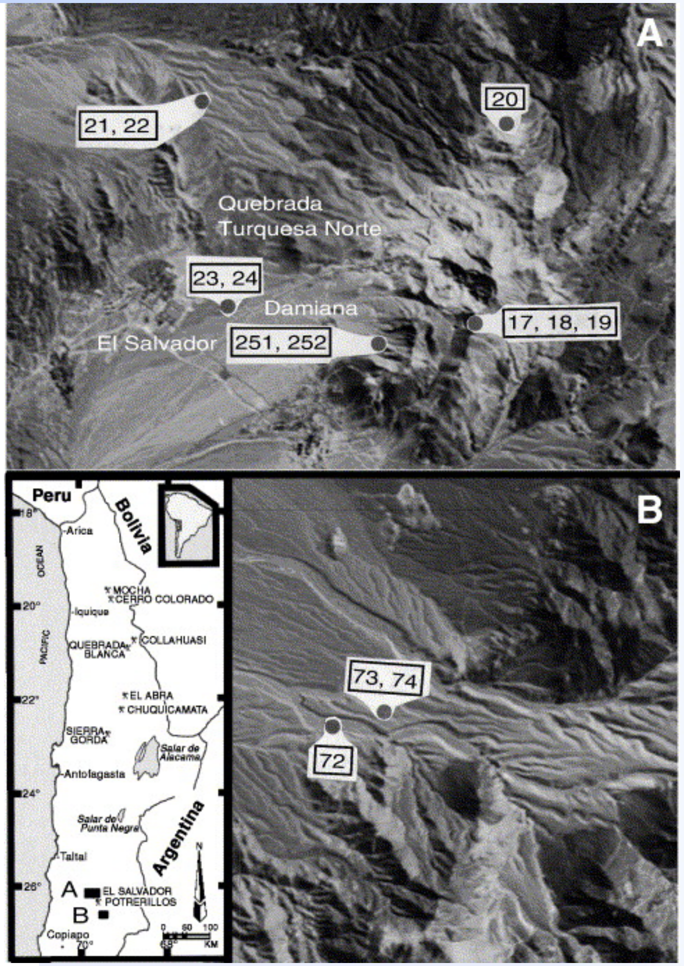
Systematics of terrestrial production



- Exposure ages > 10^5 yr require low erosion rates
- Long exposure ages and low erosion rates are best attained in arid conditions

Cosmogenic nuclides from the Atacama Desert

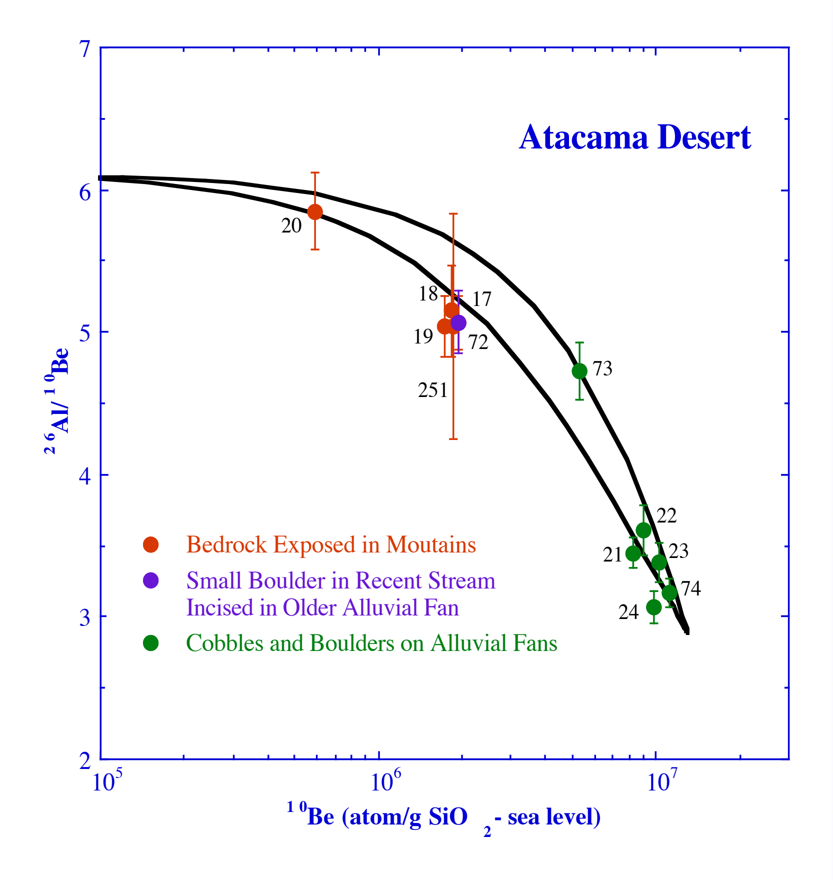




(Data and figures taken from Nishiizumi *et al*., ***237***, **EPSL**, 2005)

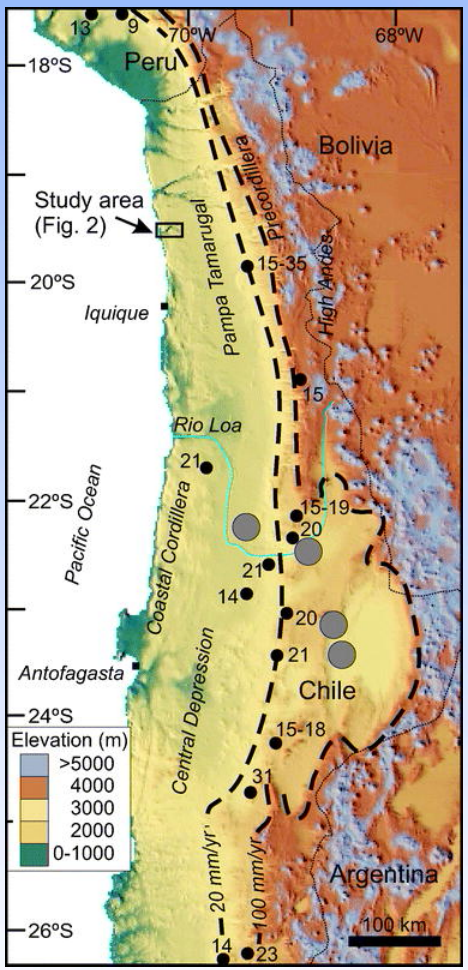
Cosmogenic exposure ages and erosion rates

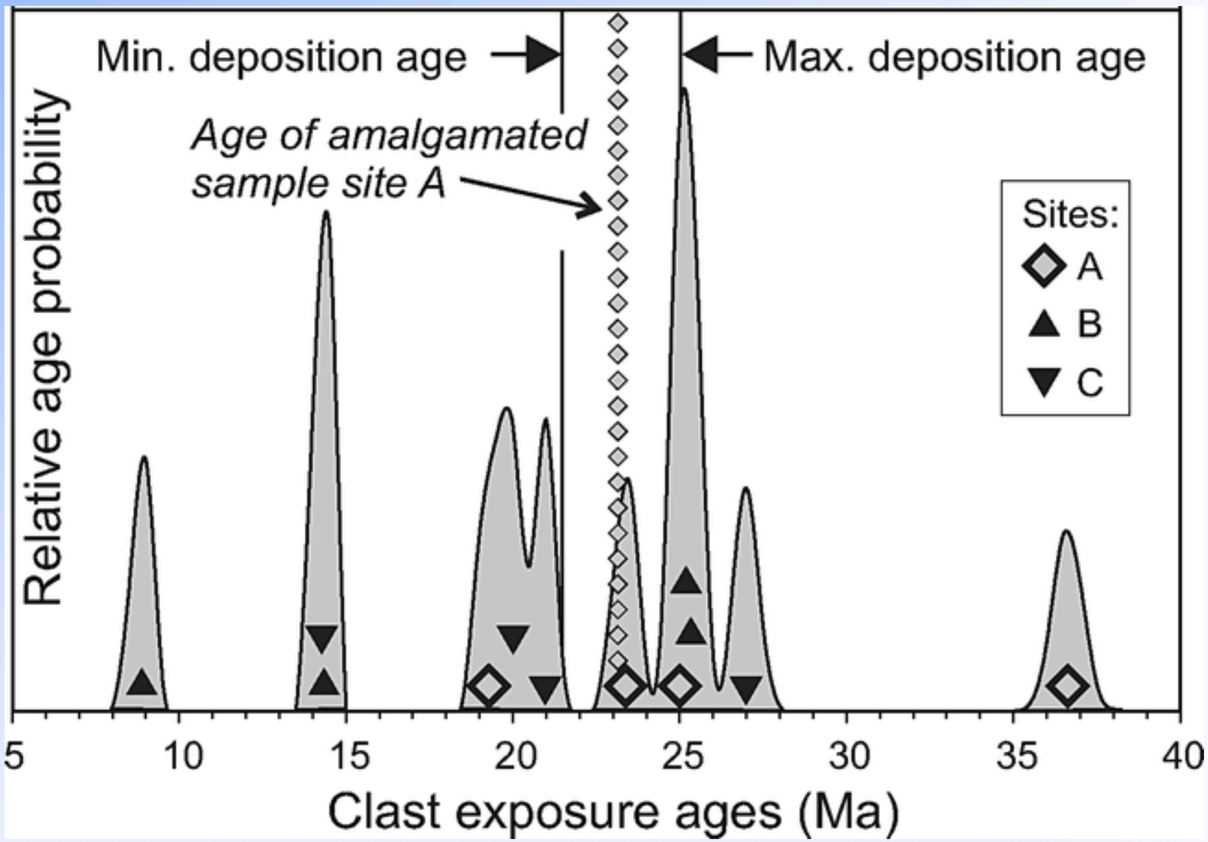
ID	Minimum ^{10}Be Exp Age (Myr)	Maximum Erosion Rate (m/Myr)
17	0.35±0.01	1.68±0.05
18	0.33±0.01	1.80±0.04
19	0.32±0.01	1.93±0.09
20	0.10±0.01	6.03±0.15
21	2.22±0.05	0.17±0.02
22	2.63±0.06	0.10±0.03
23	3.49±0.24	0.06±0.02
24	3.08±0.19	0.12±0.04
72	0.36±0.01	1.67±0.04
73	1.14±0.03	0.36±0.09
74	4.41±0.29	0.03±0.01
251	0.34±0.01	1.67±0.04



