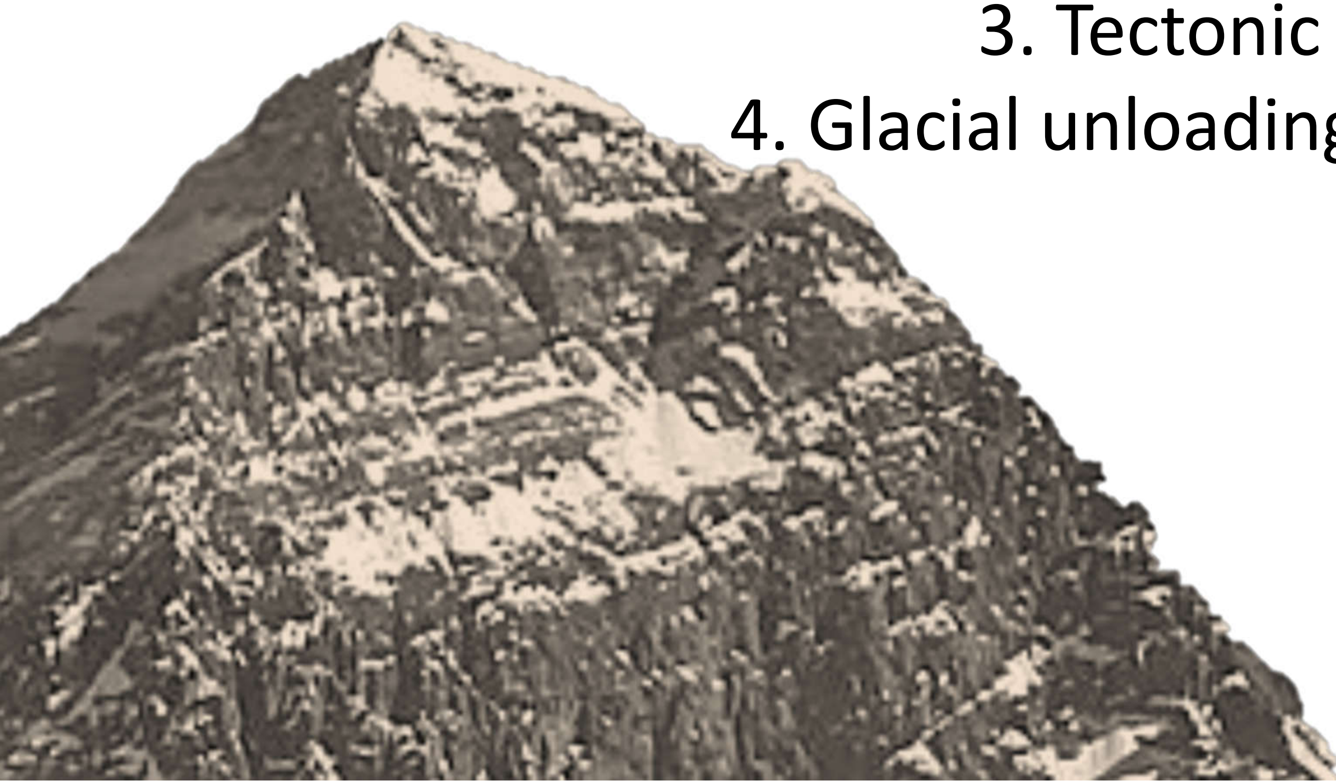
Height Measurements Mt Everest

1. History: triangulation, leveling, and space geodesy
2. Variable ice thickness - snow, ice, dissolution
3. Tectonic motions of the summit
4. Glacial unloading and monsoon loading
5. Error analysis



Roger Bilham
University of Colorado
Boulder

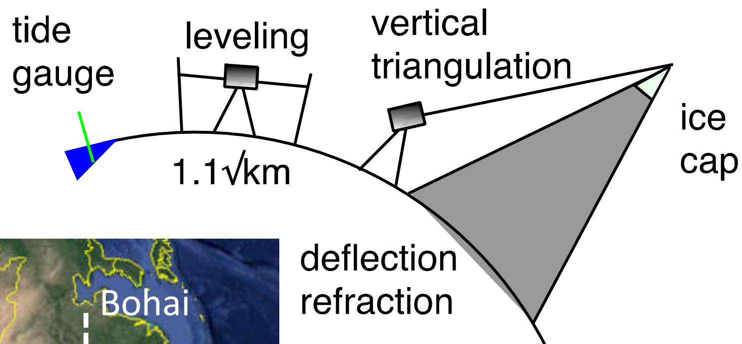
Kathmandu 11/12 Dec

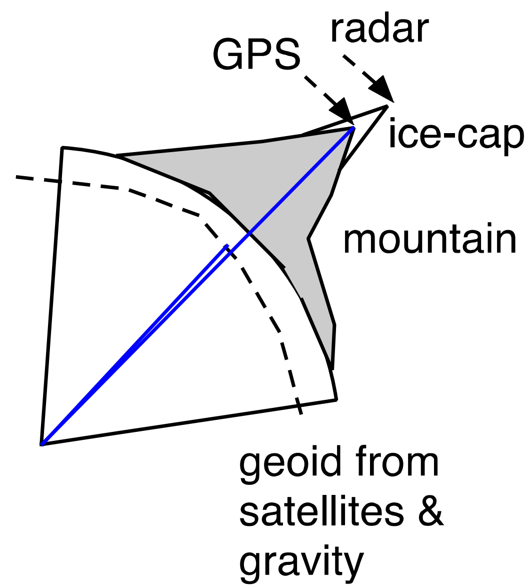
Terrestrial geodesy (1800-present)

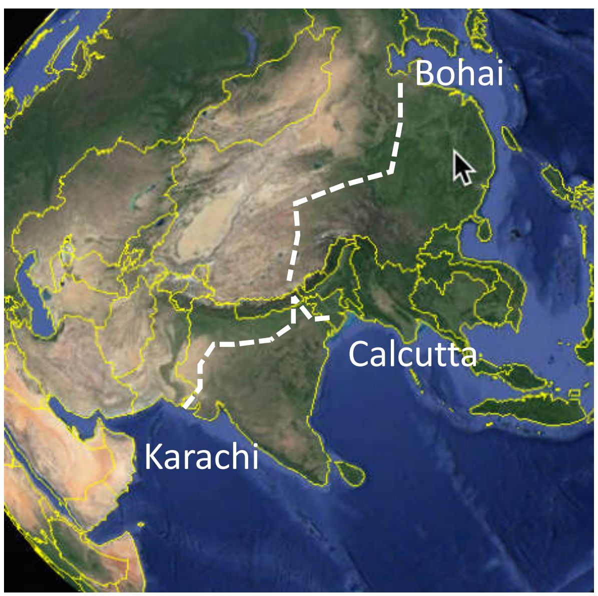
1. measure sea level
2. transfer height to BM at base of mountain using precision leveling
3. measure summit target relative to BM using vertical triangulation
4. correct for refraction, deflection-of-vertical and geoid height.
5. correct for variable thickness of ice on summit

Space geodesy (post-GPS 1989)

1. measure position of summit relative to center of mass
2. calculate geoid height center-of-mass distance
3. correct for variable ice thickness



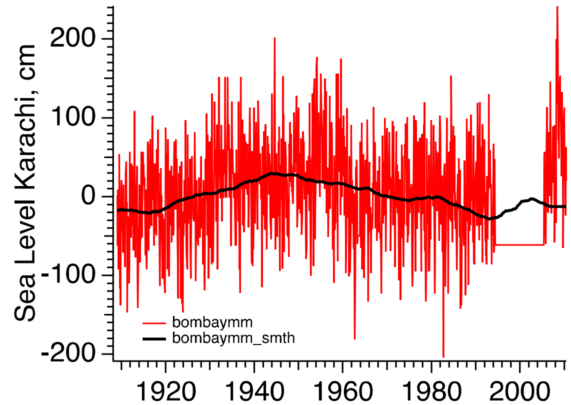




levelling errors =1.1√km
√1800 km=43mm
√3200 km=56mm

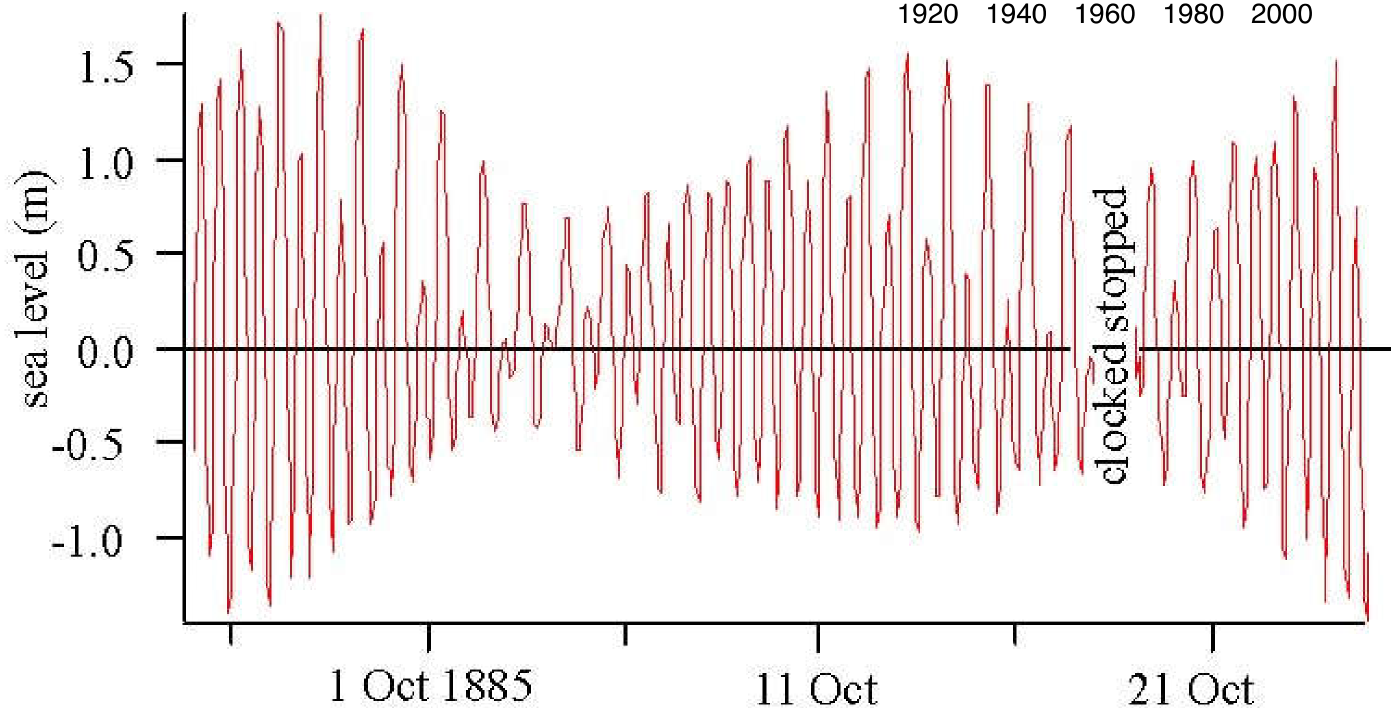
- methods are independent and give same result (after corrections)
- Space geodesy in principle more accurate (fewer corrections)
- space geodesy easier to update and check in future

Everest measured relative to sea level in Karachi 1885 and from Sea of Bohai in 1968 gave same height (±1 m)!



