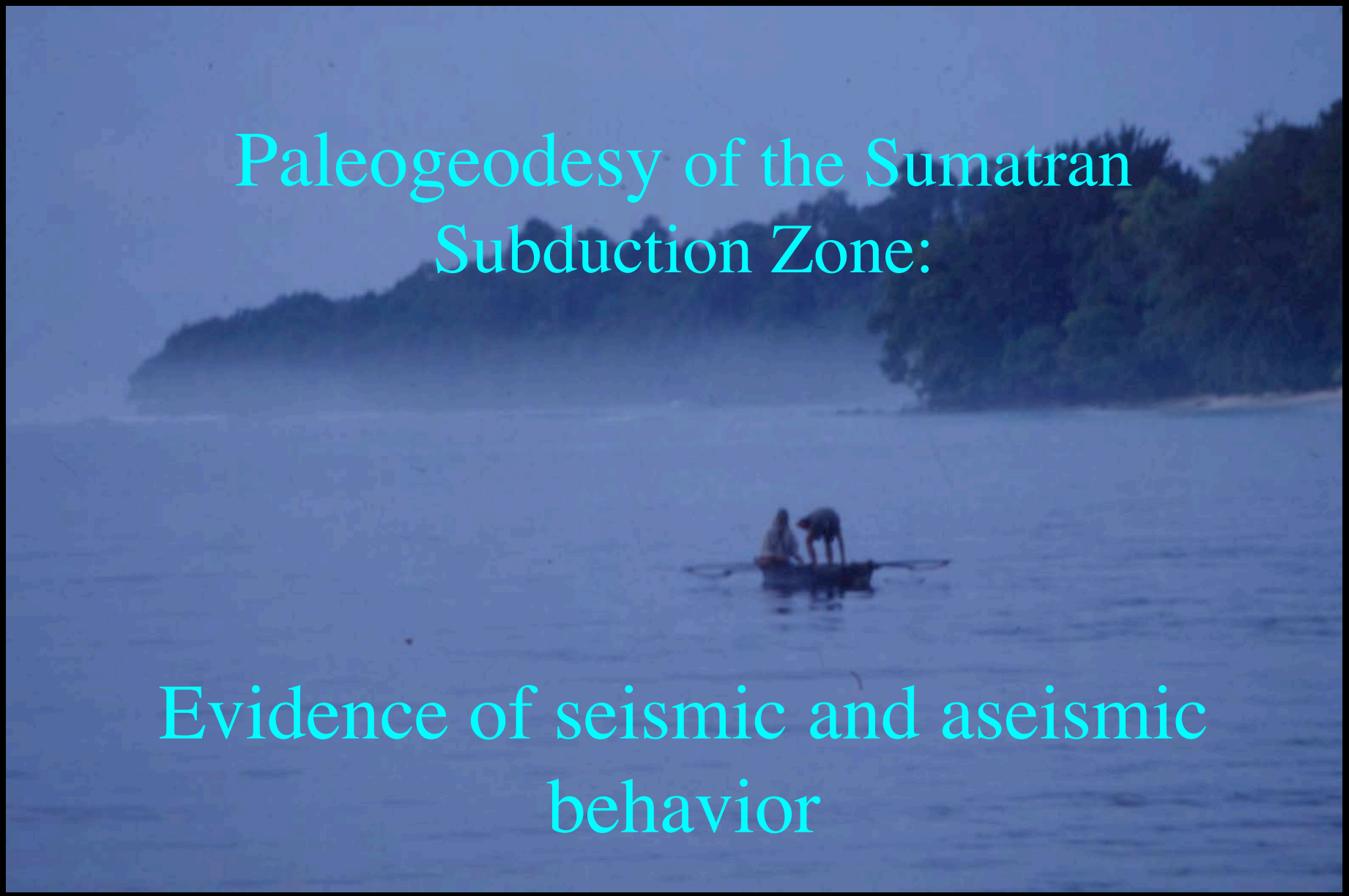
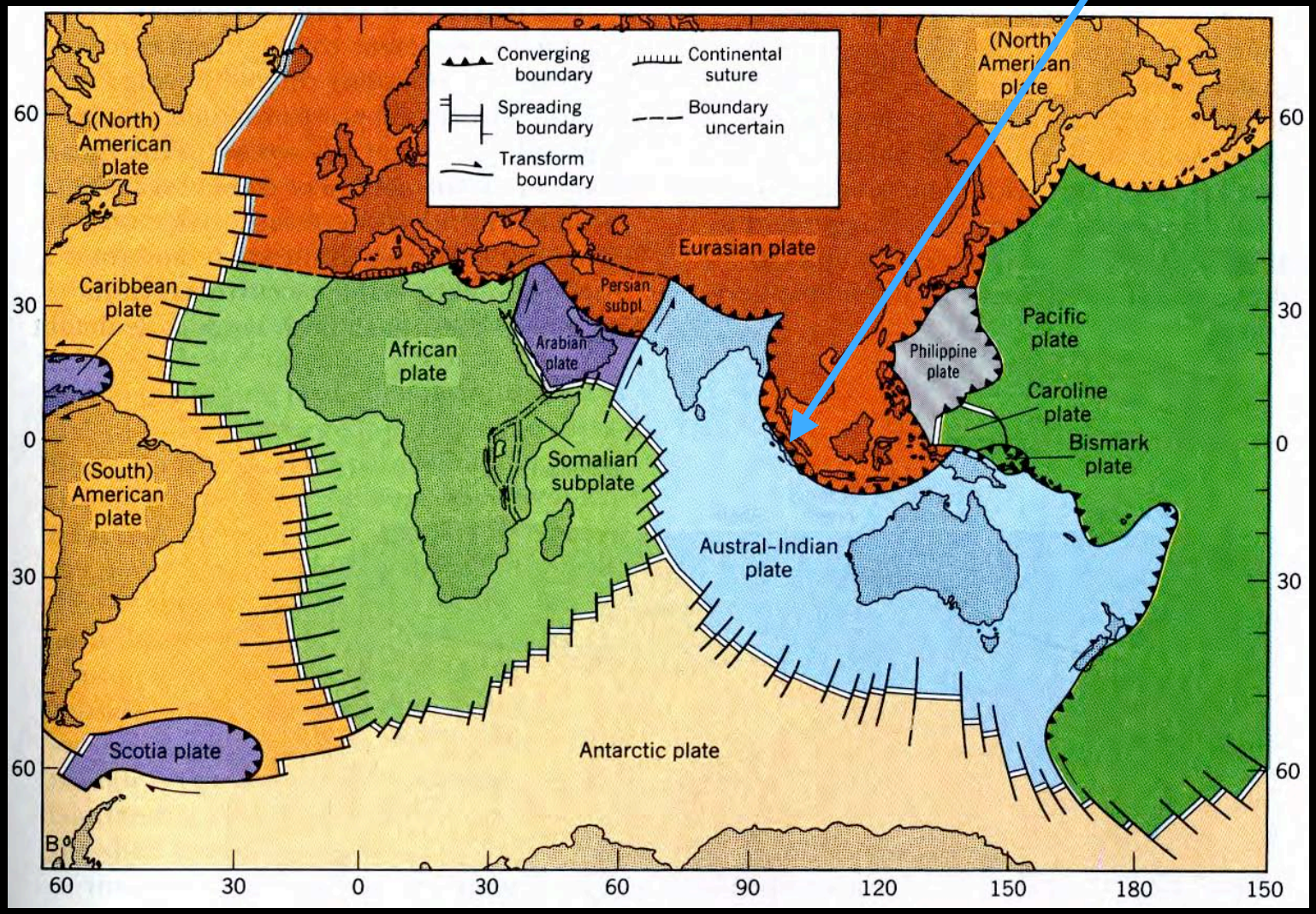

Paleogeodesy of the Sumatran Subduction Zone:
Evidence of seismic and aseismic behavior

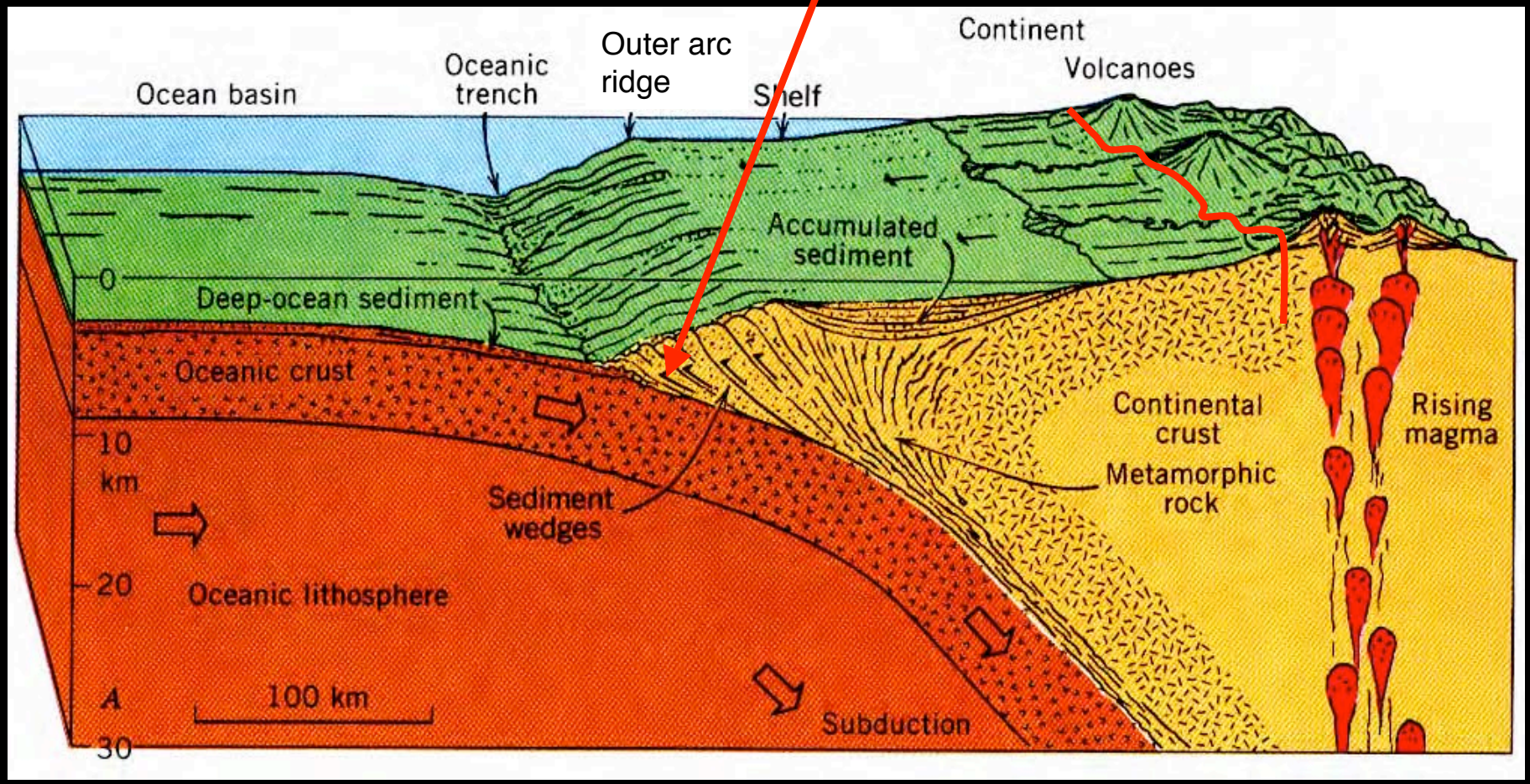
Some fundamental questions about active faults

- What determines whether a fault fails seismically or aseismically?
- Does fault behavior vary with time?
- How uniform are slip events?
  - In space?
  - In time?

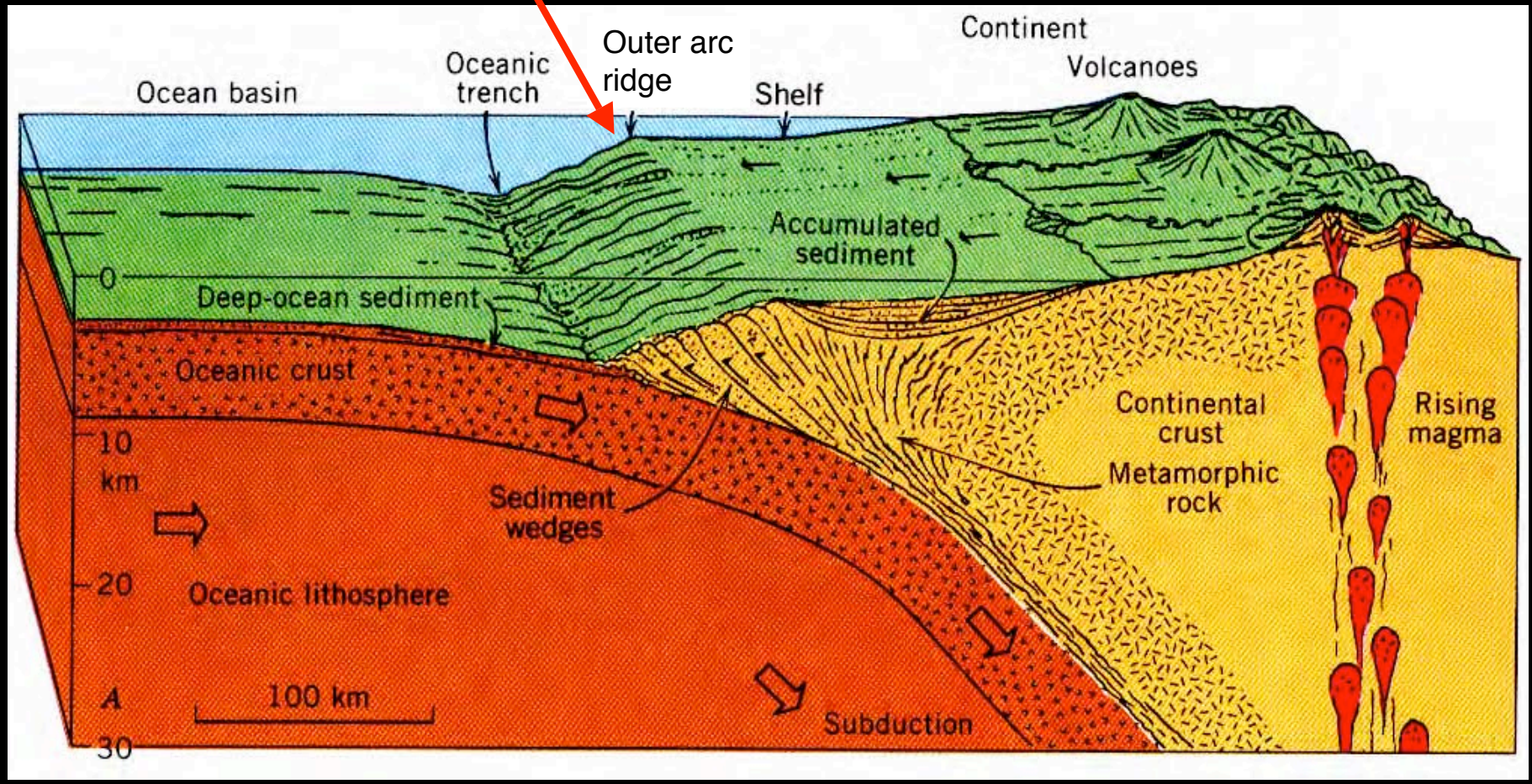
Why go all the way to Sumatra to investigate fault behavior?



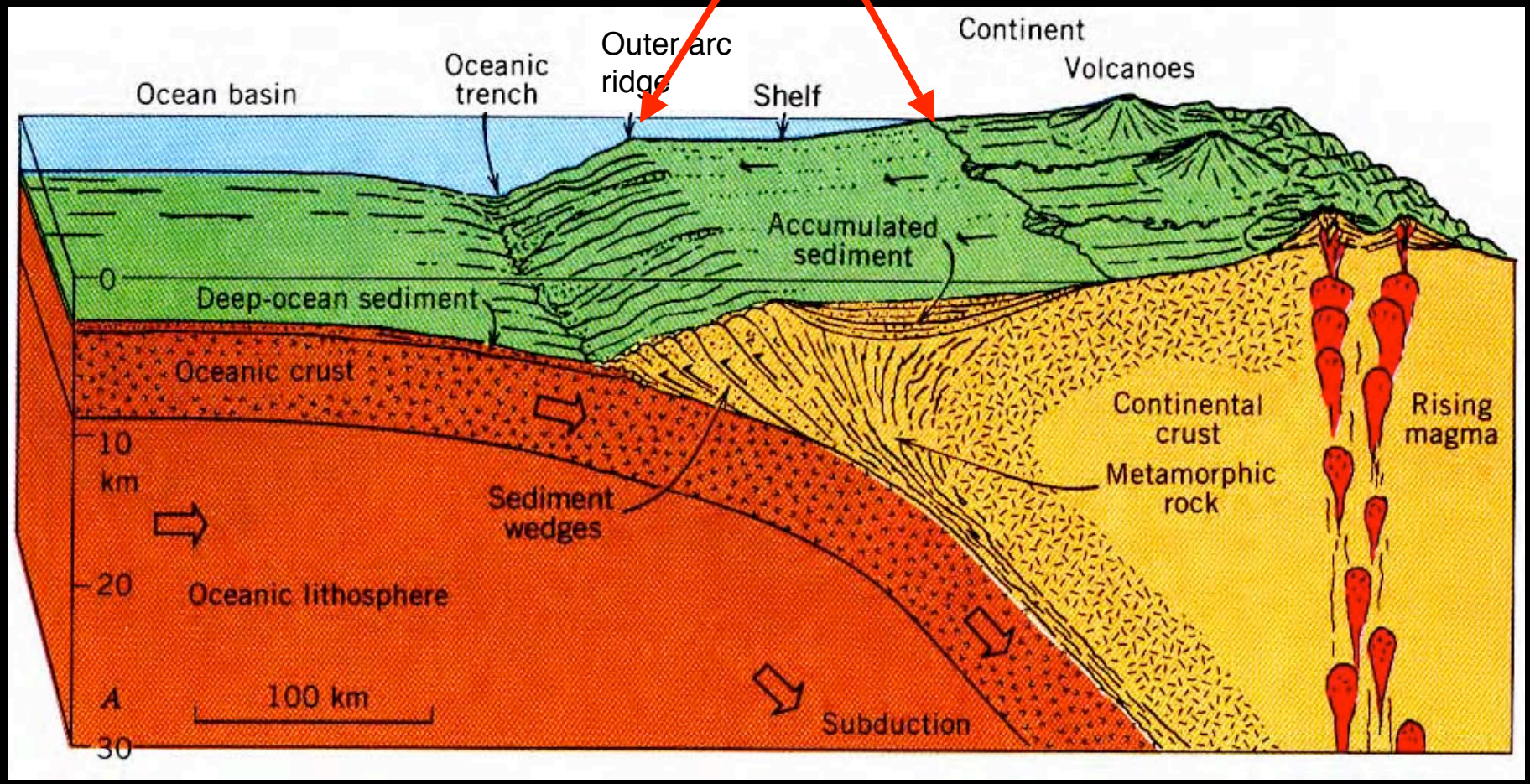
The Sumatran subduction zone is a large, isolated fault, unlikely to be influenced by its neighbors



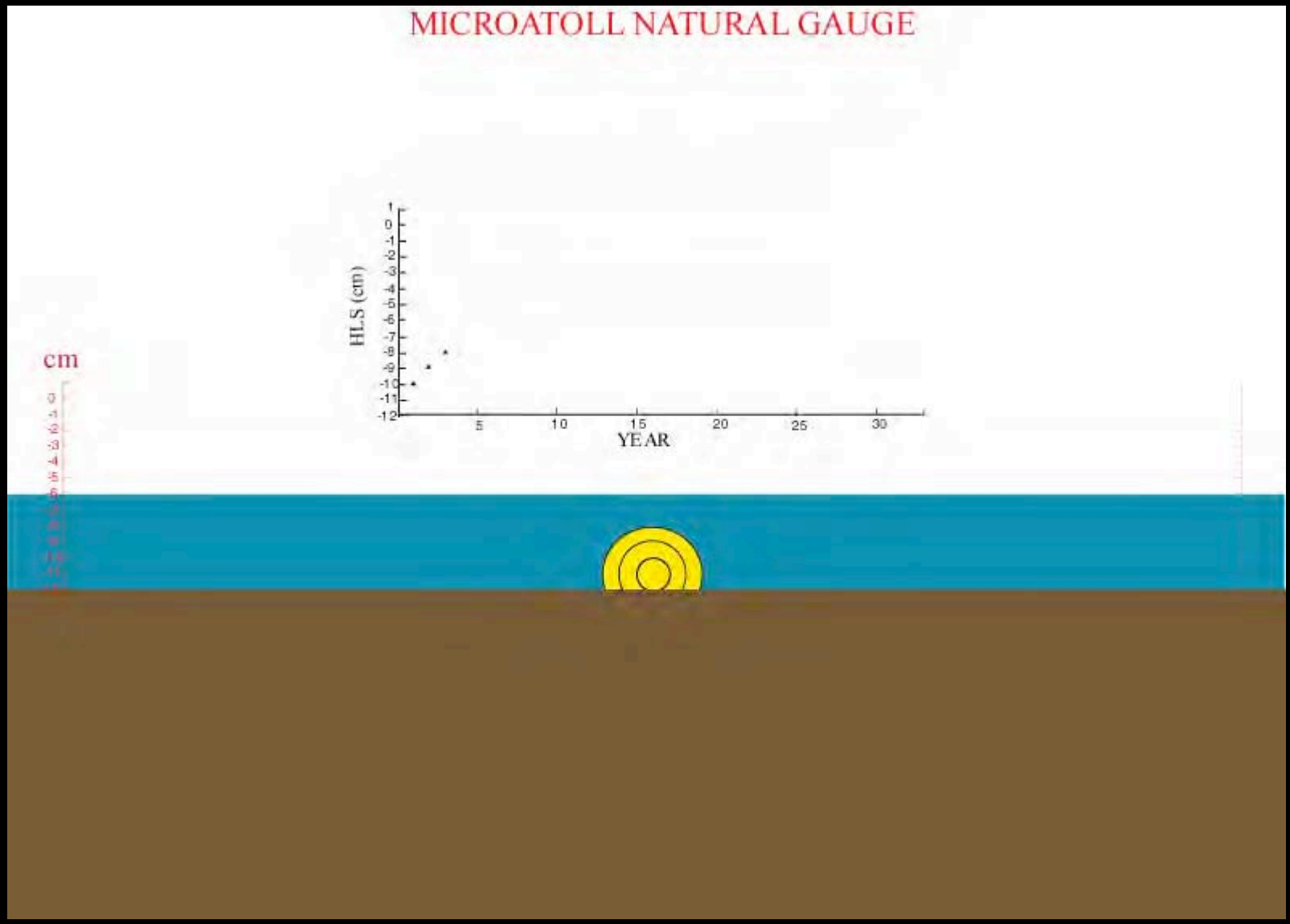
The Sumatran outer-arc ridge is largely above water …



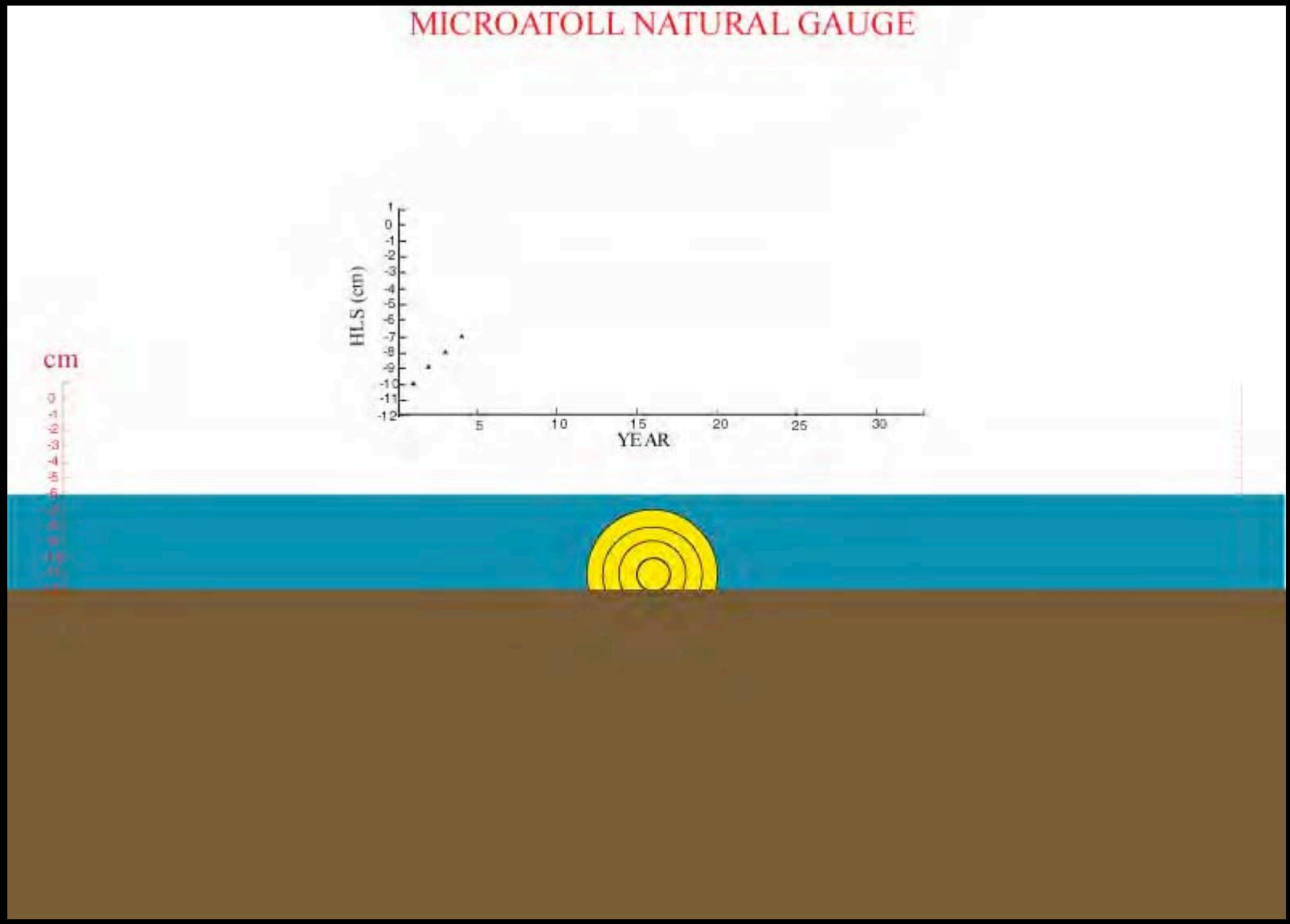
and coral “microatolls” are abundant on its fringing reefs