(Data and figures taken from Nishiizumi *et al.*, ***237***, **EPSL**, 2005)

Cosmogenic ^{21}Ne from the Atacama Desert



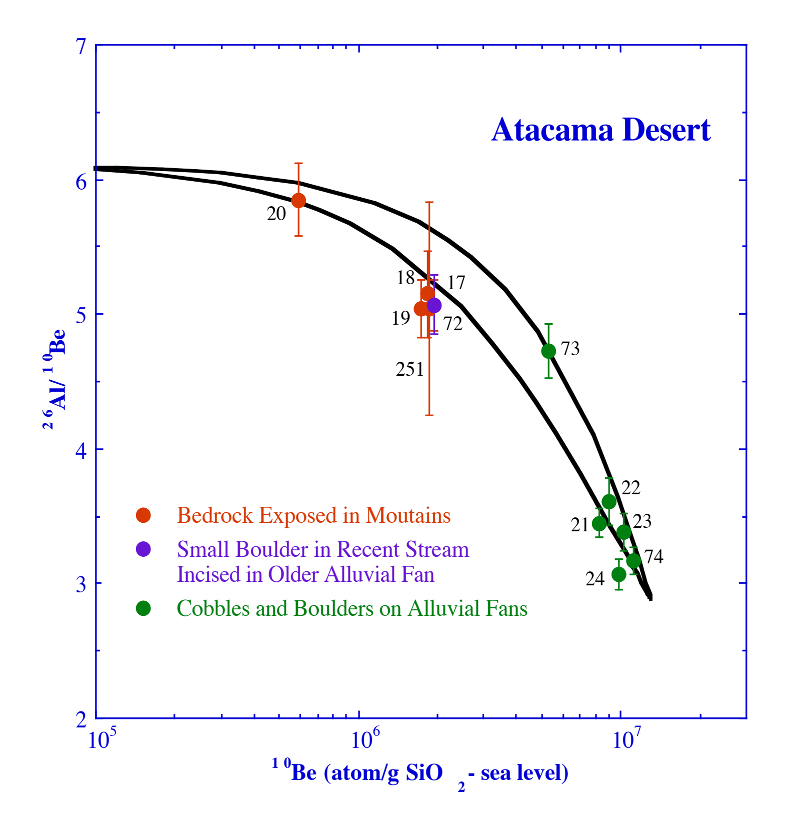


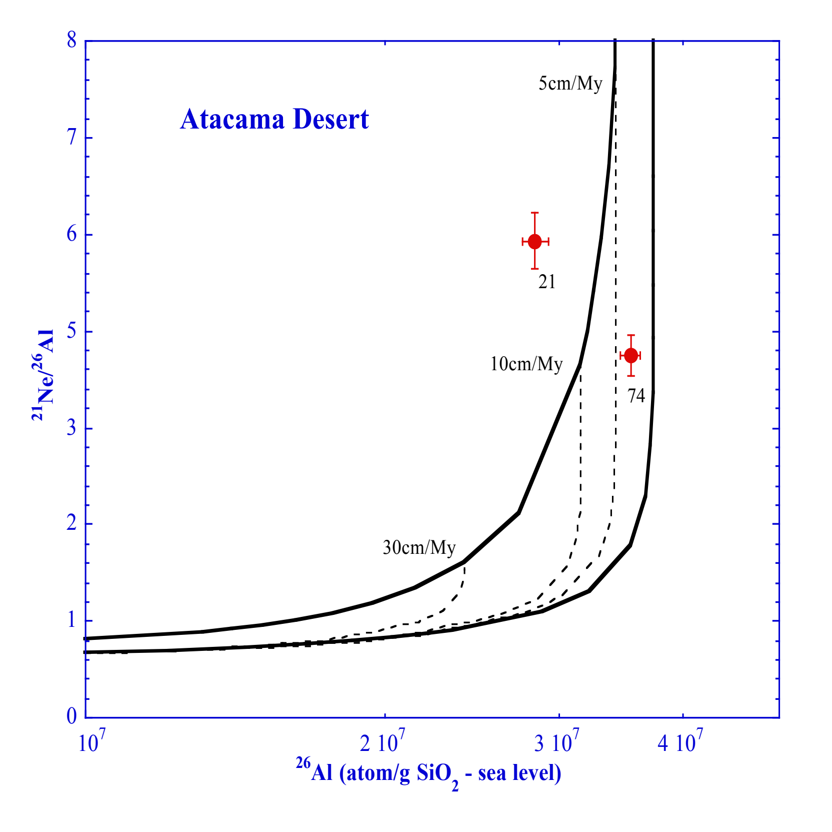
(Data and figures from Dunai *et al*., ***33*** **Geology** 2005)

First order observations

- Cosmogenic nuclide measurements of cobbles from the Atacama Desert demonstrate a Miocene age for these landscapes
- Maximum erosion rates are < 0.1 m/Myr from cobbles taken from alluvial fans
- Bedrock erosion rates are ~ an order of magnitude higher than cobble erosion rates
- Although cobbles have long exposure histories they are not necessarily simple exposure histories

Complex exposure histories

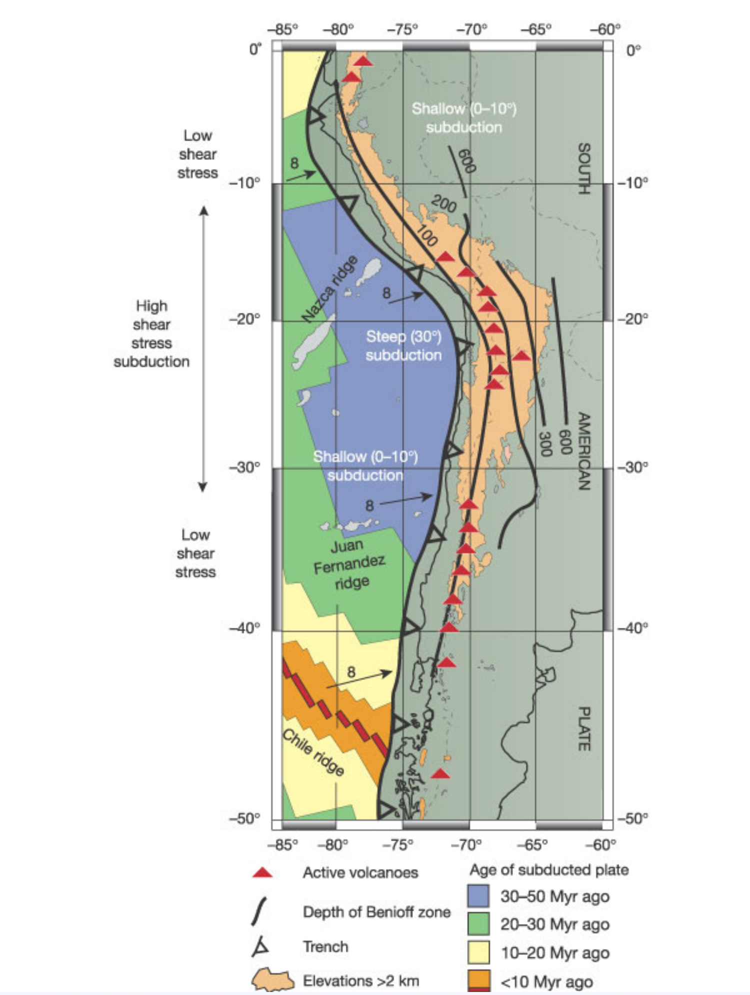




$$N(z,t) = \left[N(z,0)e^{-\lambda t_e} + \frac{P(0)}{\lambda + \mu\varepsilon} e^{-\mu z}\left(1 - e^{-(\lambda+\mu\varepsilon)t_e}\right) \right] e^{-\lambda t_b}$$

