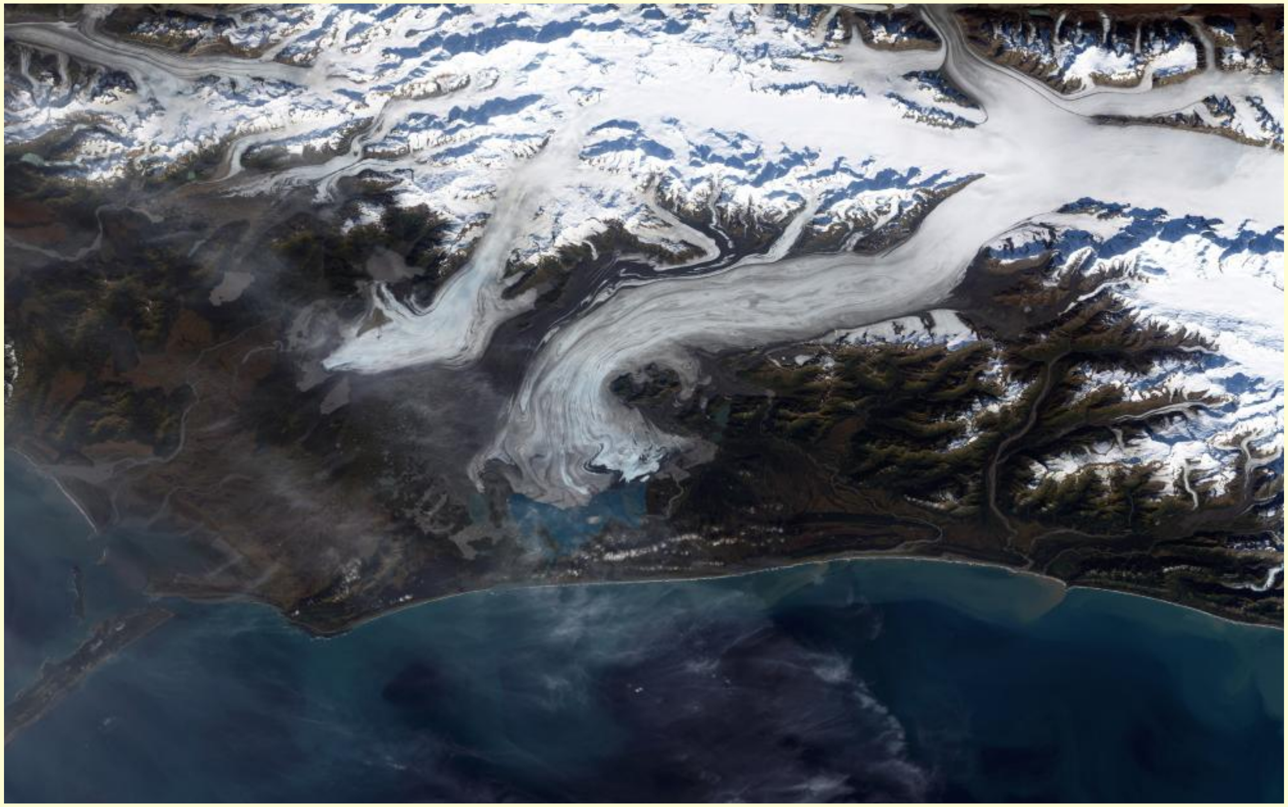
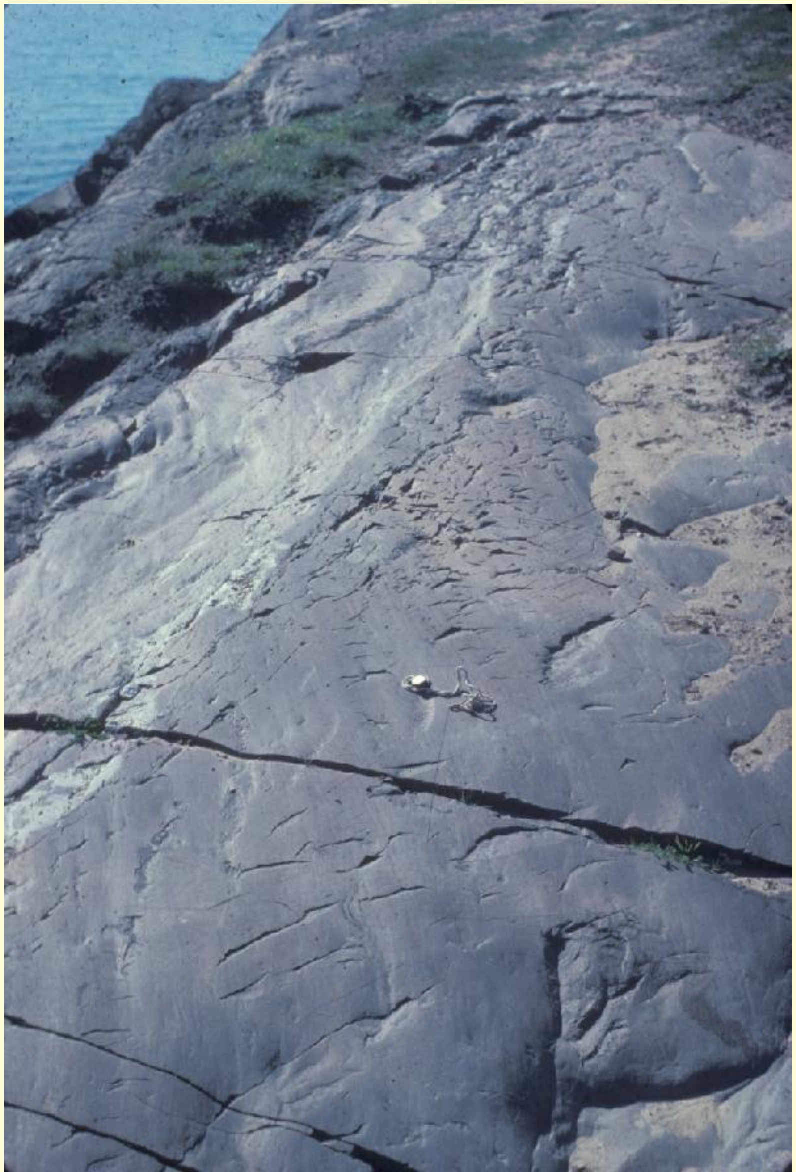


The observation that sediment accumulation rates in the oceans increased several-fold during the last 5 Ma (Hay et al., 1988; Peizhen et al., 2001; Molnar, 2004), in association with multiple glaciations during this time interval has led to the common assumption that mountain denudation increases during glaciations with the corollary that glaciers are more effective than rivers at eroding landscapes (e.g., Yanites and Ehlers, 2012; Herman et al., 2013). Indeed, glacial erosion is proposed to be a first-order control on mountain range exhumation and isostatic adjustments through the removal and evacuation of crustal material from orogens (e.g., Molnar et al., 1990; Montgomery et al., 2001; Burbank, 2002; Blisniuk et al., 2006; Egholm et al., 2009).

Braun and Sambridge (1997) and Syvitski and Milliman (2007) provide means of estimating sediment discharge that helps constrain erosion rates, but glacial erosion is a harder cat to skin.

Fluvial erosion is primarily controlled by geomorphic and tectonic influences (basin area and relief), geography (temperature, runoff), geology (lithology, ice cover), and human activities (reservoir trapping, soil erosion),

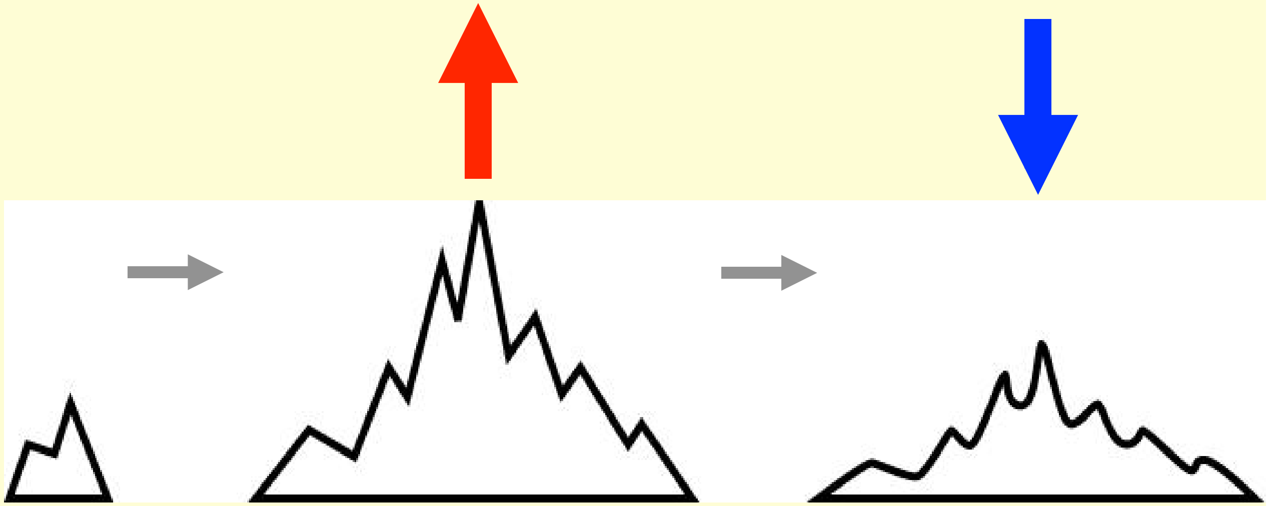
Glacial erosion by abrasion and plucking

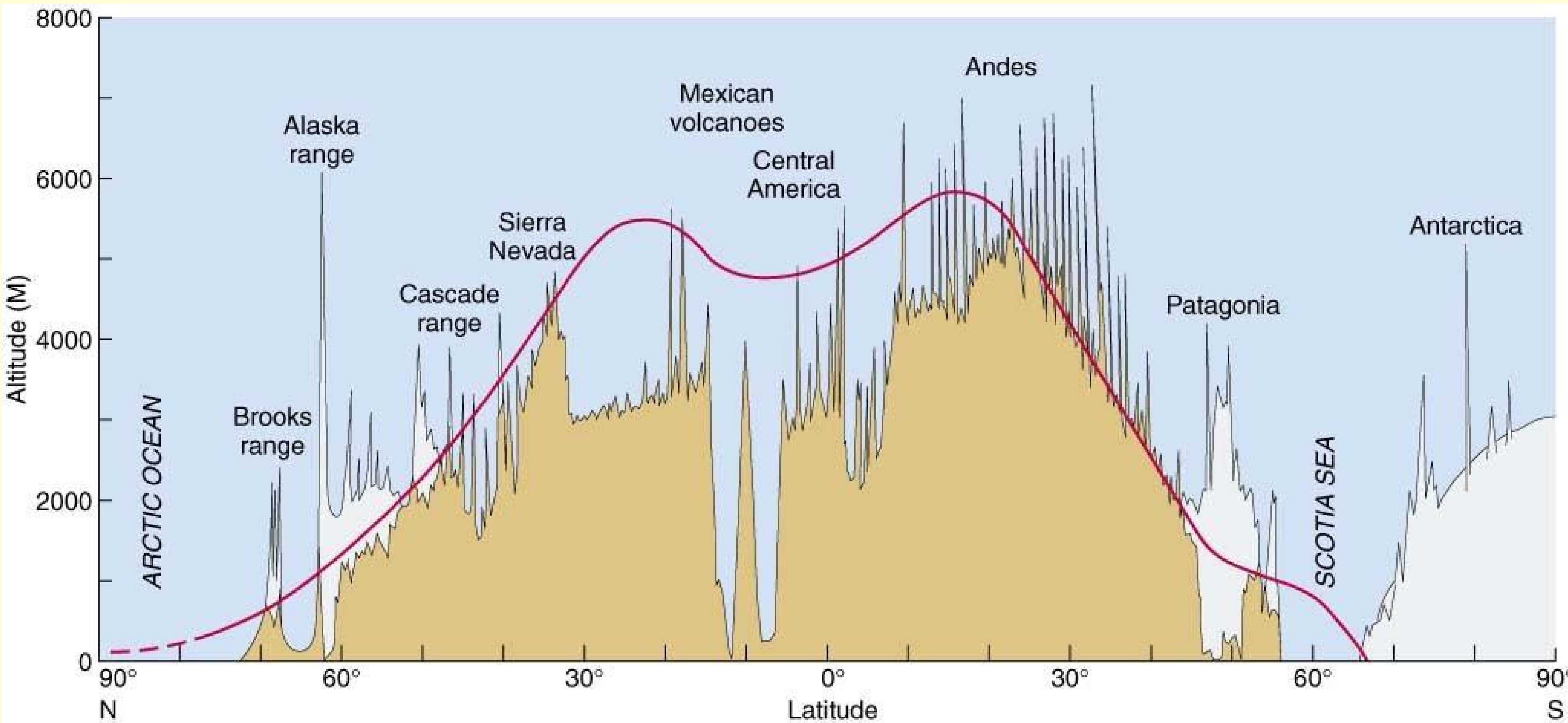


Glacial Buzz saw

Rock uplift produces mountain relief

As relief grows, erosion increases, reducing relief





Equilibrium Line Altitude "ELA"