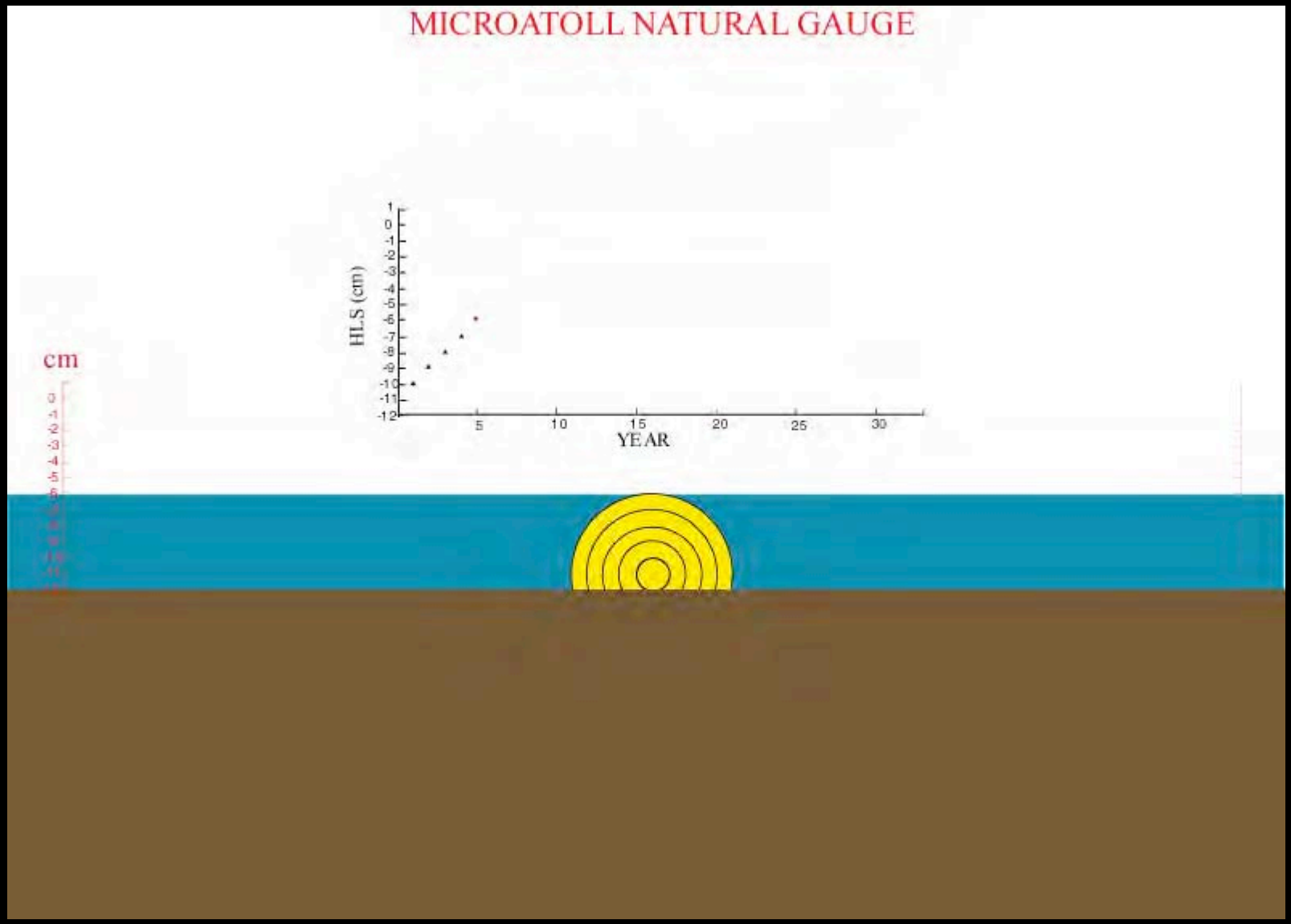
MICROATOLL NATURAL GAUGE



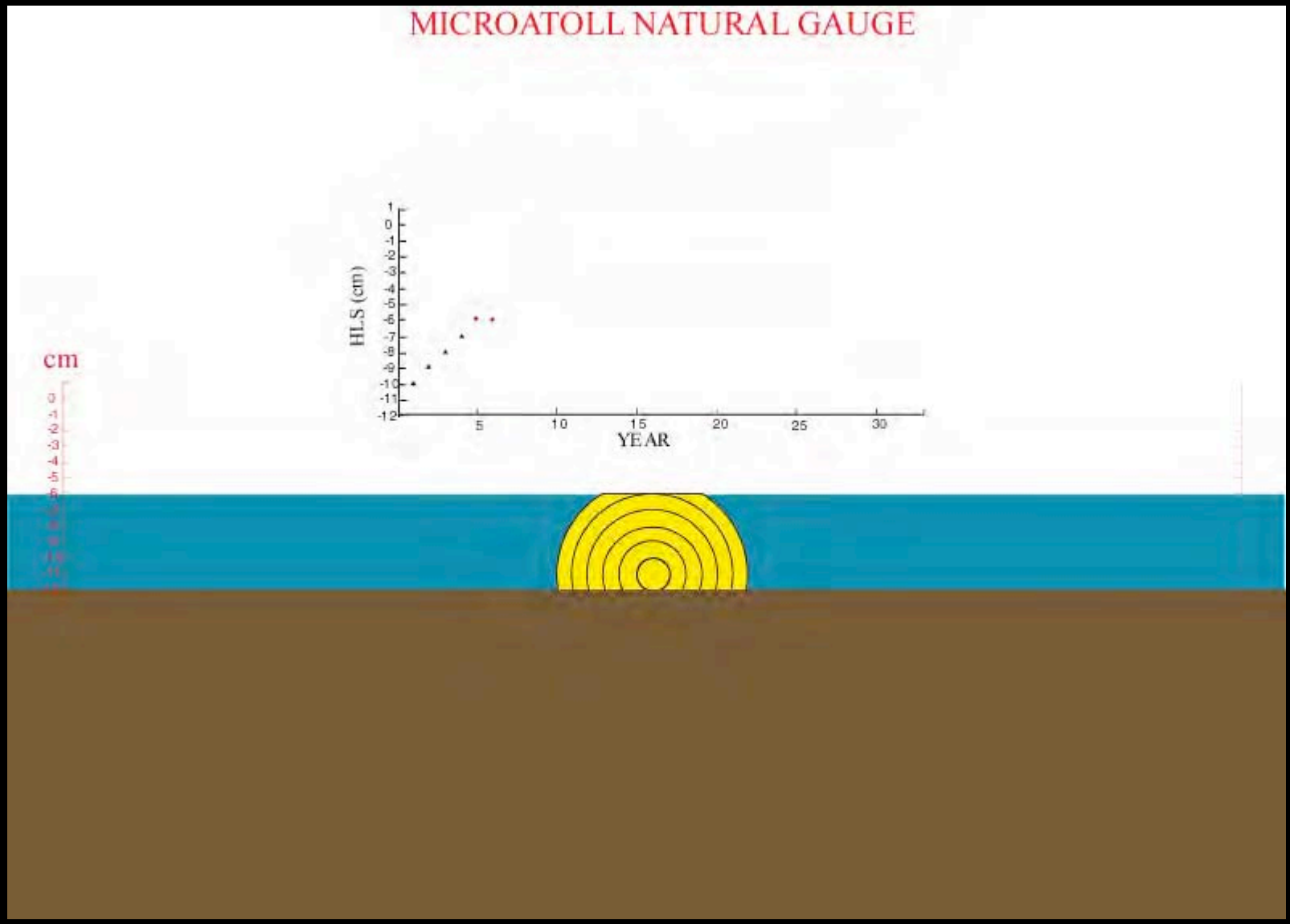
MICROATOLL NATURAL GAUGE



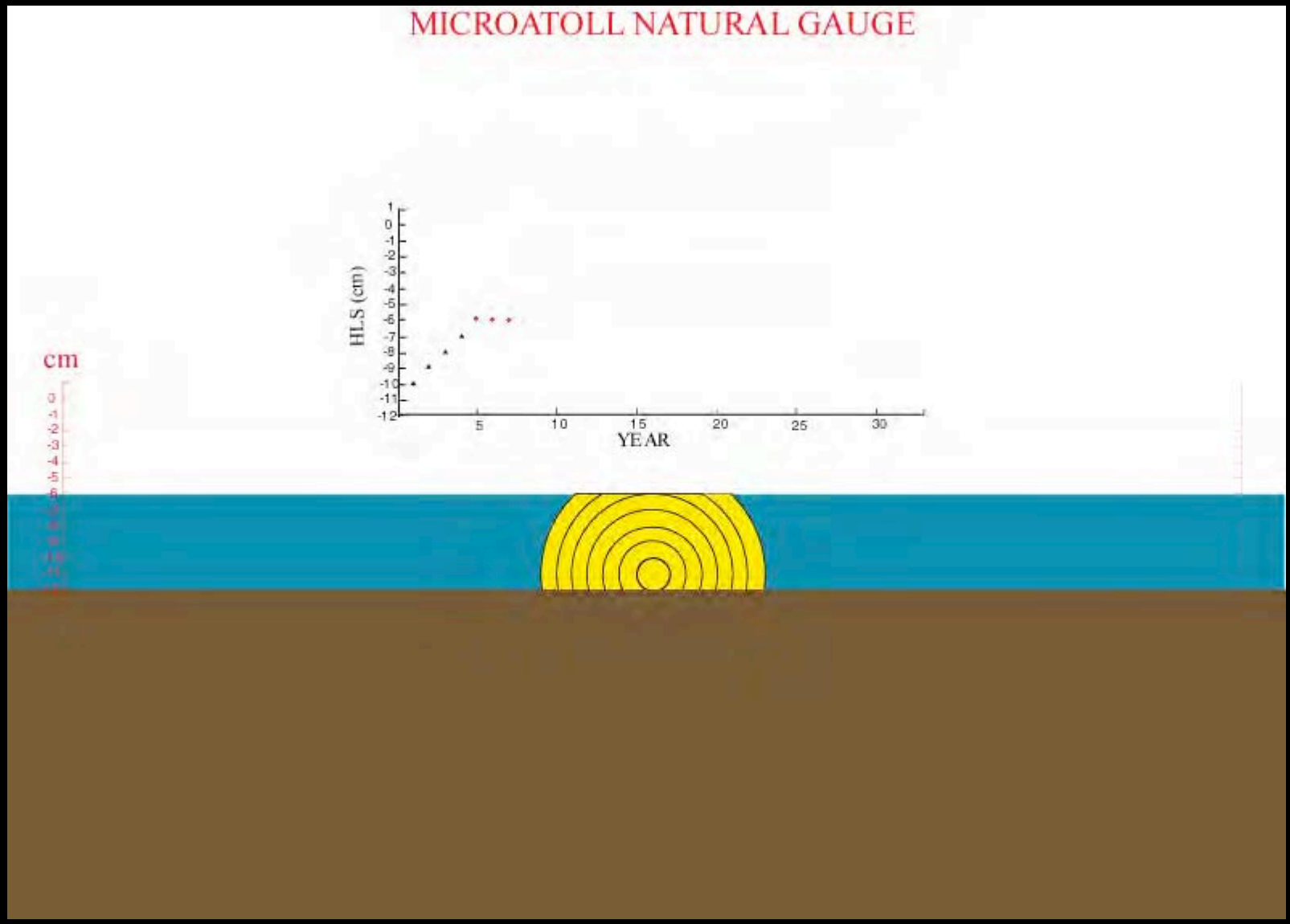
MICROATOLL NATURAL GAUGE



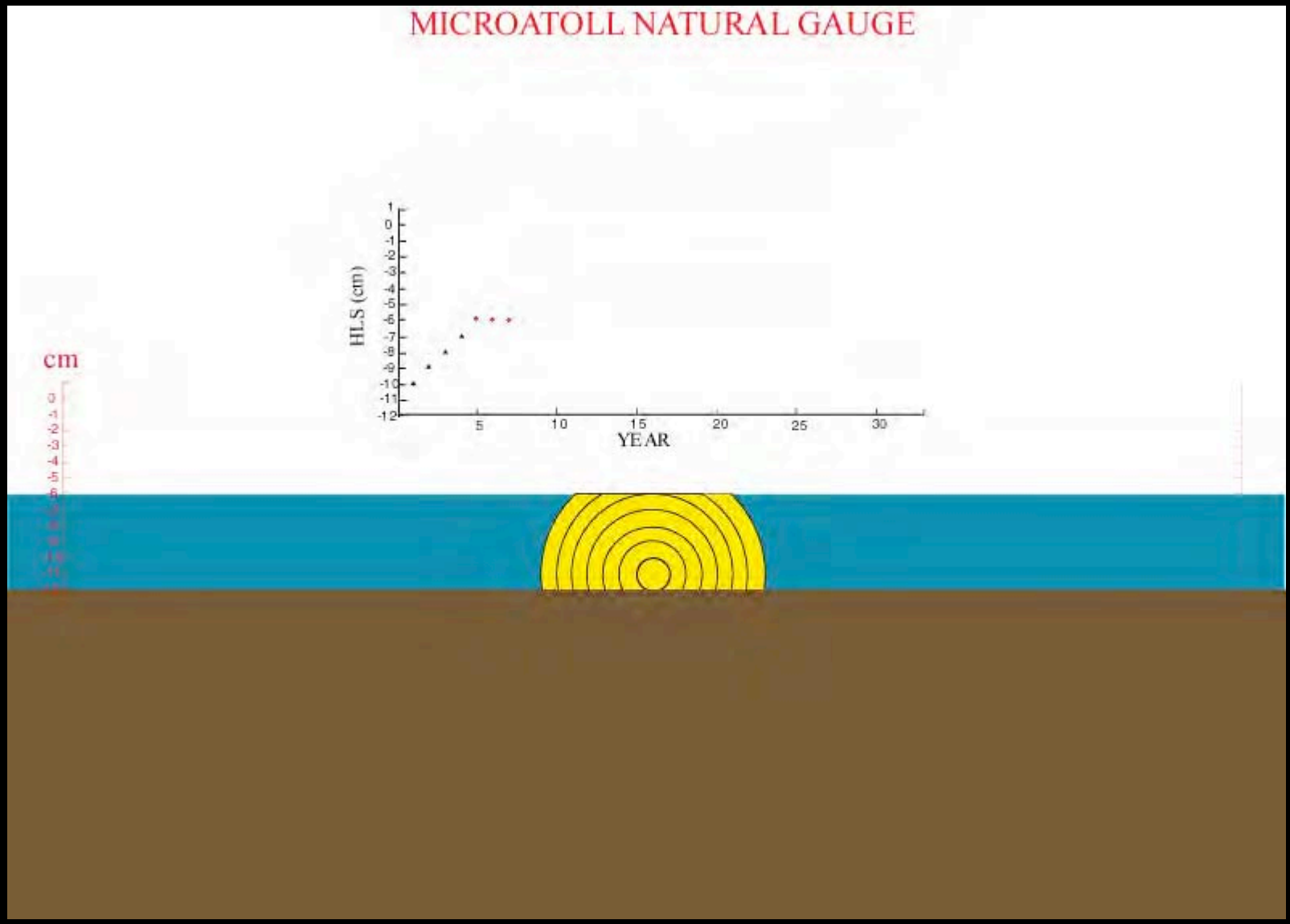
MICROATOLL NATURAL GAUGE



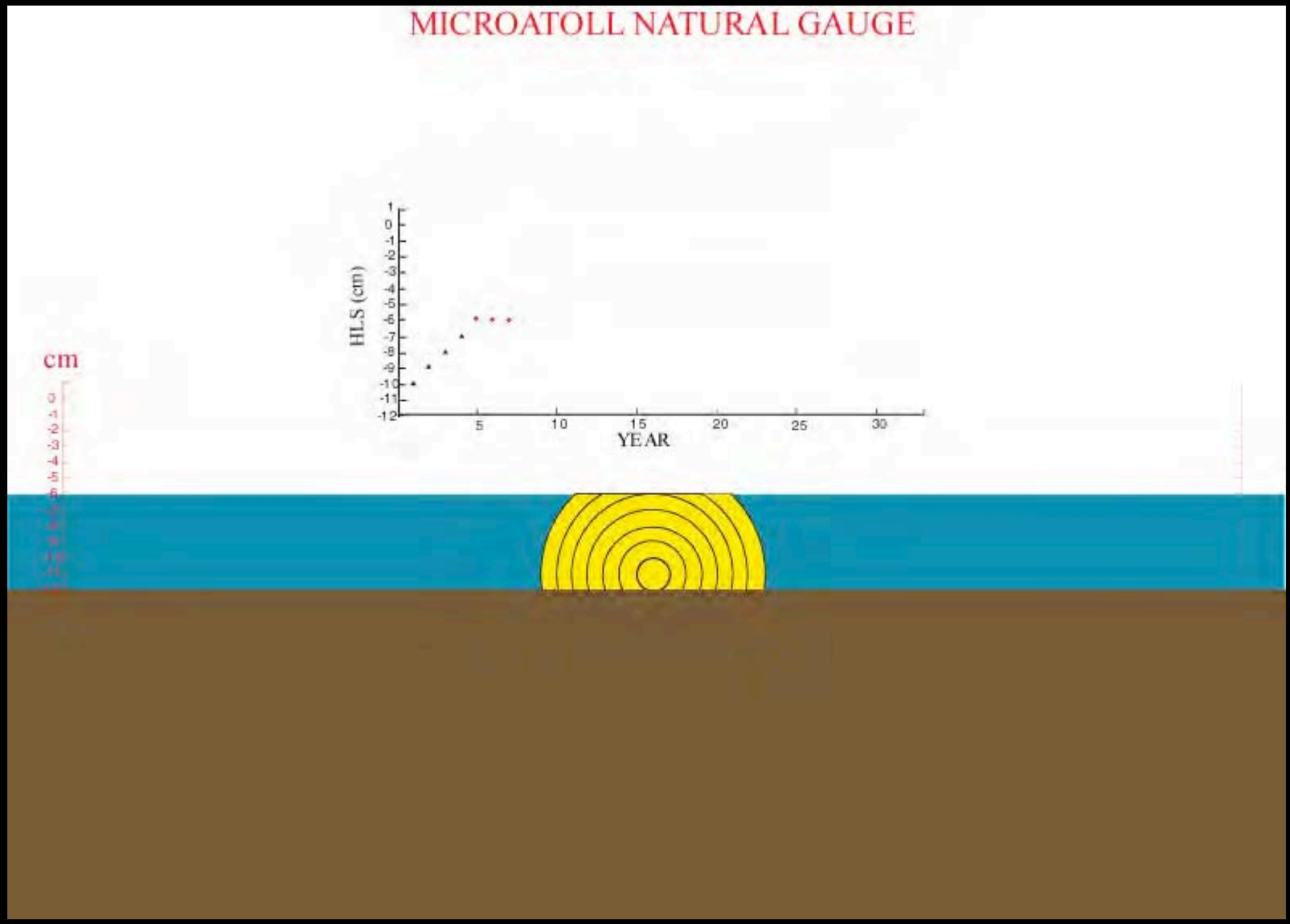
MICROATOLL NATURAL GAUGE



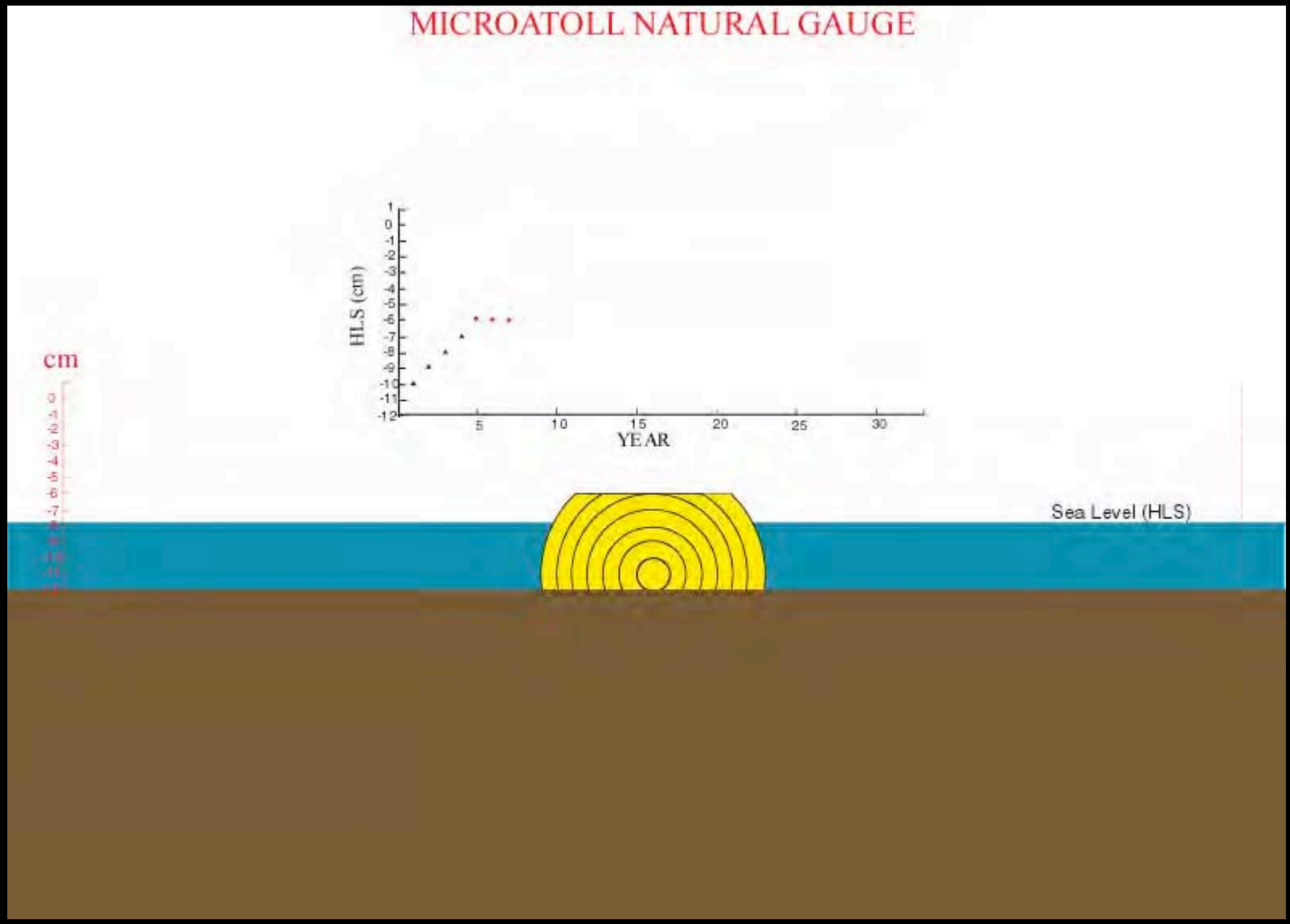
MICROATOLL NATURAL GAUGE



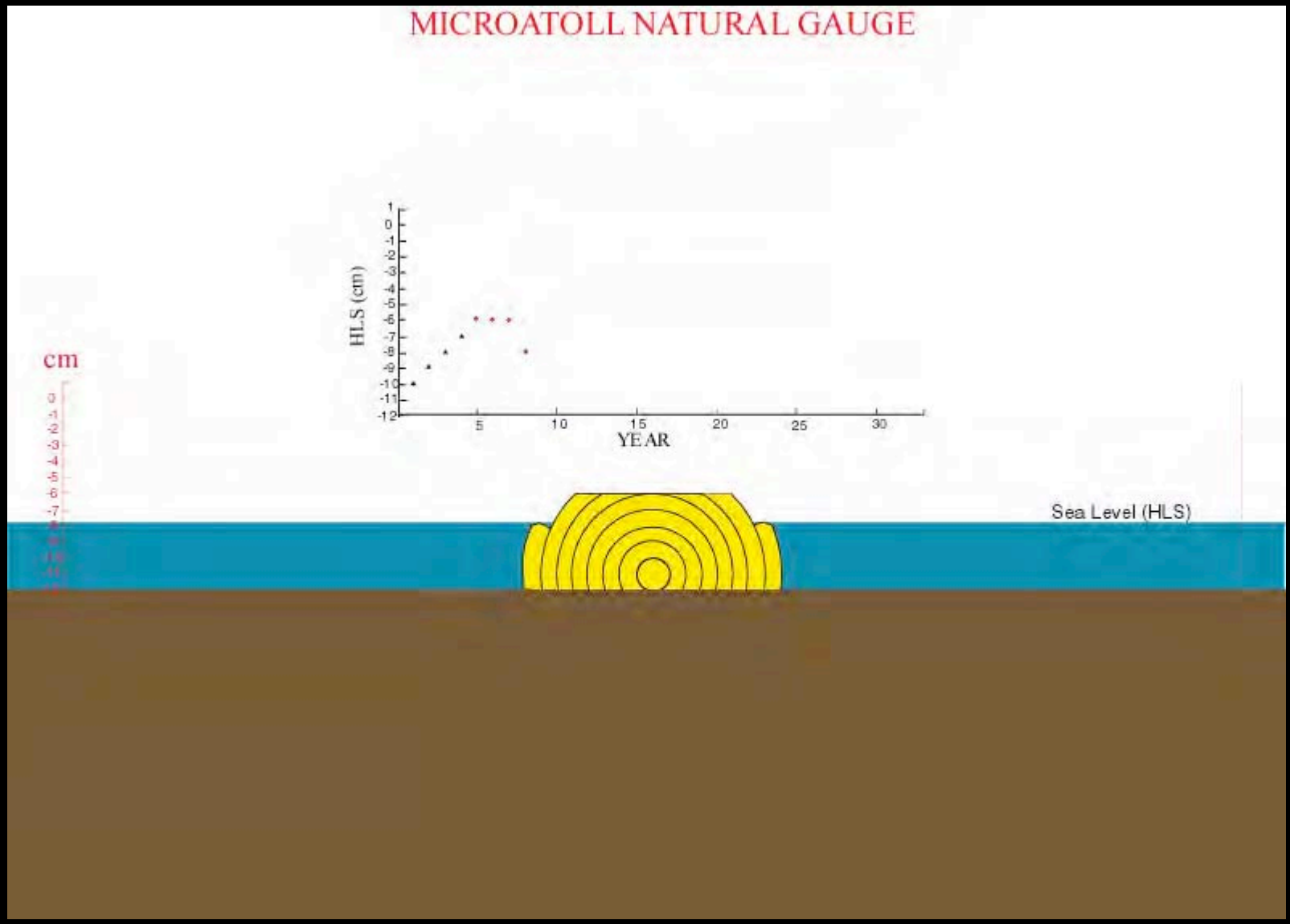
MICROATOLL NATURAL GAUGE



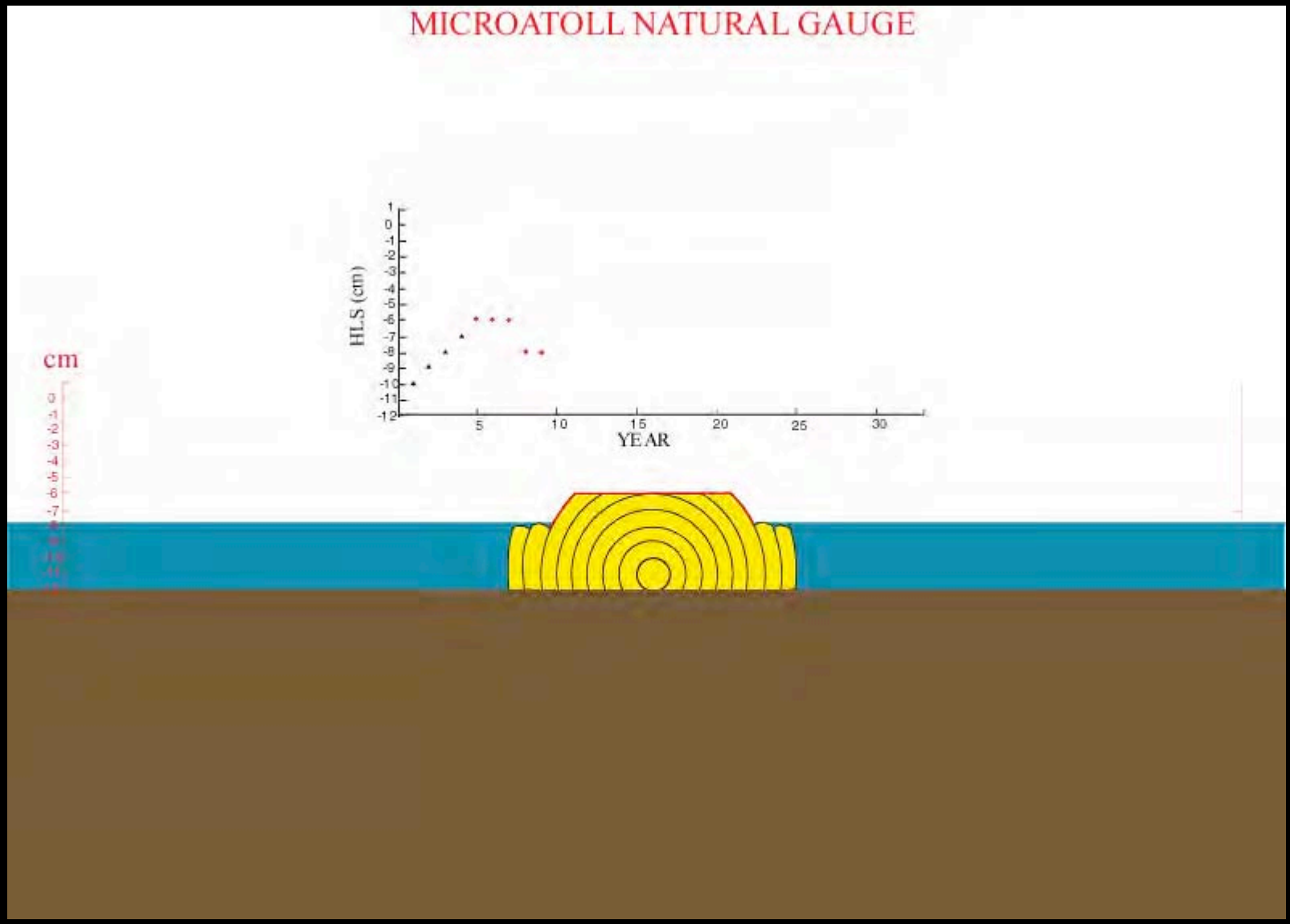