(Data and figures taken from Nishiizumi *et al*., ***237***, **EPSL**, 2005)

Climate change and uplift

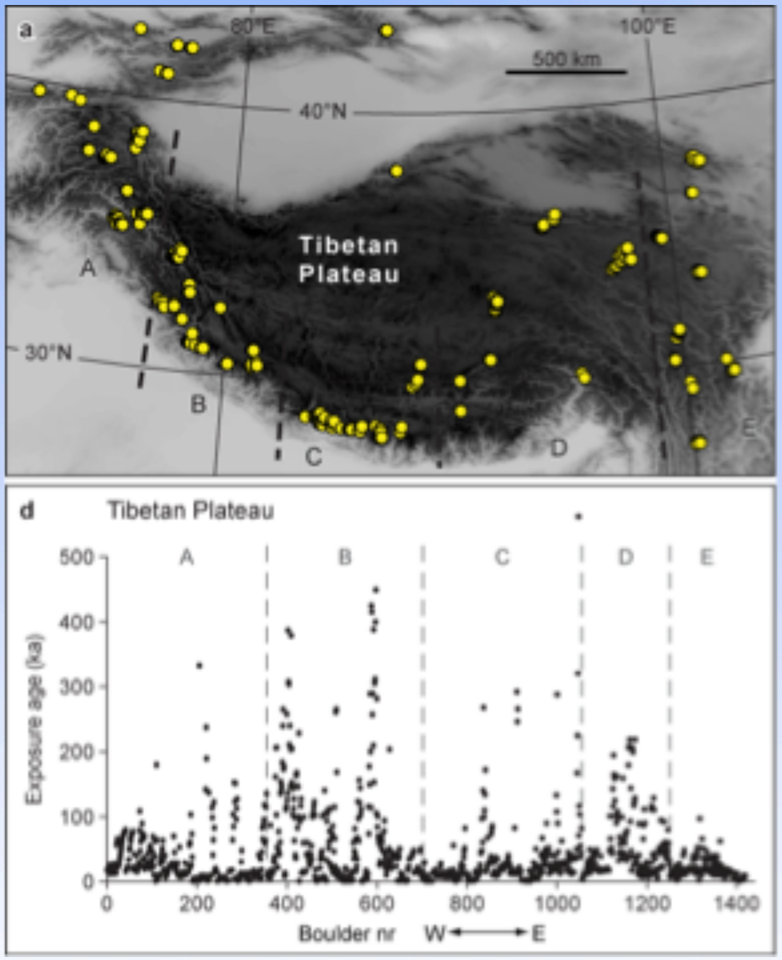


- Lamb and Davis (**Nature**, ***425***, 2003) propose that the dynamics of subduction and mountain building are controlled by the availability of erosion
- Dunai et al (**Geology**, ***33***, 2005) note that low erosion rates in the Atacama Desert have been prevalent for ~ 25 Myr

Cosmogenic nuclides in arid environments

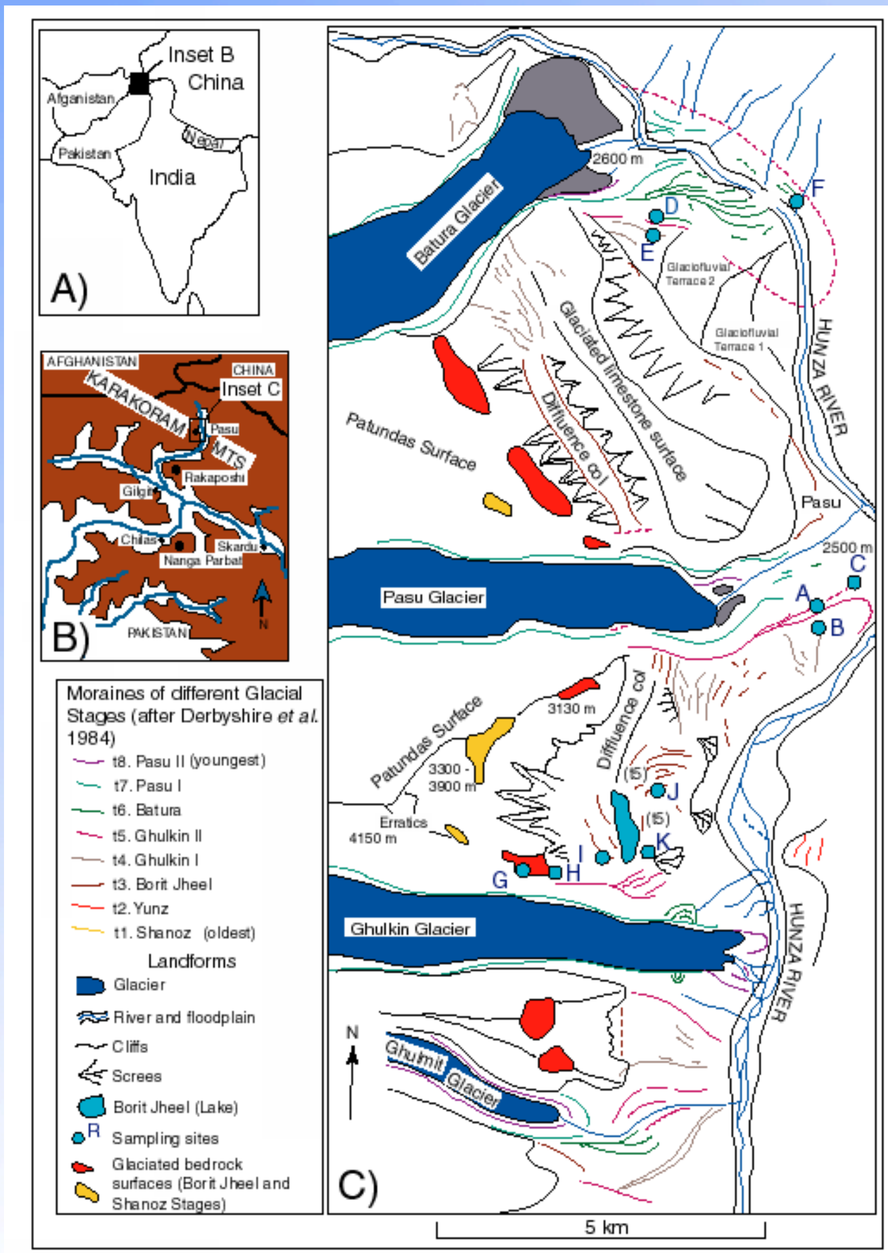
- Cosmogenic nuclides are readily measured from arid and hyper-arid environments
- These environments are ideal testing grounds for cosmogenic nuclides
- These measurements unequivocally demonstrate the antiquity of landforms
- Ages and erosion rates determined using cosmogenic nuclides in turn are being used to reconstruct climate change chronologies and understand relationships between climate change and tectonic activity