1,000

• Temperate/tidewaterglaciers
• Alpine/polar glaciers
/::; Volcanic rivers
li Himalayan rivers
O Taiwaneserivers
O World & PNW rivers

o

0.001+----.--------r---U----.------,----~---____.---____I

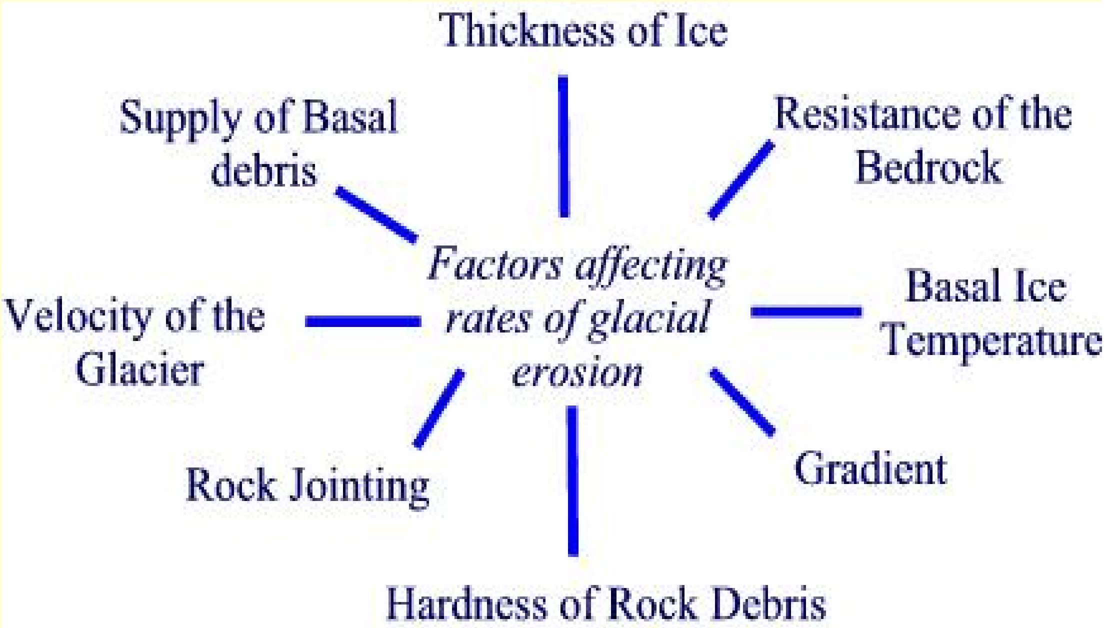
lao 10' 103 10 lOS 10 10'

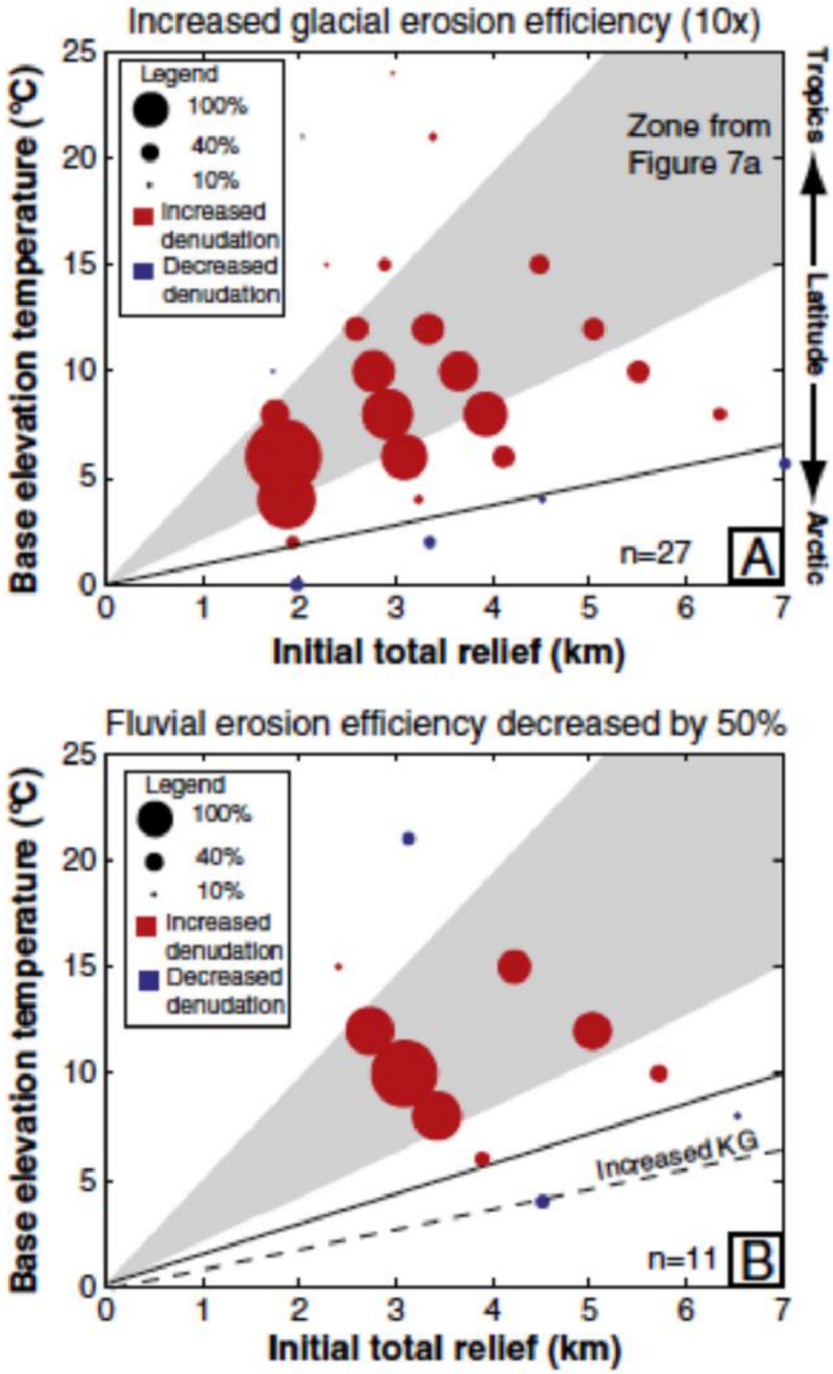
Basin size " "
Clem»

Figure 1(eo.....,arison of glacial, fluvial and composite landscape erosion rates versus contributing basin area, as me.aswed by sediment yiekl data coUeded over 1-20 years. Auvial basins are represented bycircle-s and triangles: world rivers15 and basins in the Paelie Northwest (PNW; refs 4, 29) are open circles; flwial catchments in tectcrically actjlA! orogens are grey circles and triangle.s4·10·16and votcanic rivers are open trian:g1esT7G ladated basins

Koppes and Montgomery, 2009

ShOrt-term cOntrOlS On glacIal erOSIO n

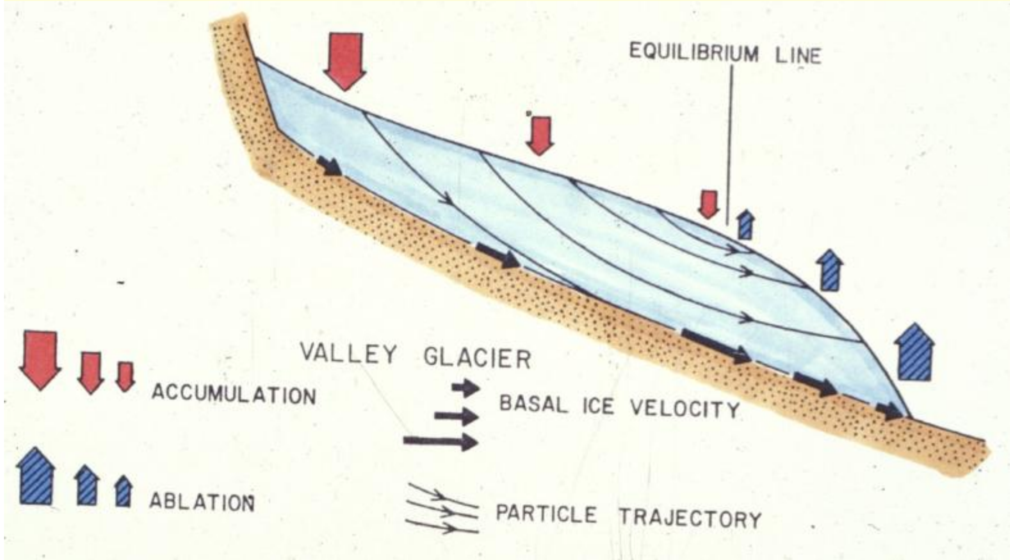




del sensitivity to (A) glacial erosion ciency, Kg by 10-fold and (B) reased fluvial erosion efficiency, Kf by half with respect to temperature

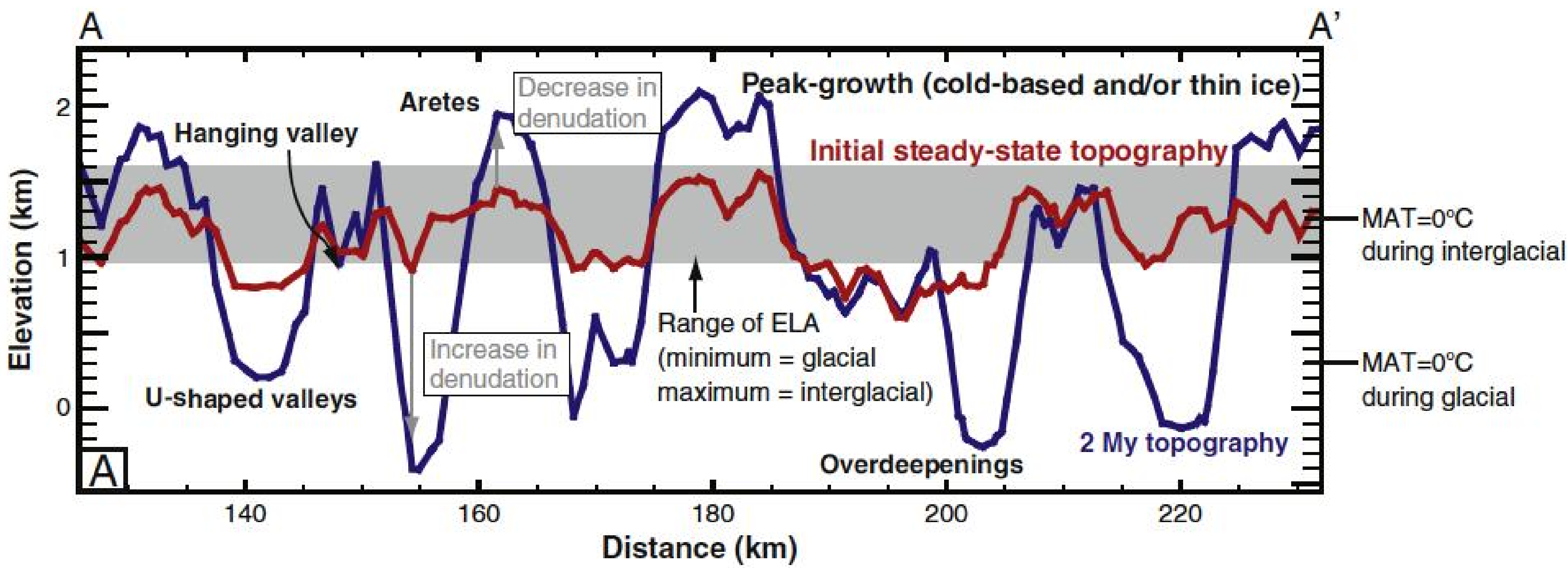
ther words, glaciers are far more sitive to temperature when it comes to sion efficiency