MICROATOLL NATURAL GAUGE



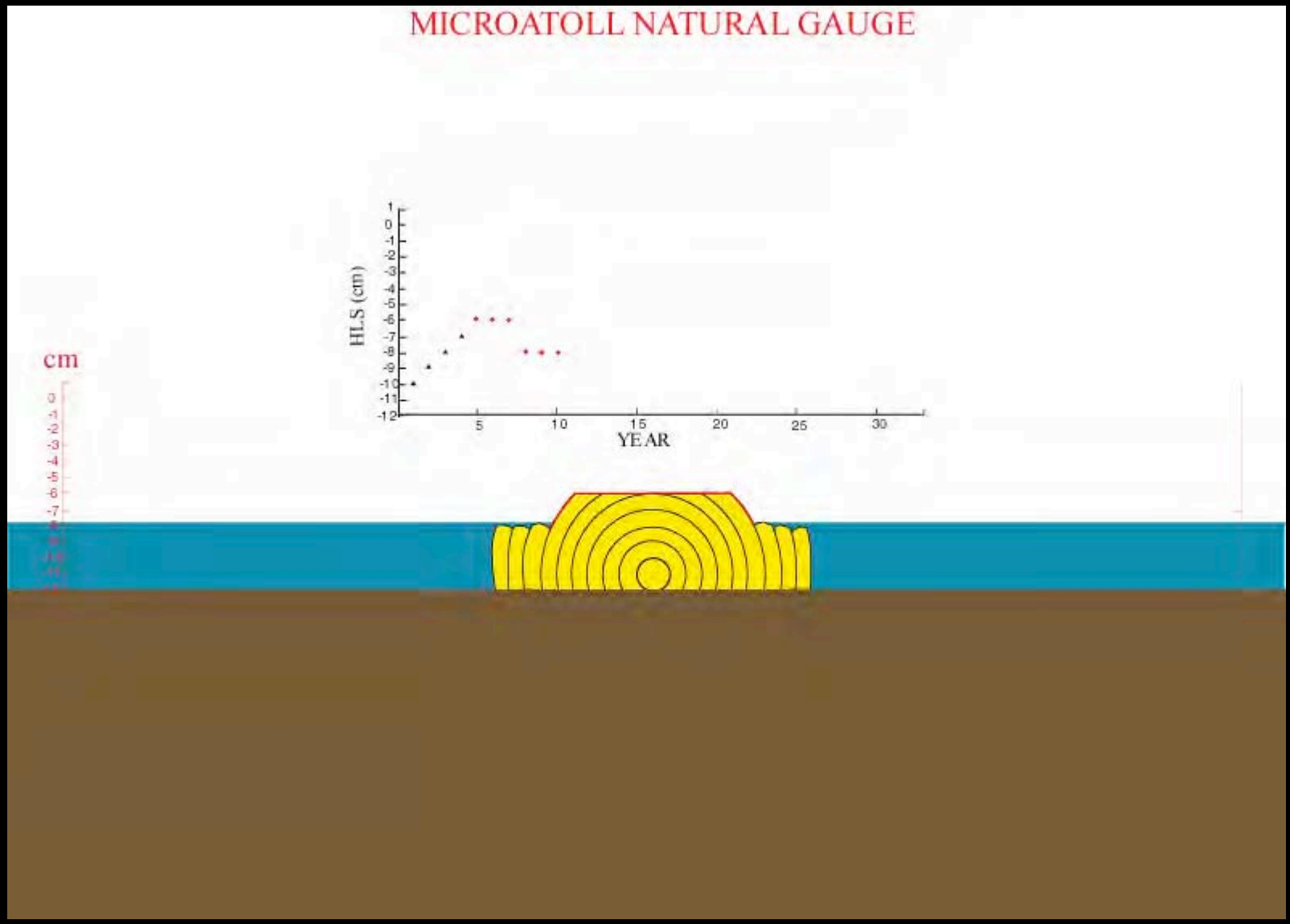
MICROATOLL NATURAL GAUGE



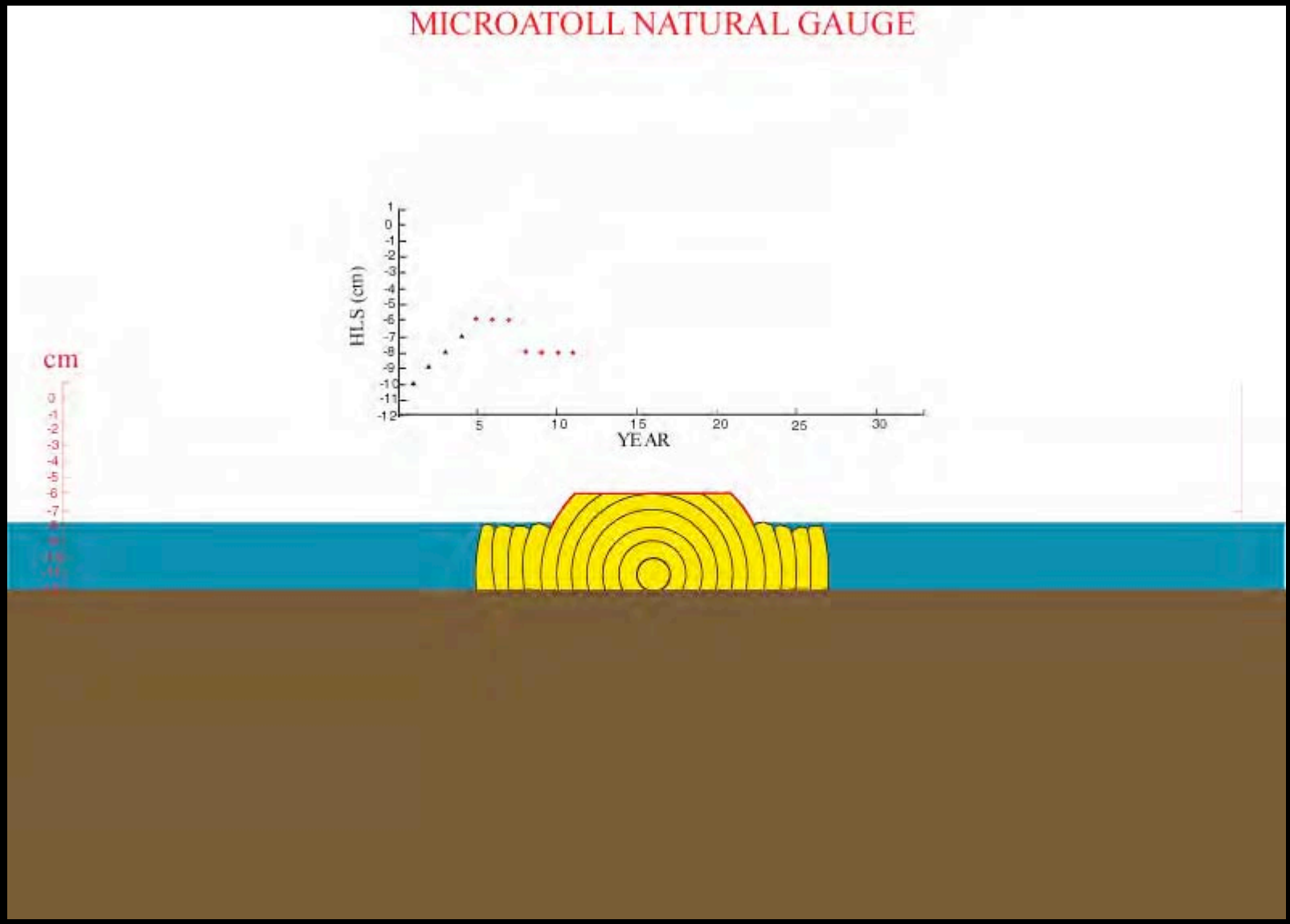
MICROATOLL NATURAL GAUGE



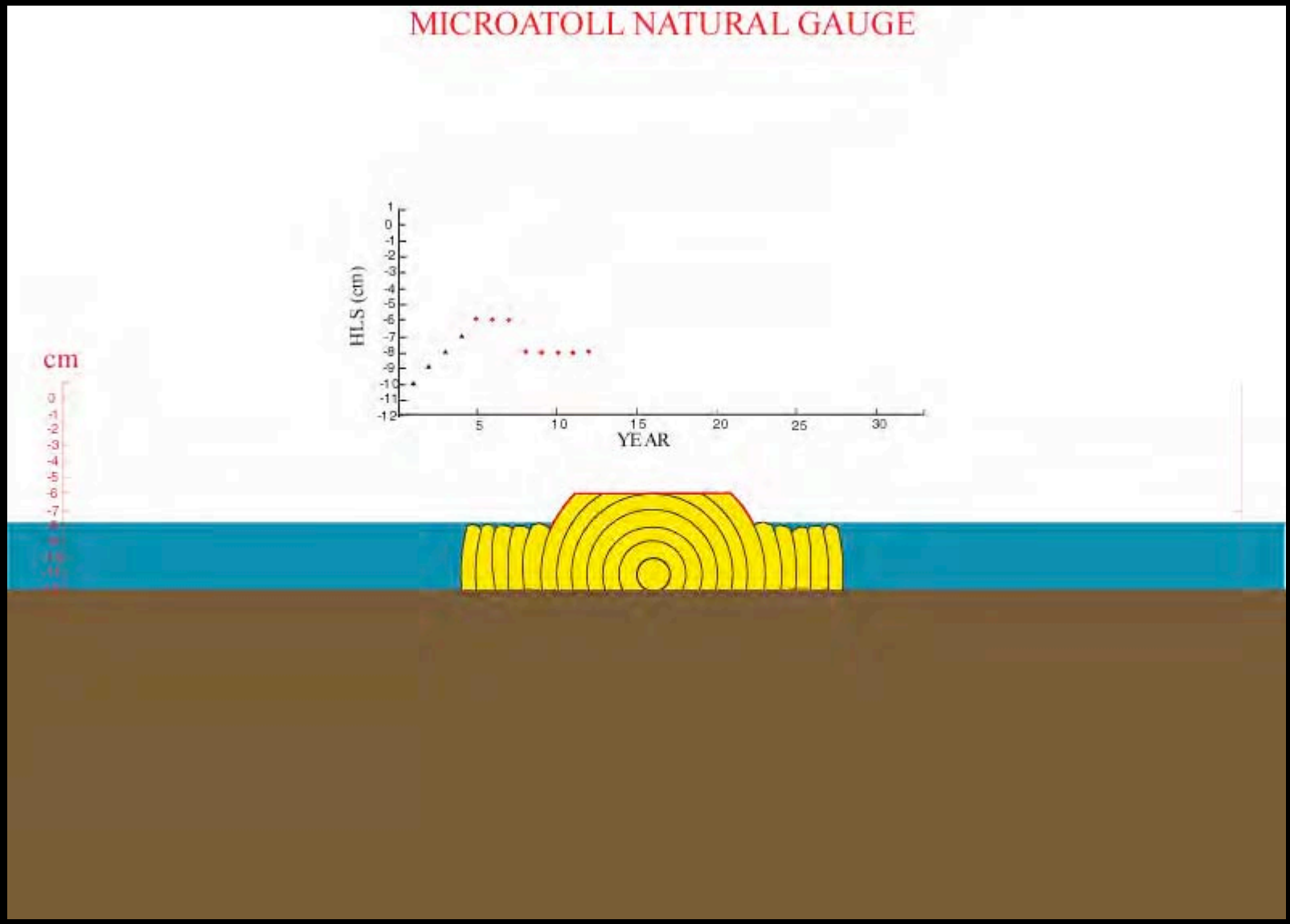
MICROATOLL NATURAL GAUGE



MICROATOLL NATURAL GAUGE

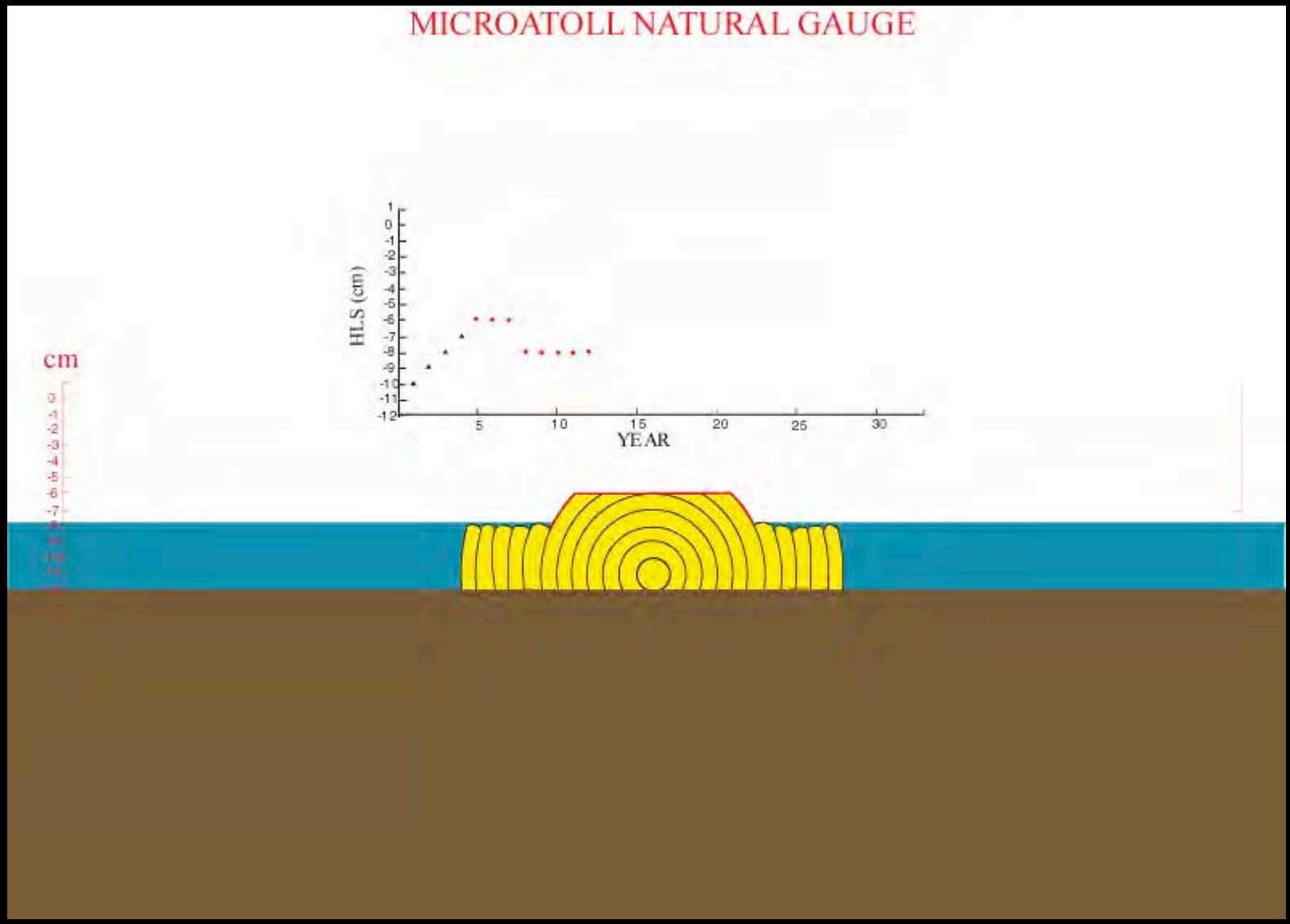


MICROATOLL NATURAL GAUGE

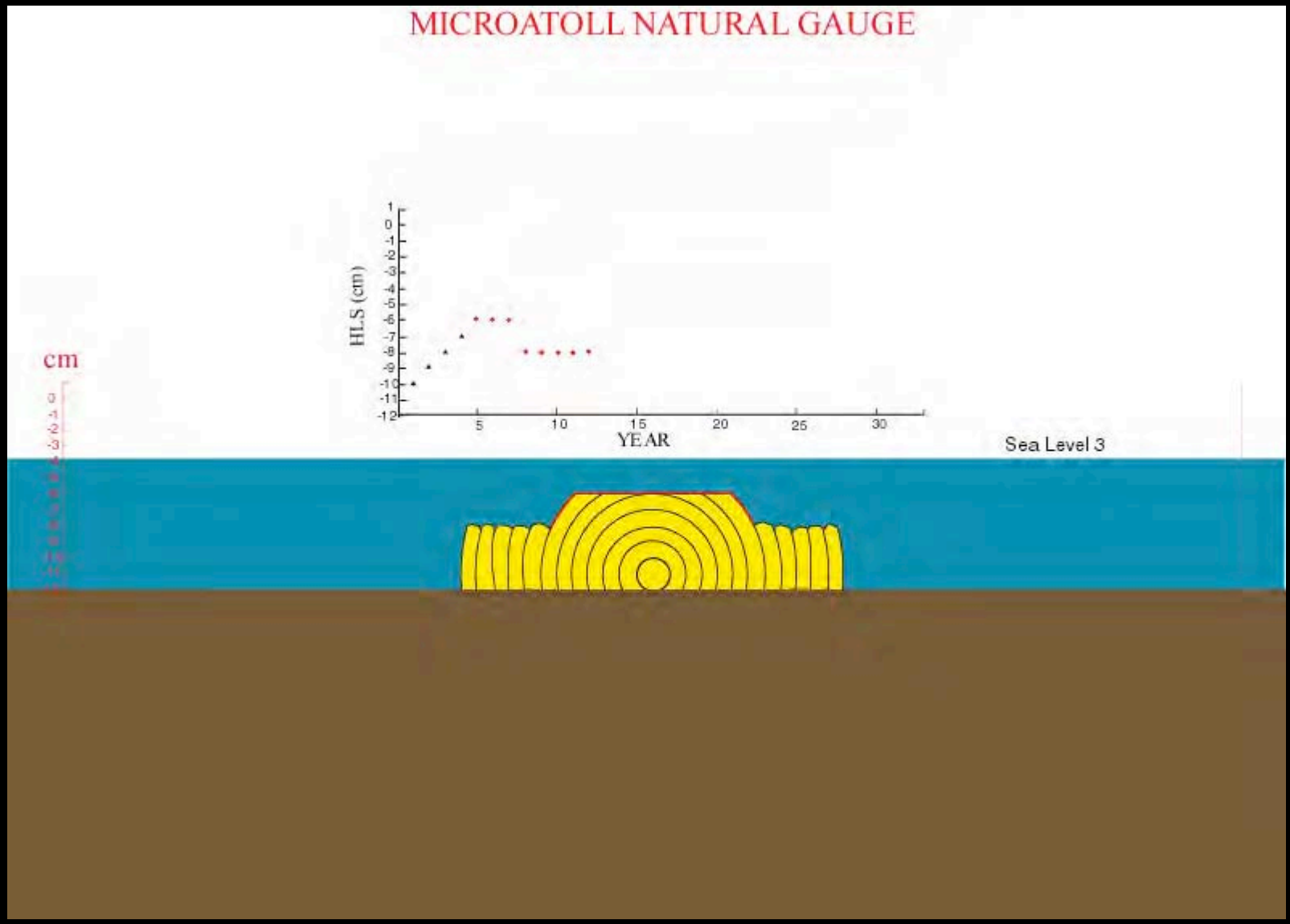


A small emergence event

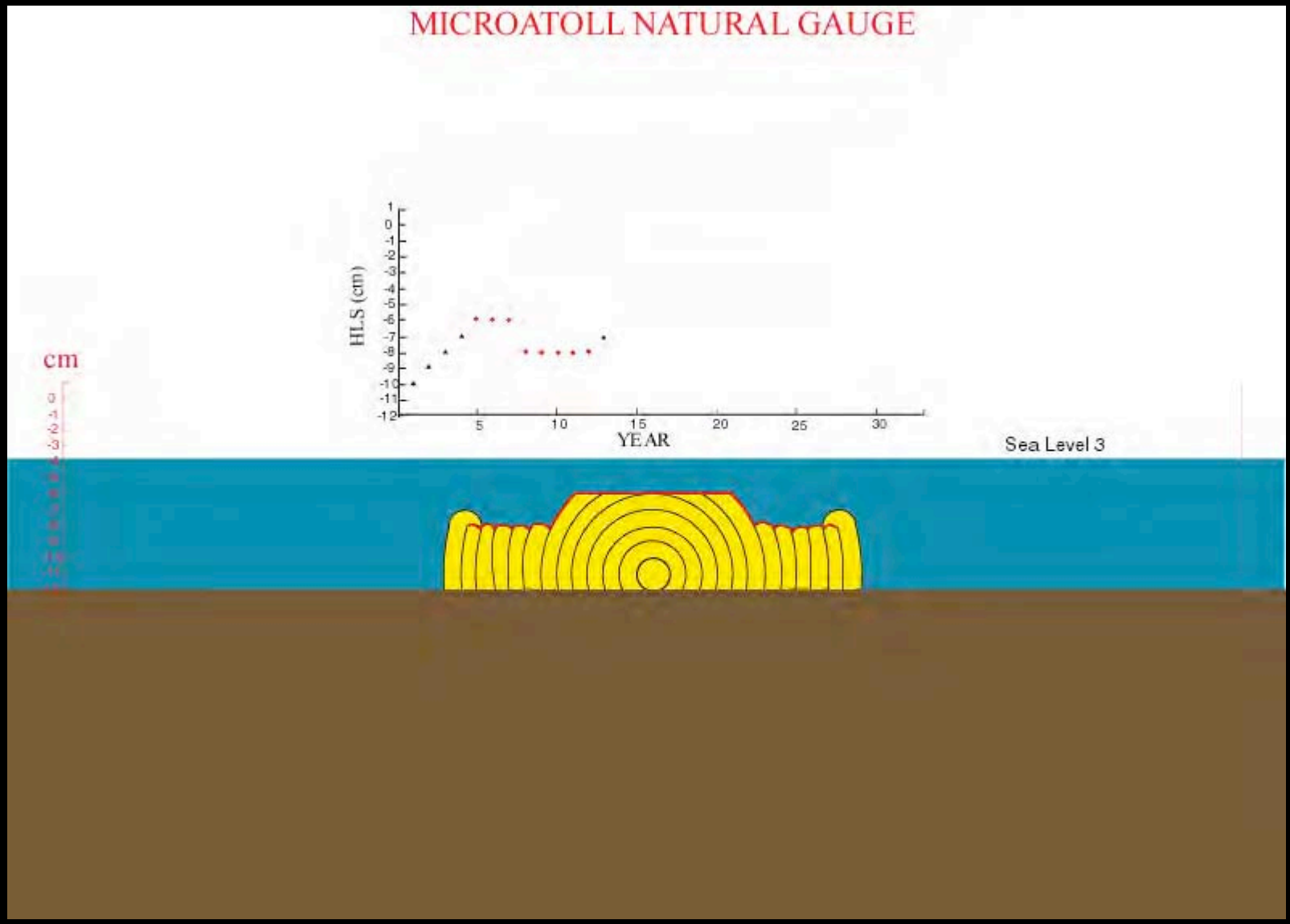
MICROATOLL NATURAL GAUGE



MICROATOLL NATURAL GAUGE



MICROATOLL NATURAL GAUGE