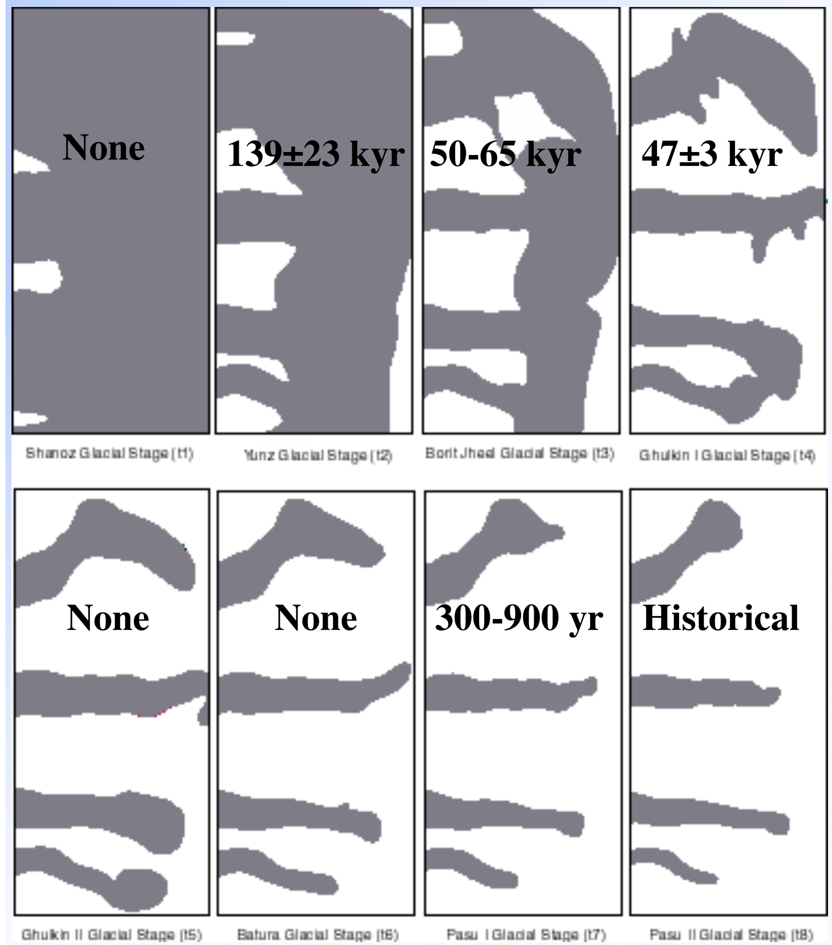
Exposure ages of boulders across the Himalaya and Tibet



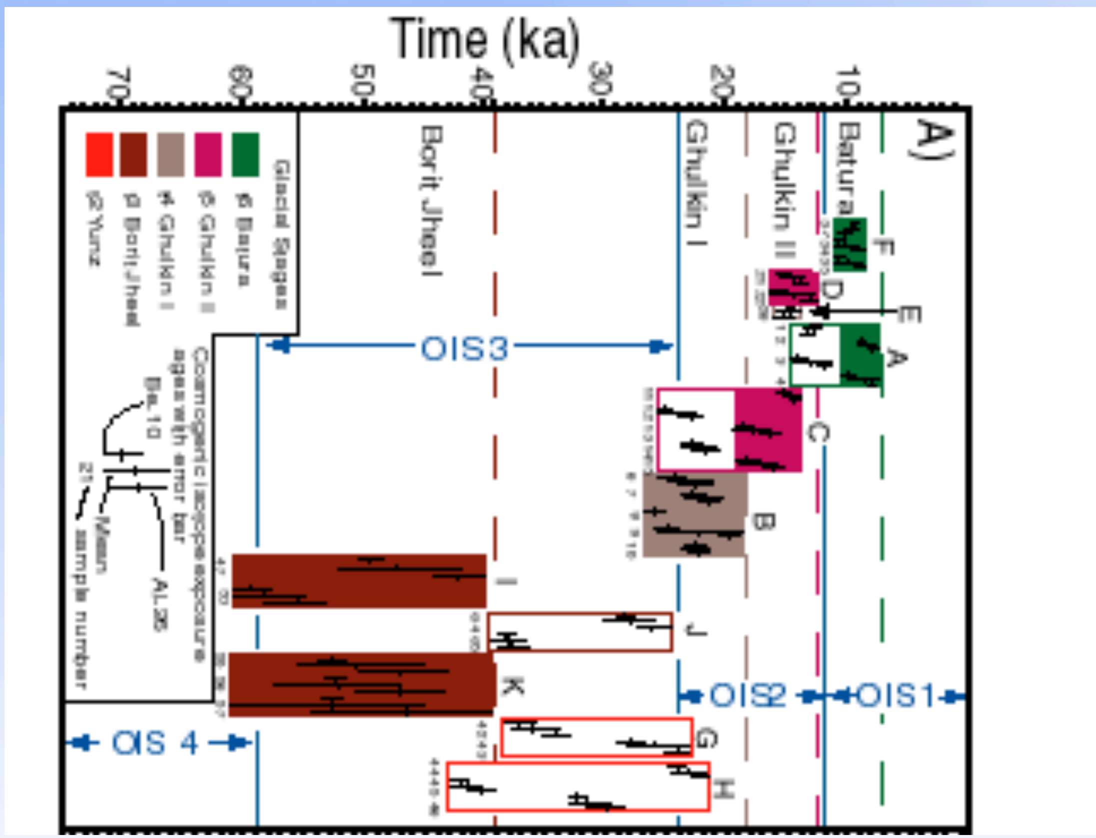
- Cosmogenic nuclide exposure ages do not always yield well-defined ages for individual landforms
- Does the minimum age or maximum boulder age best represent the moraine age?
- What geologic processes account for the spread in ages?