Yanites and Ehlers, 2012

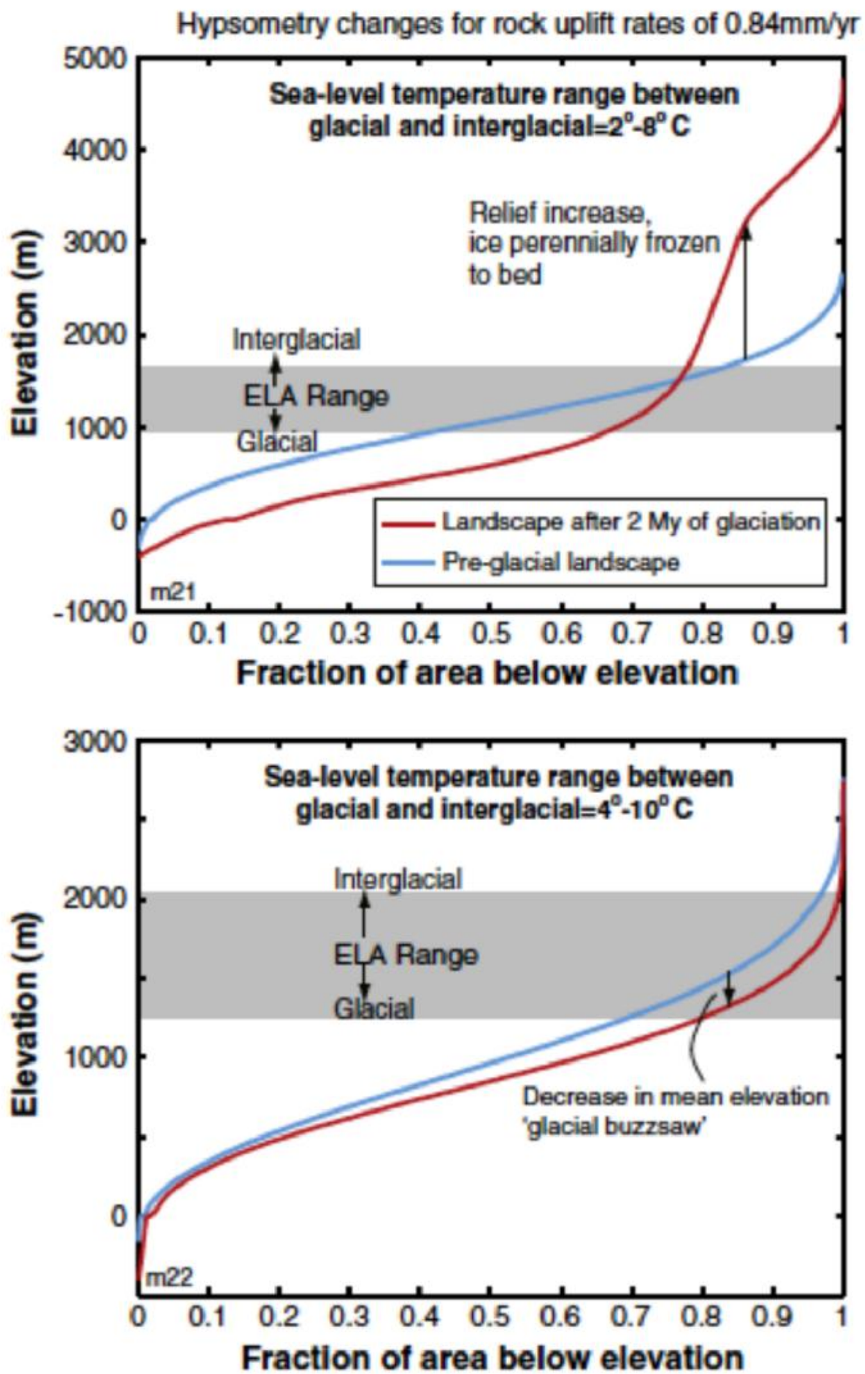


Below ELA there is more water
which leads to greater erosion efficiency
and sediment evacuation

B.J. Yanites, T.A. Ehlers / Earth and Planetary Science Letters 325–326 (2012) 63–75



Spatial variability in mountain denudation. Red line in A-A' topographic cross section is pre-glacial topography and blue line is topography after 2 My of glaciation and the development of glacial features (u-shaped valleys, hanging valleys etc) highlighting variability in denudation following glacial onset and with an uplift rate of 0.42 mm/yr. This figure also highlights role of hypsometry (ELA elevation relative to mountain range). Areas above ELA experience minimal erosion while below the ELA wet-based glaciers erode more efficiently.



ergoing an uplift rate of 0.84 mm/yr.
glacial landscape(in blue) and the
dscape after 2 My of glaciation (in red)
strating how shifts in the ELA influences
ography

Some key observations and oversights of Yanites and Ehlers

- Measuring localized changes in erosion rate (e.g. using thermrochronlogical methods) does not capture the true spatial complexity of mountain denudation
- Glacial erosion rates are highly variable over a range of time scales so that measurements made at relatively short time scales do not capture the full range of denudation rates.
- Glacial erosion is highly sensitive to uplift rates. Faster rates of uplift limit glacial erosion by elevating mountains above ELA
- Glacial denudation increases as the pace of glacial/interglacial cycles increases (e.g. 100 ka to 40 ka)
- Glacial erosion rates are highly non-linear and tend to decrease with time.

Some Oversights

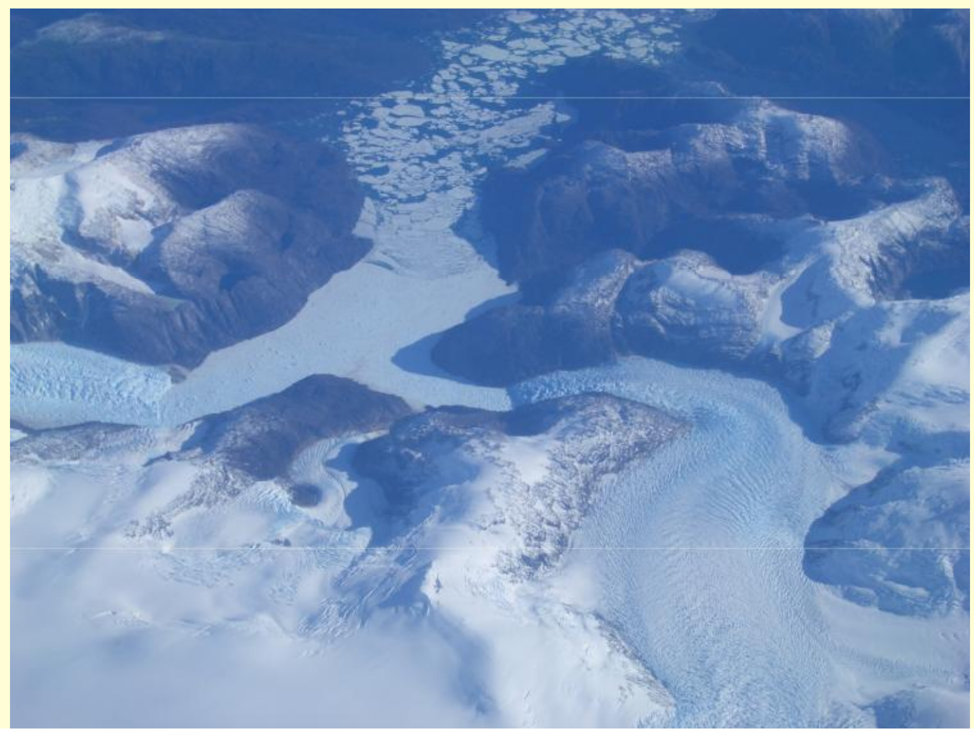
- They do not consider temporal or spatial changes in bedrock geology
- They underscore the importance of the relative timing of orogenic uplift versus glacial history
- Over geological time scales sedimentary rocks are eroded, leaving more resistant rocks to be eroded by the ice

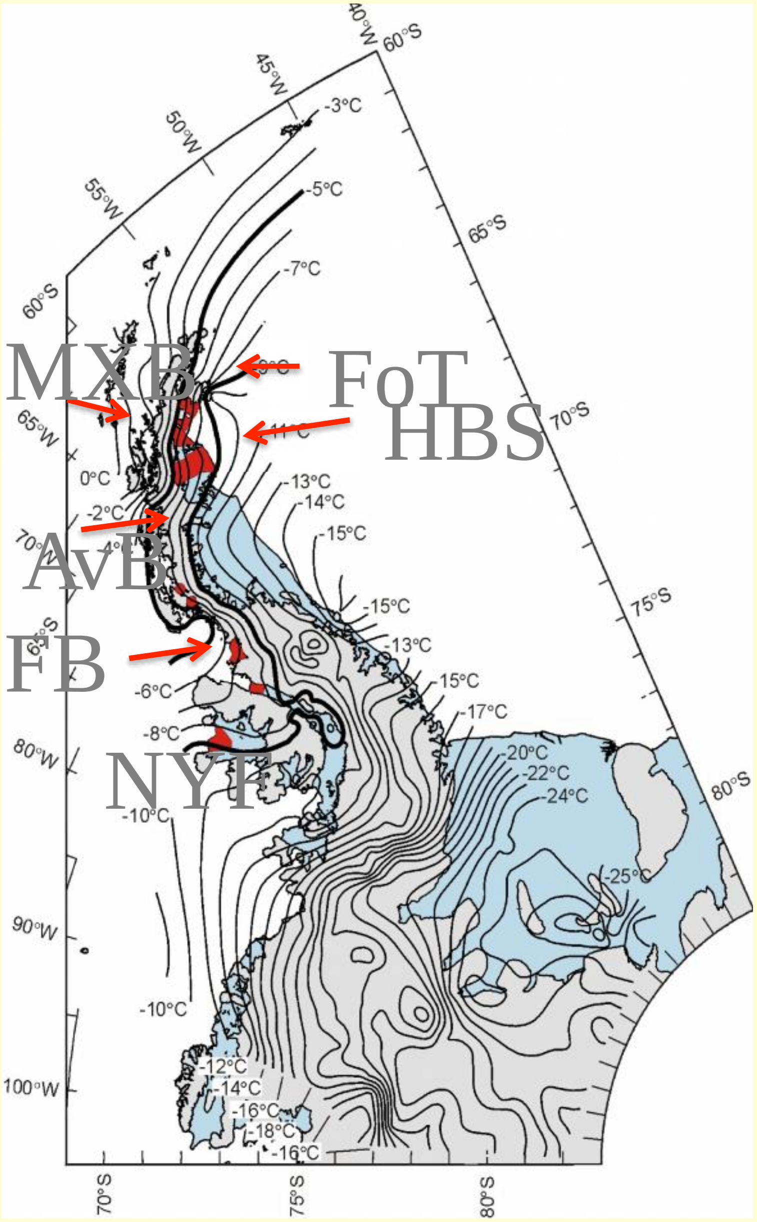
Latitudinal variation in glacial erosion rates from Patagonia and the Antarctic Peninsula (46°-65° S)

Rodrigo A. Fernandez[1], John B. Anderson[2], Julia S. Wellner[3], Rebecca L. Minzoni[2], and Bernard Hallet[4]

Span of mean annual temperatures of =+10.0 to -15.0°C

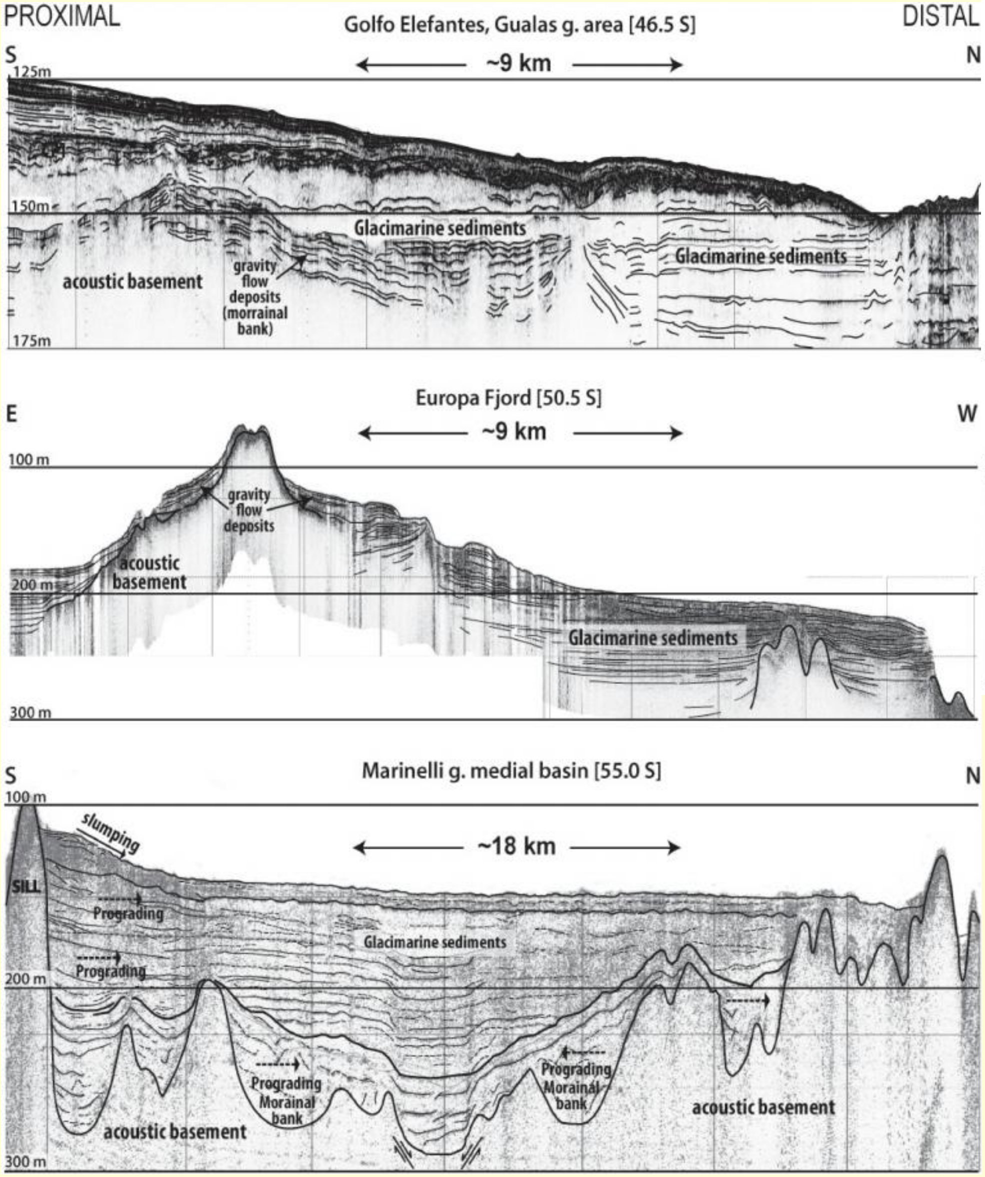
Duration of glaciation- Eocene for AP versus Pleistocene for Patagonia