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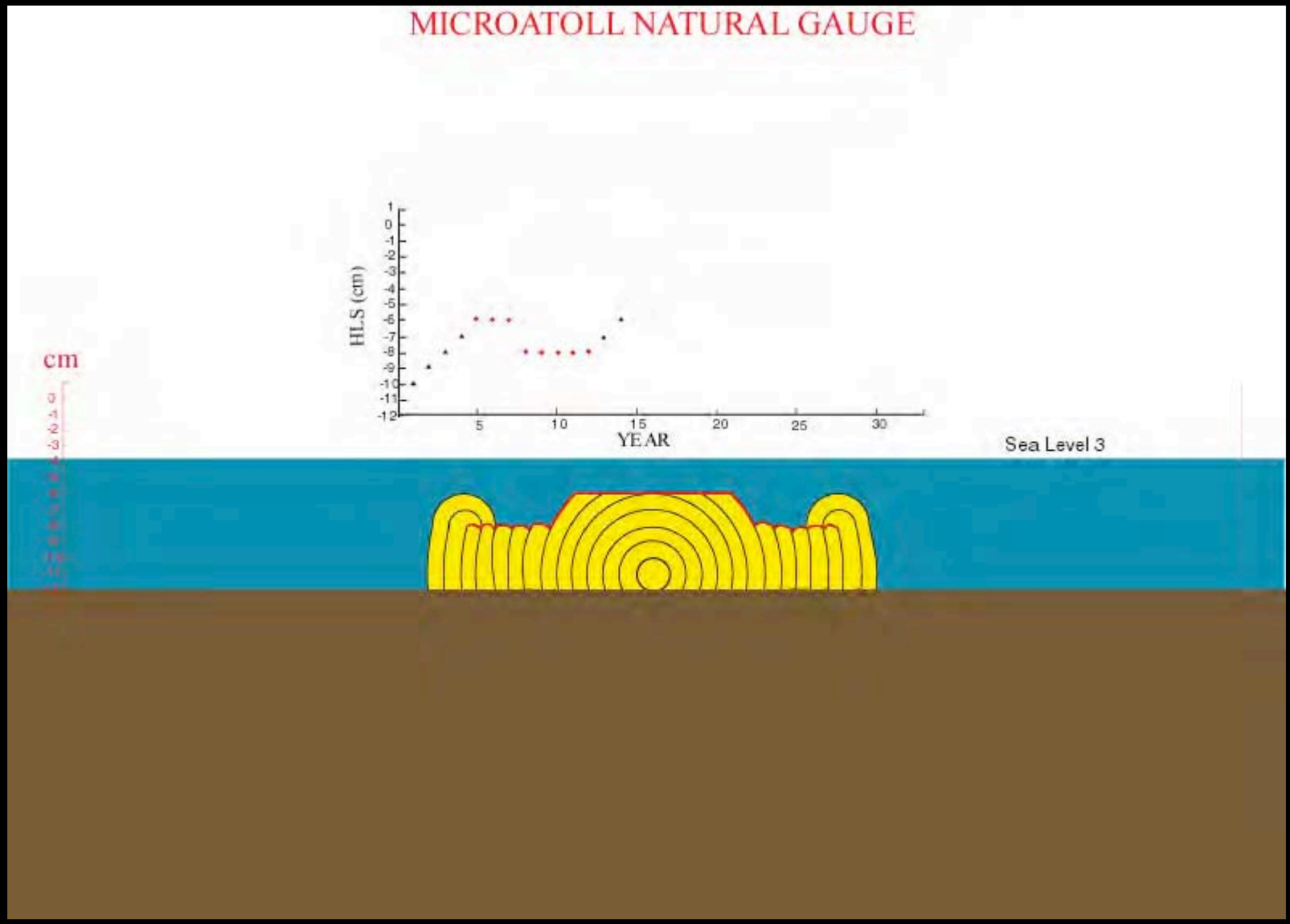

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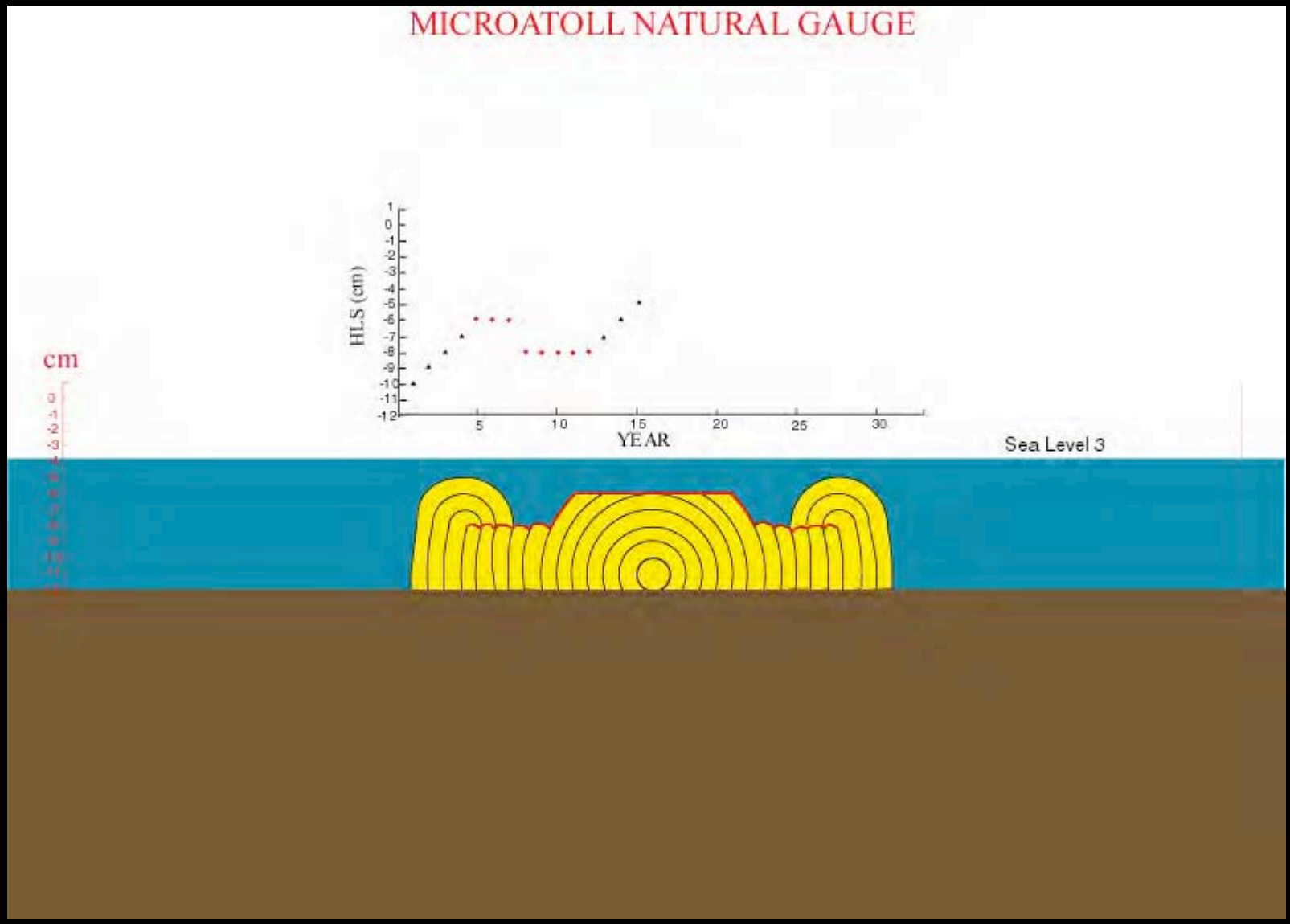

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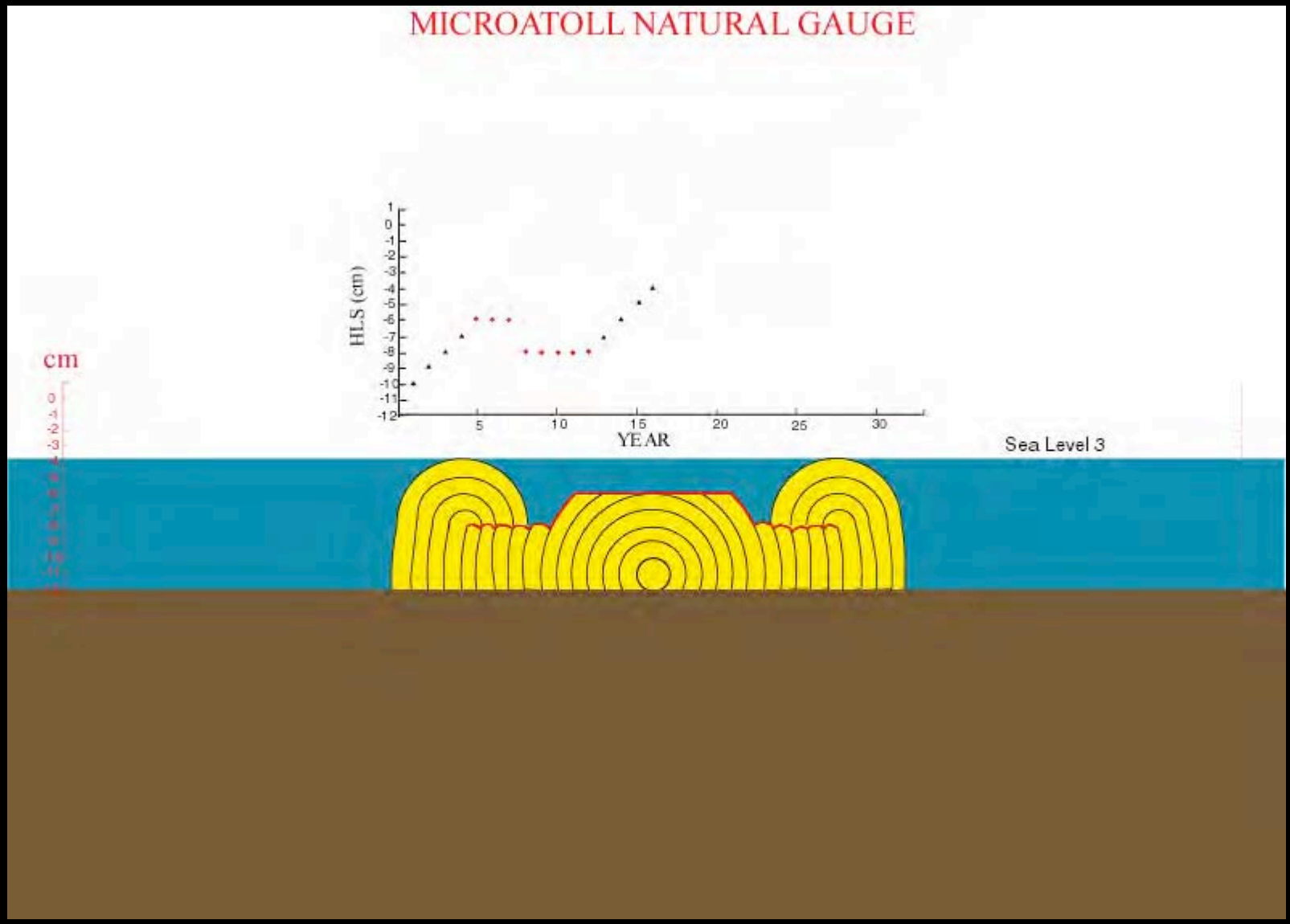
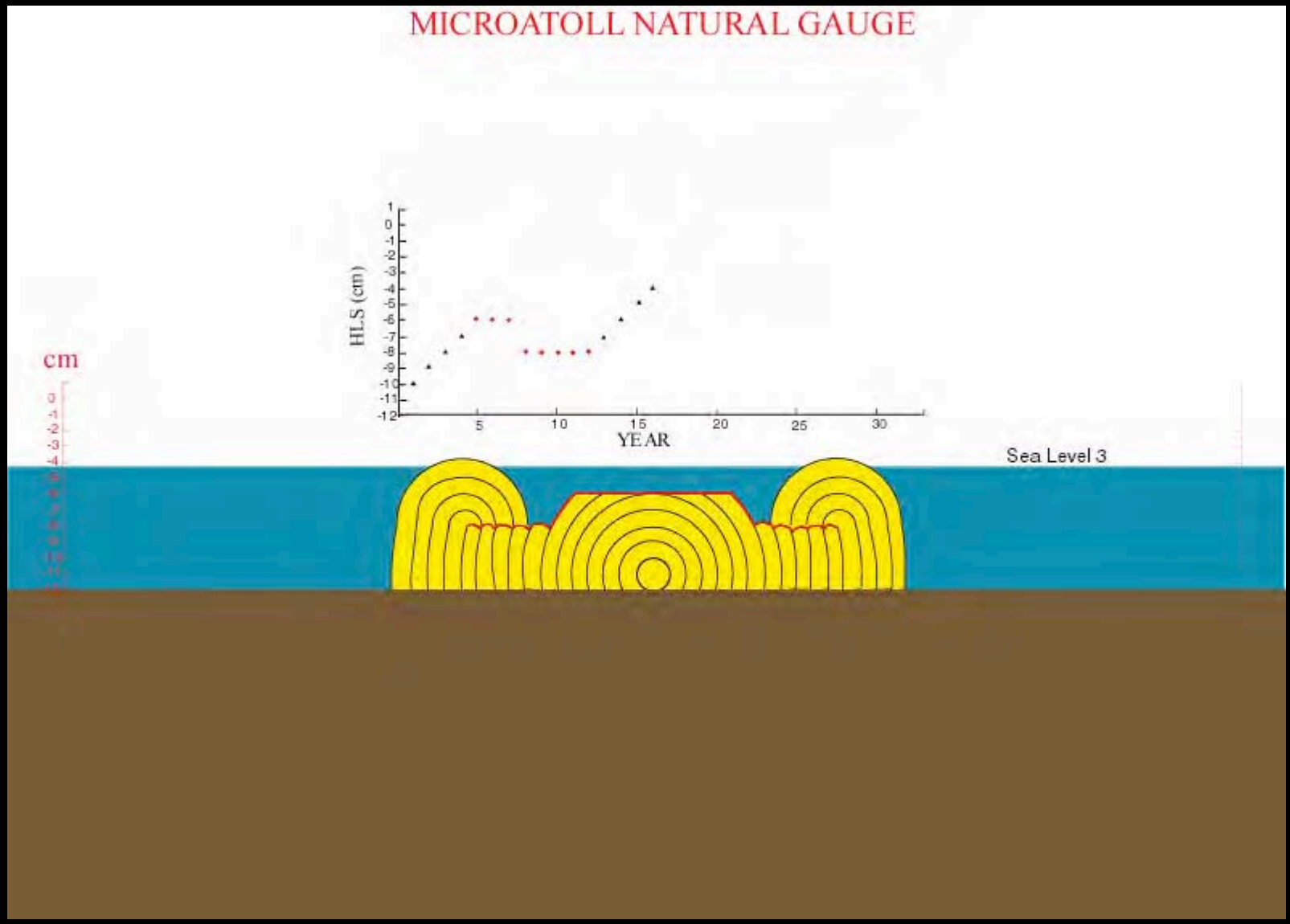


MICROATOLL NATURAL GAUGE



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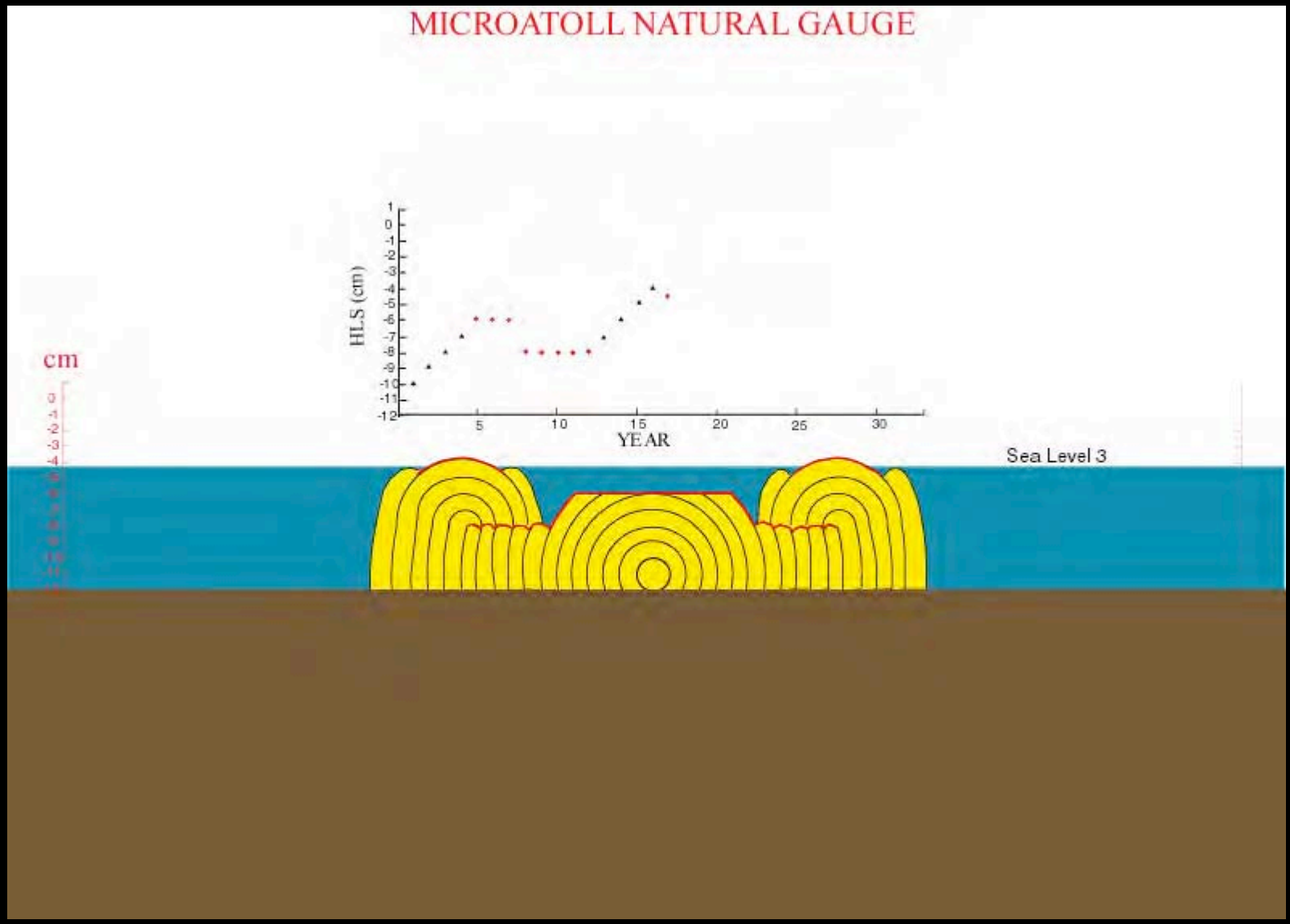
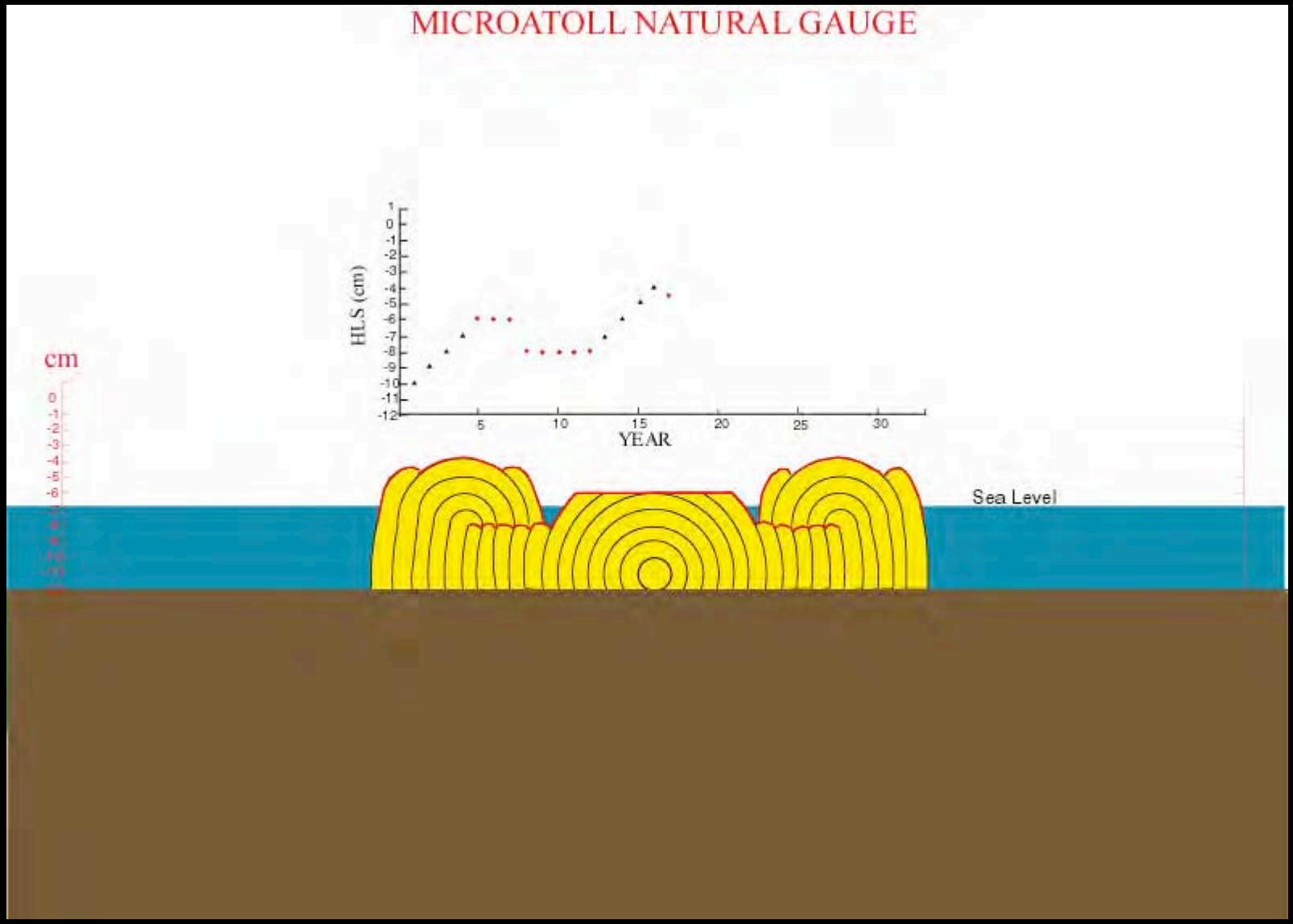
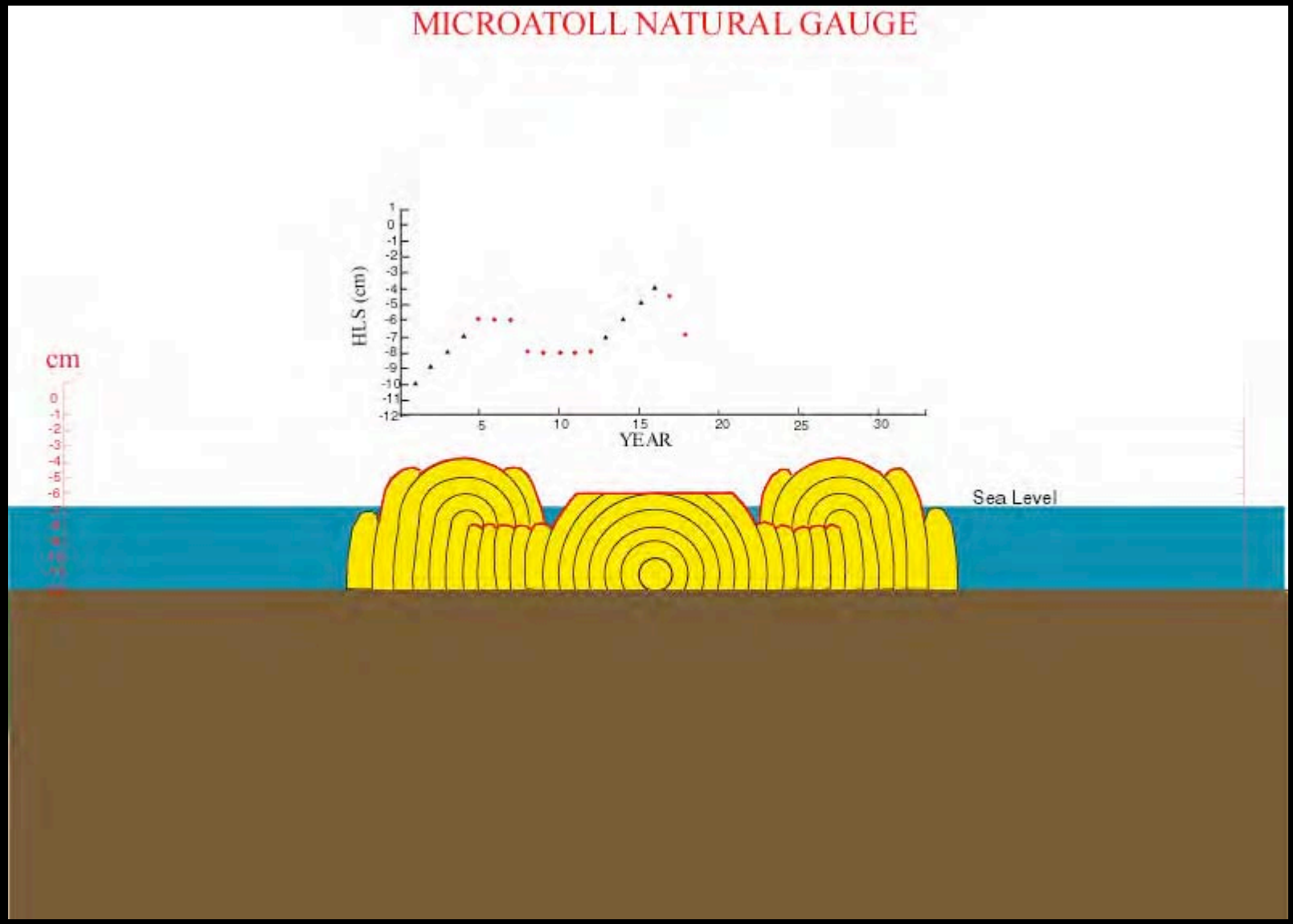