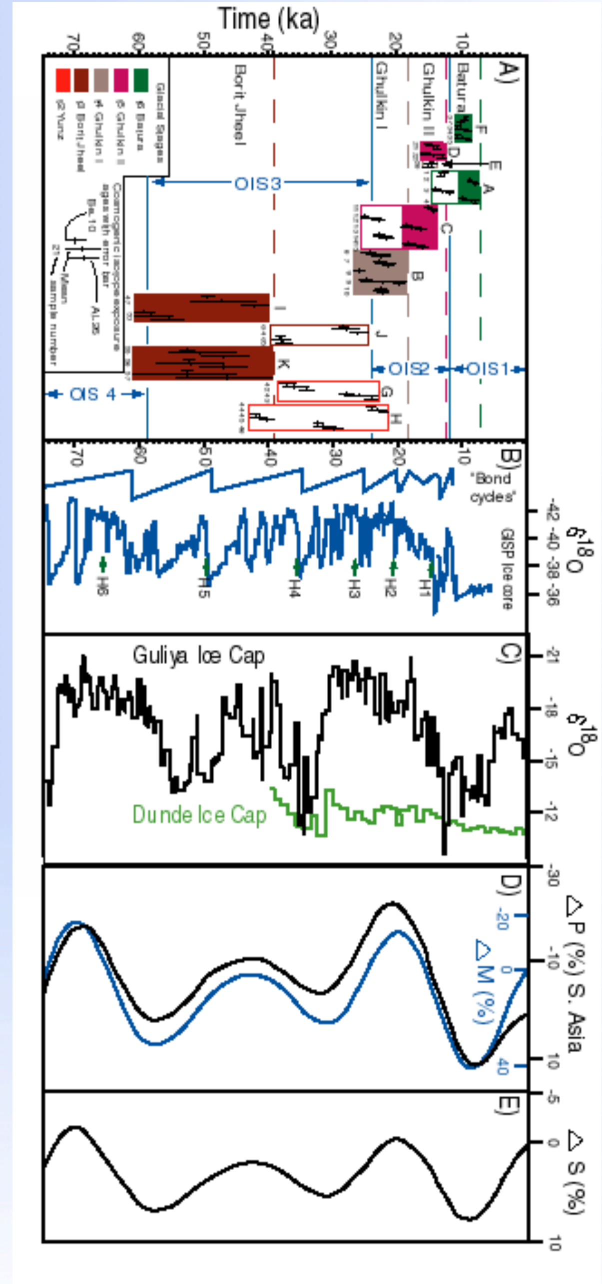
Glacial cycles in Hunza



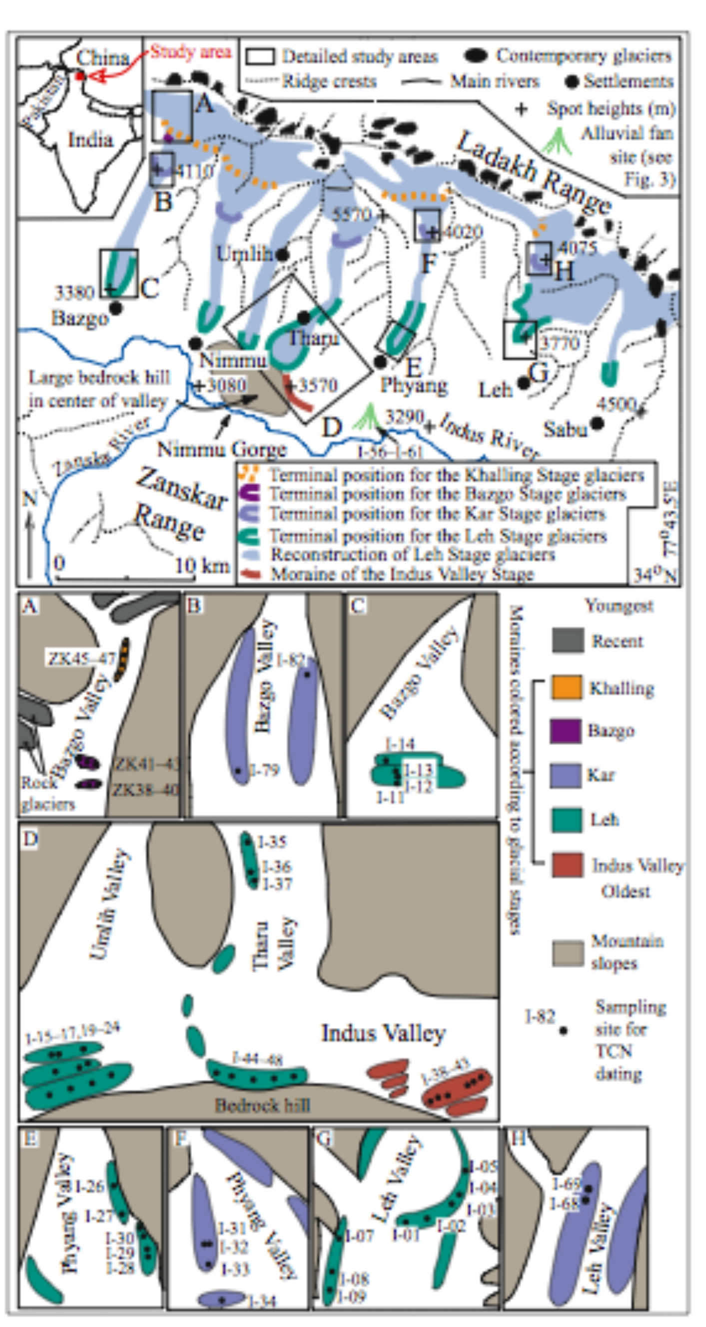


Glacial cycles in Hunza



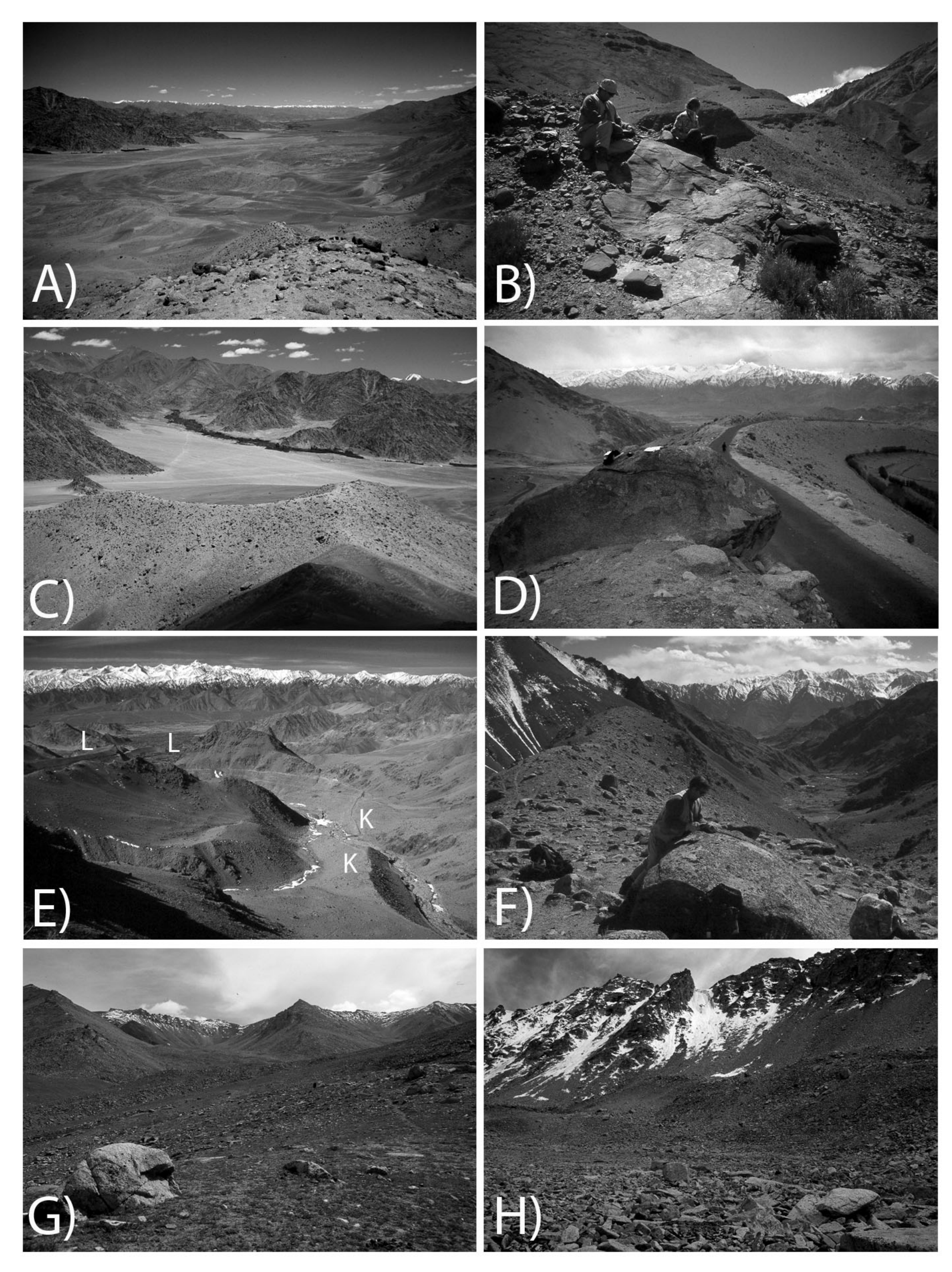


Ladakh glacial chronologies



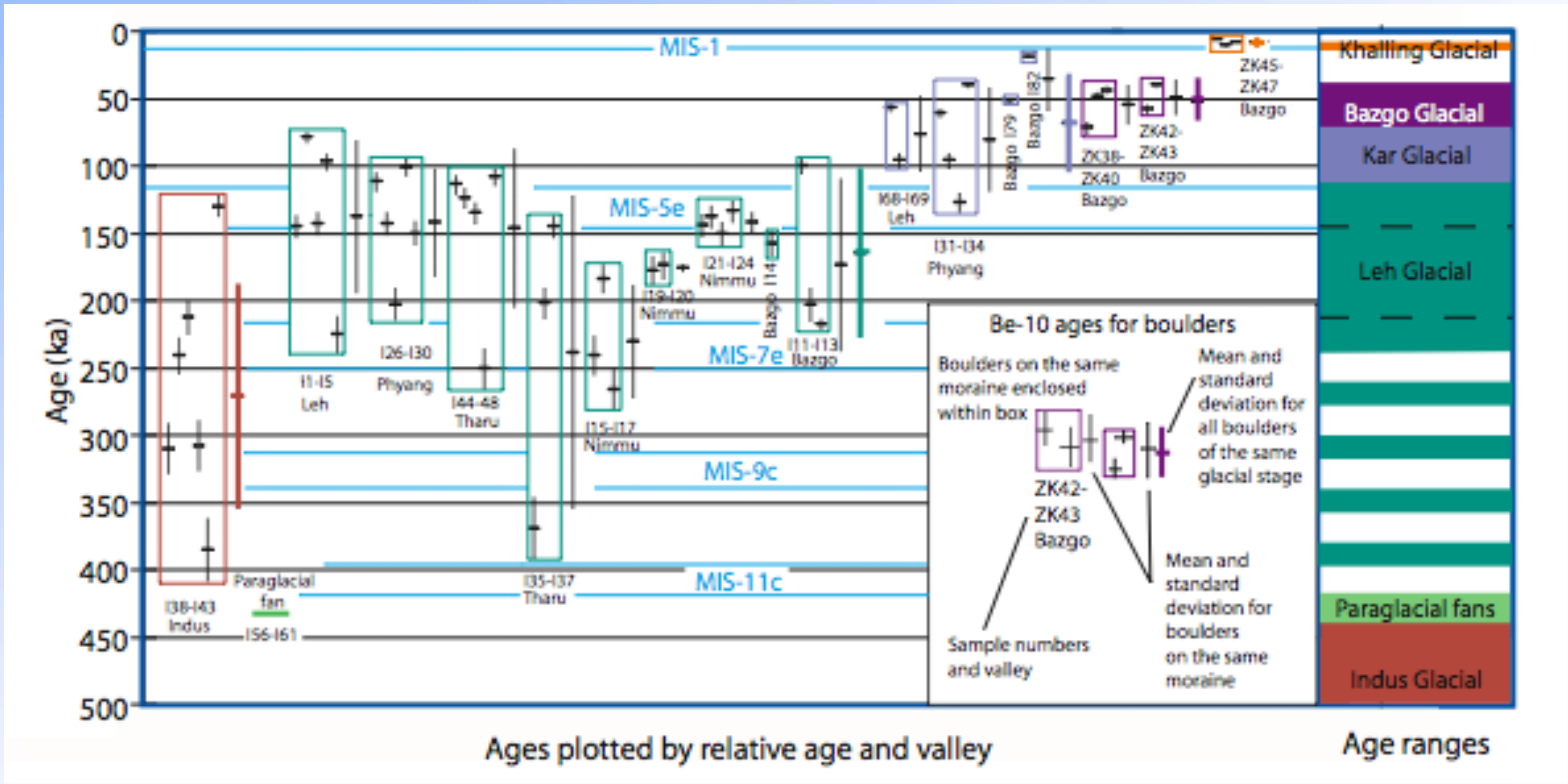
(Owen et al, 2005)