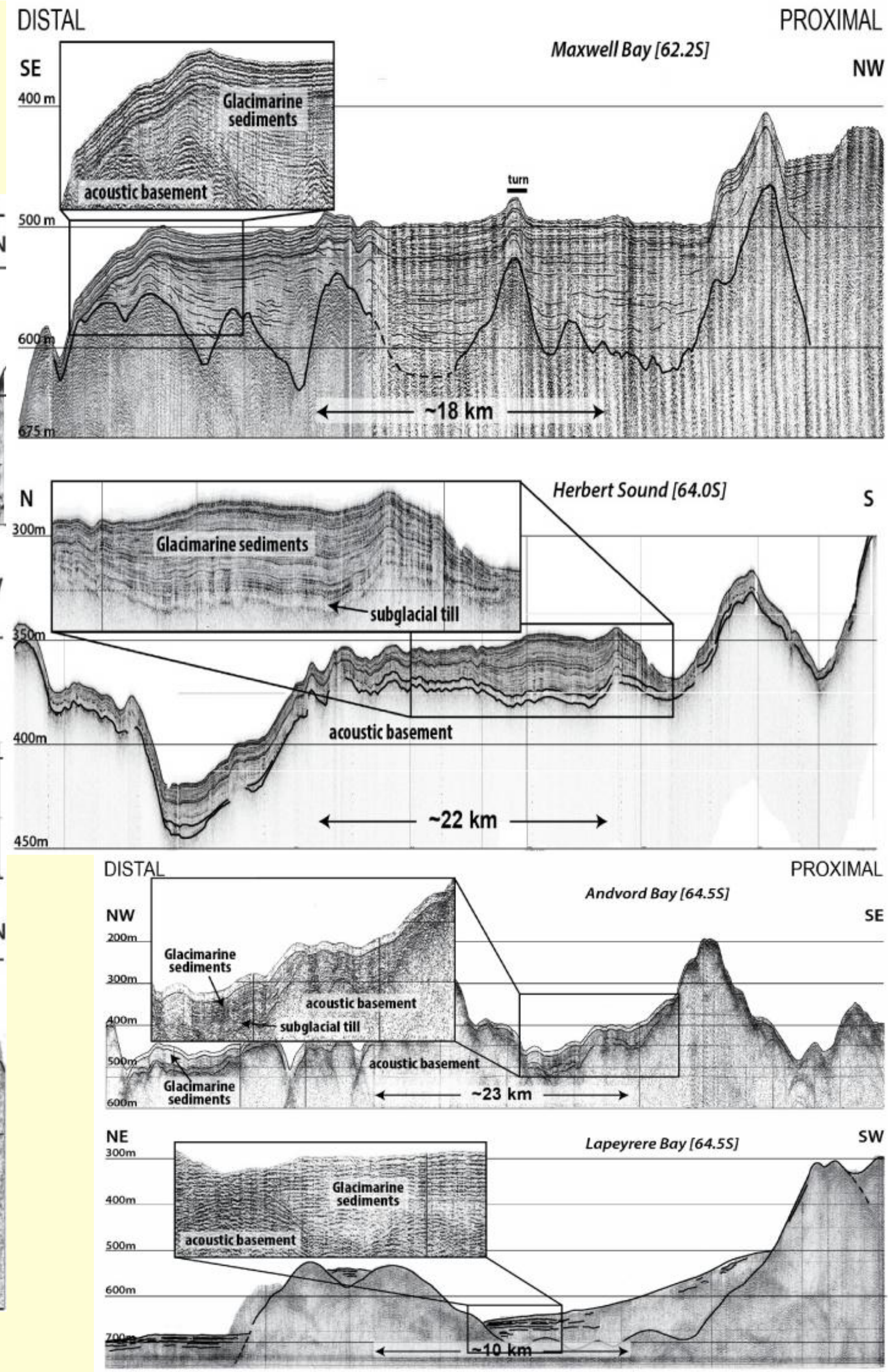




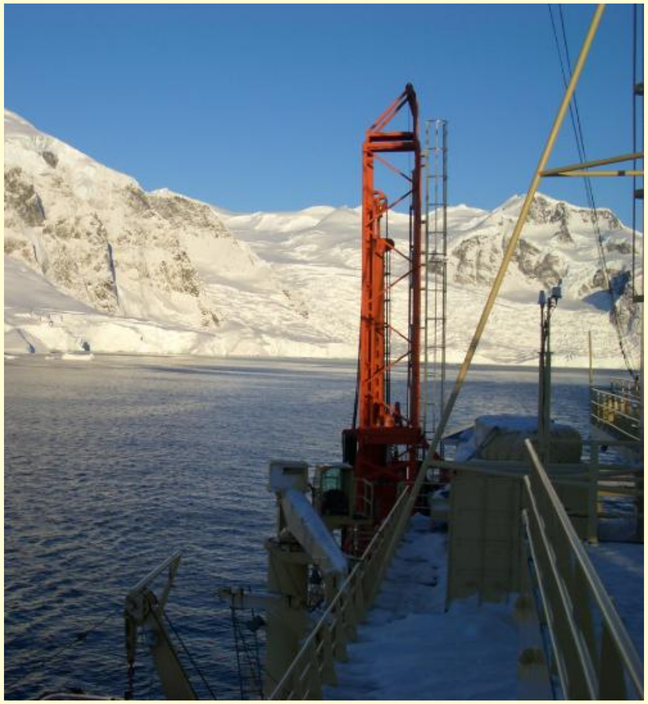
Fjord/Bay	Geology	Mean T°
T° mean		
MXB=Maxwell Bay	Volcanic	0°
HBS=Herbert Sound	Volcanic	_5°
FoT=Firth of Tay	Sed/Met	_5°
AvB=Anvord Bay	Met/Ig	_3°
NYF=Neny Fjord	Met/Ig	_5°
FB=Ferro Bay	Met/Ig	_16°

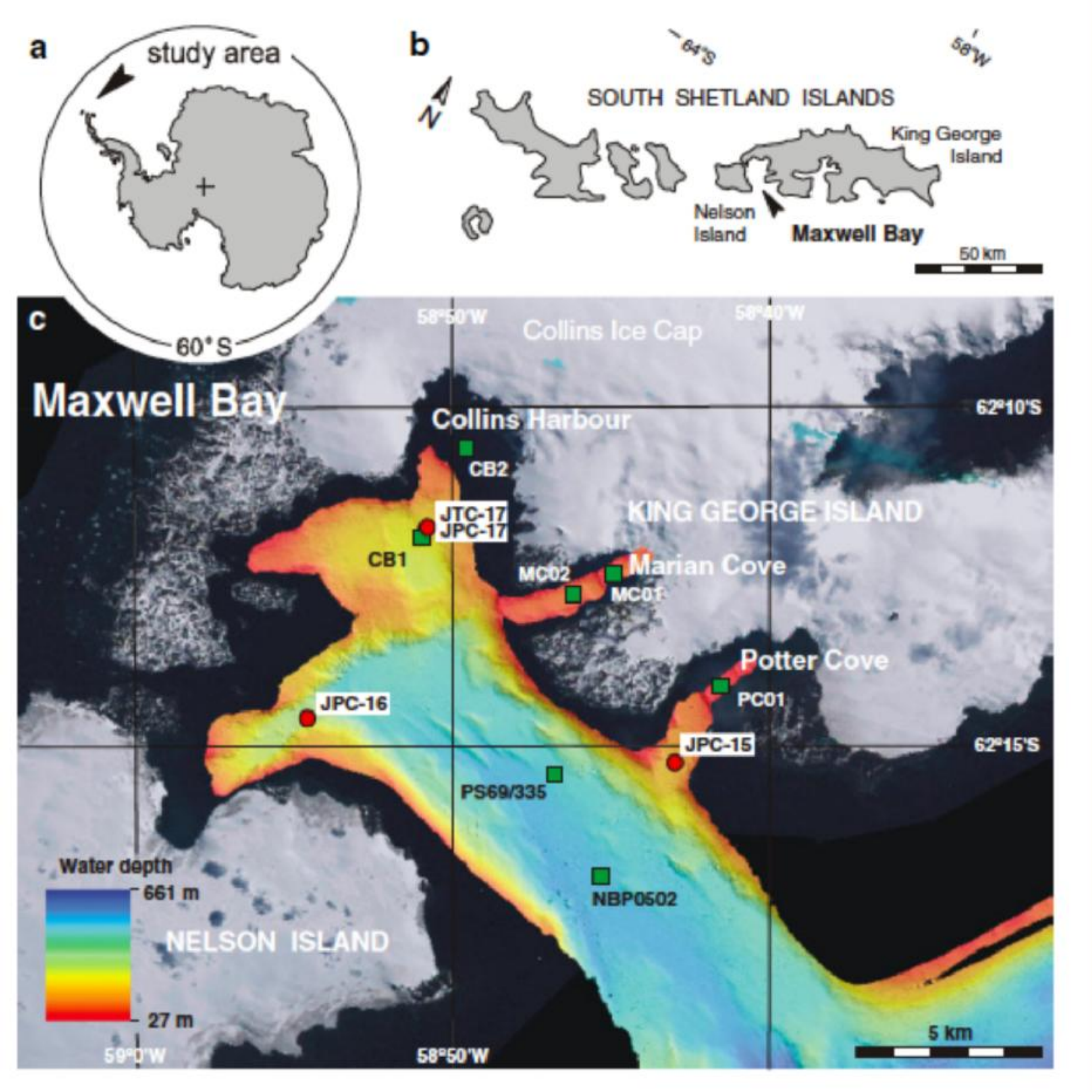
Variable Sediment Thickness and Distribution