MICROATOLL NATURAL GAUGE
HLS (cm)
YEAR
cm
Sea Level

MICROATOLL NATURAL GAUGE



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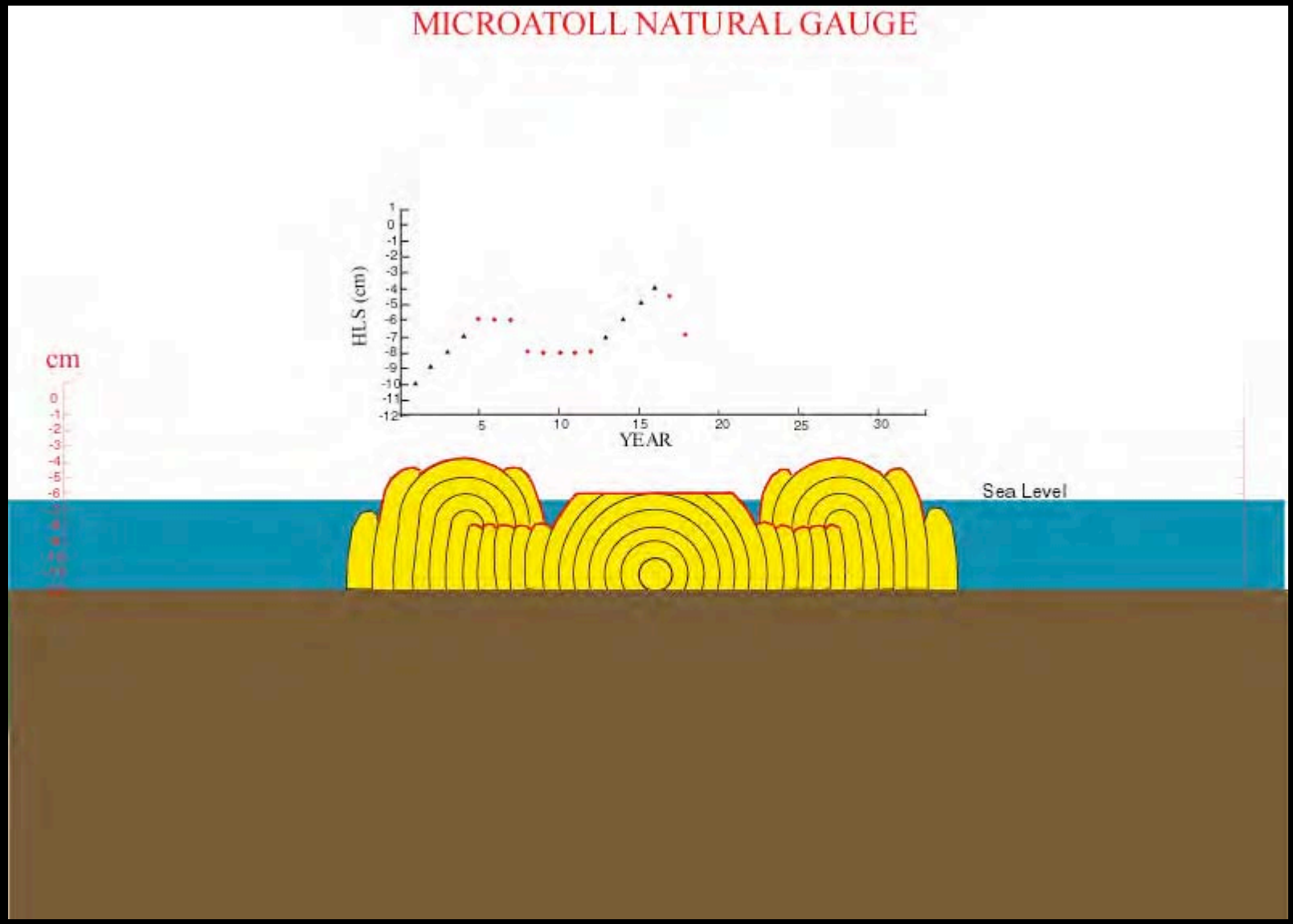

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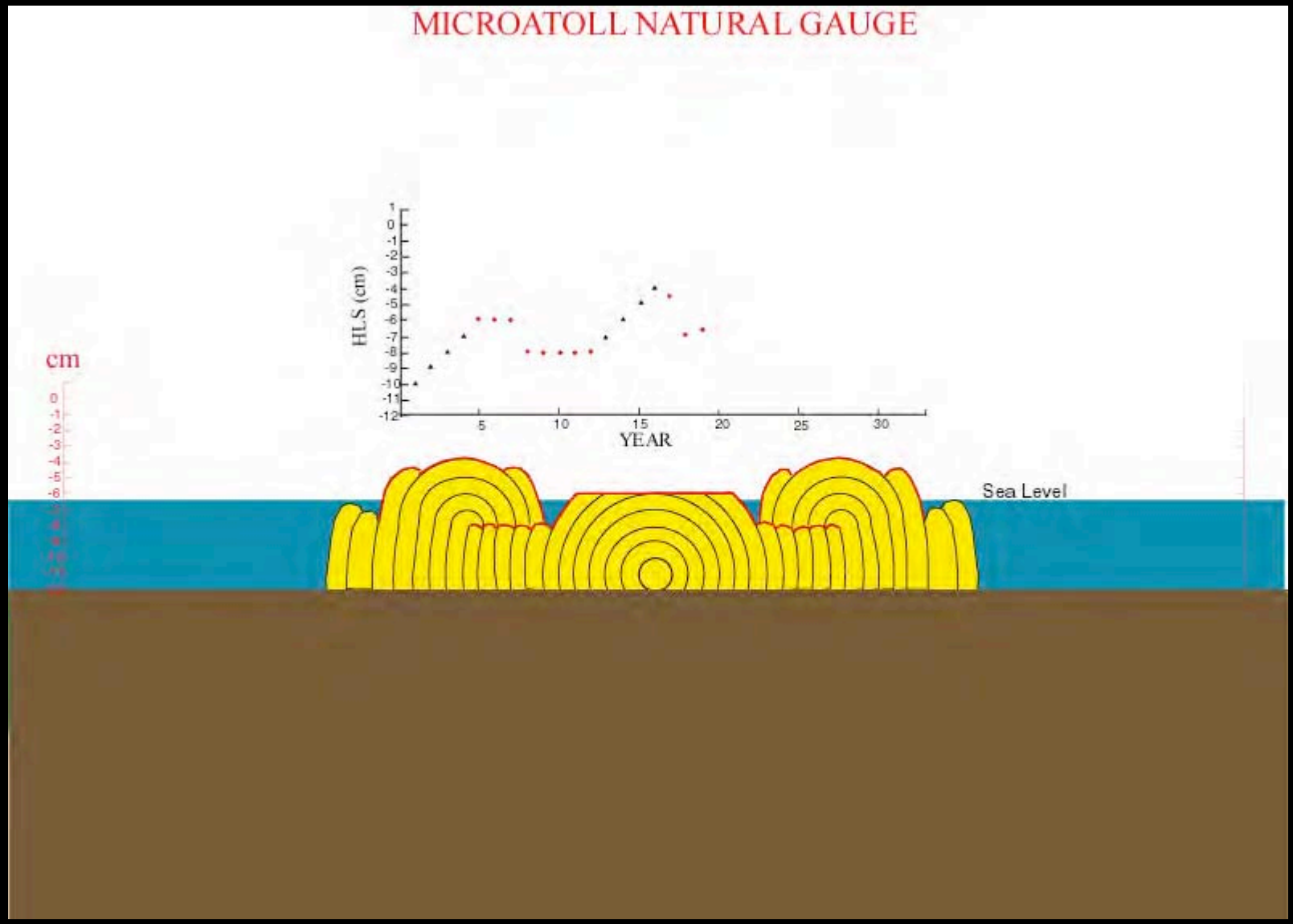

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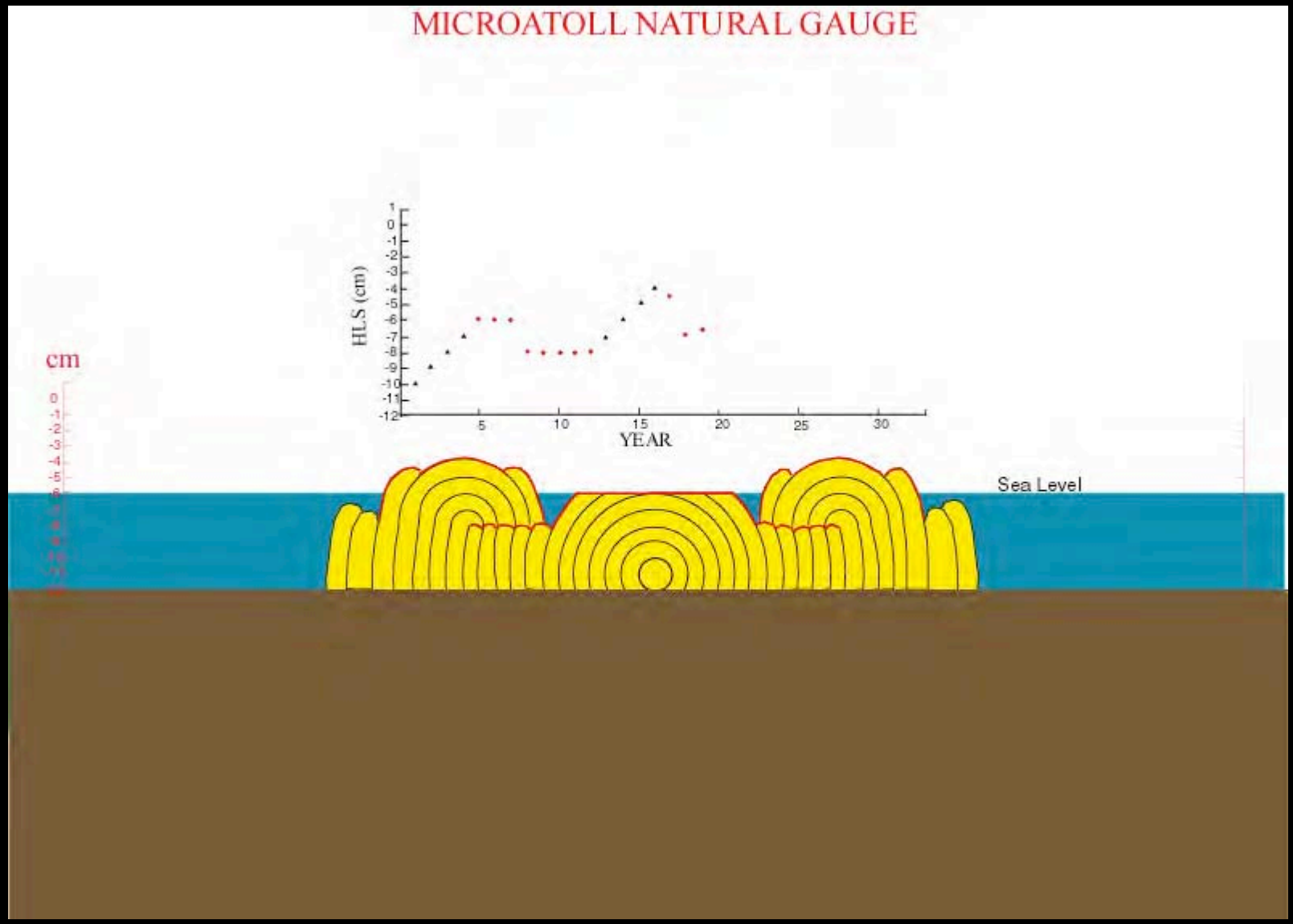

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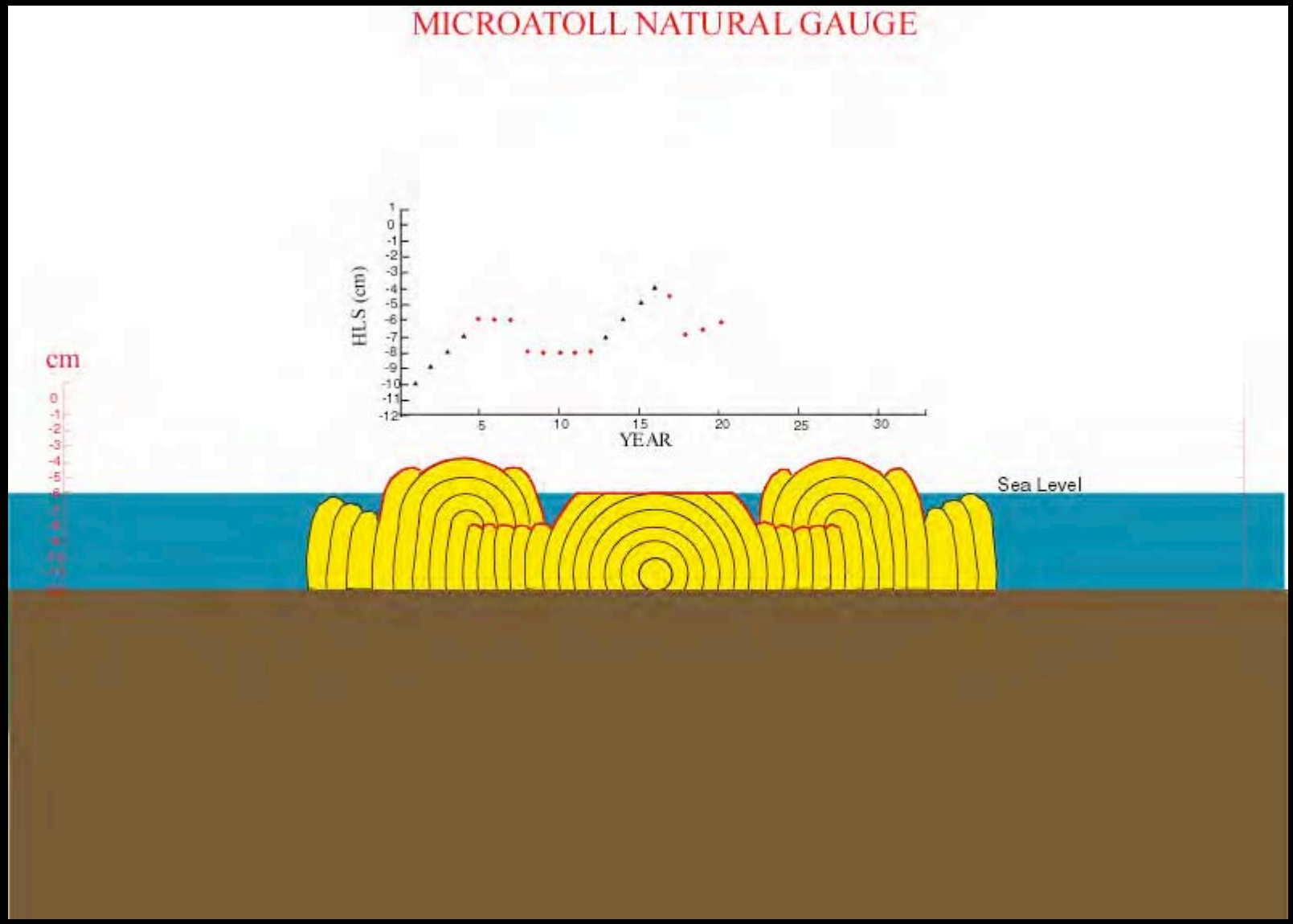

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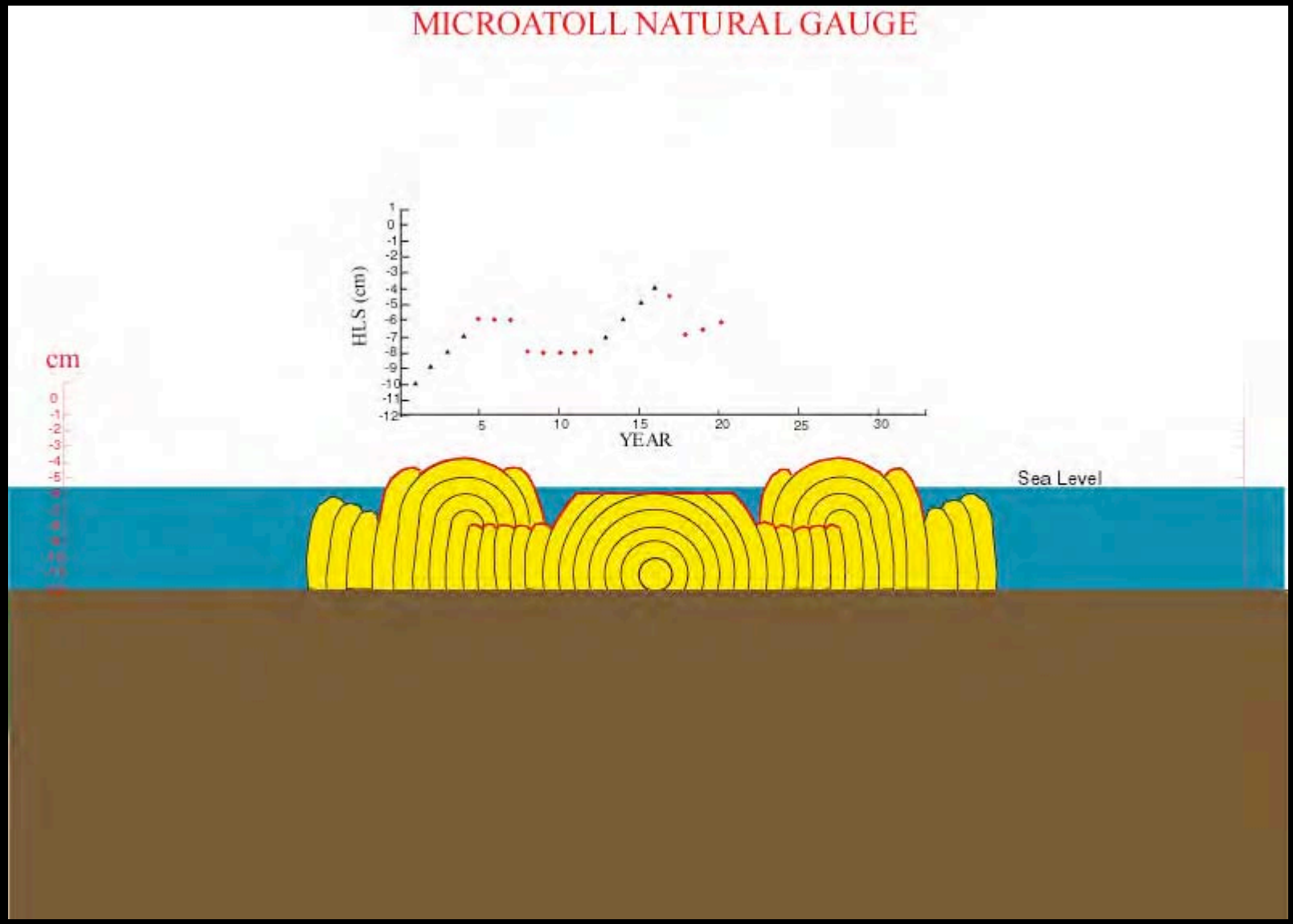