Ladakh glacial moraines



(Owen et al, 2005)

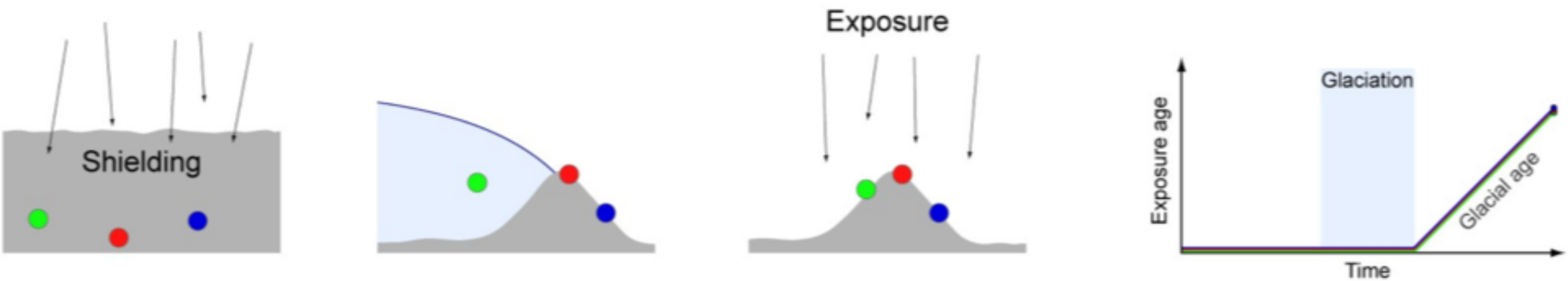
Ladakh glacial chronolgy



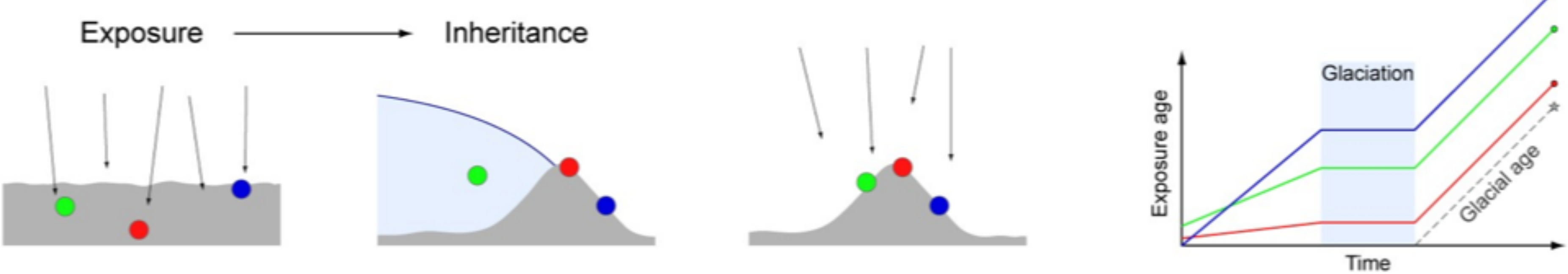
(Owen et al, 2005)