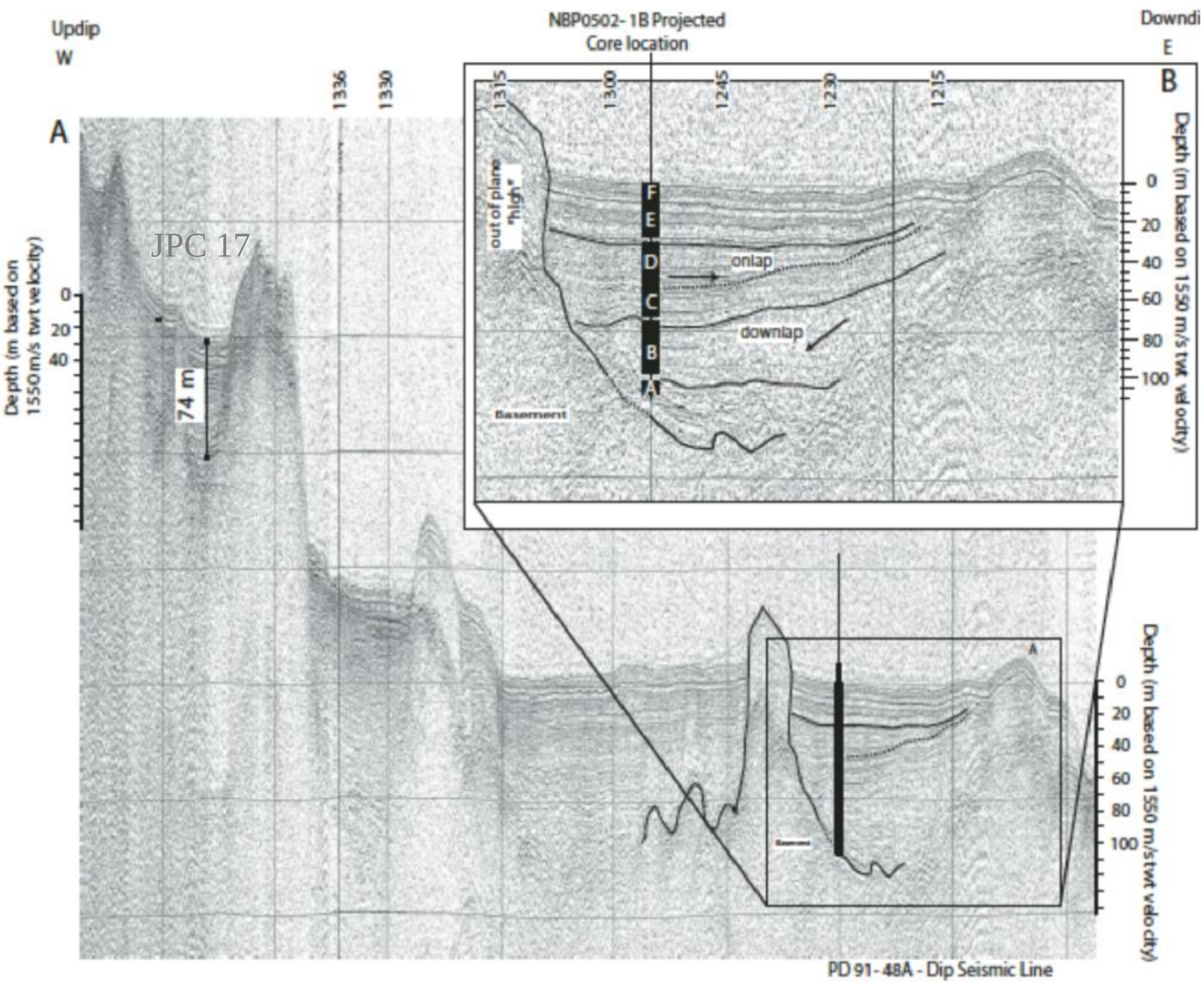


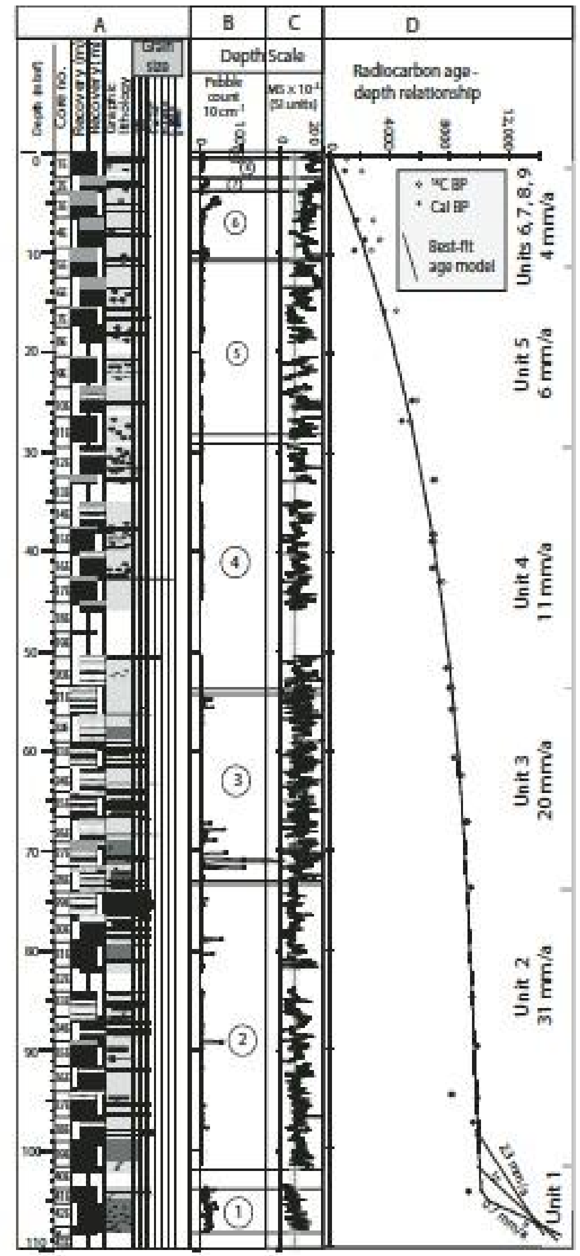
Methodology

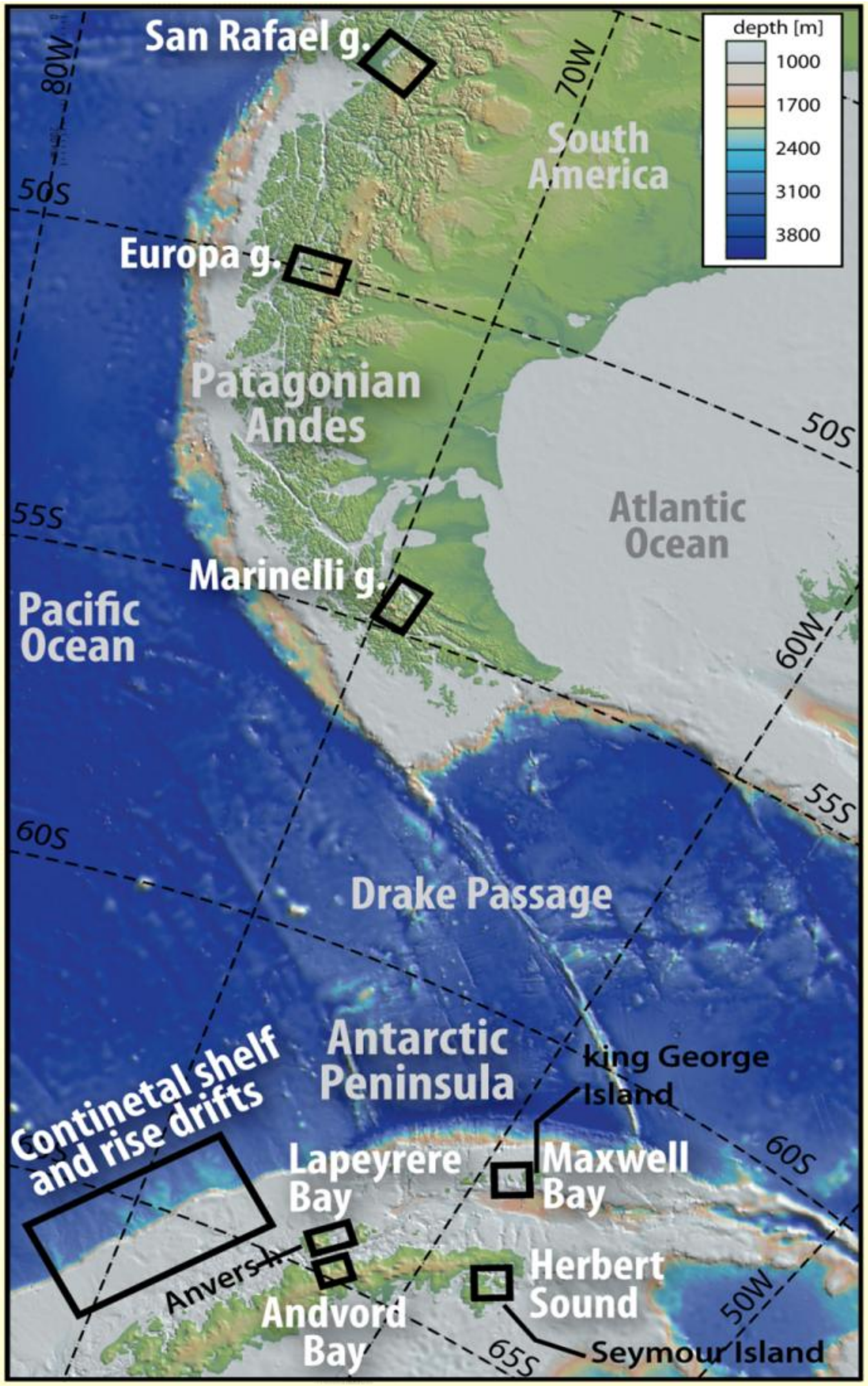


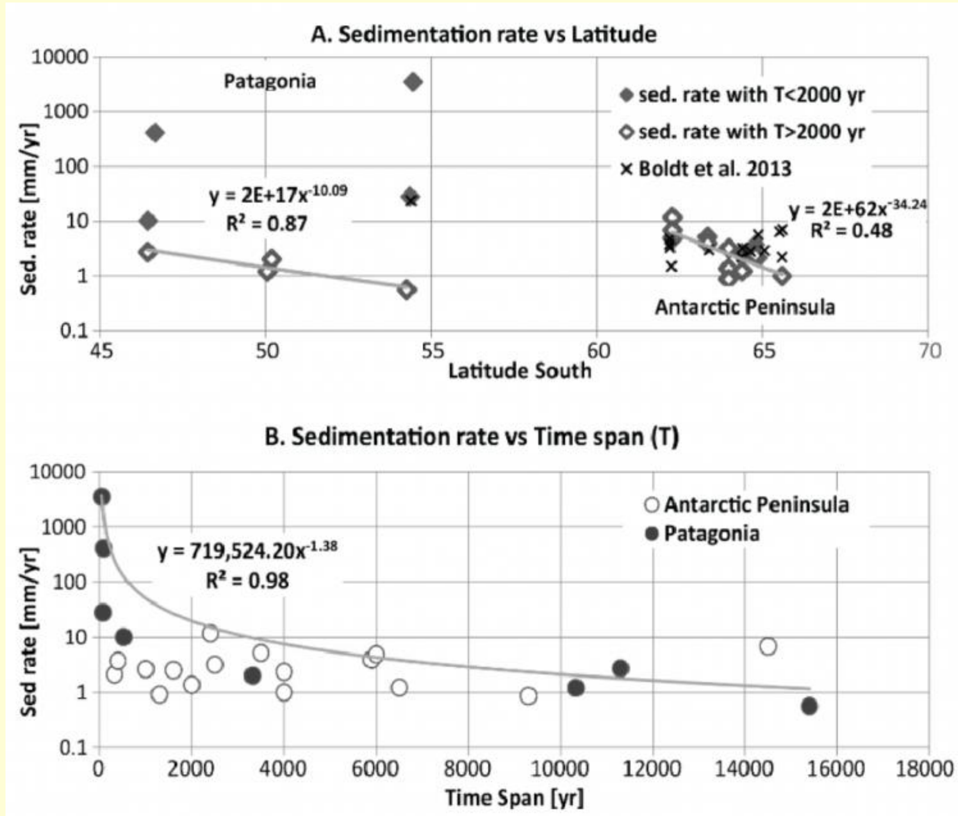


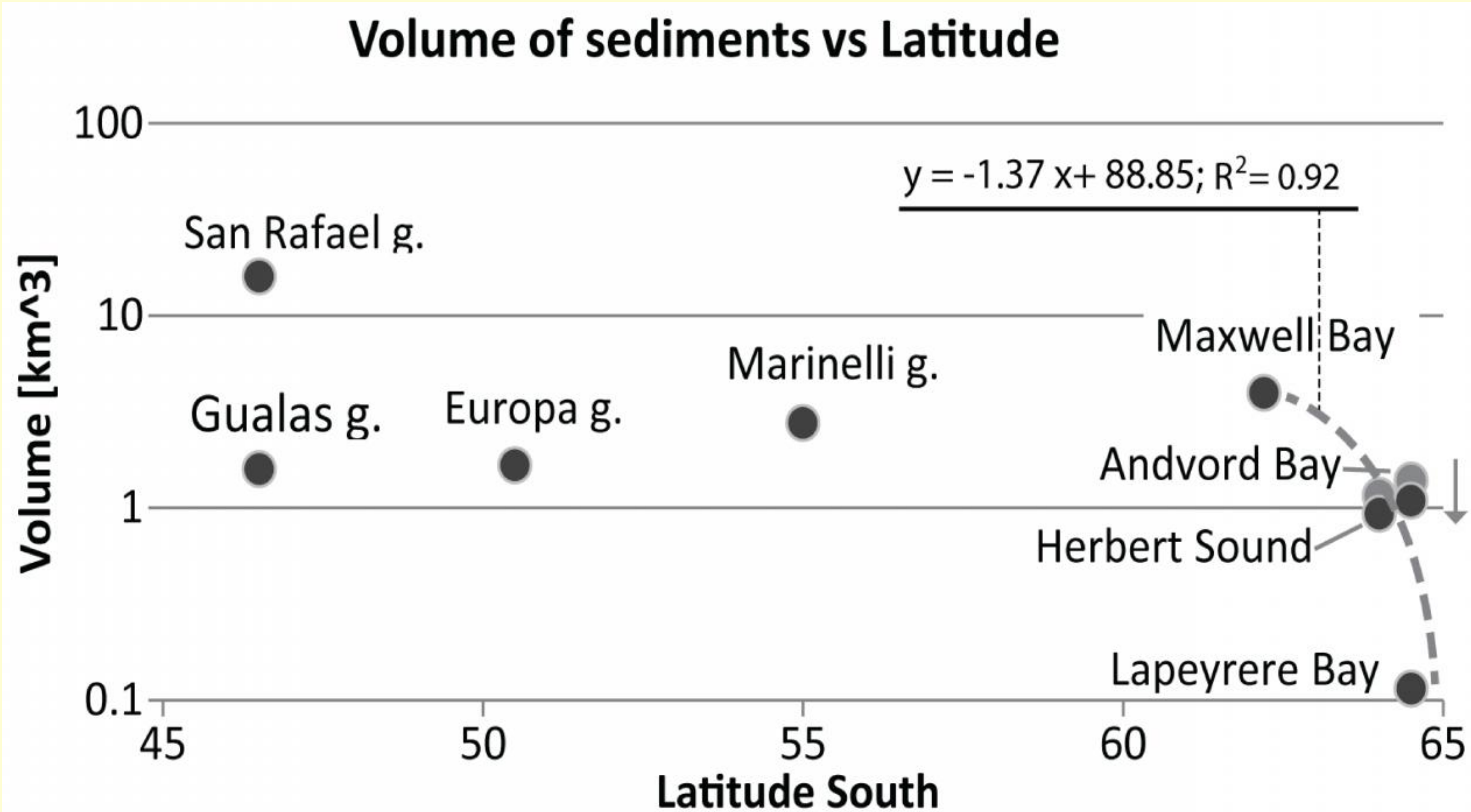
Back-stepping glacier terminus results in order of magnitude decrease in sedimentation at Shaldrill site