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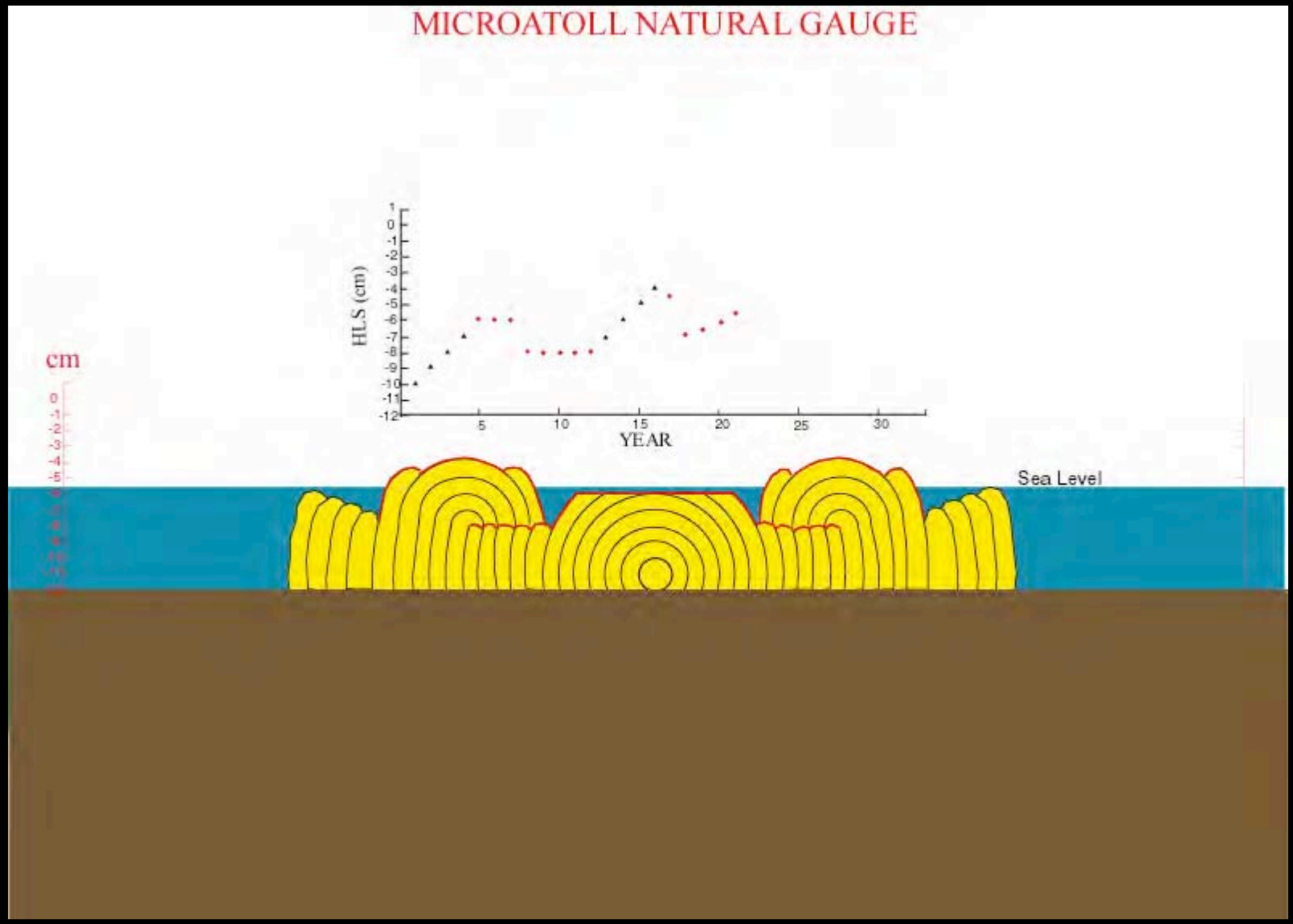
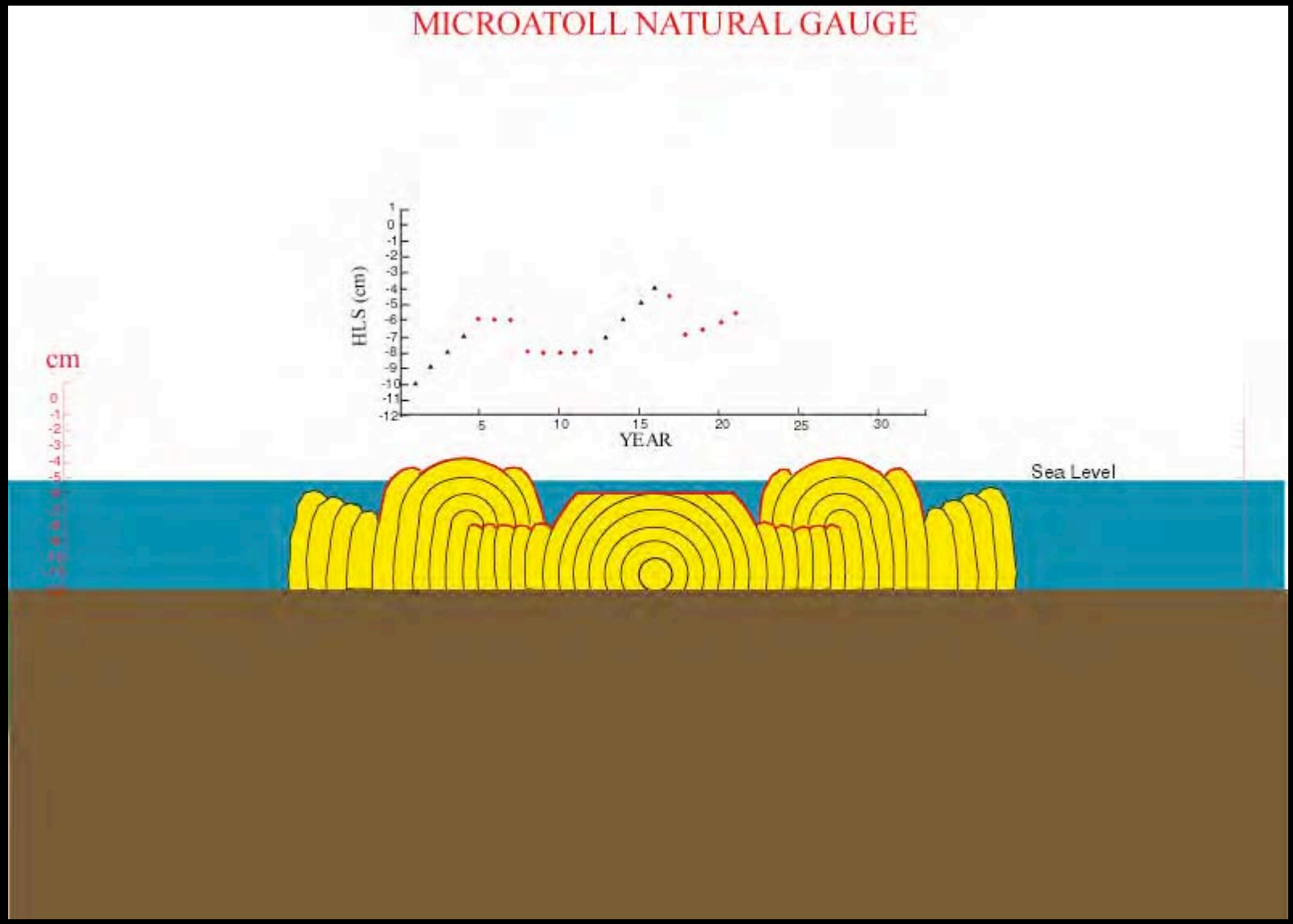
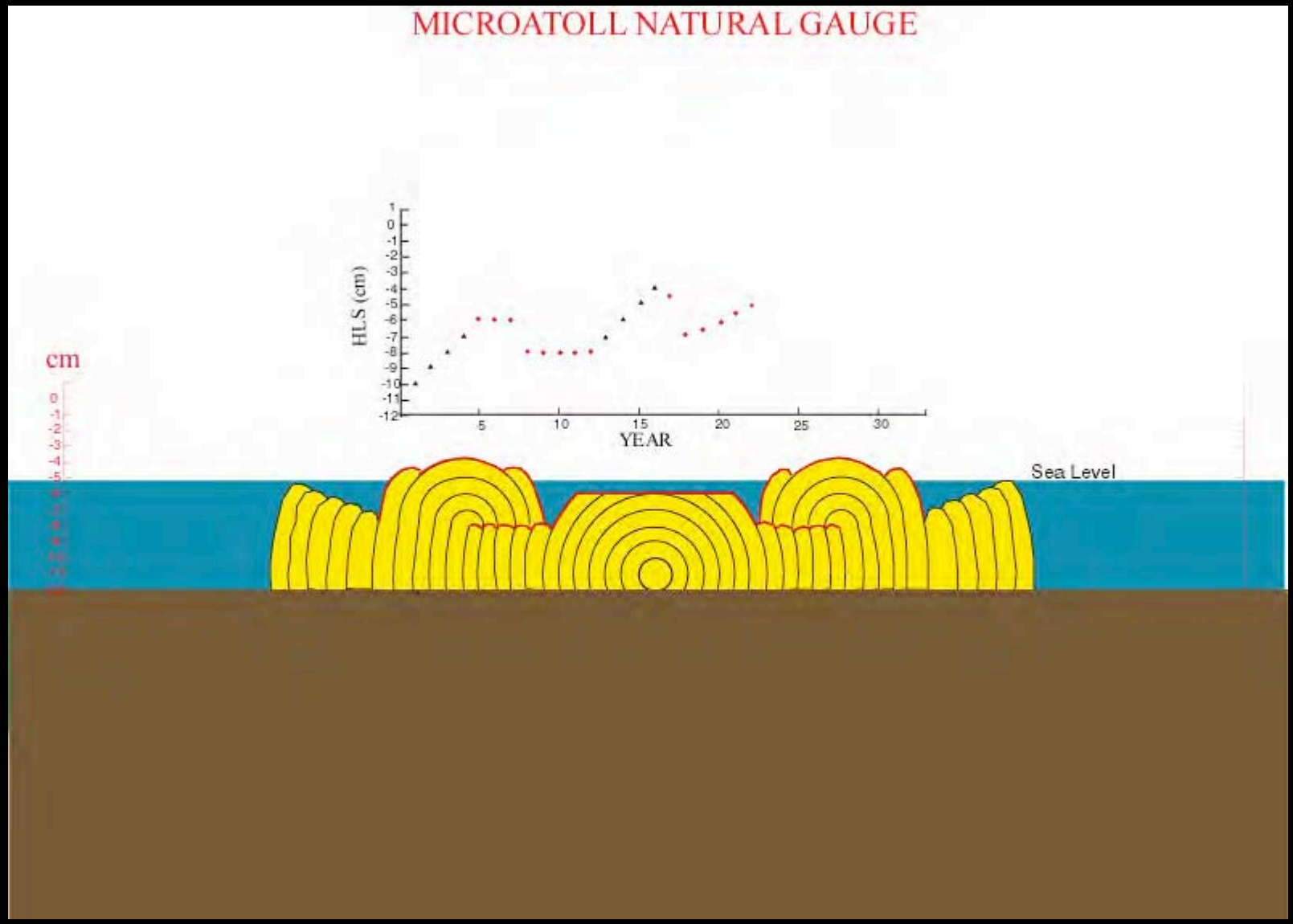


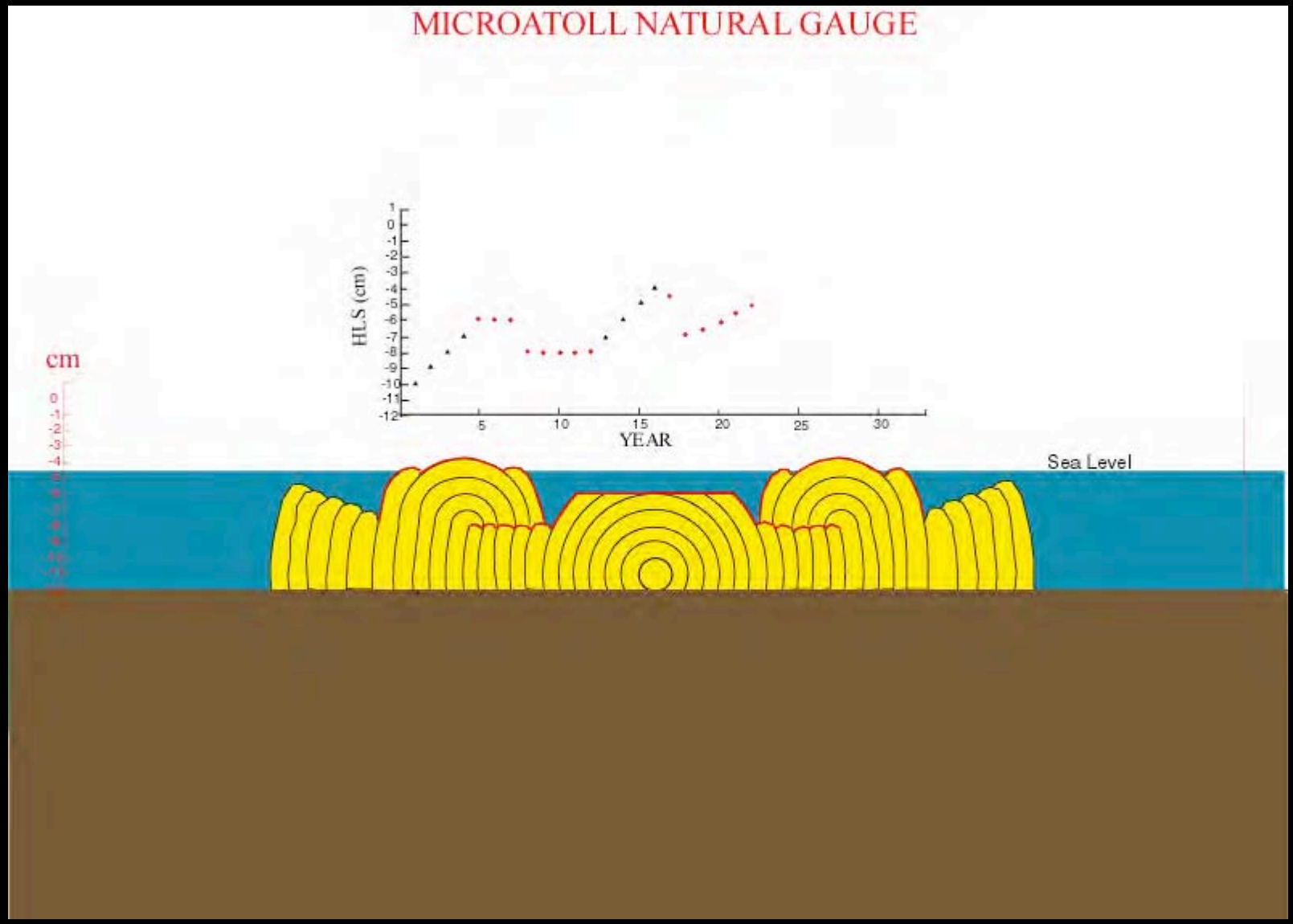
MICROATOLL NATURAL GAUGE



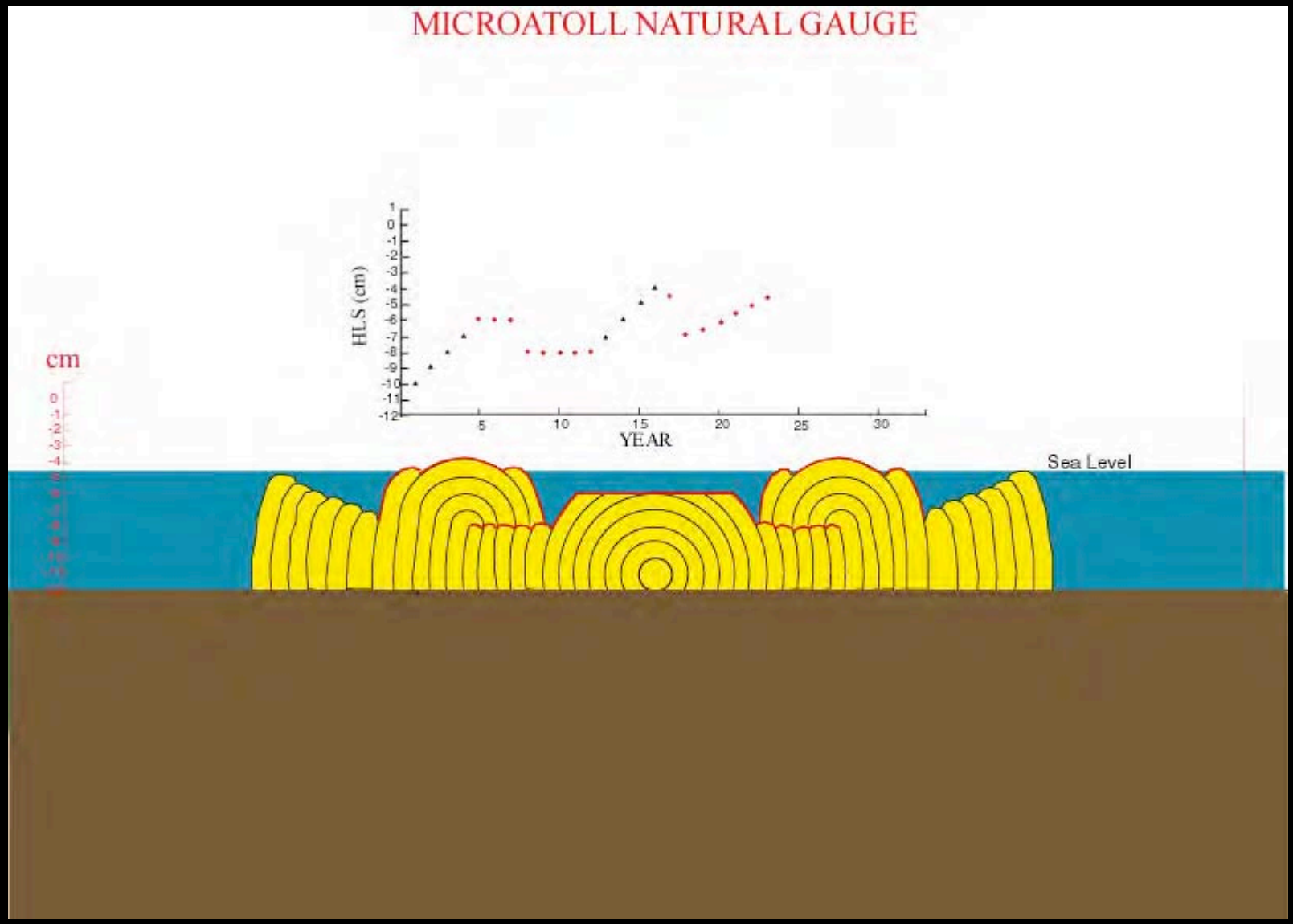
MICROATOLL NATURAL GAUGE



MICROATOLL NATURAL GAUGE



MICROATOLL NATURAL GAUGE



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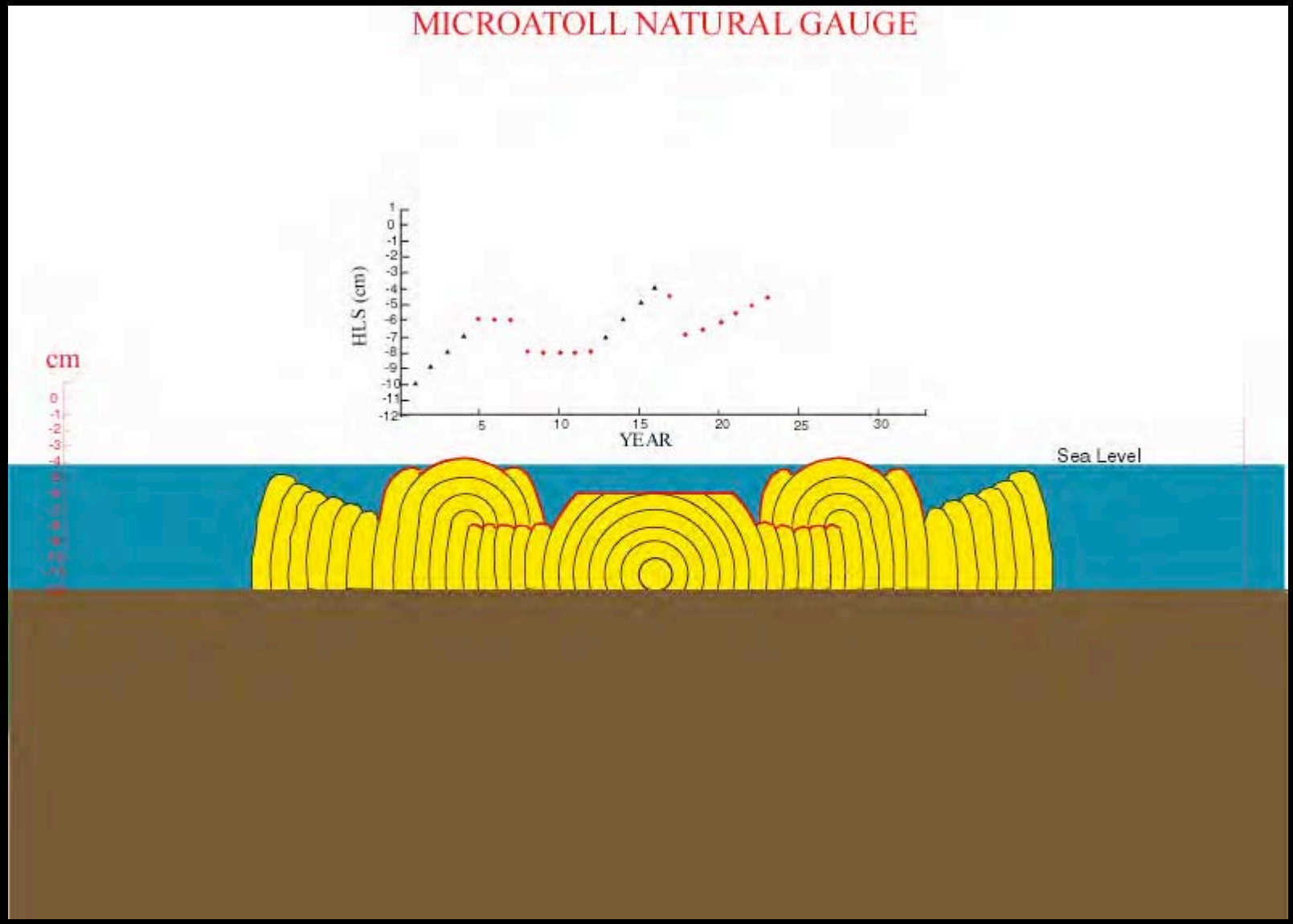

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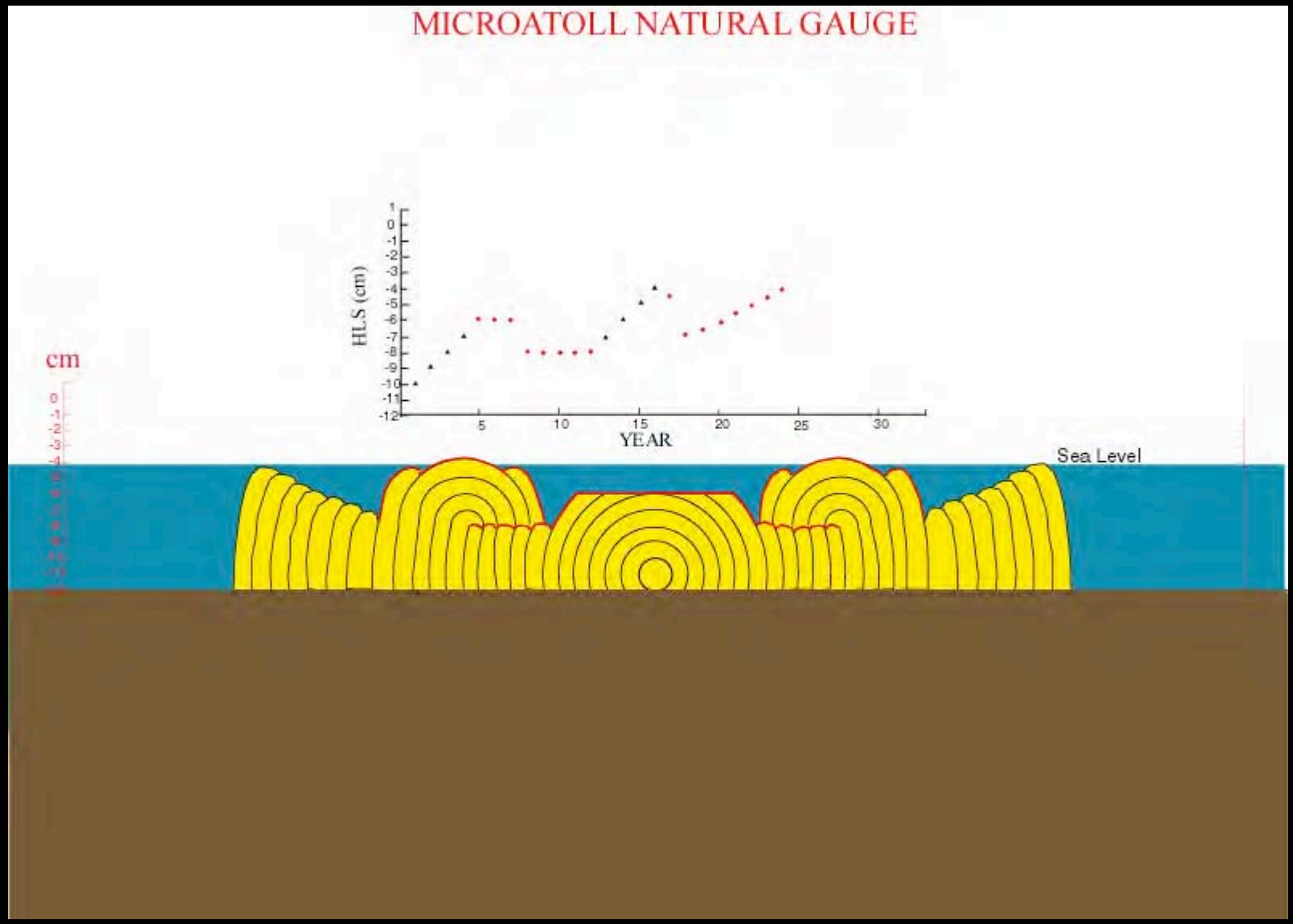