Geological sources of error

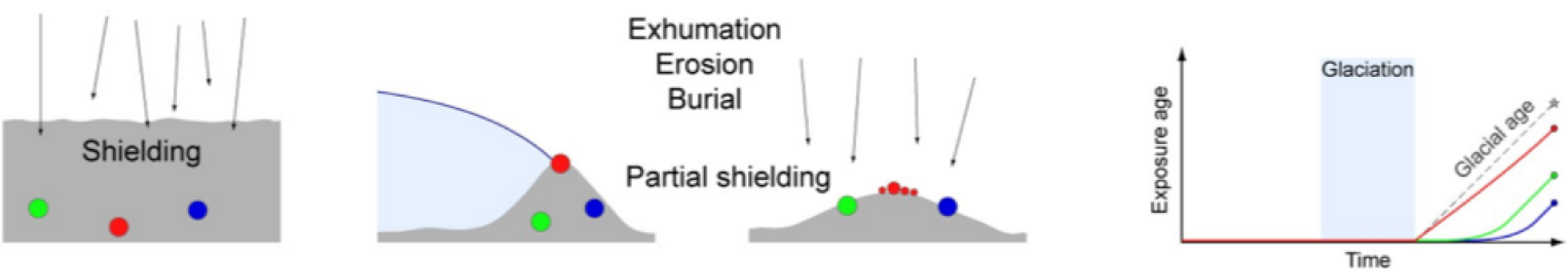
IDEAL CASE



PRE-GLACIAL EXPOSURE

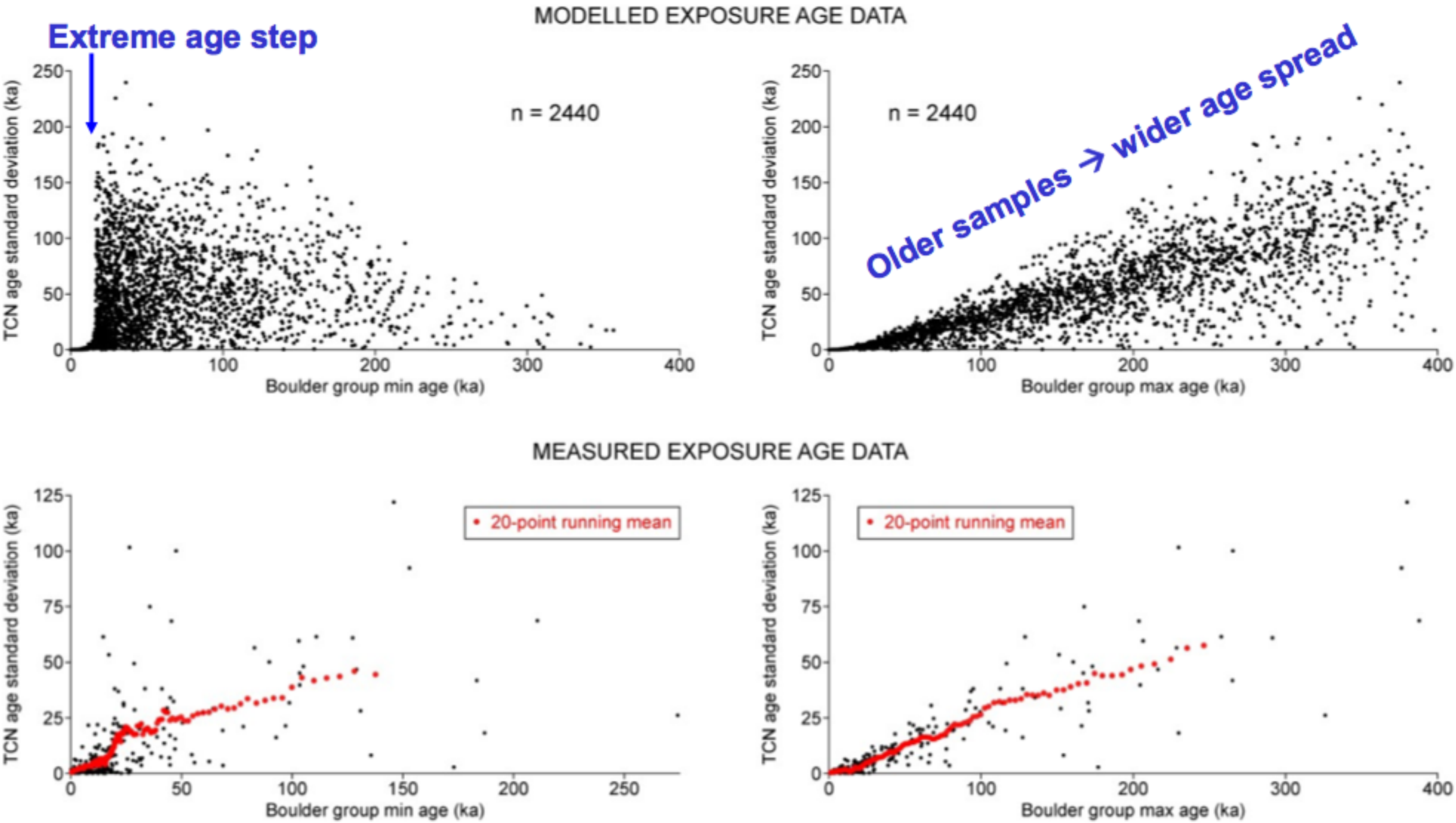


POST-GLACIAL SHIELDING

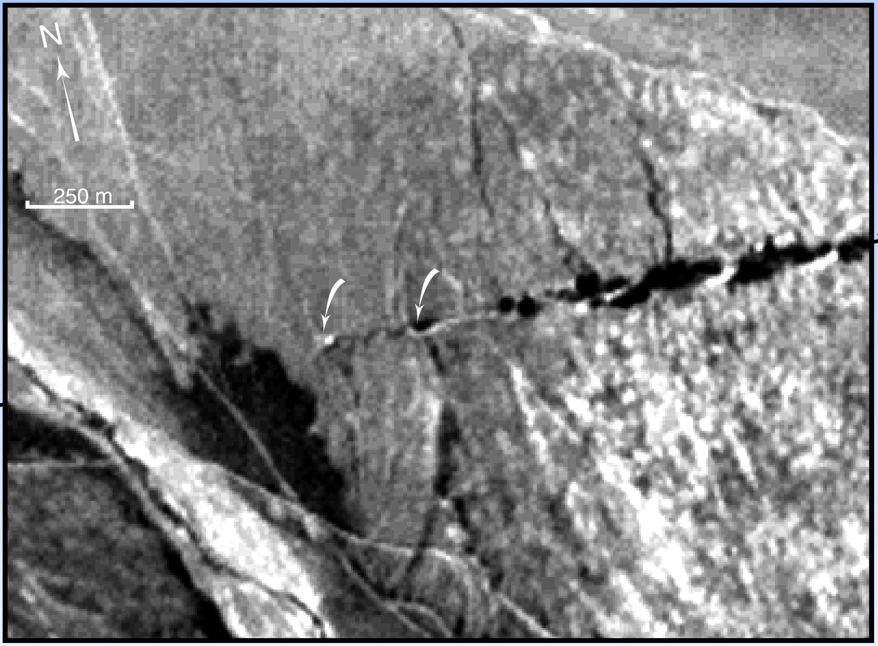


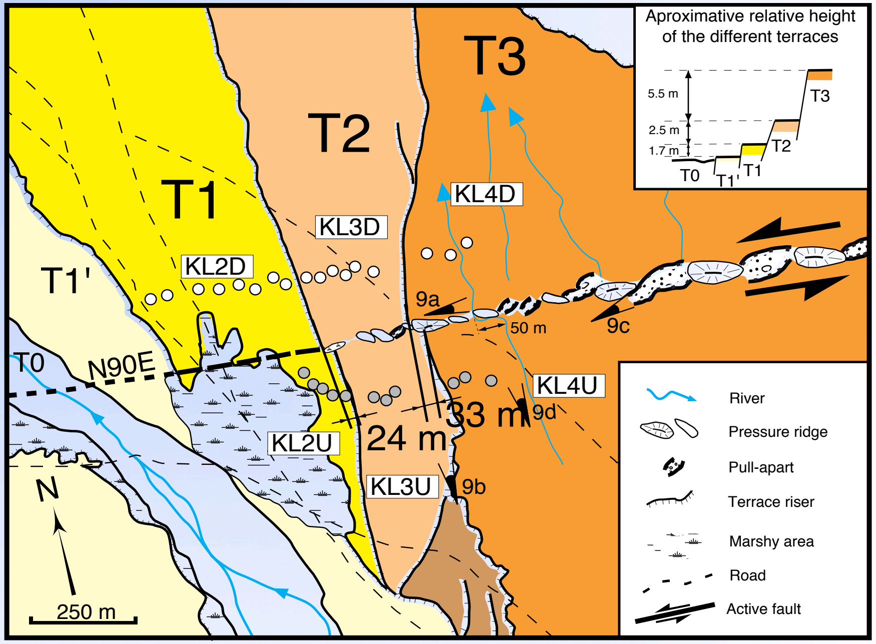
Post-glacial shielding by boulder exhumation

Numerical model assuming constant boulder exhumation (5 cm/ka) through till (2.0 g/cm^3, 165 g*cm^{-2})