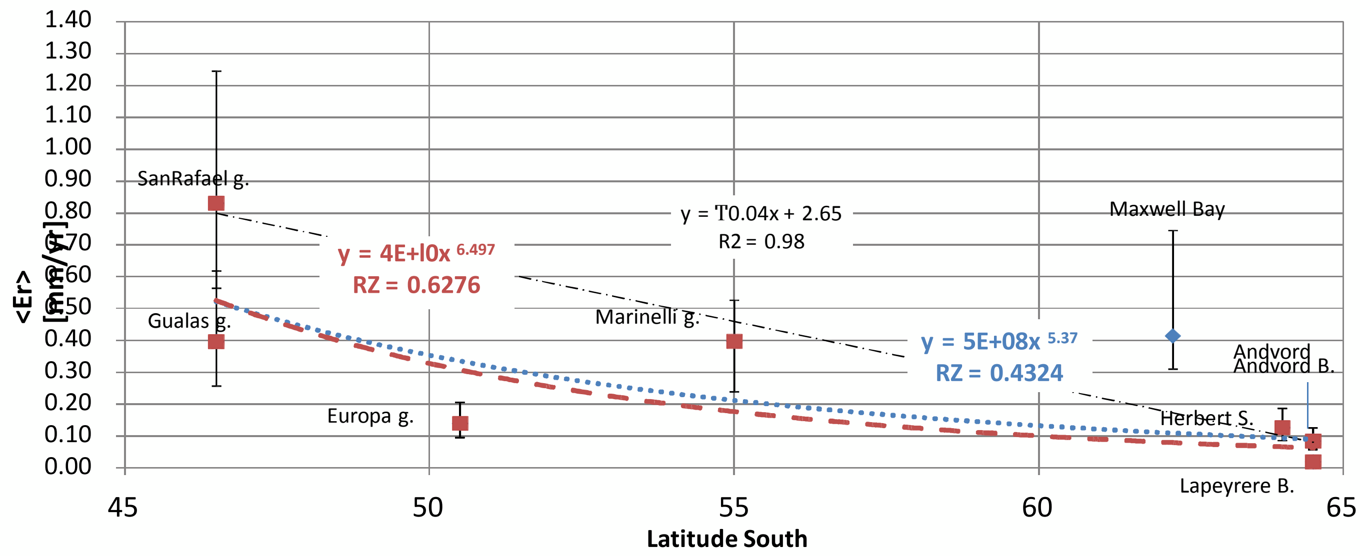

San Rafael g.
Europa g.
Patagonian Andes
Marinelli g.
South America
Atlantic Ocean
Pacific Ocean
Drake Passage
Antarctic Peninsula
Continetal shelf and rise drifts
Lapeyrere Bay
Maxwell Bay
king George Island
Anvers I.
Andvord Bay
Herbert Sound
Seymour Island
depth [m]
1000
1700
2400
3100
3800
80W
70W
60W
50W
50S
55S
60S
65S


A. Sedimentation rate vs Latitude
Sed. rate [mm/yr]
Latitude South
Patagonia
Antarctic Peninsula
sed. rate with T<2000 yr
sed. rate with T>2000 yr
× Boldt et al. 2013
y = 2E+17x^-10.09
R² = 0.87
y = 2E+62x^-34.24
R² = 0.48
B. Sedimentation rate vs Time span (T)
Sed rate [mm/yr]
Time Span [yr]
Antarctic Peninsula
Patagonia
y = 719,524.20x^-1.38
R² = 0.98



The arrows represent the correction for biogenic sediment made at Andvord and Herbert Sound. Light grey circles: total volume; dark grey circles: volume of siliciclastic sediments excluding bigenic material. The equation and dashed line shows the linear regression of biogenic-corrected Antarctic Peninsula basin volumes.

Figure 4: Millennial scale <Er> vs latitude



The time averaged erosion rate is defined as:

$E = Vol_{Rx}/(A_{dr} * T)$

Where Vol_{Rx} = Source Rock Equivalent volume, A_{dr} is the effective area of the drainage basin, which includes all areas that potentially supplied sediment to the fjord or bay, and

T=time span of accumulation of each seismic unit

The source rock-equivalent volumes were calculated using the following equation:

$Vol_{Rx} = (Q_{sed} / Q_{source})\ Vol_{Sed}$

where,

Q_{sed} = average dry density of the sediments, [kg/m^3].

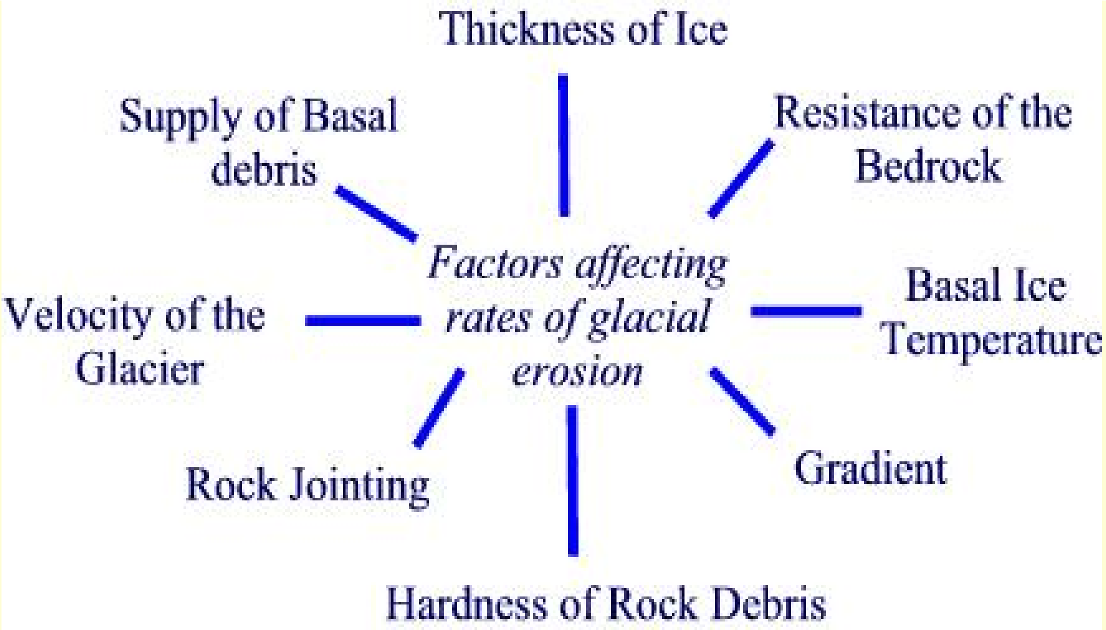
Vol_{Sed} = volume of siliciclastic sediments of each seismic unit, [m^3].

Vol_{Rx} = source rock-equivalent volume of sediments, [m^3].

Q_{source} = estimate of the average density of the source rocks, [kg/m^3].

The density used for the parental rock (Q_{source}) was 2700 kg/m^3, a commonly used value for metasedimentary and igneous rocks.

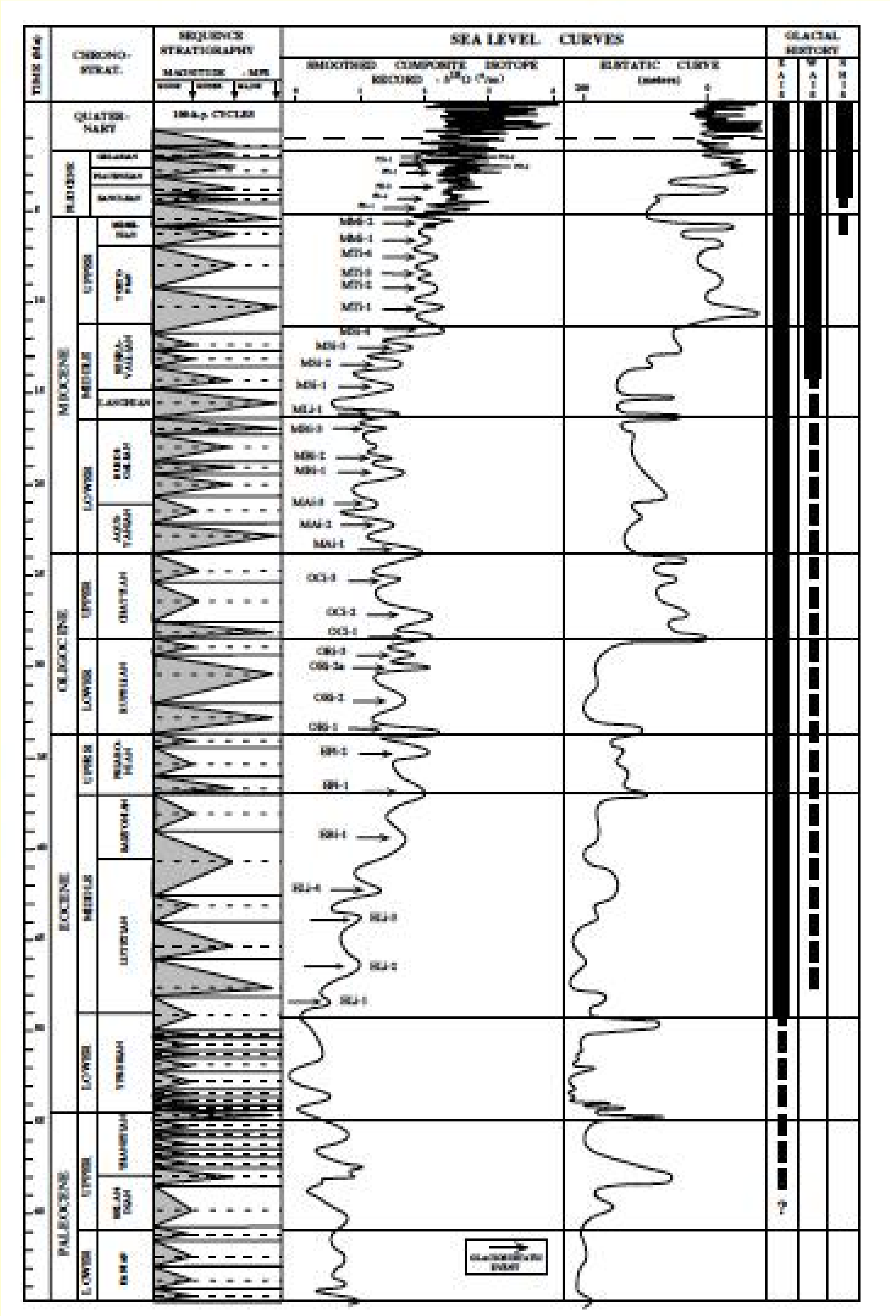
To understand the effects of glacial systems on the evolution of mountain ranges, it is necessary to consider erosion on tectonic time scales. Generally, studies of glacier effects on mountain denudation rely on the interpretation of exhumation rates derived from low temperature thermochronometers to estimate million-year timescale erosion rates (e.g., Spotila et al., 2004; Koppes et al., 2009). However, the erosional component of thermal history of the minerals used for these analyses is convolved with the regional thermal structure of the crust, thermal influence of local magmatic events, and recent tectonic evolution, of which only the latter is relatively well known in our study areas.



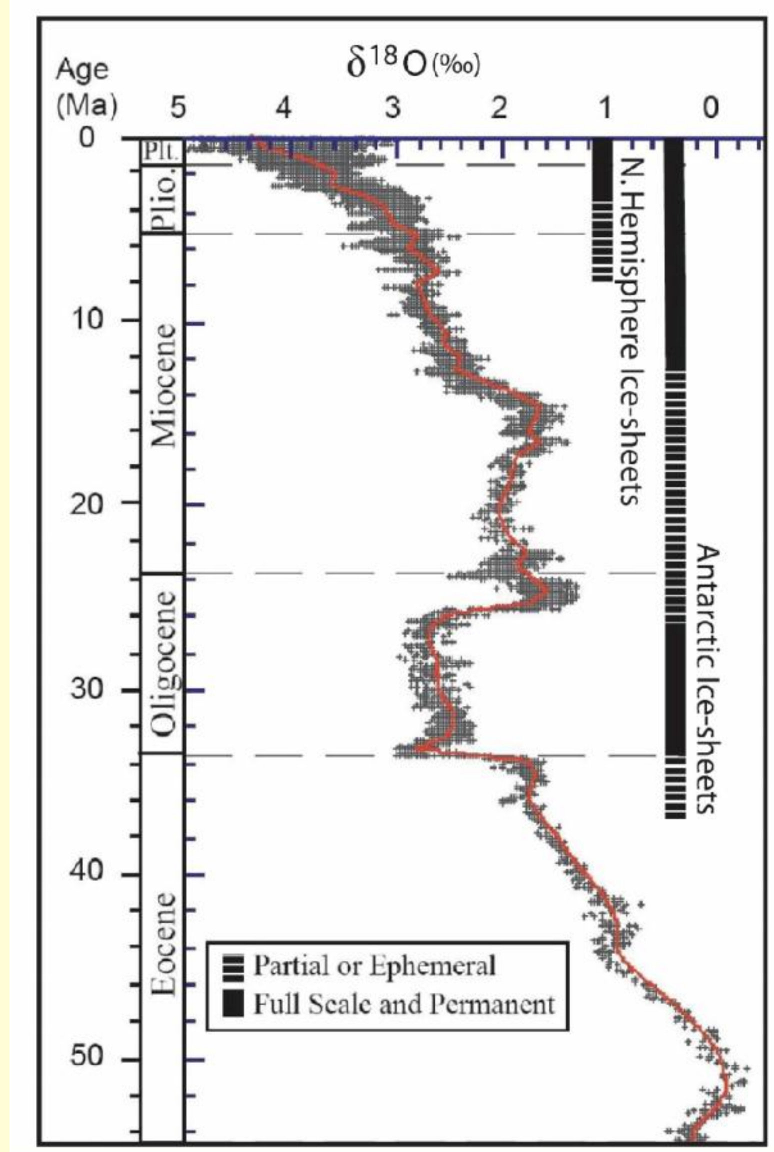
Over Short Time Scales

Over Long Time Scales

- Rate of Tectonic Uplift
- Hypsometry
- Duration of glaciation
- Duration of glacial-interglacial cycles
- Climate Change