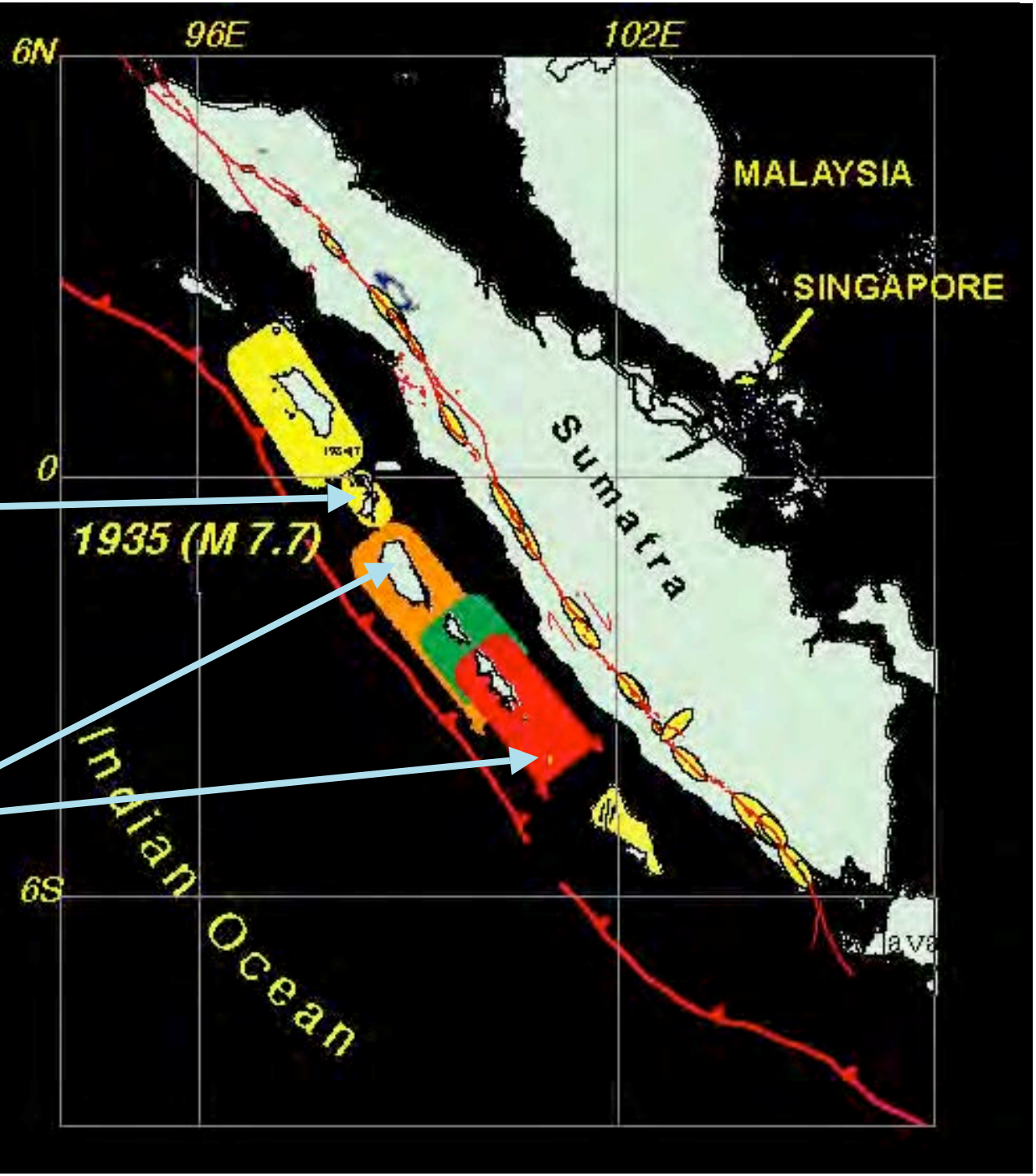
Submergence followed by emergence

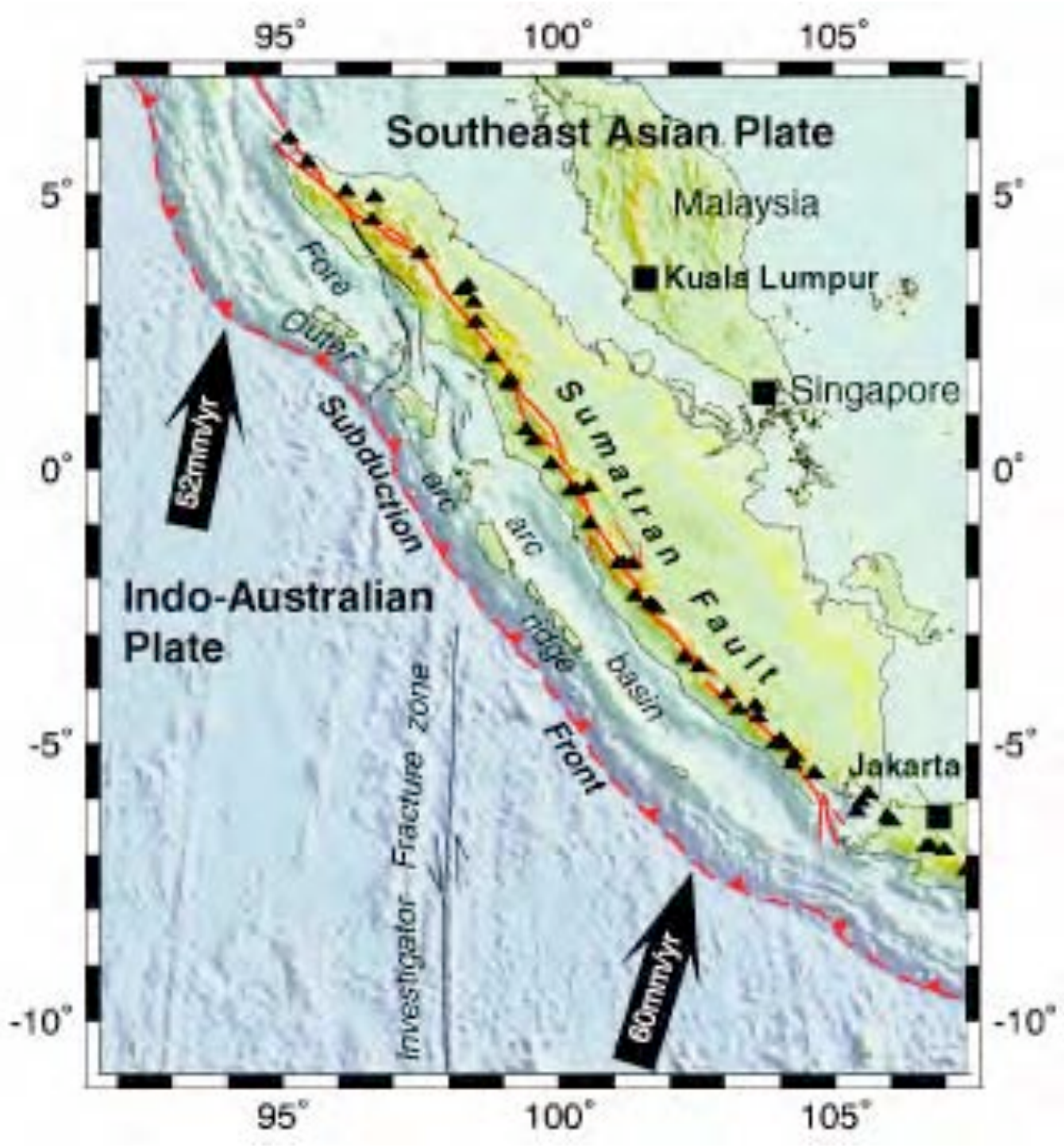
The sampling operation

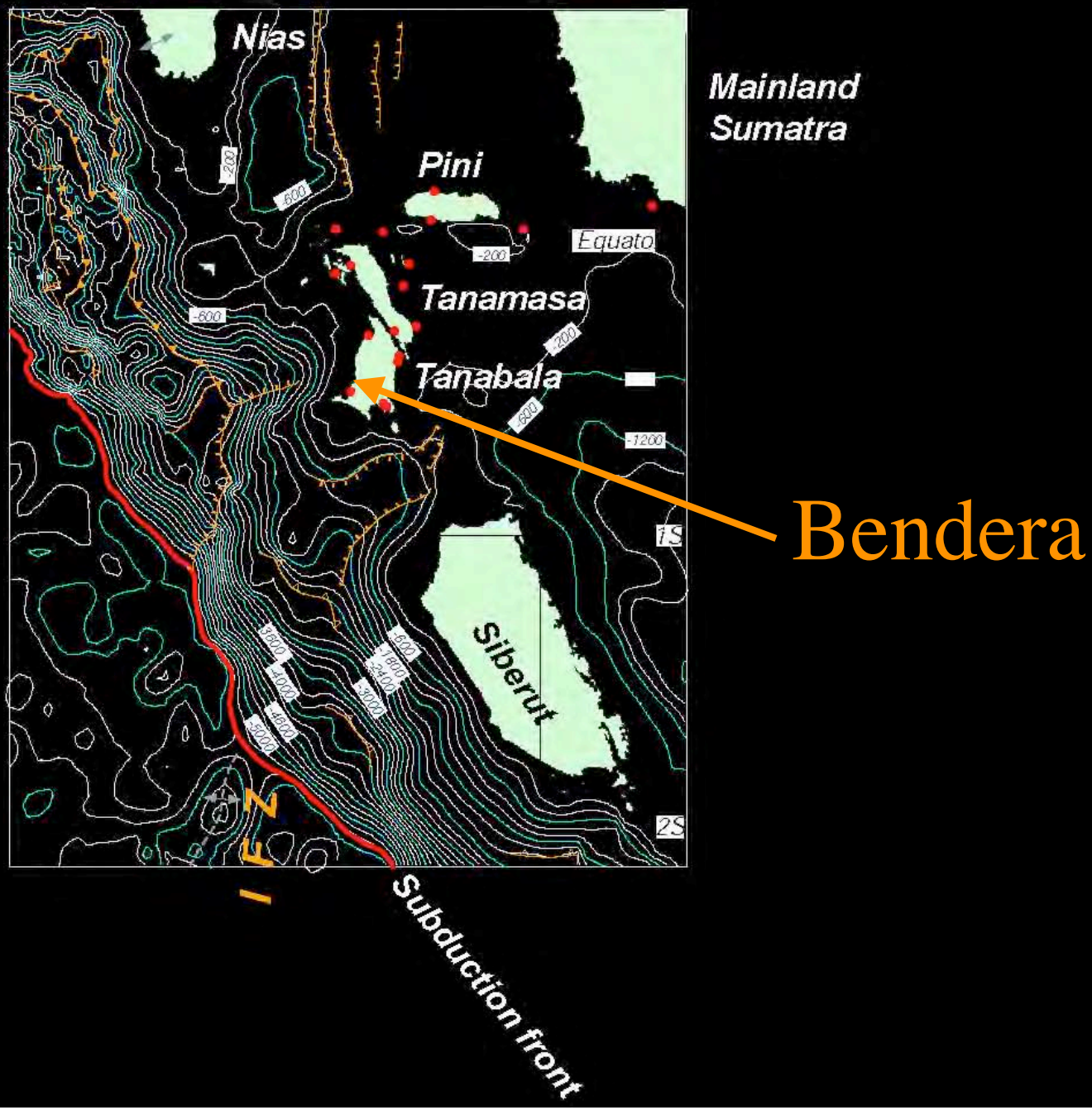
We have focused in two areas

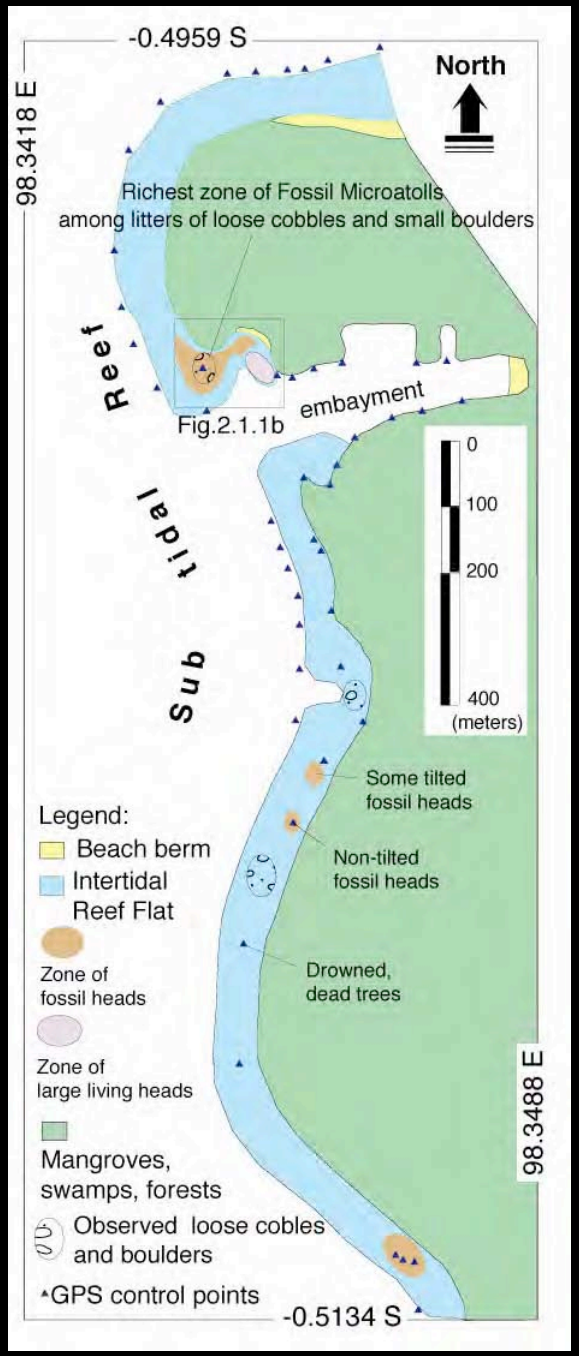
This region of smaller earthquakes

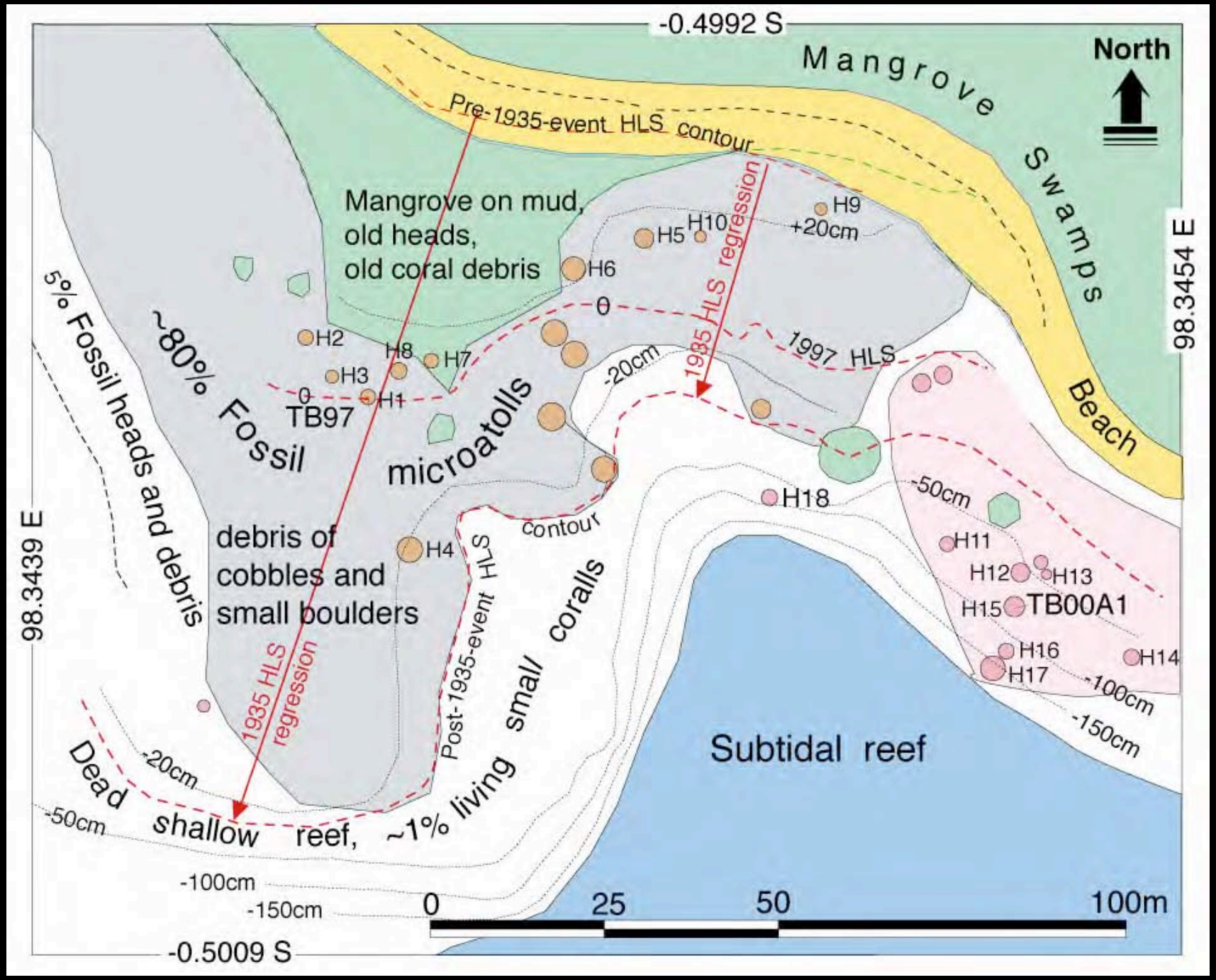
And this region of very large earthquakes



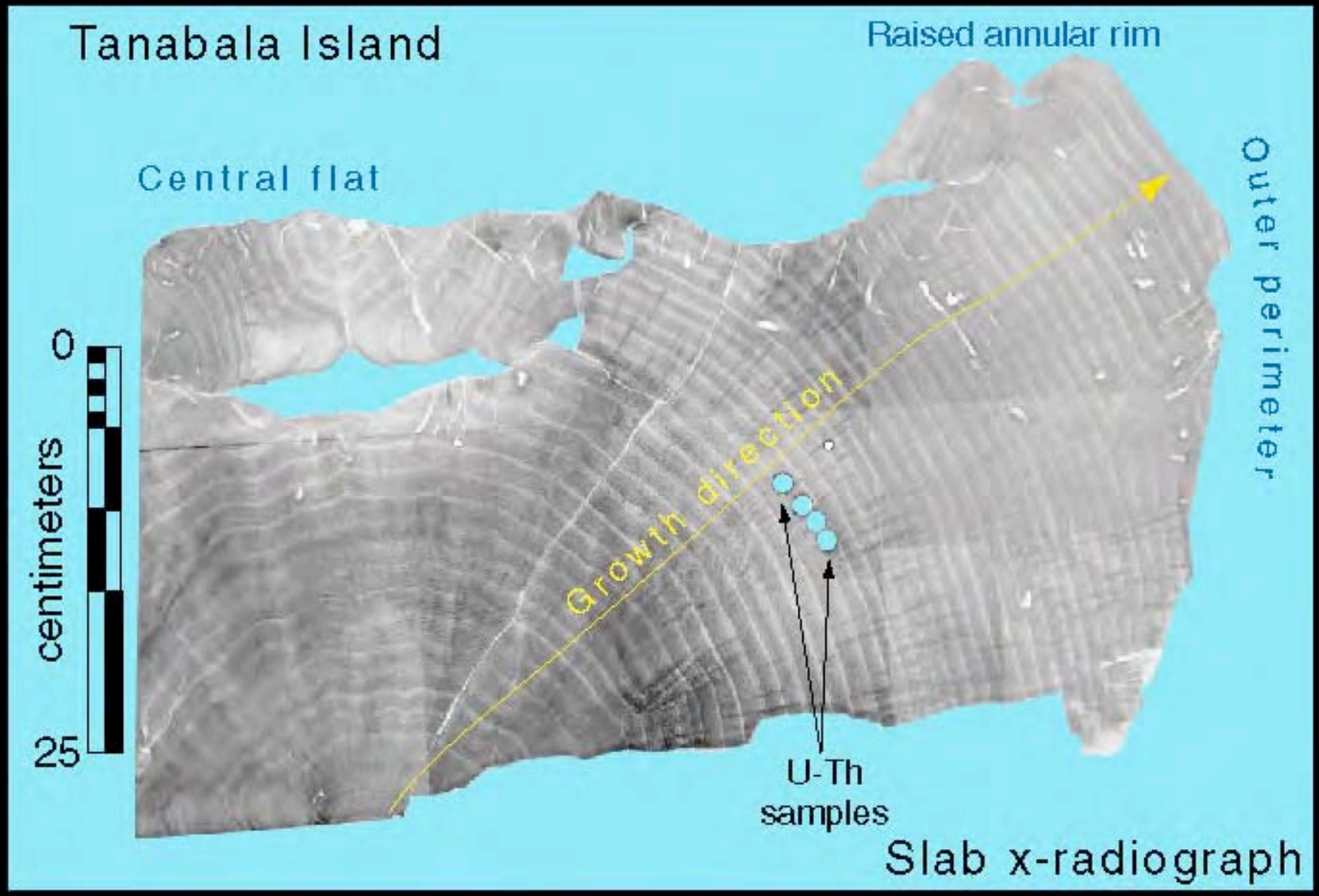

95°
100°
105°
5°
0°
-5°
-10°
Southeast Asian Plate
Malaysia
Kuala Lumpur
Singapore
Jakarta
Sumatran Fault
Fore
Outer
Subduction
arc
arc
ridge
basin
Front
Indo-Australian Plate
Investigator Fracture zone
62mm/yr
60mm/yr

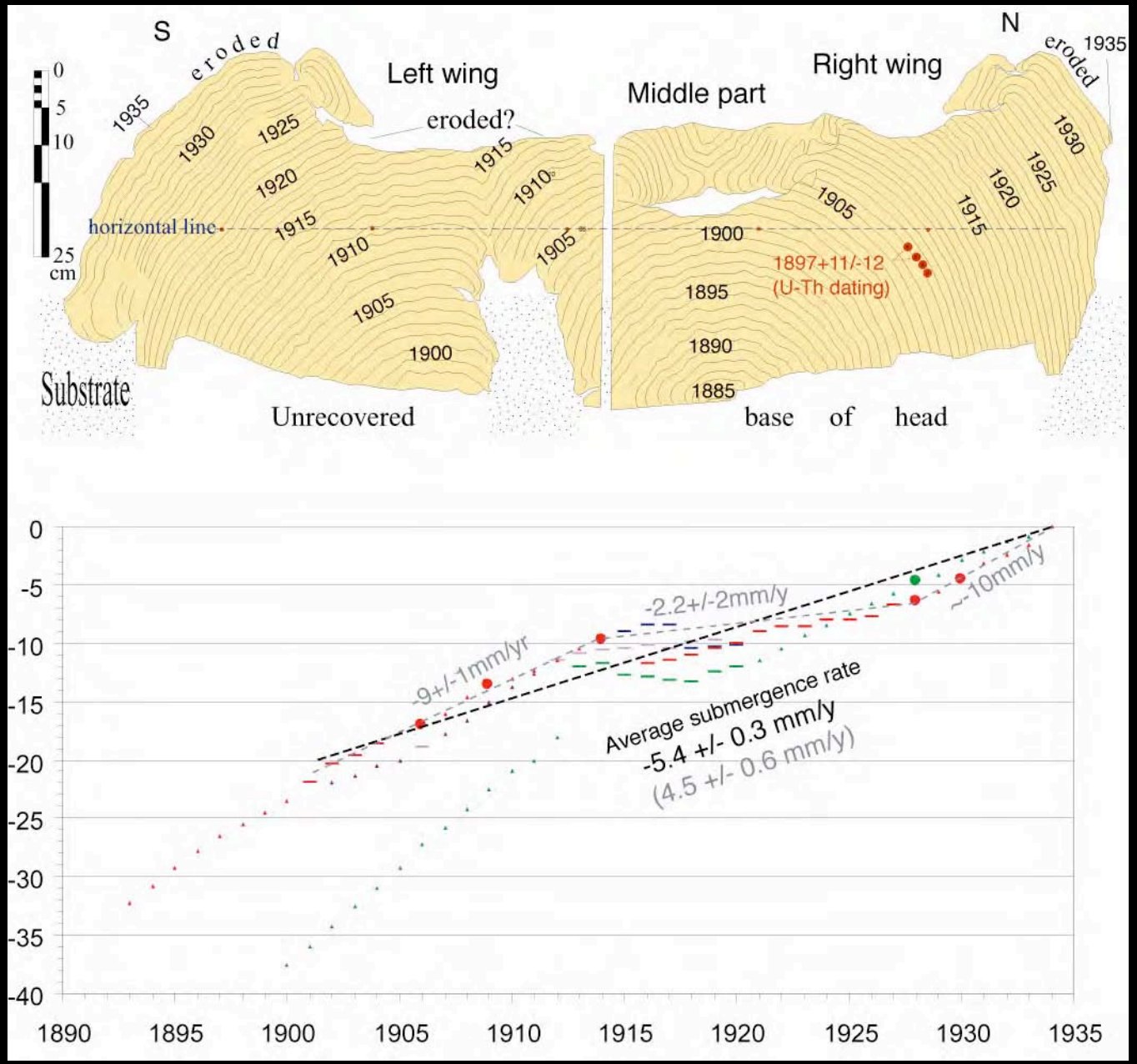

Nias
Mainland
Sumatra
Pini
Equato
Tanamasa
Tanabala
Bendera
Siberut
1S
2S
Subduction front