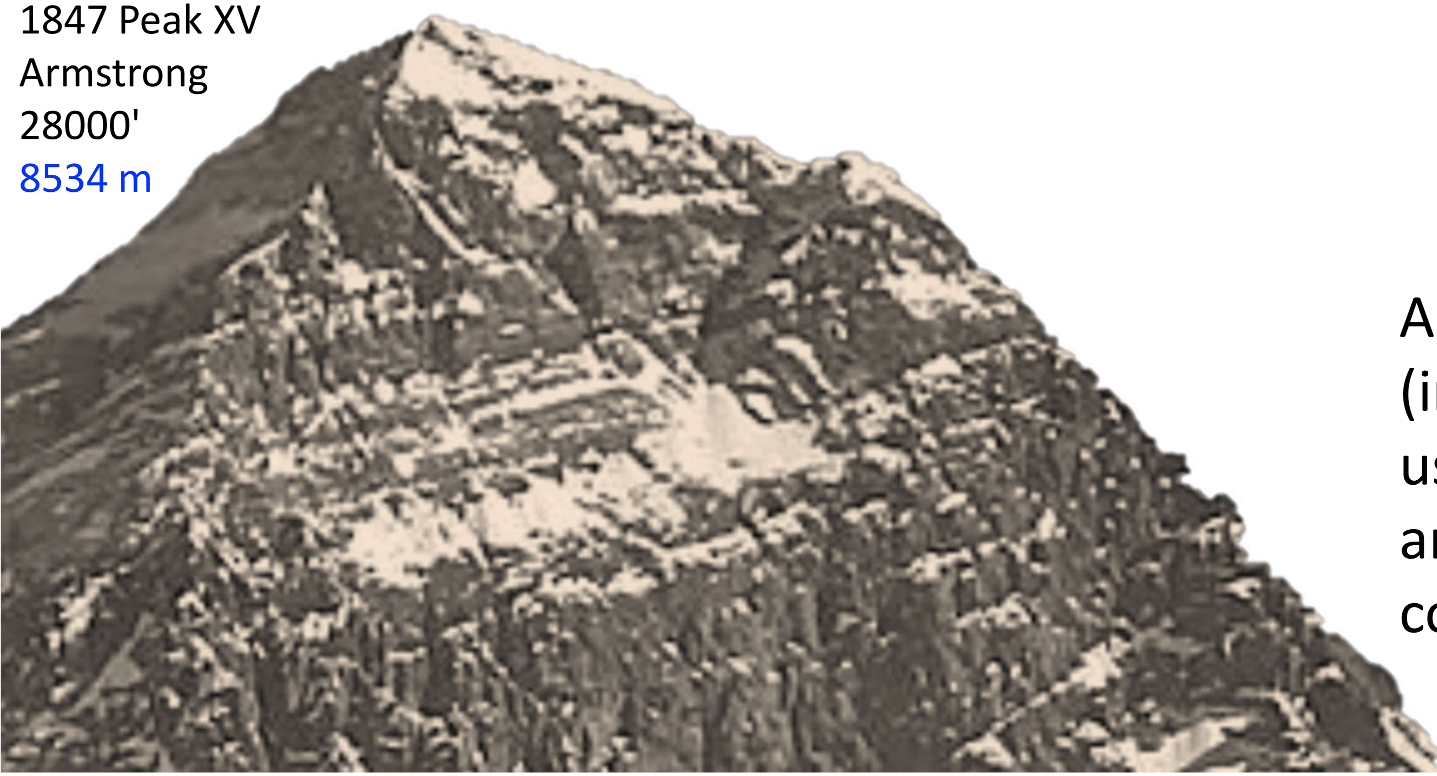
a hundred years of sea level data from Arabian Sea

decadal sea level ±25 cm



This is the original month of sea level data used by Andrew Waugh used to measure Everest

1. Triangulation, Leveling, and GPS



1847 Peak XV
Armstrong
28000'
8534 m

Armstrong sighted *Peak b* (inverted!) from 200 km, used the wrong geoid, and a poor refraction correction

Peak 15 – a mountain identified by mathematics in 1855

1849 Waugh and Lane add two intersections of *Peak gamma*

1850 Nicholson adds 6 intersections of *Peak h*

1852 *gamma*, *b* & *h* are newly designated *Peak XV* for position calculations

1855 Waugh announces *Peak XV* as the highest peak and names it after George Everest

29002±13'

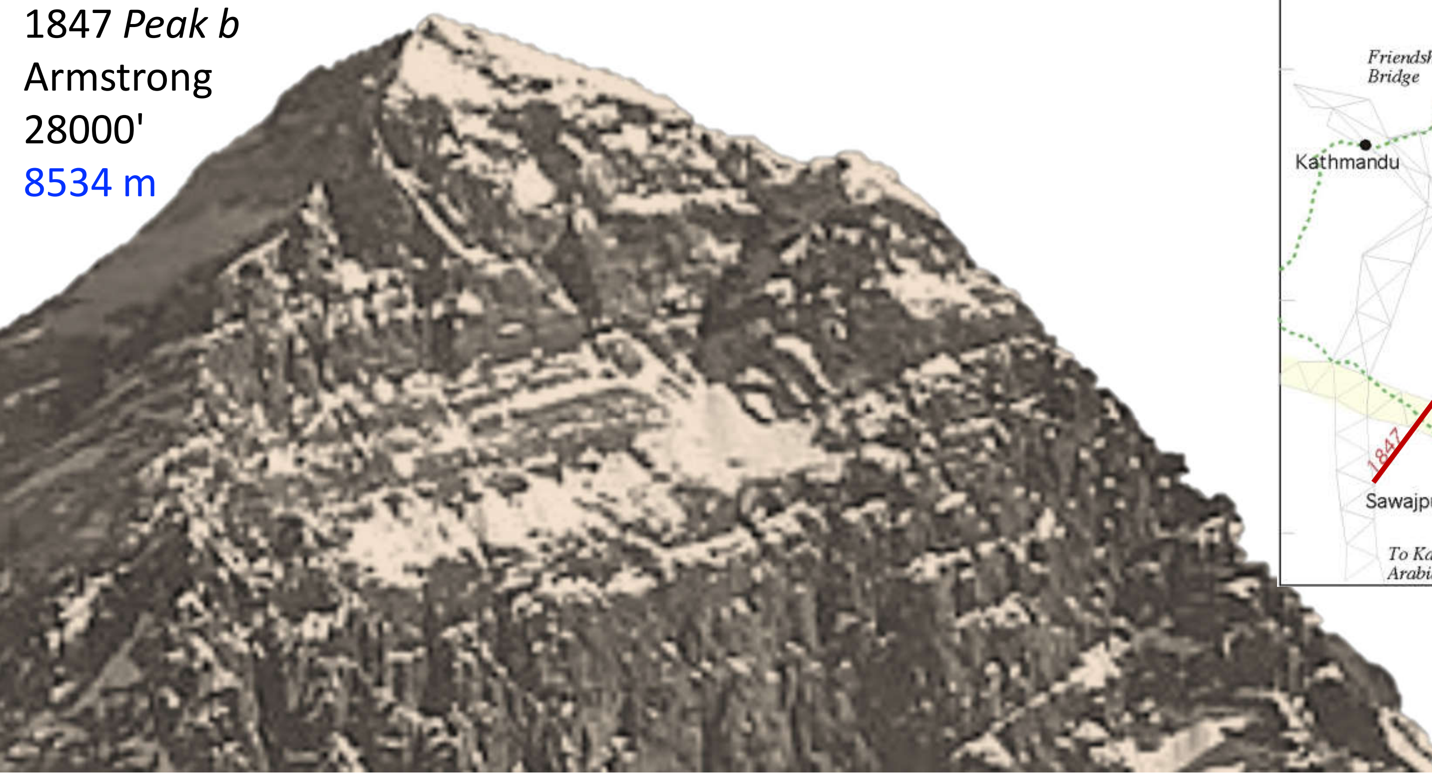
8839.81 m

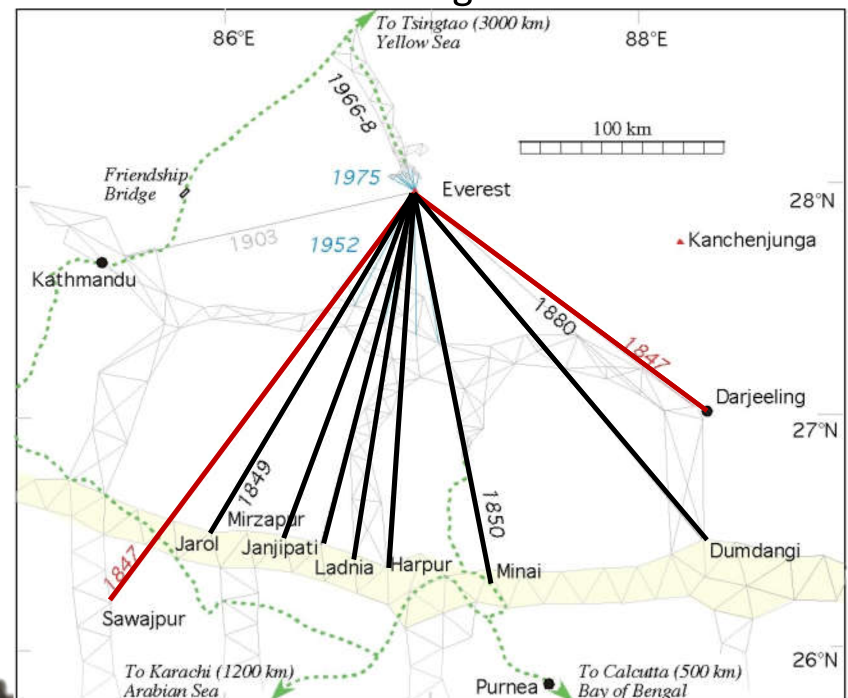
1847 *Peak b*

Armstrong

28000'