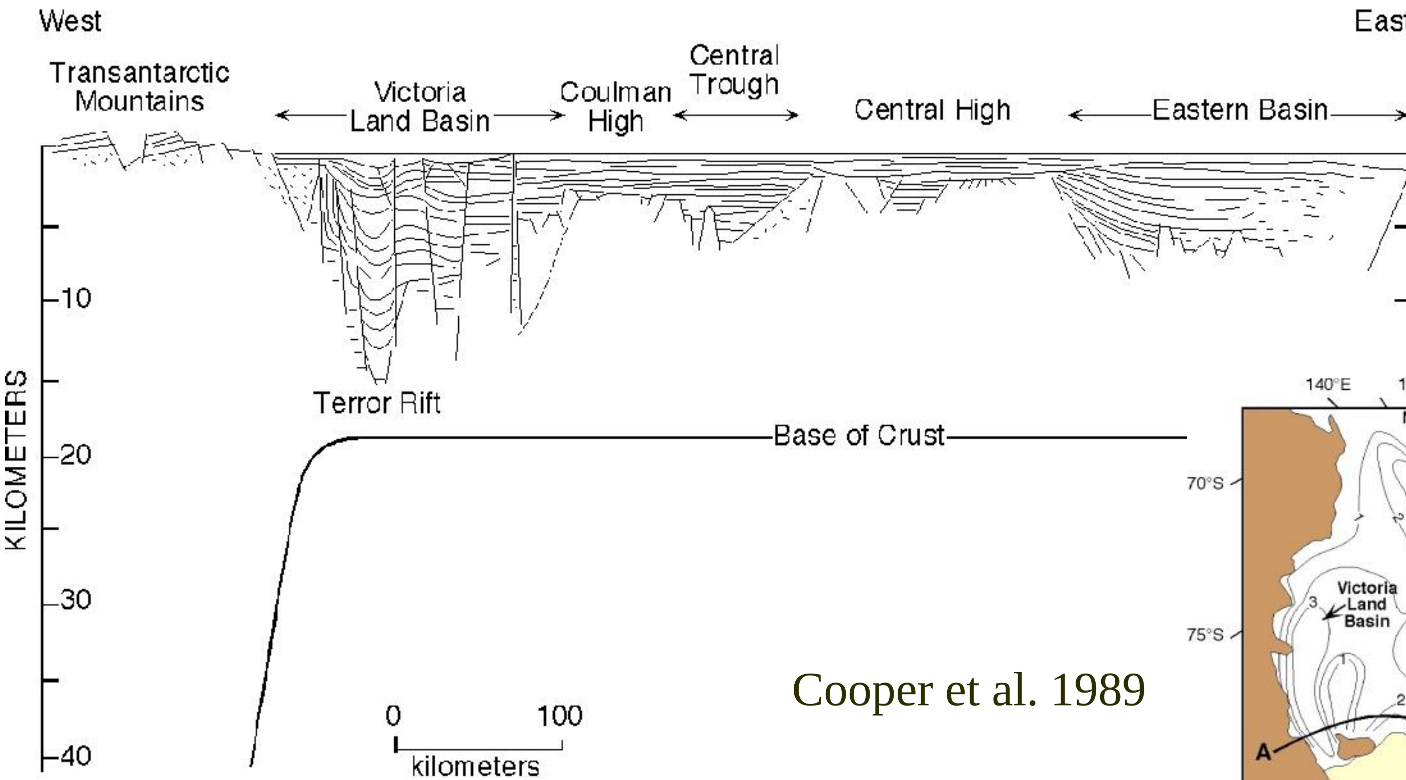
Abreu and Anderson, 1998



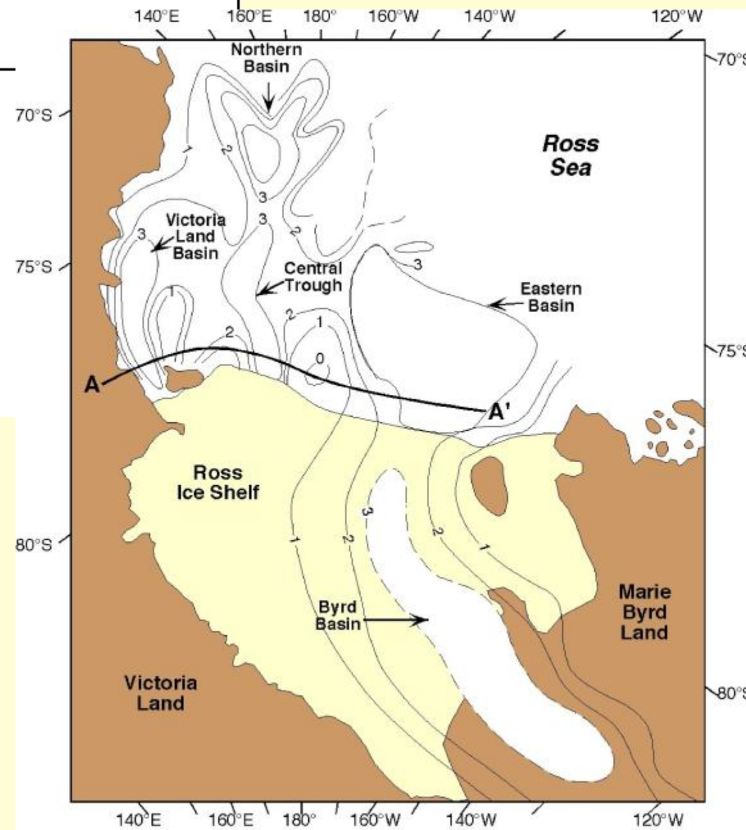
Zachos et al., 2003

Transantarctic Mountains formed prior to glaciation of the continent and underwent significant denudation with onset of glaciation during the Eocene-Oligocene. Rates of erosion since then have been minimal, resulting in a landscape that is frozen in time.

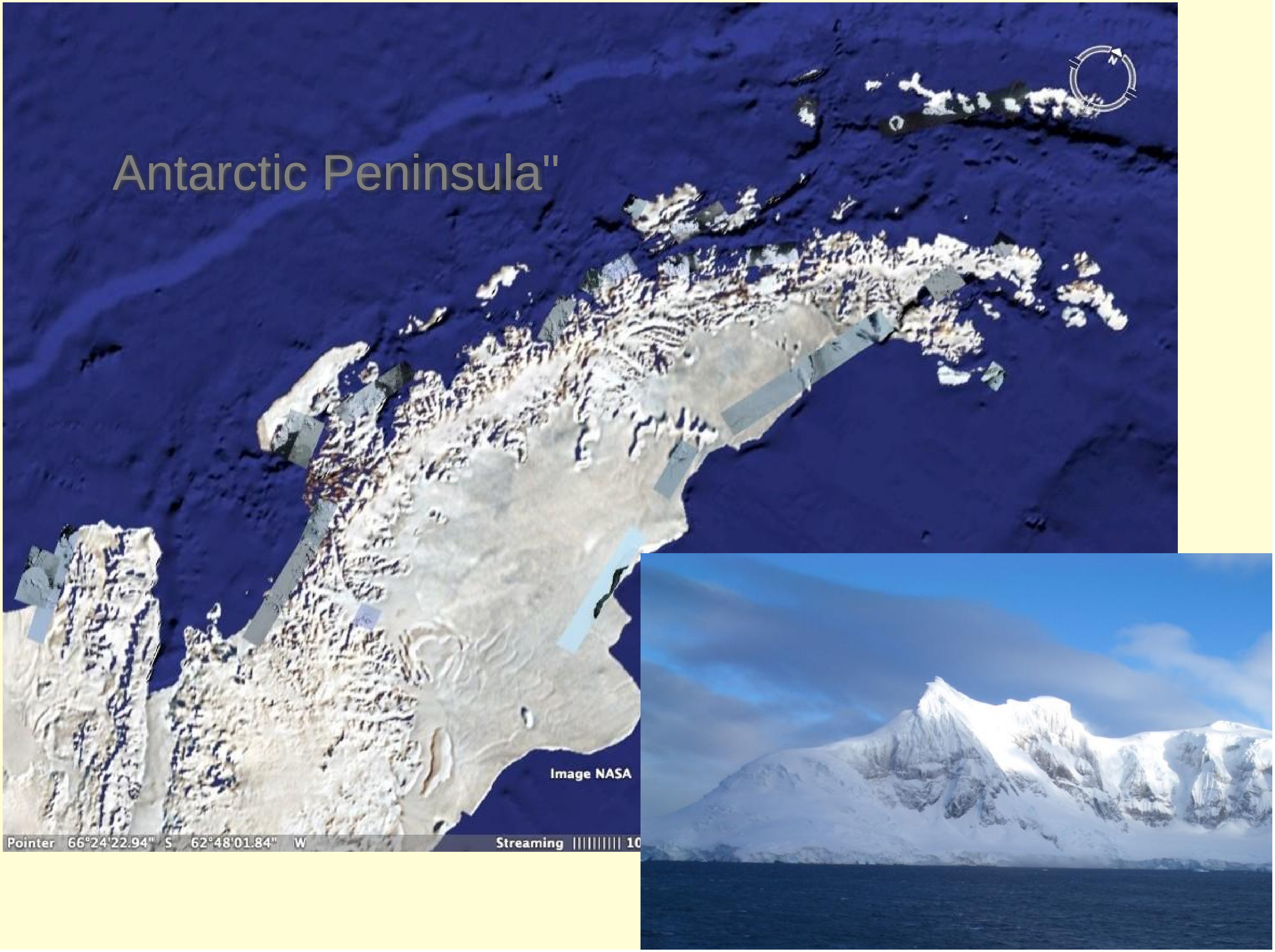
Uplift of the AP mountain belt was time transgressive but occurred after onset of glaciation in the latest Eocene.