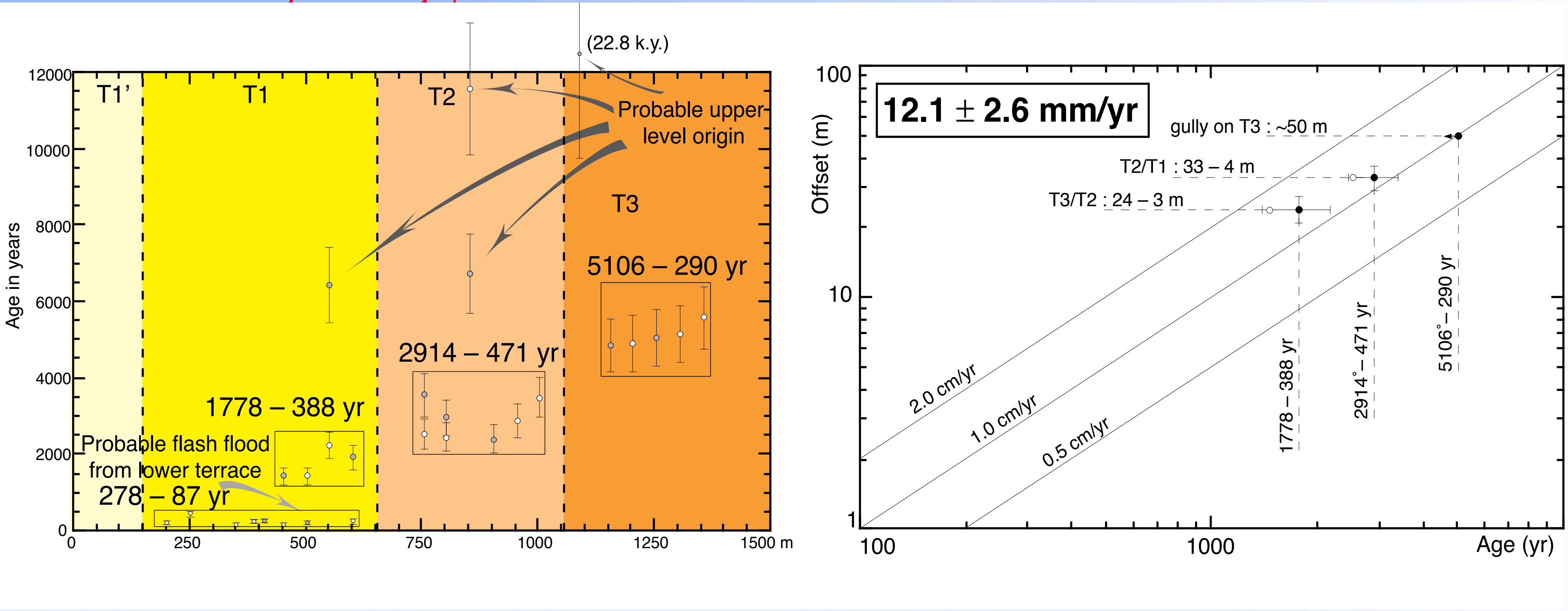


Cosmogenic nuclides can be used to study large-scale tectonics



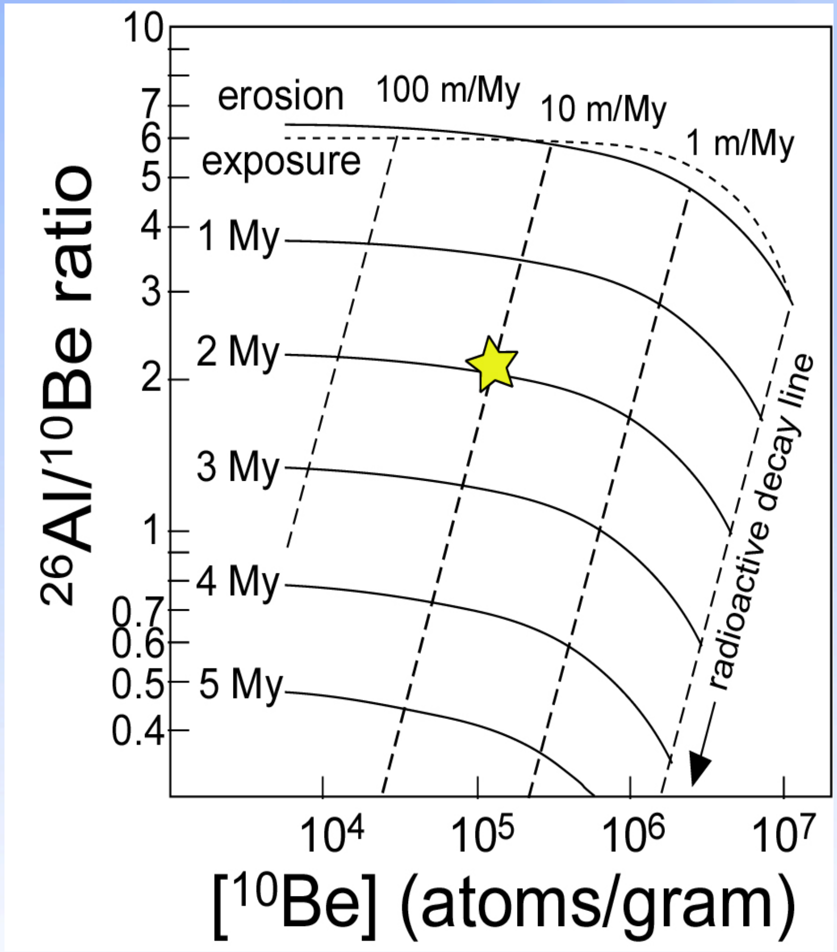


Cosmogenic nuclides can be used to study large-scale tectonics



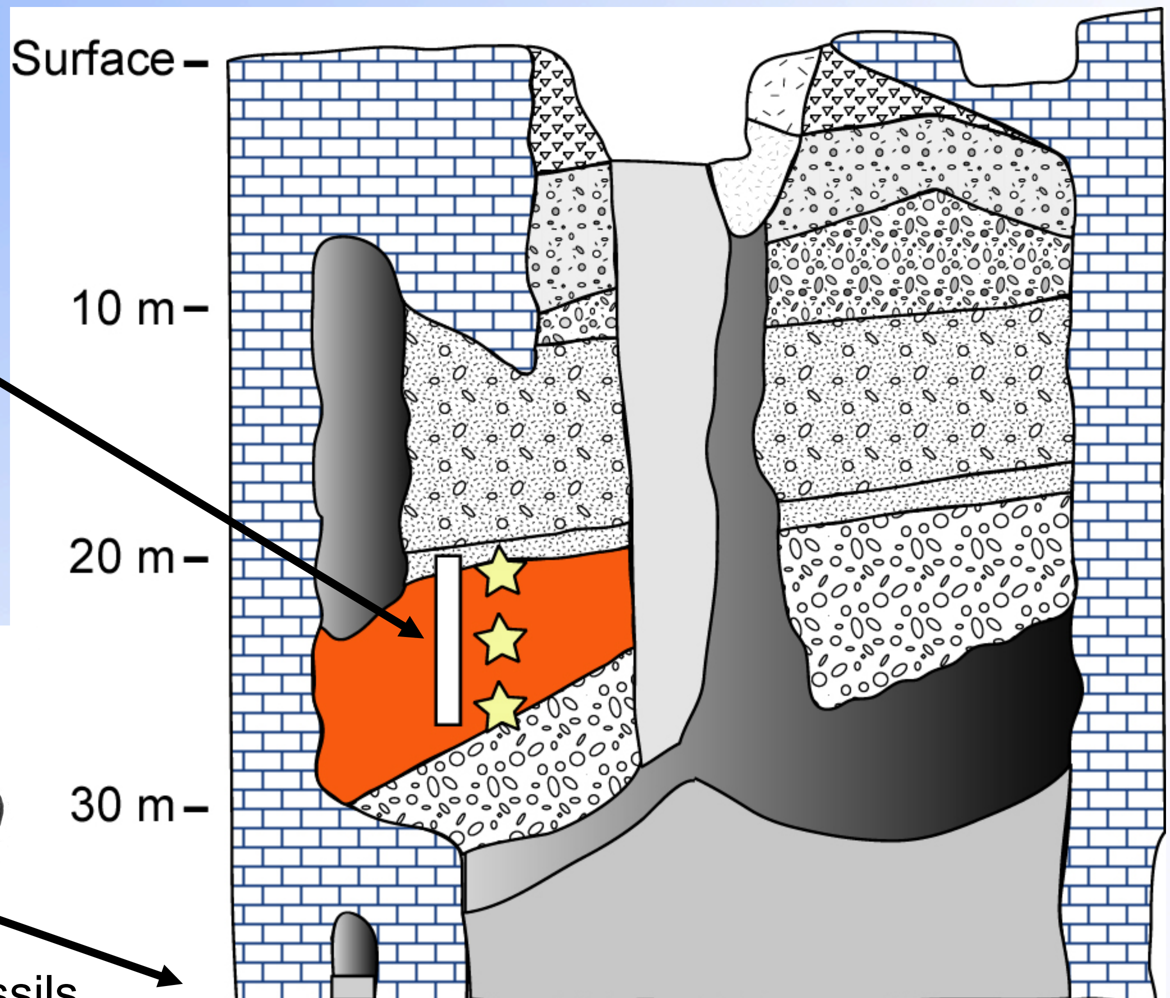
- There is considerable disparity between cosmogenic-nuclide-based slip rates and geodetic-based slip rates - the latter are less

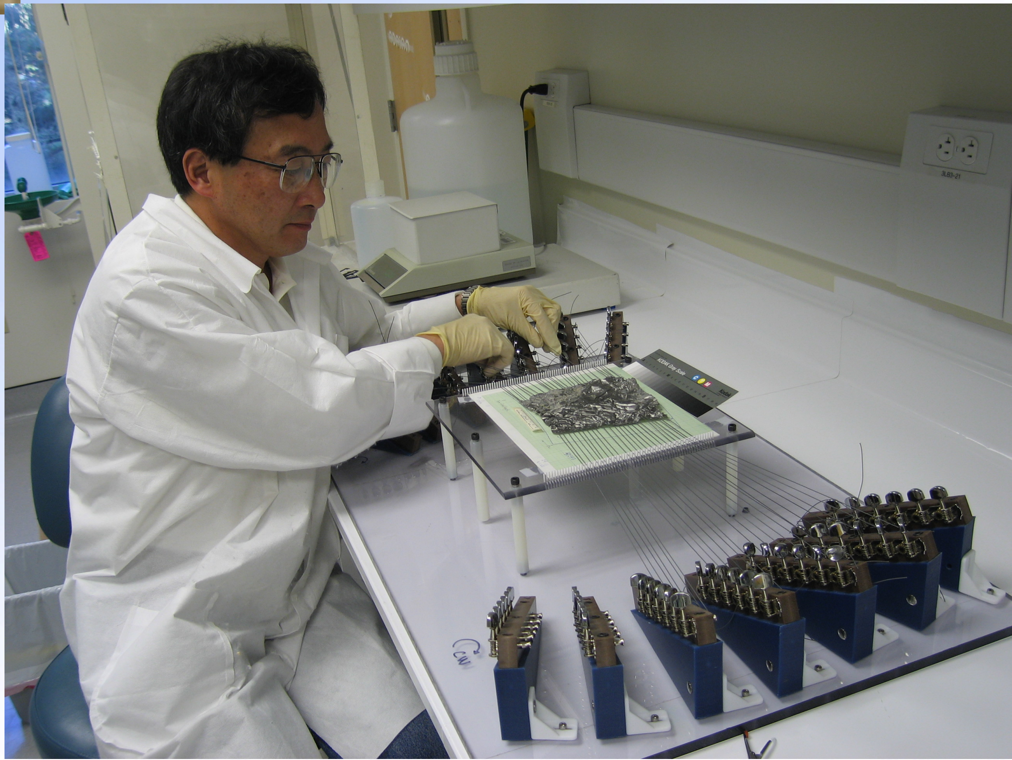
Burial times and pre-burial erosion rates can be inferred



Australopithecus fossils at Sterkfontein, South Africa

Oldest *Australopithecus* fossils





AMS at Purdue