8534 m

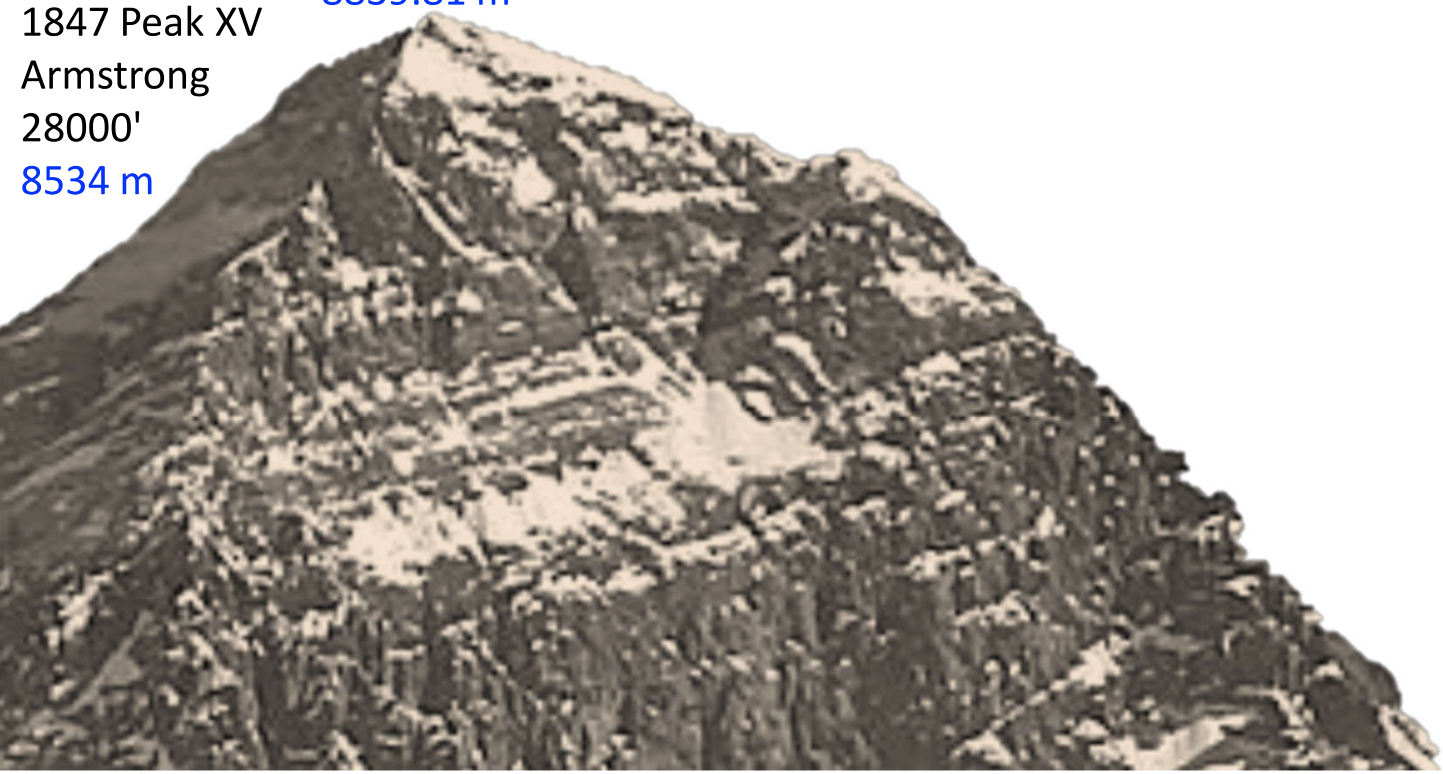




1907 Burrard adds new intersections from Darjeeling
and improves the refraction correction
29032±6'
8849 m

1855 Everest
Waugh
29002±13'
8839.81 m

1847 Peak XV
Armstrong
28000'
8534 m

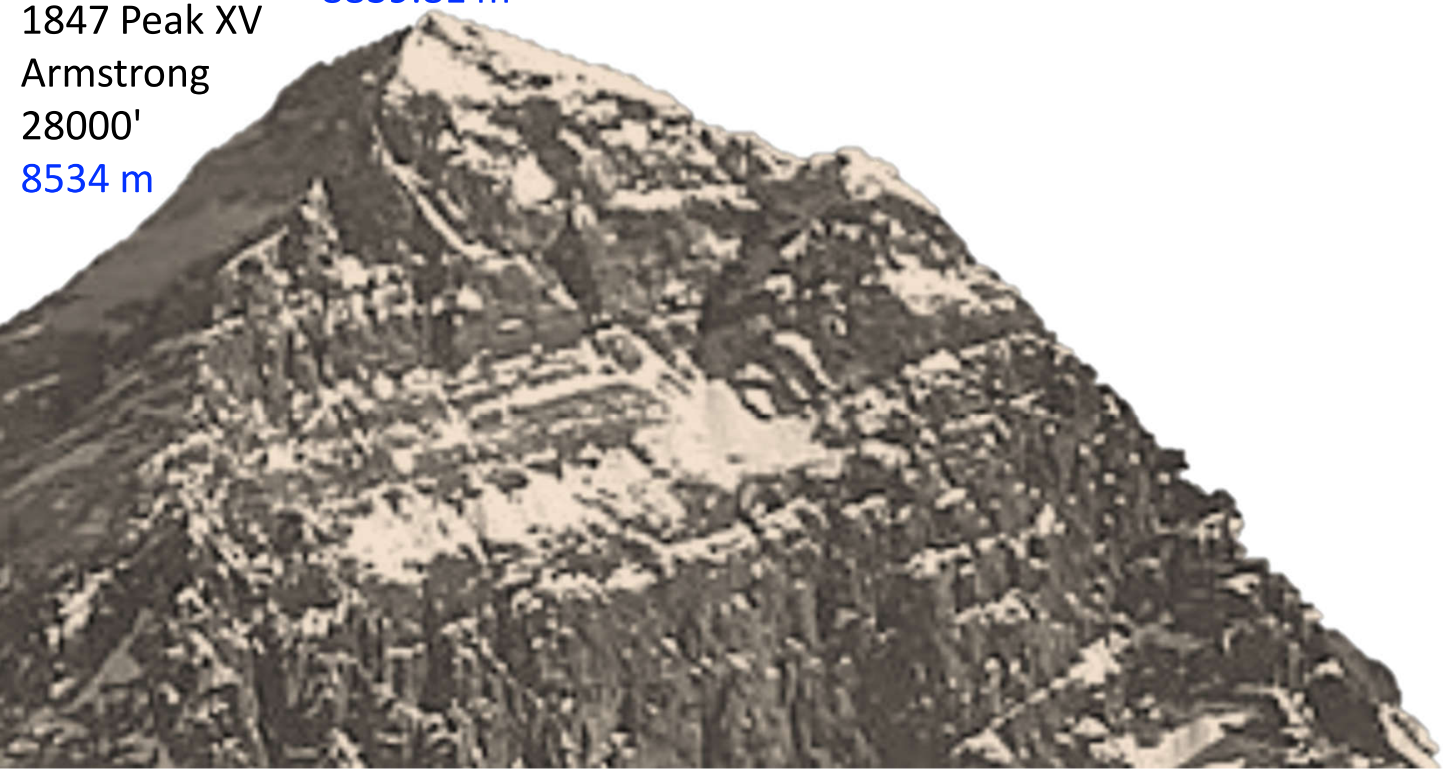


1922 DeGraff Hunter calculates a new refraction correction and new geoid
29040±6' 8852 m

1907 Burrard
29032±6'
8849 m

1852 Everest
Waugh
29002±13'
8839.81 m

1847 Peak XV
Armstrong
28000'
8534 m



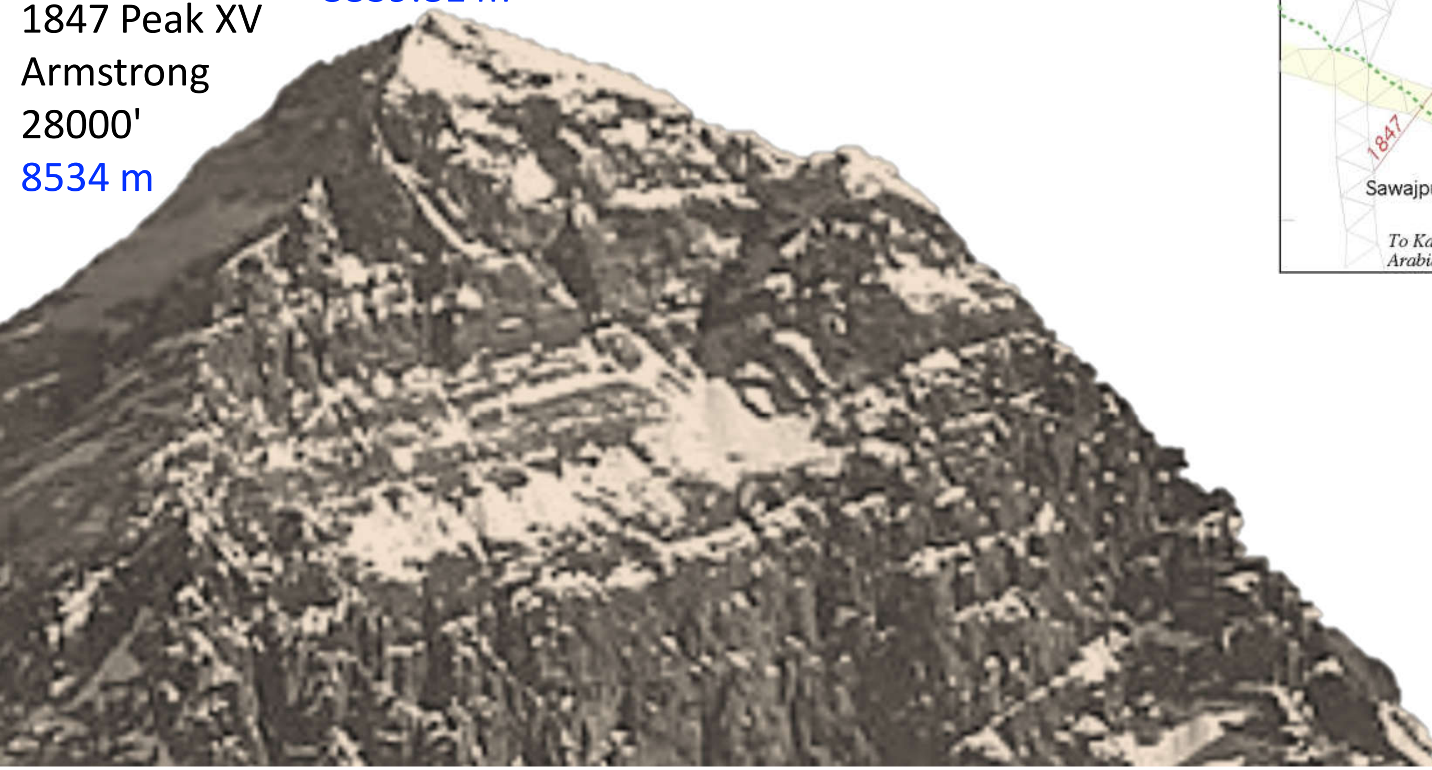
1922 DeGraff Hunter 29040±6'
8852 m

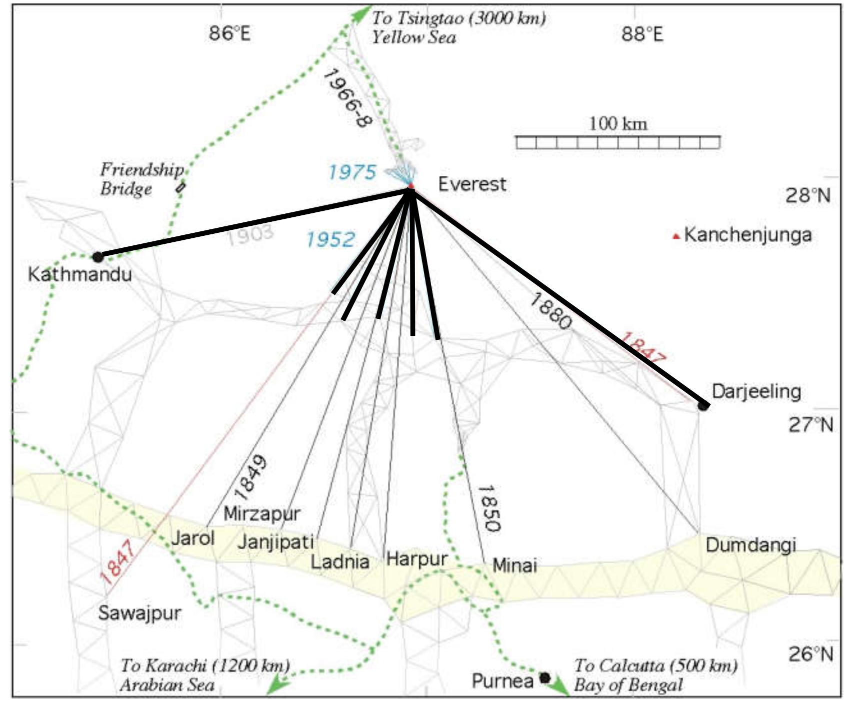
1907 Burrard 29032±6'
8849 m

1952 Gulatee 29028±10'
8847.7 m

1852 Everest Waugh 29002±13'
8839.81 m

1847 Peak XV Armstrong 28000'
8534 m





Gulatee adds 30 km summit intersections from new triangulation in mid-Himalaya

1922 DeGraff Hunter 29040±6' 8852 m

1907 Burrard 29032±6' 8849 m

1966 PRC 29035' 8849.9 m

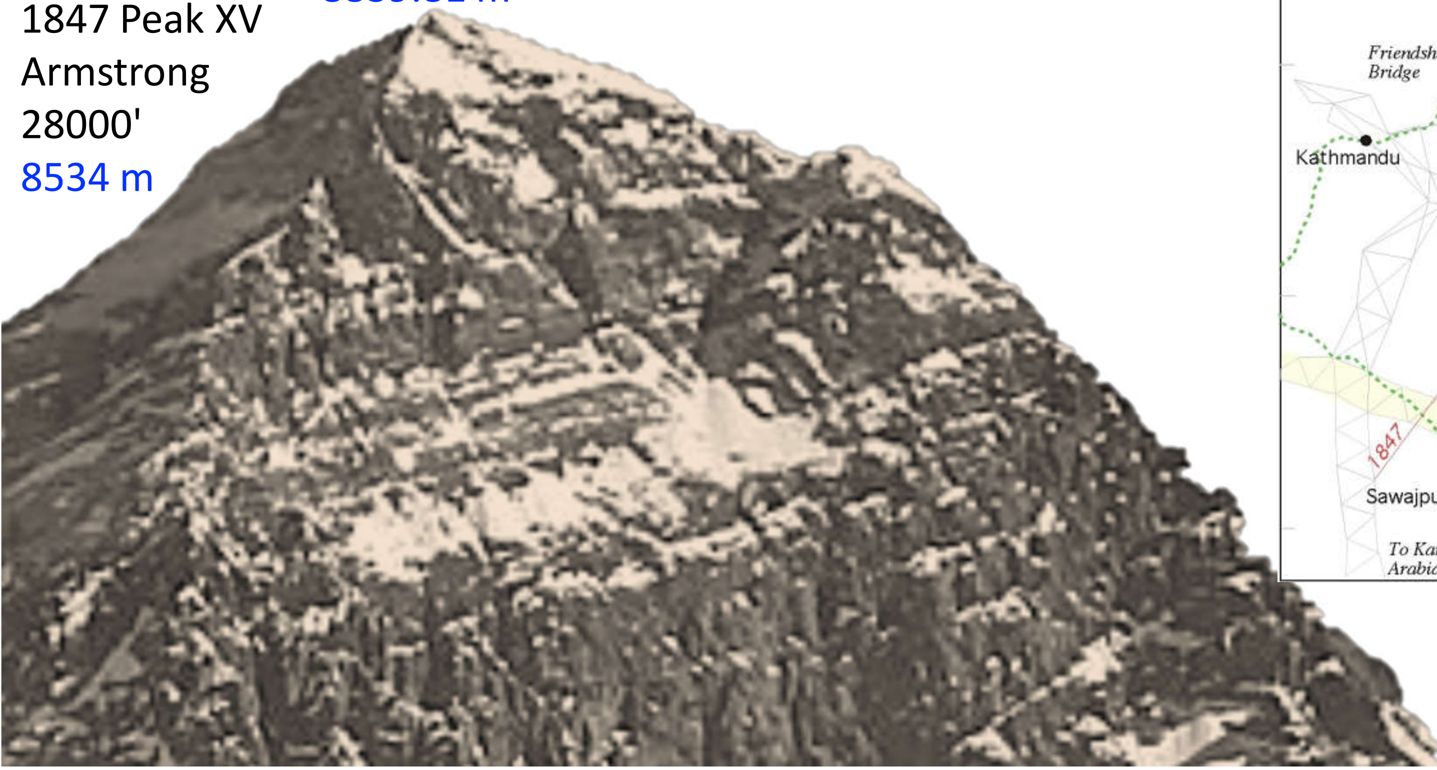
1966 PRC levels to within 20 km of summit with 15 km intersections