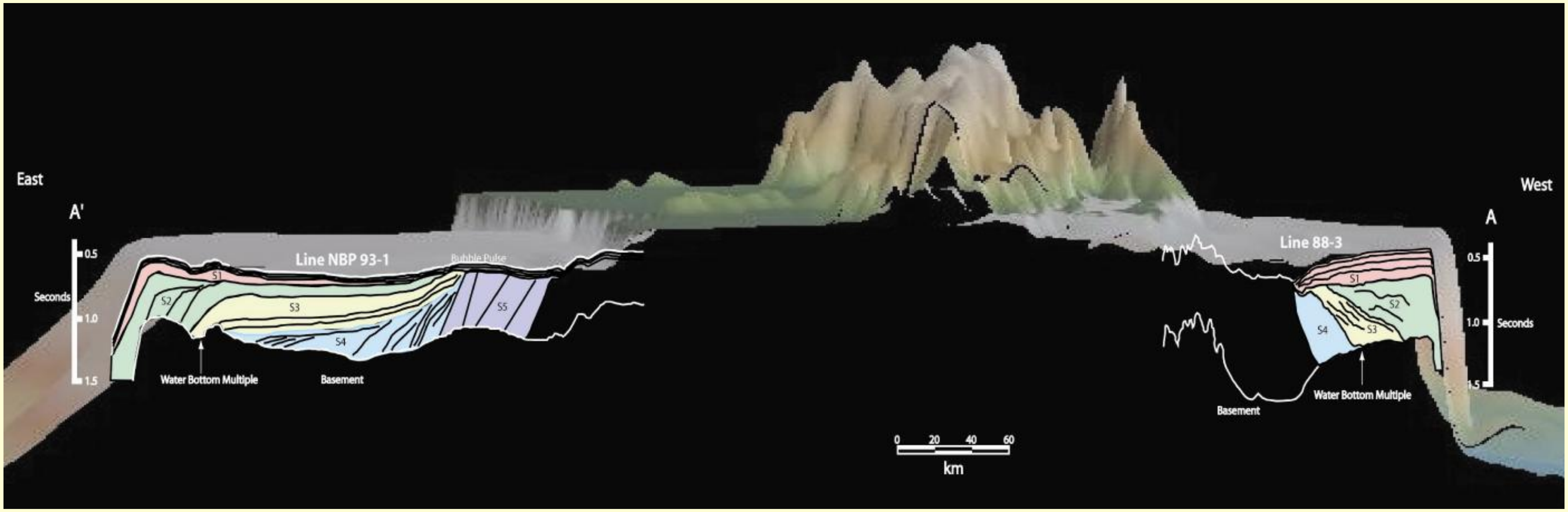
Cooper et al. 1989

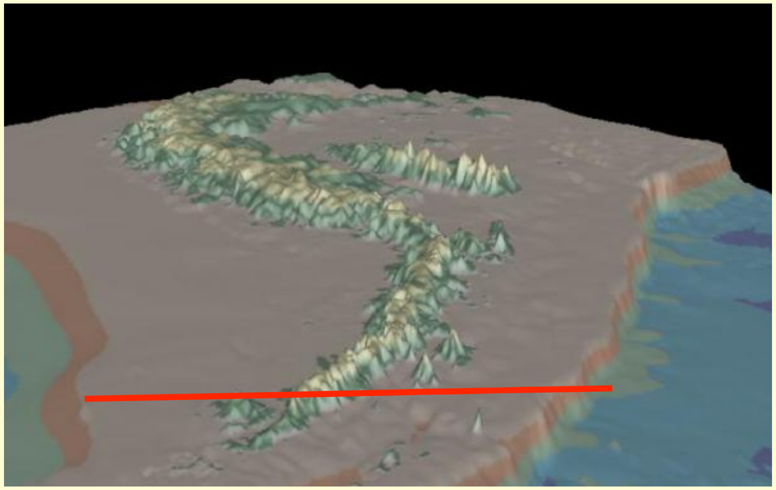


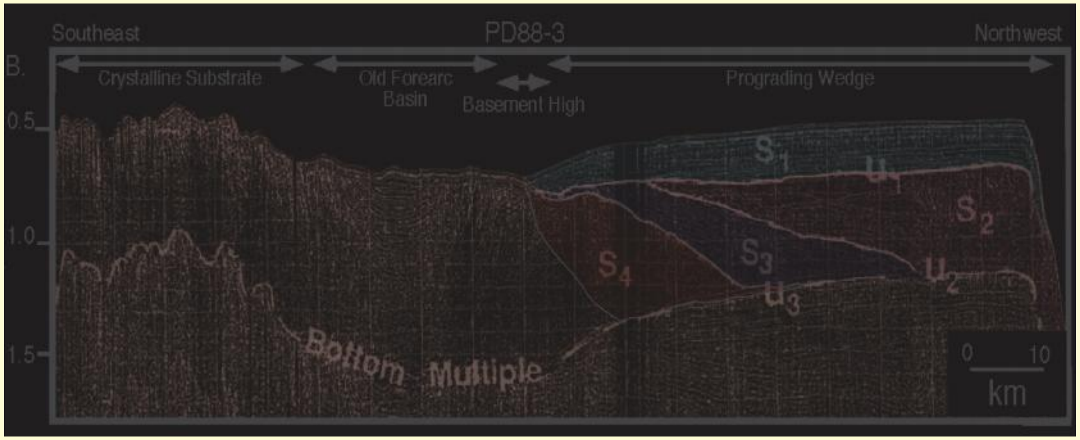
Antarctic Peninsula"

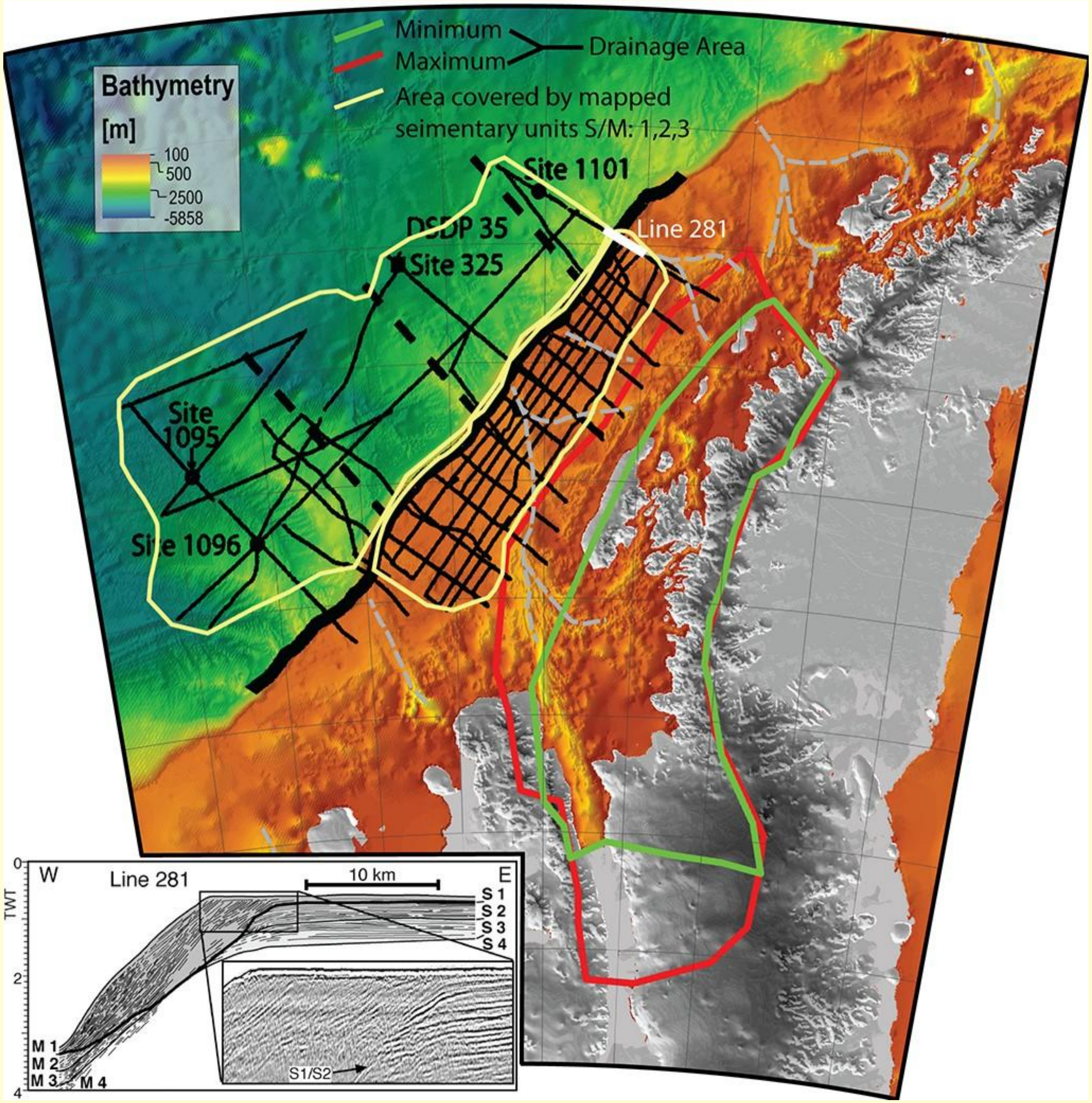


Neogene stratal packages indicate high rates of sediment flux to the margin and approximately 1 km of denudation of the northern AP

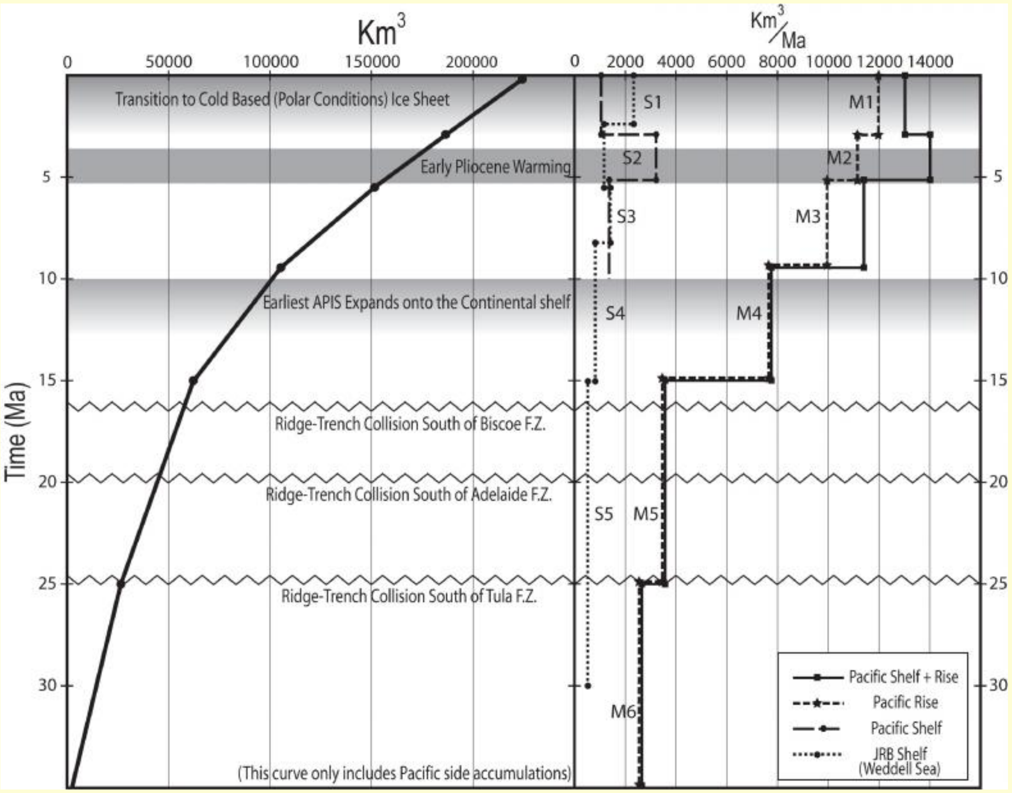








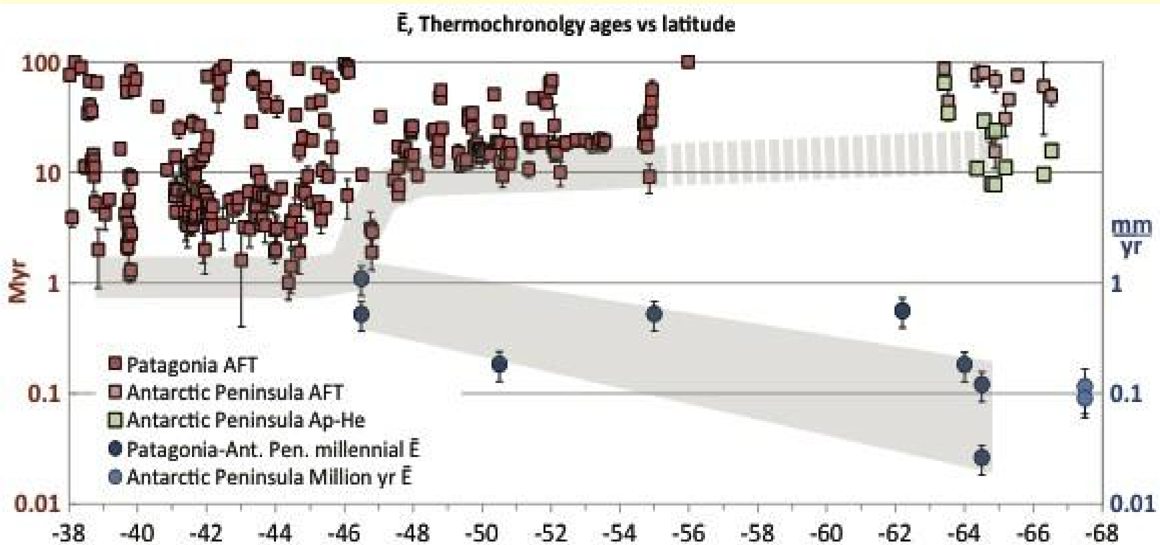
Minimum
Maximum
Drainage Area
Area covered by mapped seimentary units S/M: 1,2,3
Bathymetry
[m]
100
500
2500
-5858
Site 1101
DSDP 35
Site 325
Line 281
Site 1095
Site 1096
W
Line 281
10 km
E
TWT
0
2
4
S 1
S 2
S 3
S 4
M 1
M 2
M 3
M 4
S1/S2



We obtained values of 0.11±0.04 mm/yr for the youngest unit (timespan: ~0-2.9 Ma; volume: ~3.5x10^4 km^3), 0.12±0.05 mm/yr for the next oldest unit (timespan: ~2.9-5.3 Ma; volume: ~2.9*10^4 km^3), and 0.09±0.03 mm/yr for the oldest unit (timespan: ~5.3-9.5 Ma; volume: ~3.5*10^4 km^3). This equates to an increase in the rate of denudation of 25-30% after ~5.3 Ma and to at least ~1 km of denudation over the last 10 million years

Smith and Anderson, 2010

There are no comparable million-year time scale estimates of E for Patagonia. However, extensive thermochronology datasets show that the youngest apatite (U-Th)/He and fission-track ages are ~1-2 Ma north of ~45° S, and increase rapidly southward, reaching values of ~10-15 Ma south of ~45° S (Thomson et al., 2010; Fig. 9). This pattern implies roughly a ten-fold decrease in exhumation rates, from ~2-4 to 0.2-0.3 mm/yr (with the assumptions that exhumation is entirely due to erosion, linear temperature-depth path, apatite fission-track closure temperatures ~100-125 °C, geothermal gradient ~25-35 °C/km for the whole study region).



Comparison of the existing mountain exhumation and erosion rate datasets. Squares represent apatite fission track ages (red: Patagonia; pink: Antarctic Peninsula), and circles represent our erosion rates data (blue: Patagonia; light blue: Antarctic Peninsula). The narrower grey band highlights the approximate trend defined by the youngest apatite fission track (AFT) data for both regions (increasing ages reflect a decrease in exhumation rate). The wide grey band highlights the general trend of decreasing millennial scale erosion rates with increasing latitude (this study). AFT data for Patagonia are from Thomson et al. (2010), AFT and (U-Th)/He ages for the Antarctic Peninsula are from Guenthner et al. (2010).

Ongoing Research on potential controls:

- **<u>Provenance</u>** may control range of silt variability
  - Volcanic (65-85%) vs. Graniticl Metamorphic (65-80%)
- **Proximity** to glacier terminus
  - Significant decrease in sediment production through time is not reflected by %silt
  - Efficient sediment dispersal
- **<u>Erosive efficiency as a product of glacier flow velocity?????</u>**