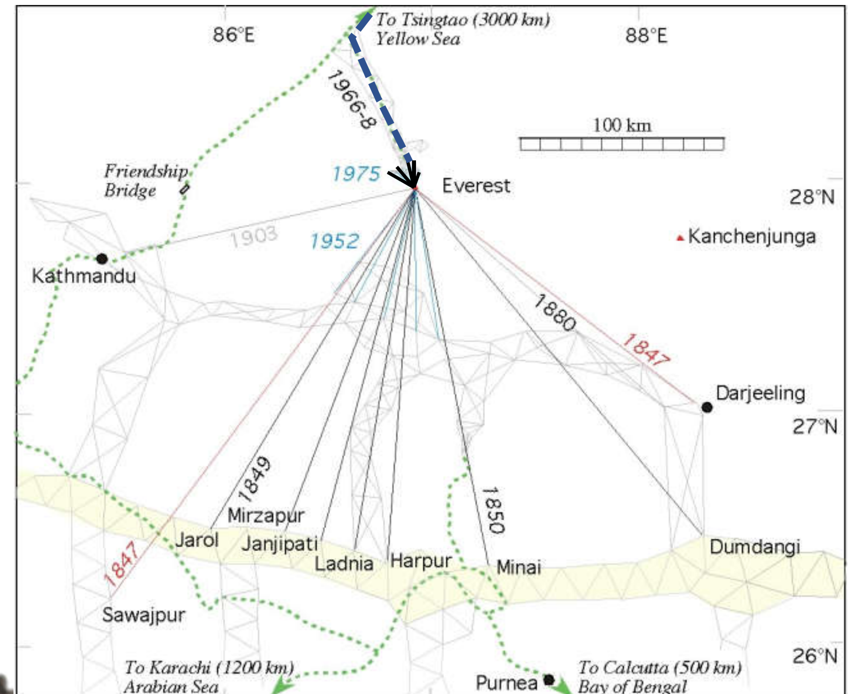
1852 Everest Waugh 29002±13' 8839.81 m

1952 Gulatee 29028±10' 8847.7 m

1968 Chen & Gun 29029'

1847 Peak XV Armstrong 28000' 8534 m





1847 Peak XV
Armstrong
28000'
8534 m

1852 Everest
Waugh
29002±13'
8839.81 m

1907 Burrard
8849±2 m

1922 DeGraff
Hunter
8852±2 m

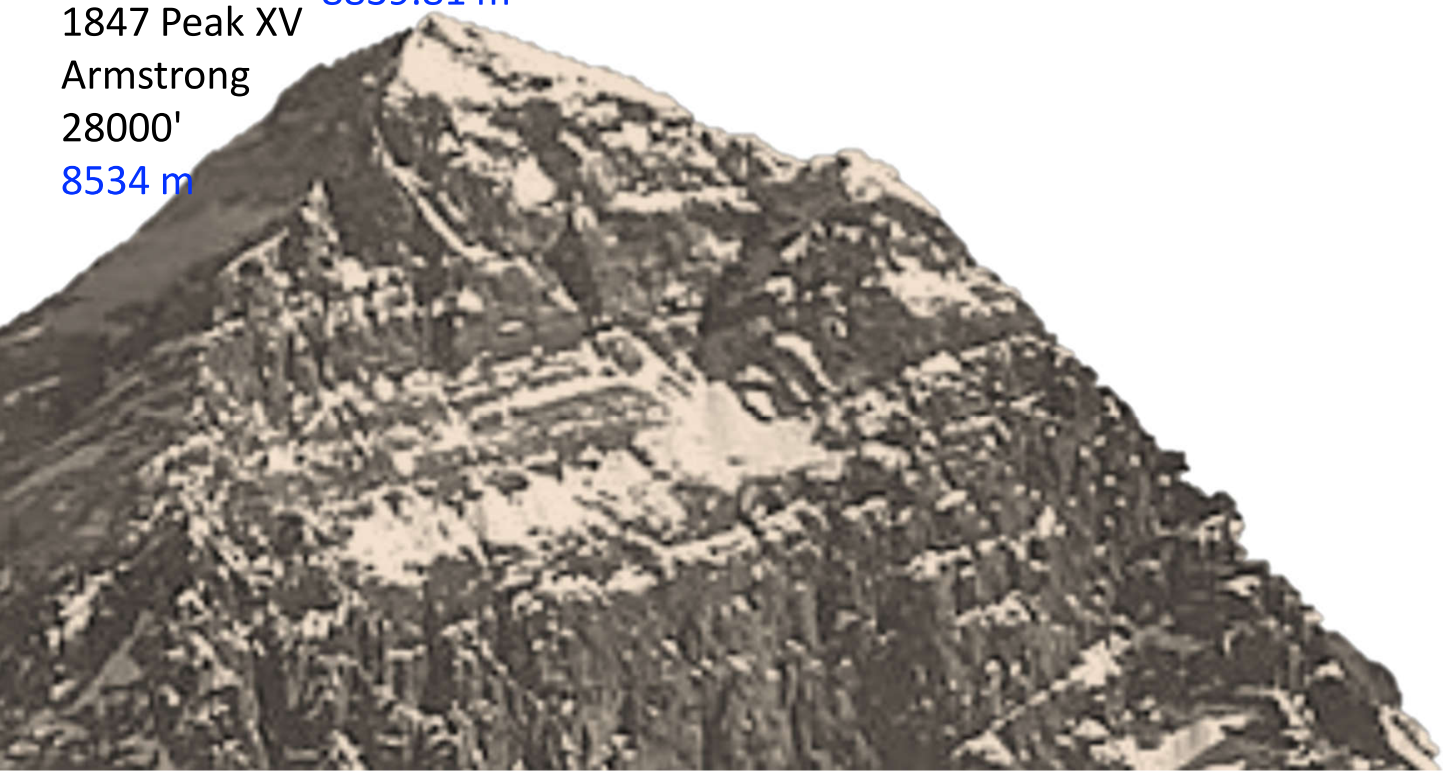
1952 Gulatee
8847.7±3 m

1966 PRC
8849.9 m

1968 Chen &
Gun 8848.0 m

1992 Washburn
8849.9±2 m

Trimble GPS on summit
Space-based geoid
Ice cores summit



1847 Peak XV Armstrong 28000' 8534 m

1852 Everest Waugh 29002±13' 8839.81 m

1907 Burrard 29032±6' 8849 m

1922 DeGraff Hunter 29040±6' 8852 m

1952 Gulatee 29028±10' 8847.7 m

1966 PRC 29035' 8849.9 m

1968 Chen & Gun 29029' 8848.0 m

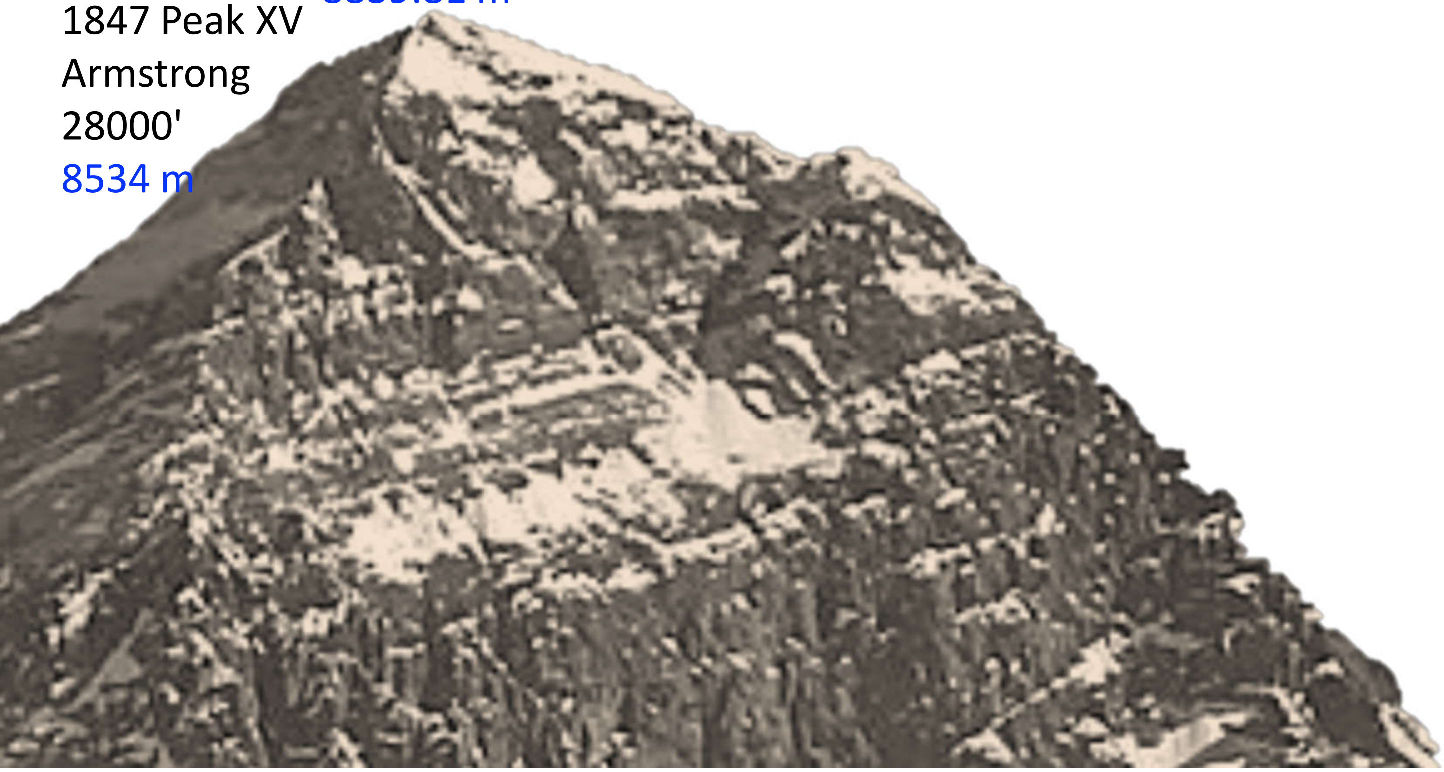
1992 Washburn 29035±6 8849.9±2 m

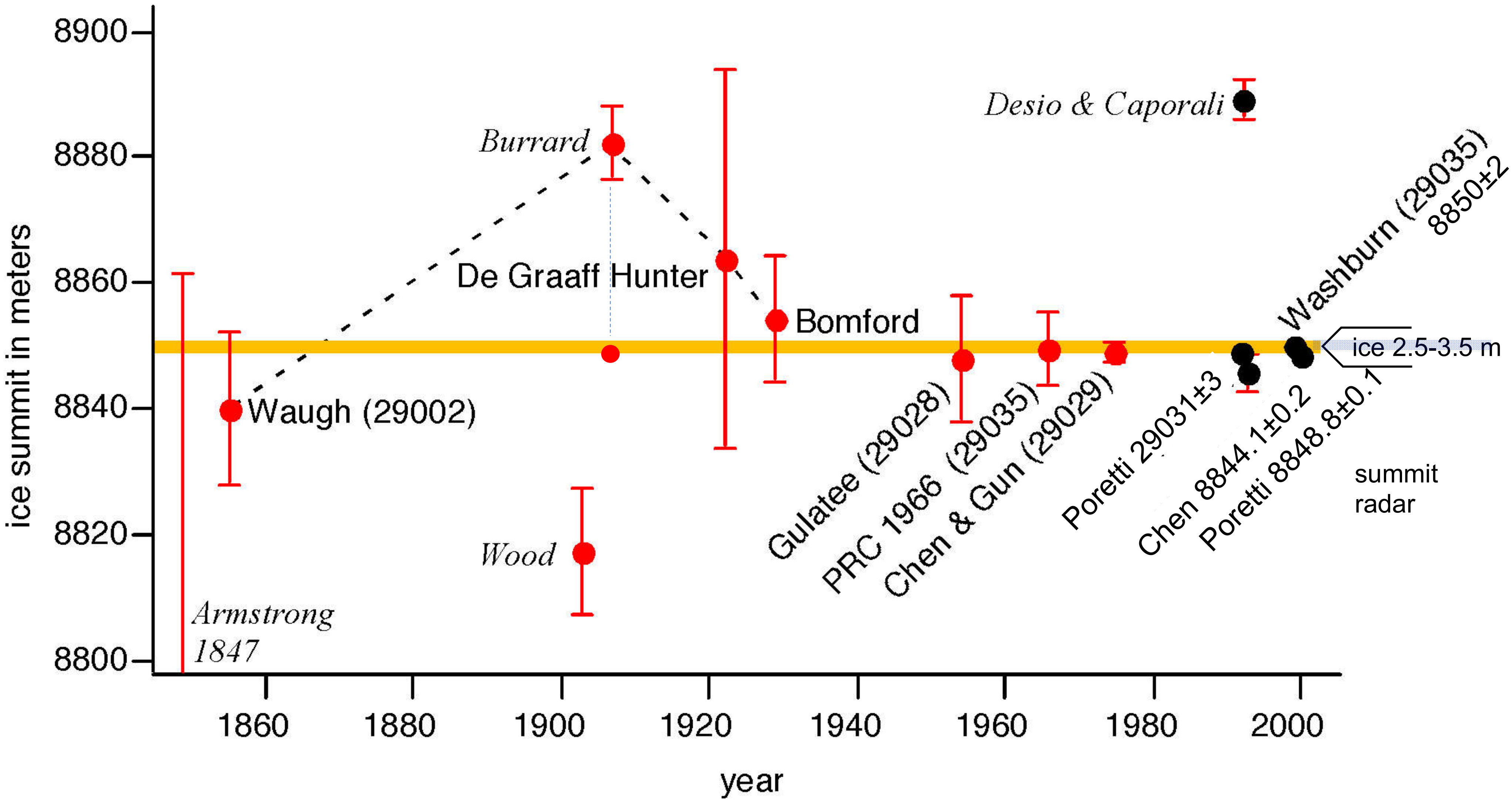
'94'04 Poretti 8852.1 snow 8848.8±0.6 rock

2005 Chen 8847.9 snow 8844.4 rock

Radar on summit & improved geoid.

Uncertainty <1 m.

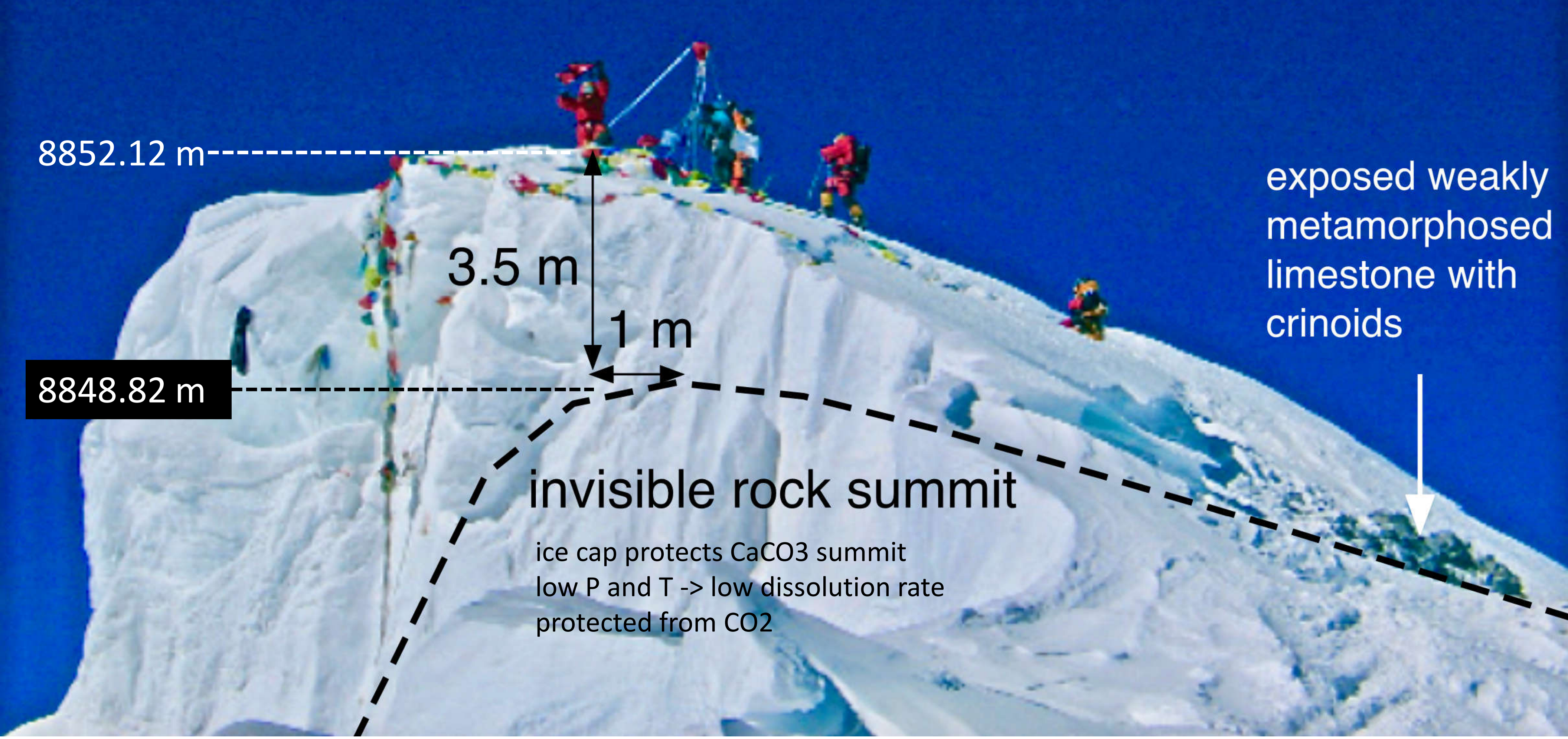




8900
8880
8860
8840
8820
8800
ice summit in meters
1860
1880
1900
1920
1940
1960
1980
2000
year
Armstrong
1847
Waugh (29002)
Wood
Burrard
De Graaff Hunter
Bomford
Gulatee (29028)
PRC 1966 (29035)
Chen & Gun (29029)
Desio & Caporali
Poretti 29031±3
Chen 8844.1±0.2
Poretti 8848.8±0.1
Washburn (29035)
8850±2
ice 2.5-3.5 m
summit
radar

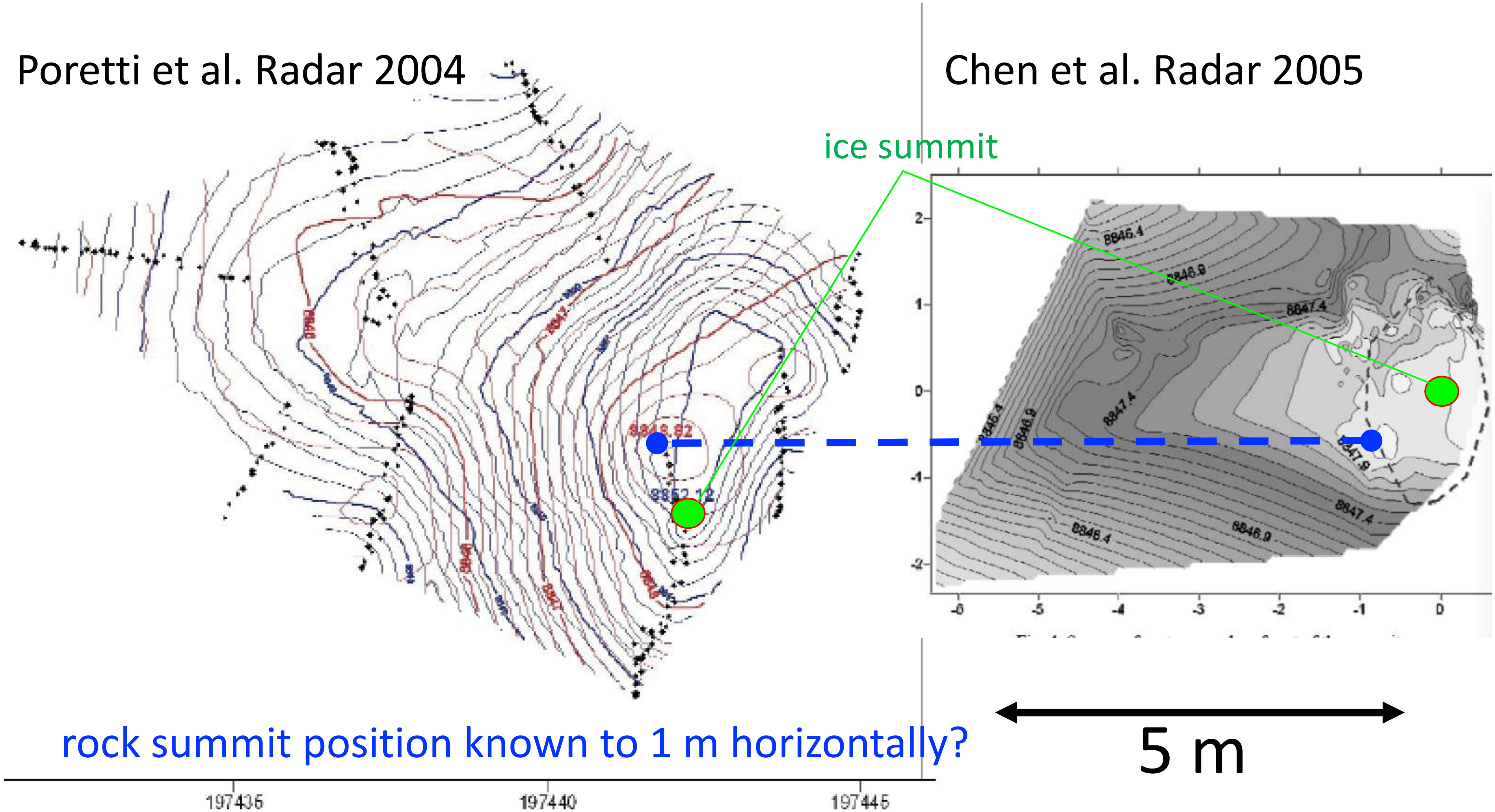
2. Variable ice thickness - snow, ice & dissolution

(major improvement by Poretti et al.)



Poretti et al. Radar 2004

Chen et al. Radar 2005

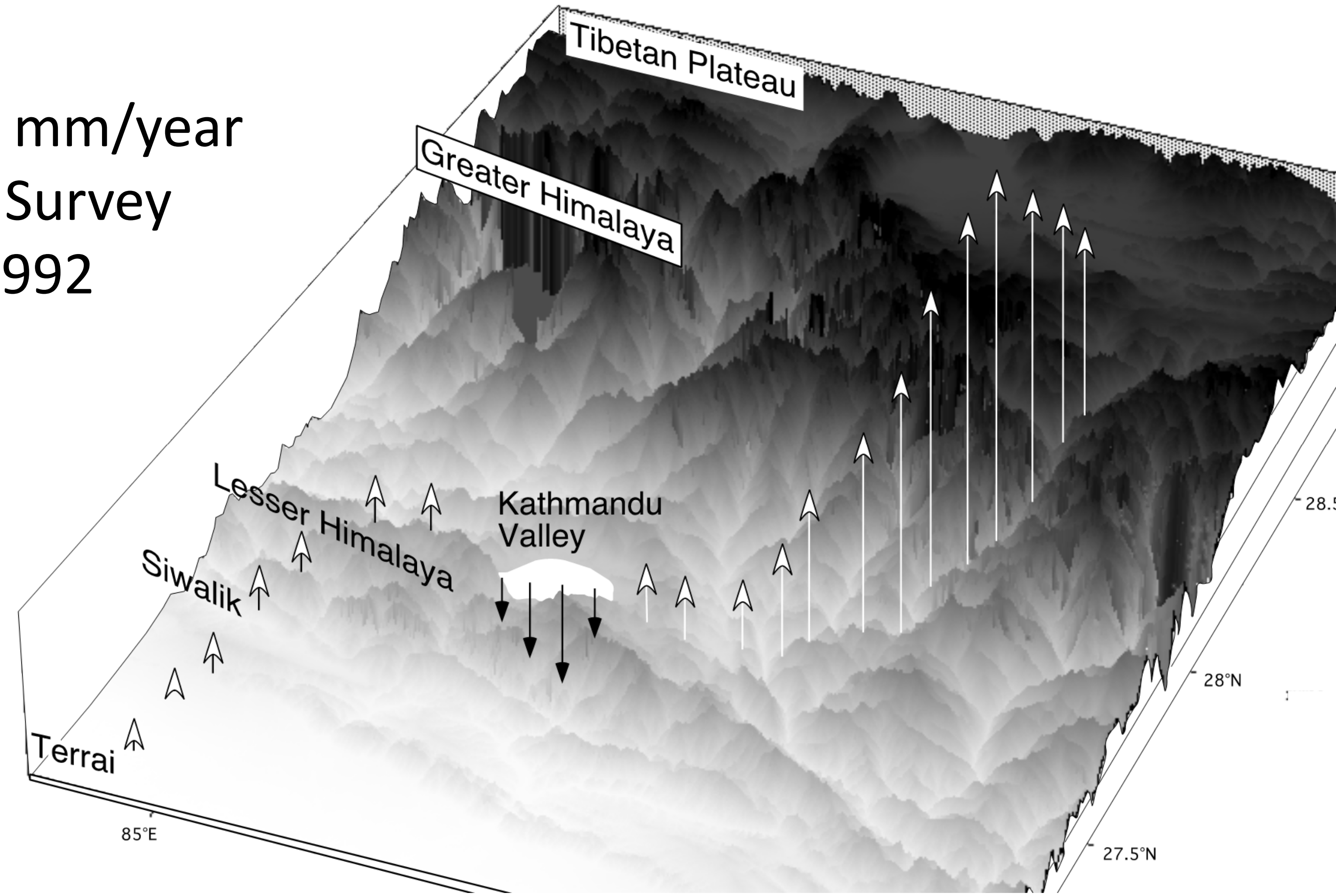


rock summit position known to 1 m horizontally?

rock summit may be exposed in <350 years if 1cm/year decadal loss

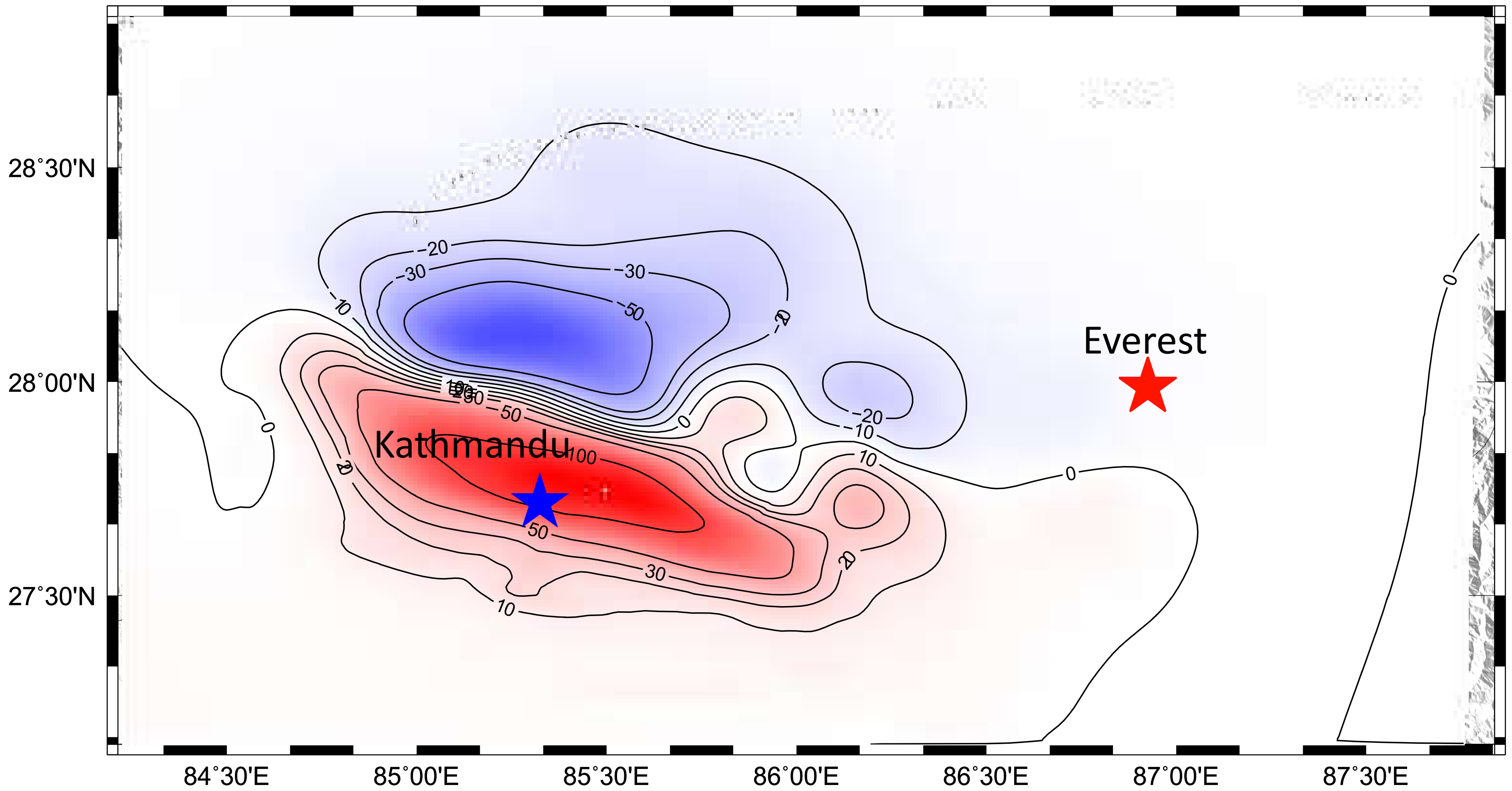
3. Tectonic motions of Mt. Everest

Interseismic uplift 5 mm/year measured by Nepal Survey Department 1975-1992

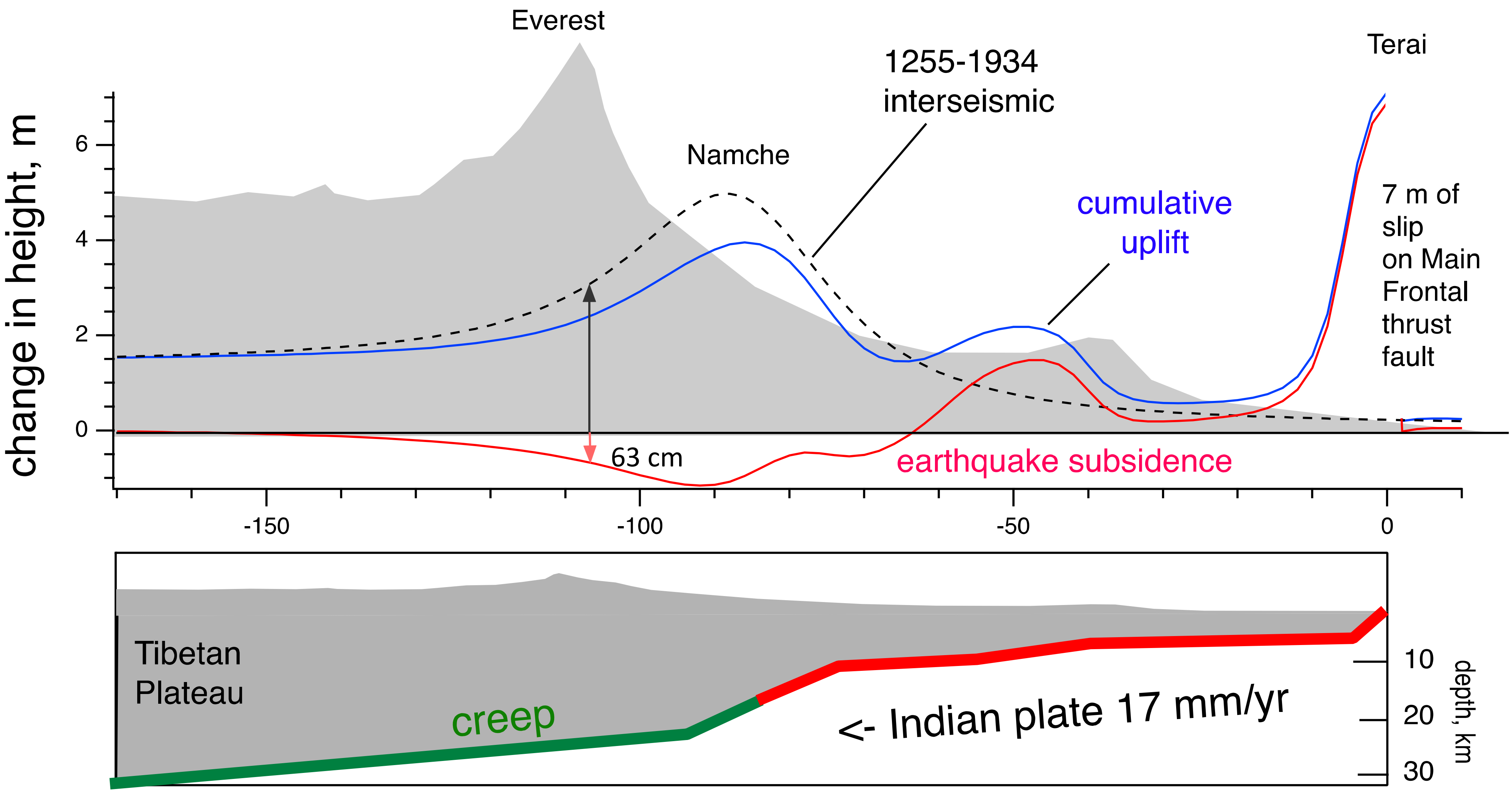


Everest sank 2.62 cm in the 2015 Mw7.8 earthquake

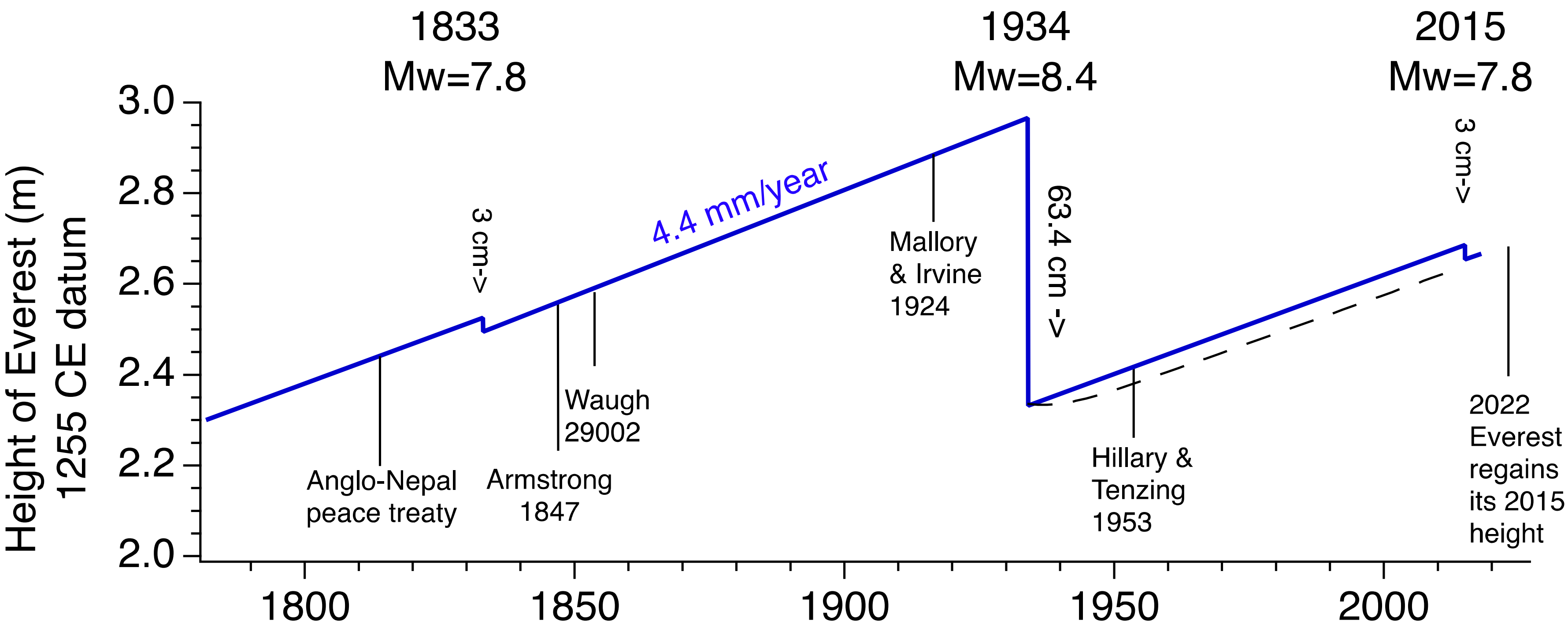
2015-04-25 M7.8 and 2015-05-12 M7.3 (Dave Mencin calculation)



Everest sank 63.4 cm in the 1934 Mw=8.4 earthquake

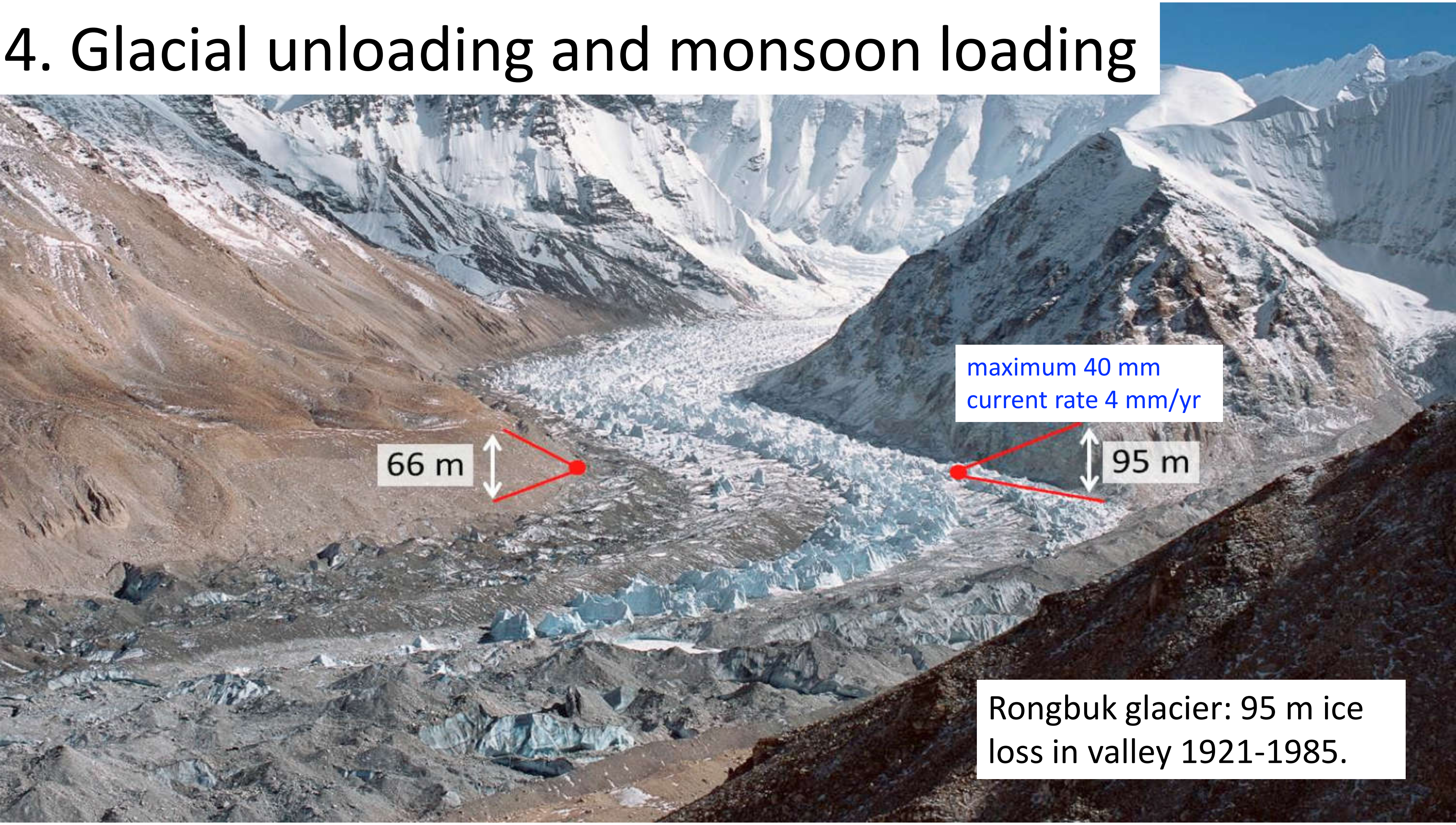


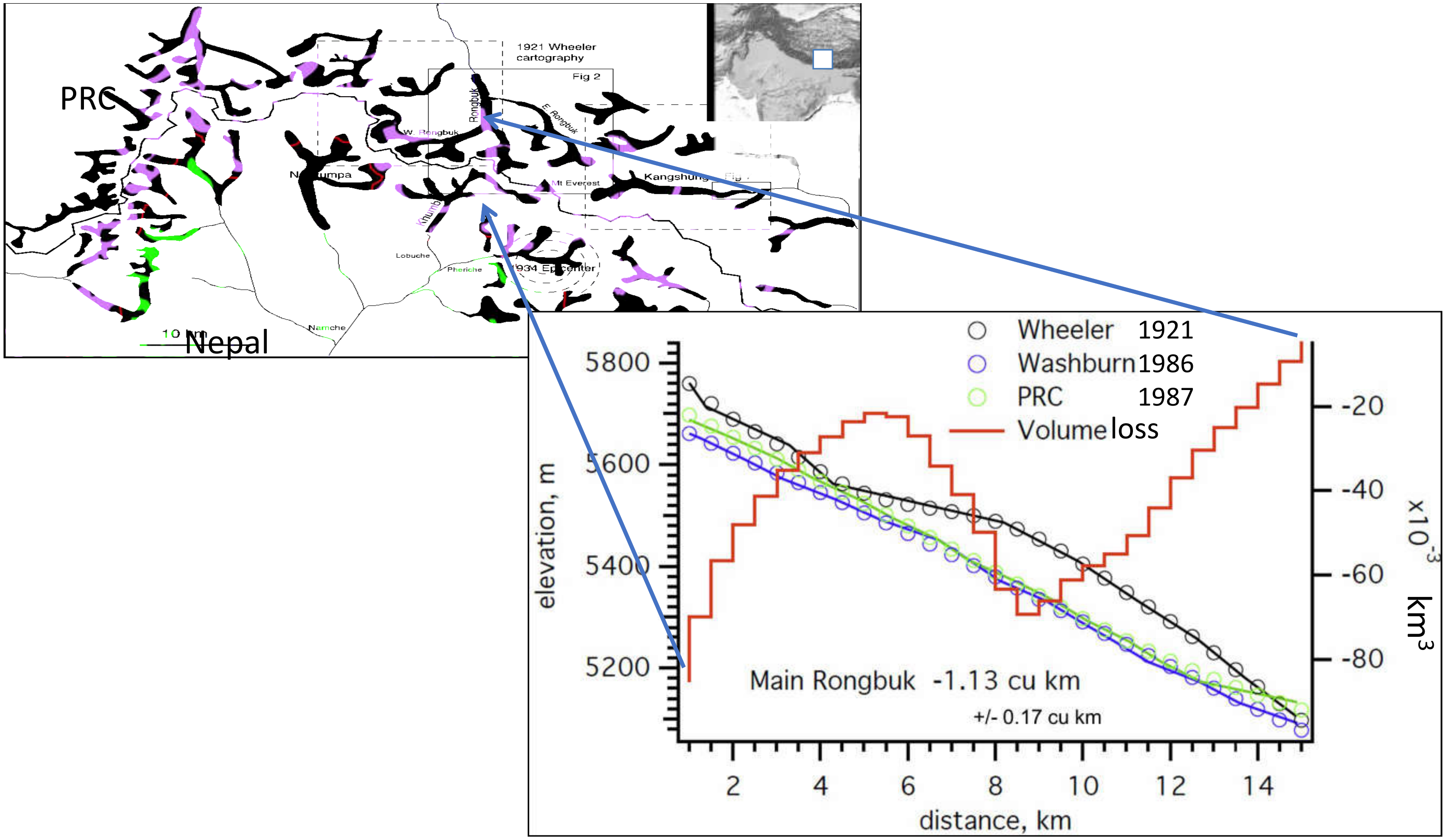
tectonic motions of Everest 1780-2022



- Everest 1995 same elevation as observed by Waugh 1852
- Hillary and Tenzing 1953 –climbed its lowest height since 1800
- Everest will exceed its 2015 elevation in 2022
- Everest will exceed its 1934 elevation in 2079
- Everest will rise a further ≈2.5 m before the next Mw-8.4 earthquake >450 years from now

4. Glacial unloading and monsoon loading





Photos and cartography in 1921 and 1985 indicate mass loss in valley glaciers north of Everest

3.72 ± 0.6 km^3. i.e. 10 cm uniform ice loss from 500 km^2 area, fluvial loss 3mm/yr=18 cm

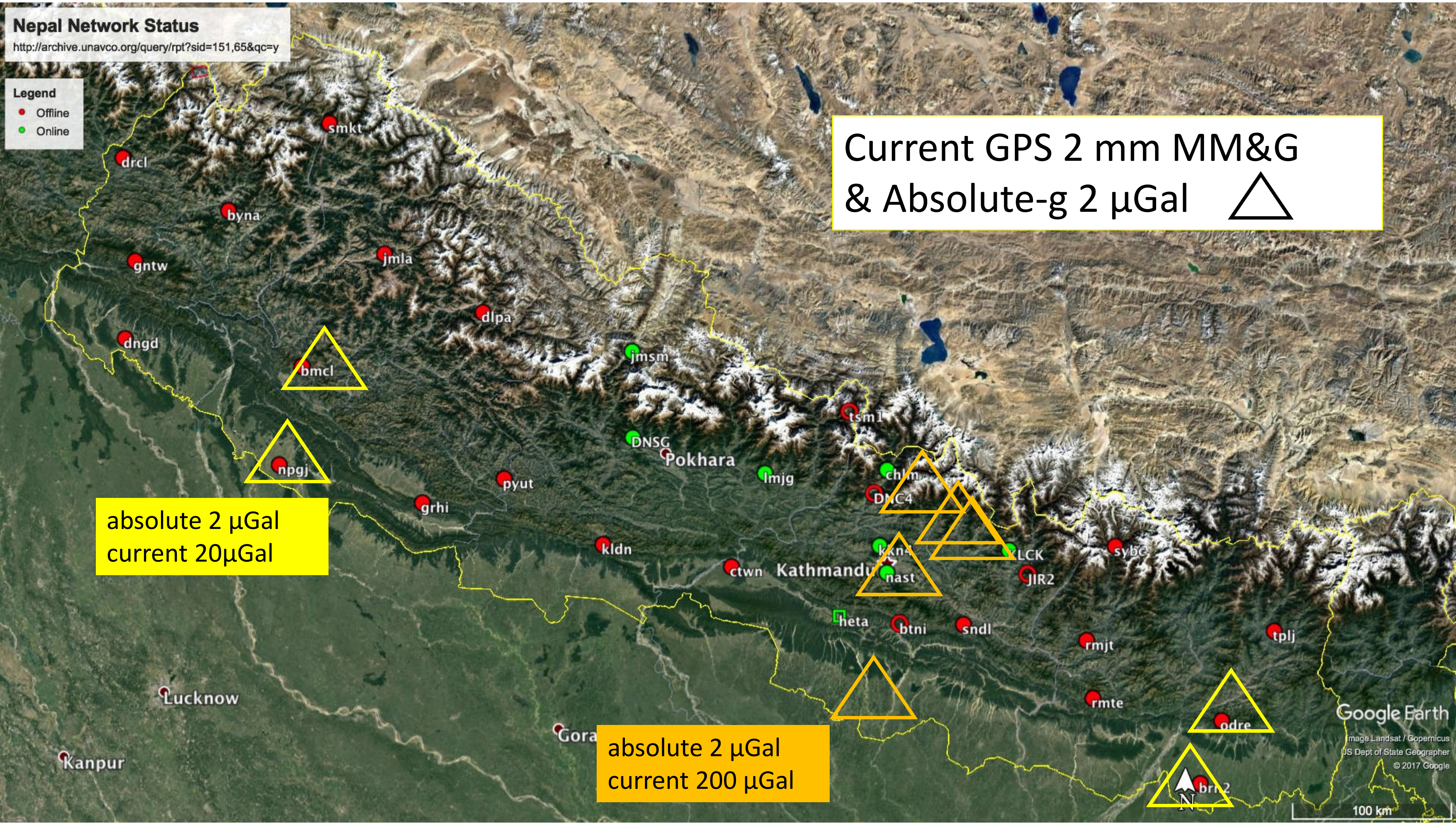
synthetic isostatic rise since 1900 ≈ 3 - 8 cm < 0.1 mm/yr

ERROR BUDGET green 3-D geodesy; blue 4-D monitoring

1. Geoid	20 cm (5 cm)	Gravity and leveling
2. Ice thickness	4 cm (2 cm)	Radar plus ice core
3. Ellipsoidal ice Height	0.3 cm (2 mm)	GPS on Radar sled
4. Tectonics	0.4 cm/yr (1 mm)	(KalaPatar or Pyramid
5. Isostatic loading	0.2 cm/yr (1 mm)	continuous GPS)
6. global warming ≈ 2°C, 2 km$\times 10^{-6}$/°C =	+0.2 mm/yr	

total error budget now ≈25 cm future ≈7 cm

potential accuracy limited by 2 cm summit spallation


Nepal Network Status
http://archive.unavco.org/query/rpt?sid=151,65&qc=y
Legend
Offline
Online
Current GPS 2 mm MM&G
& Absolute-g 2 µGal
absolute 2 µGal
current 20µGal
absolute 2 µGal
current 200 µGal
smkt
drcl
byna
gntw
jmla
dlpa
dngd
bmcl
jmsm
npgj
DNSG
Pokhara
lmjg
pyut
grhi
kldn
ctwn
Kathmandu
nast
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JIR2
sybc
heta
btni
sndl
rmjt
tplj
rmte
odre
Lucknow
Kanpur
Google Earth
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US Dept of State Geographer
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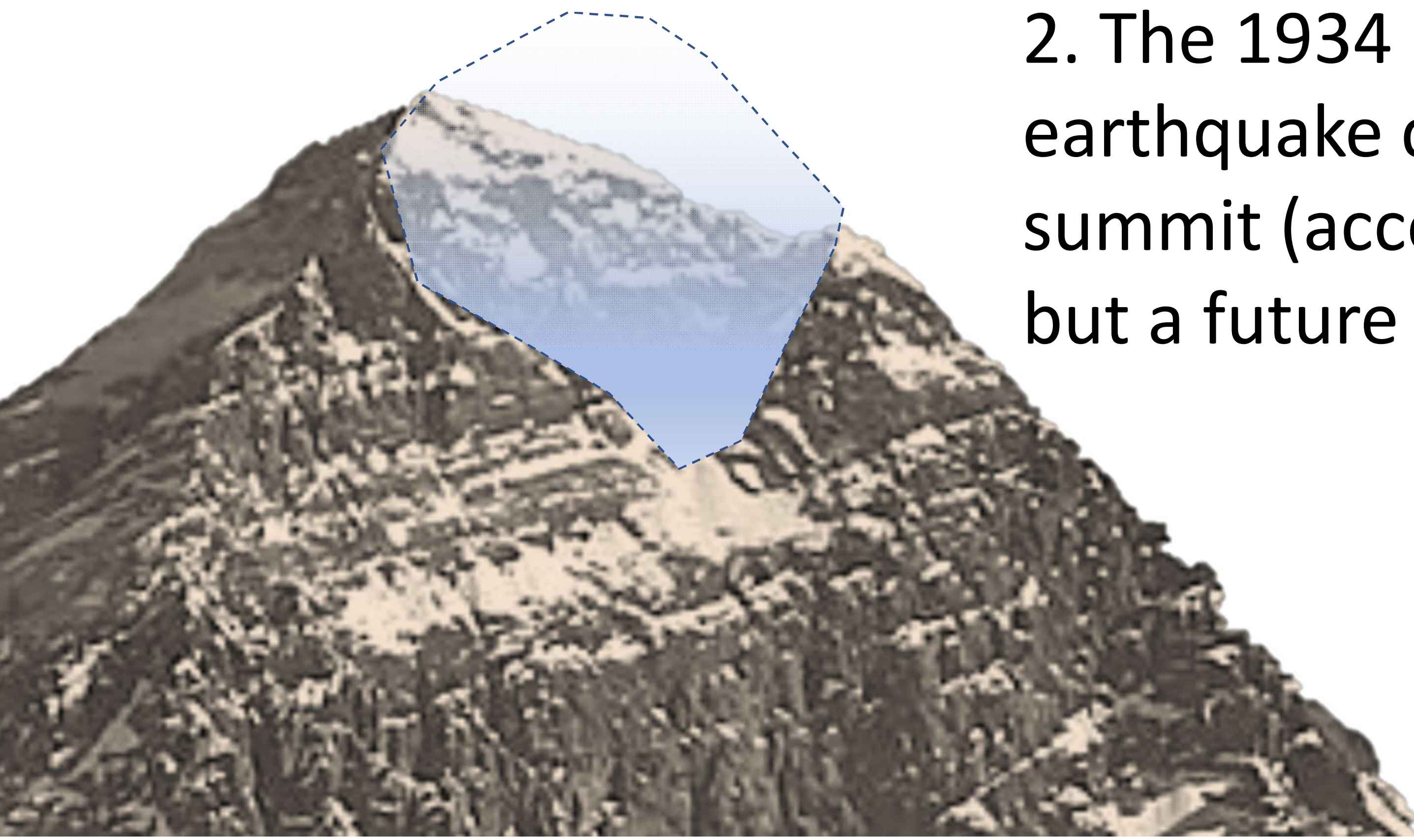
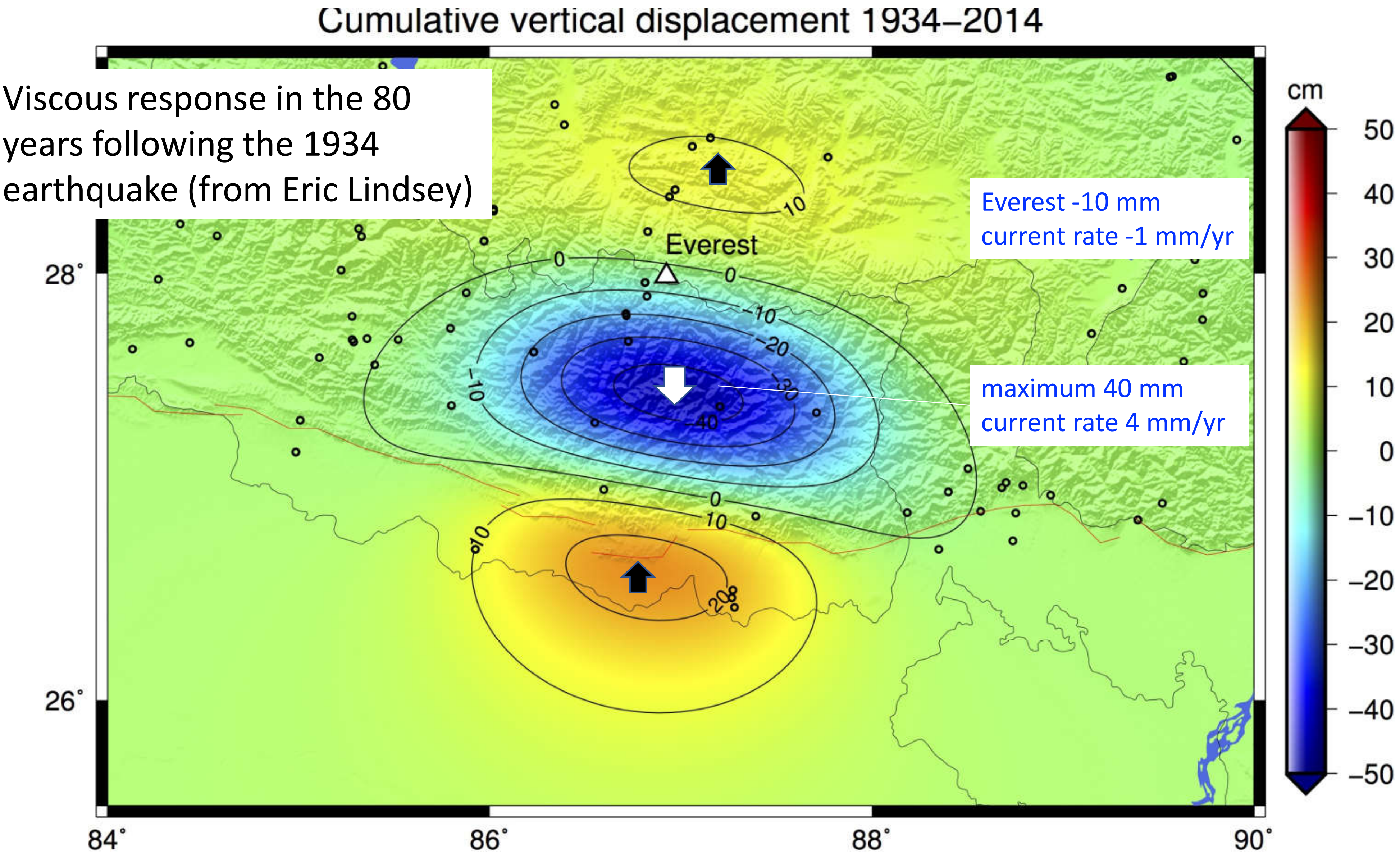
100 km

The key to Everest's future height lies in its past collapse

1. It is probable that the summit was reduced by >50 m by one of the five previous Mw=8.4 earthquakes since 3000BC.



2. The 1934 Mw8.4 Nepal earthquake did not destroy its summit (accelerations >0.5 g), but a future earthquake will.


Cumulative vertical displacement 1934–2014
Viscous response in the 80 years following the 1934 earthquake (from Eric Lindsey)
Everest
Everest -10 mm
current rate -1 mm/yr
maximum 40 mm
current rate 4 mm/yr
cm
50
40
30
20
10
0
−10
−20
−30
−40
−50
28°
26°
84°
86°
88°
90°