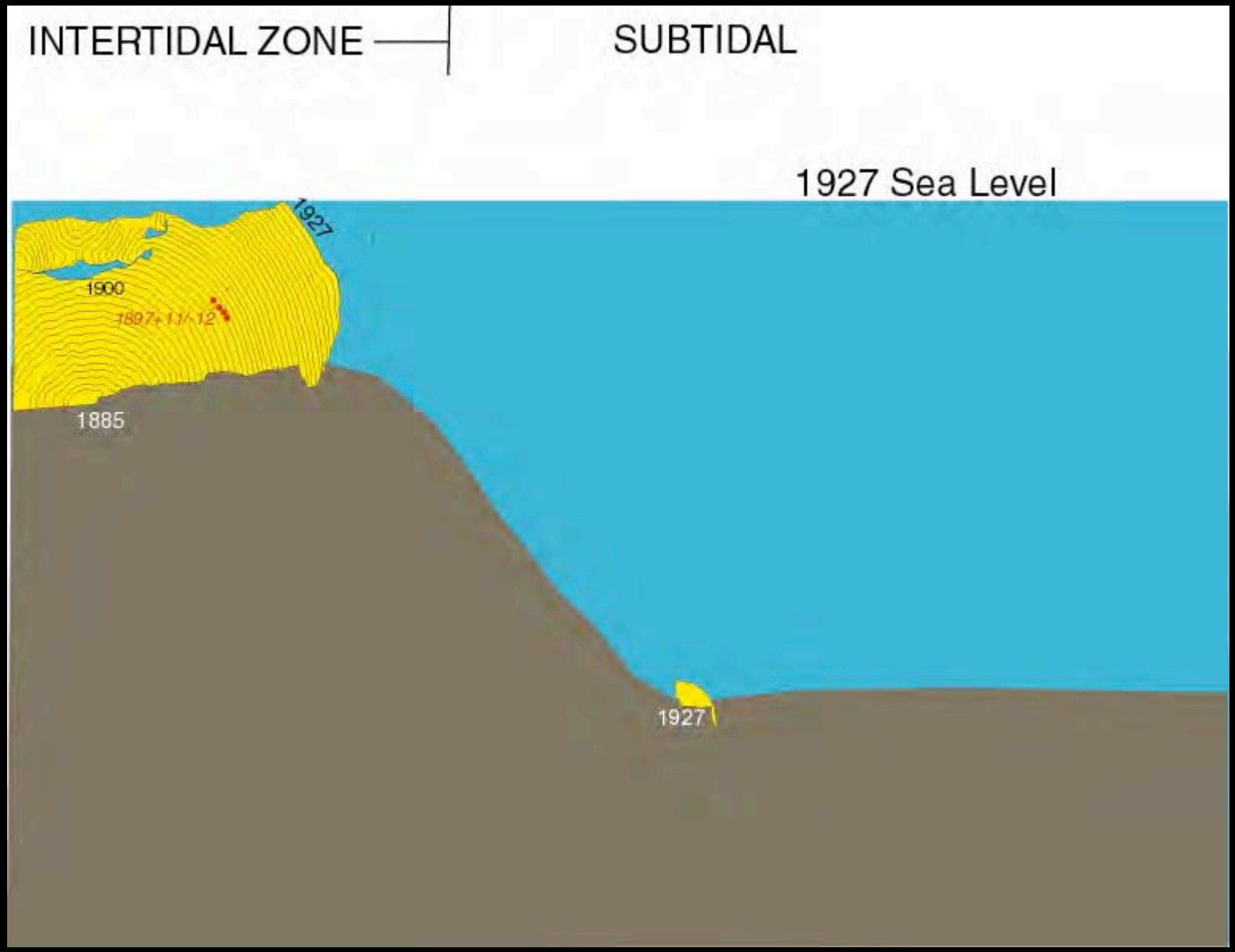

-0.4959 S
North
98.3418 E
Richest zone of Fossil Microatolls
among litters of loose cobbles and small boulders
Reef
Fig.2.1.1b
embayment
tidal
Sub
0
100
200
400
(meters)
Some tilted
fossil heads
Non-tilted
fossil heads
Drowned,
dead trees
Legend:
Beach berm
Intertidal
Reef Flat
Zone of
fossil heads
Zone of
large living heads
Mangroves,
swamps, forests
Observed loose cobles
and boulders
GPS control points
98.3488 E
-0.5134 S

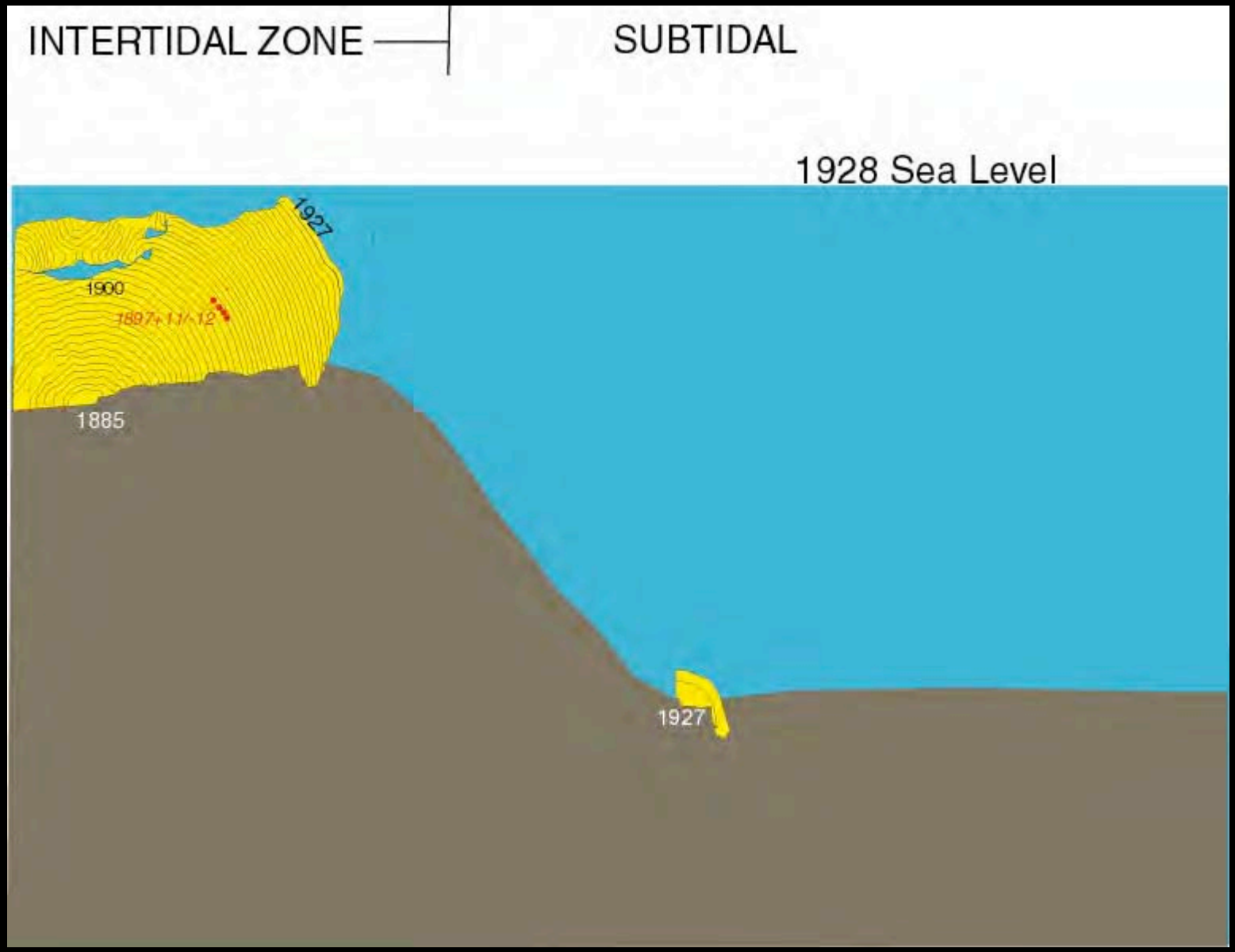

-0.4992 S
North
Mangrove Swamps
Pre-1935-event HLS contour
Mangrove on mud,
old heads,
old coral debris
H9
+20cm
H5
H10
H6
0
1935 HLS regression
1997 HLS
98.3454 E
5% Fossil heads and debris
~80% Fossil microatolls
H2
H8
H7
H3
0
TB97
H1
-20cm
Beach
H18
-50cm
98.3439 E
debris of
cobbles and
small boulders
H4
contour
H11
H12
H13
H15
TB00A1
H16
H14
H17
-100cm
-150cm
1935 HLS regression
Post-1935-event HLS
small coralls
Dead shallow reef, ~1% living
Subtidal reef
-20cm
-50cm
-100cm
-150cm
0
25
50
100m
-0.5009 S

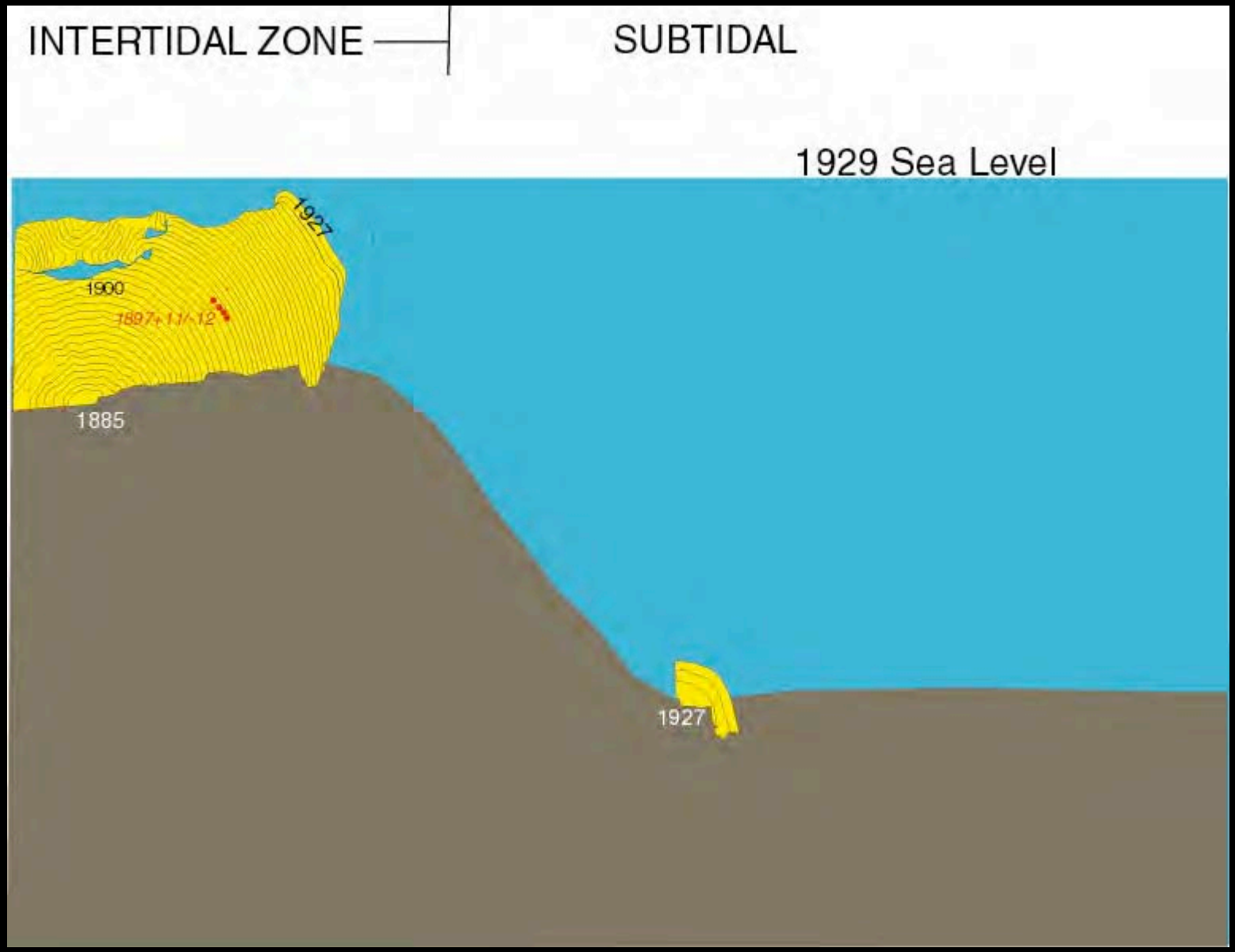
The microatoll “graveyard” in the intertidal zone

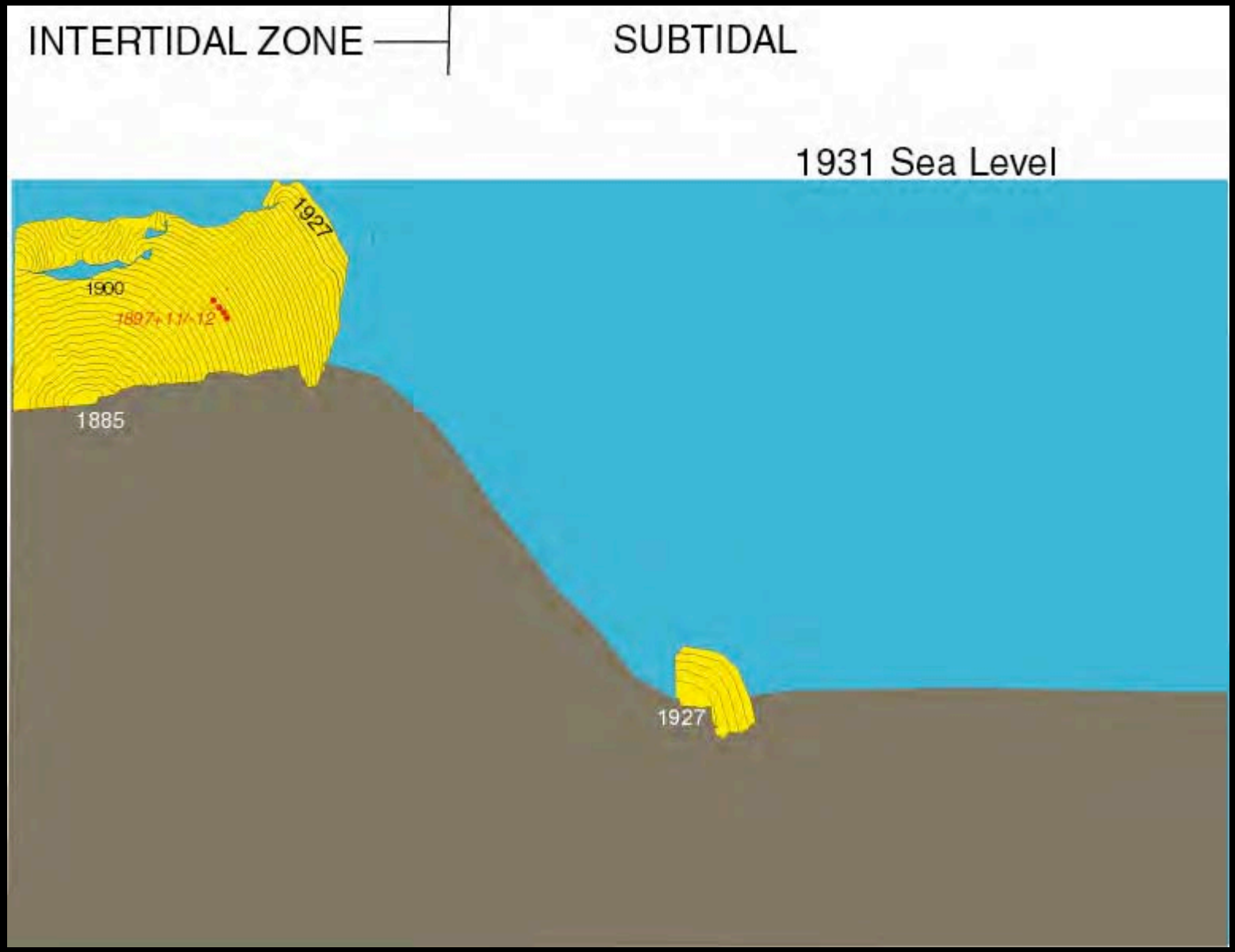

Tanabala Island
Raised annular rim
Central flat
Outer perimeter
0
centimeters
25
Growth direction
U-Th
samples
Slab x-radiograph

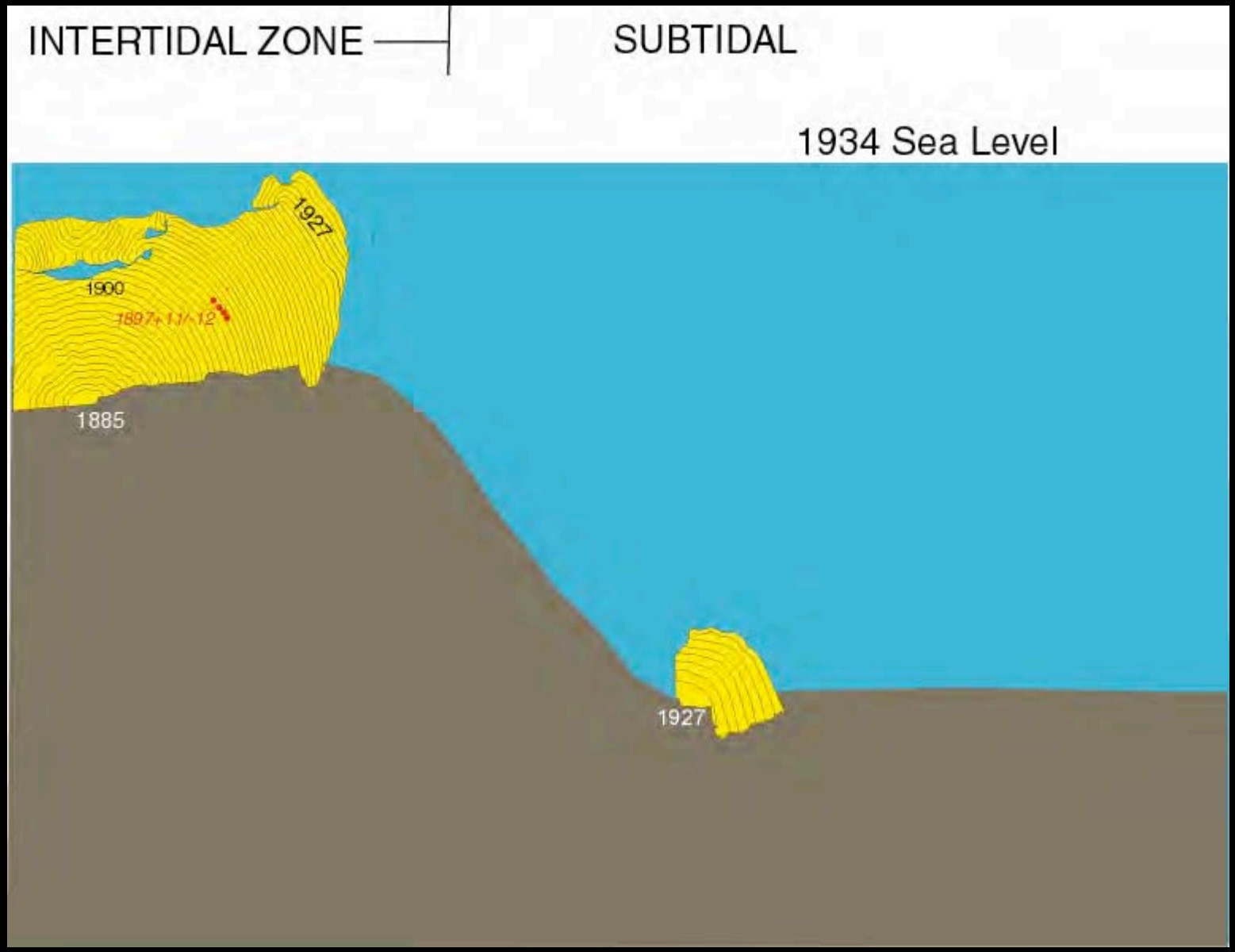

S
N
eroded
1935
Left wing
eroded?
Middle part
Right wing
eroded
1935
0
5
10
25
cm
1935
1930
1925
1920
1915
1910
1905
1900
1895
1890
1885
horizontal line
1897+11/-12
(U-Th dating)
Substrate
Unrecovered
base of head
0
-5
-10
-15
-20
-25
-30
-35
-40
1890
1895
1900
1905
1910
1915
1920
1925
1930
1935
-2.2+/-2mm/y
-9+/-1mm/yr
-10mm/y
Average submergence rate
-5.4 +/- 0.3 mm/y
(4.5 +/- 0.6 mm/y)

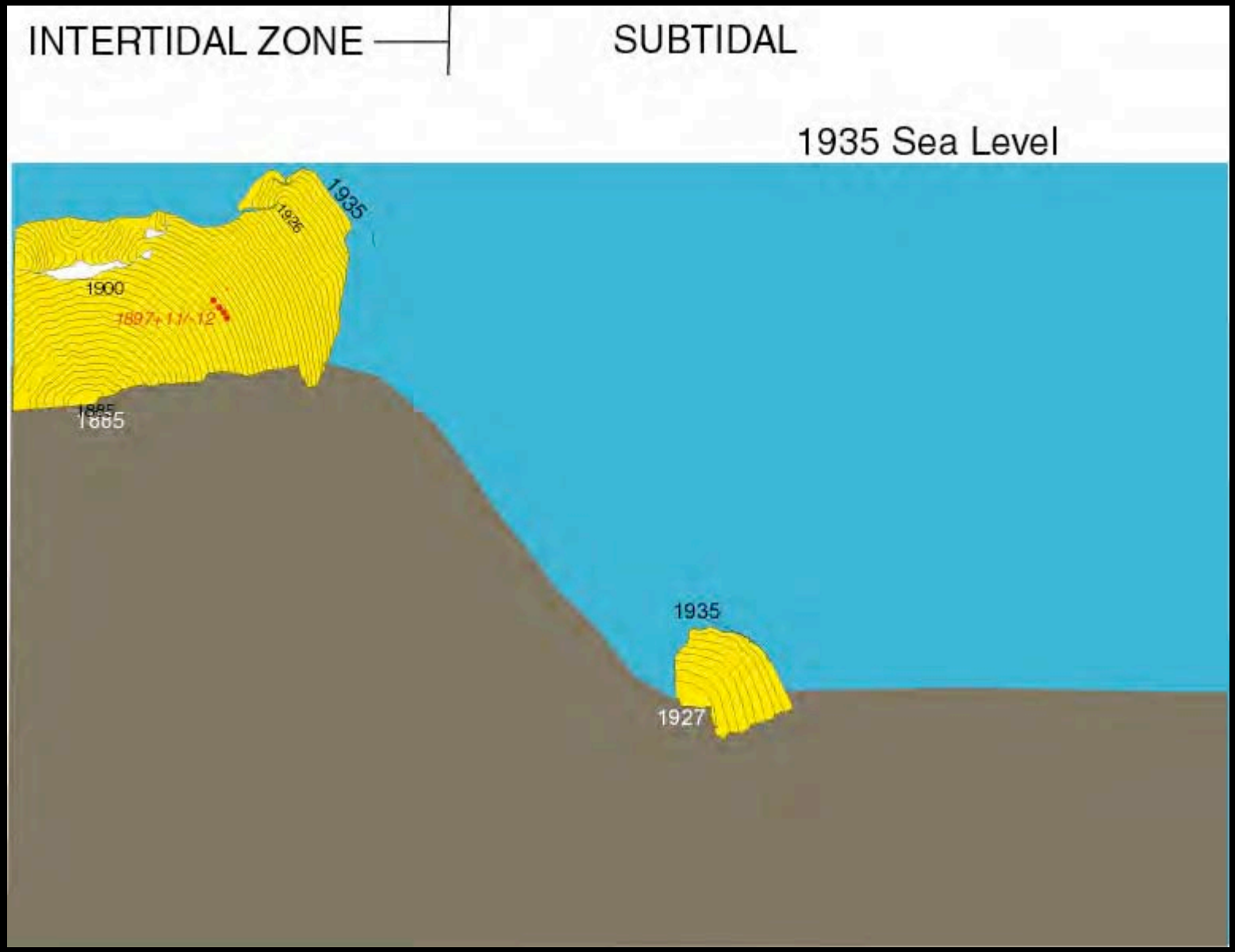

INTERTIDAL ZONE
SUBTIDAL
1927 Sea Level
1927
1900
1897+11/-12
1885
1927

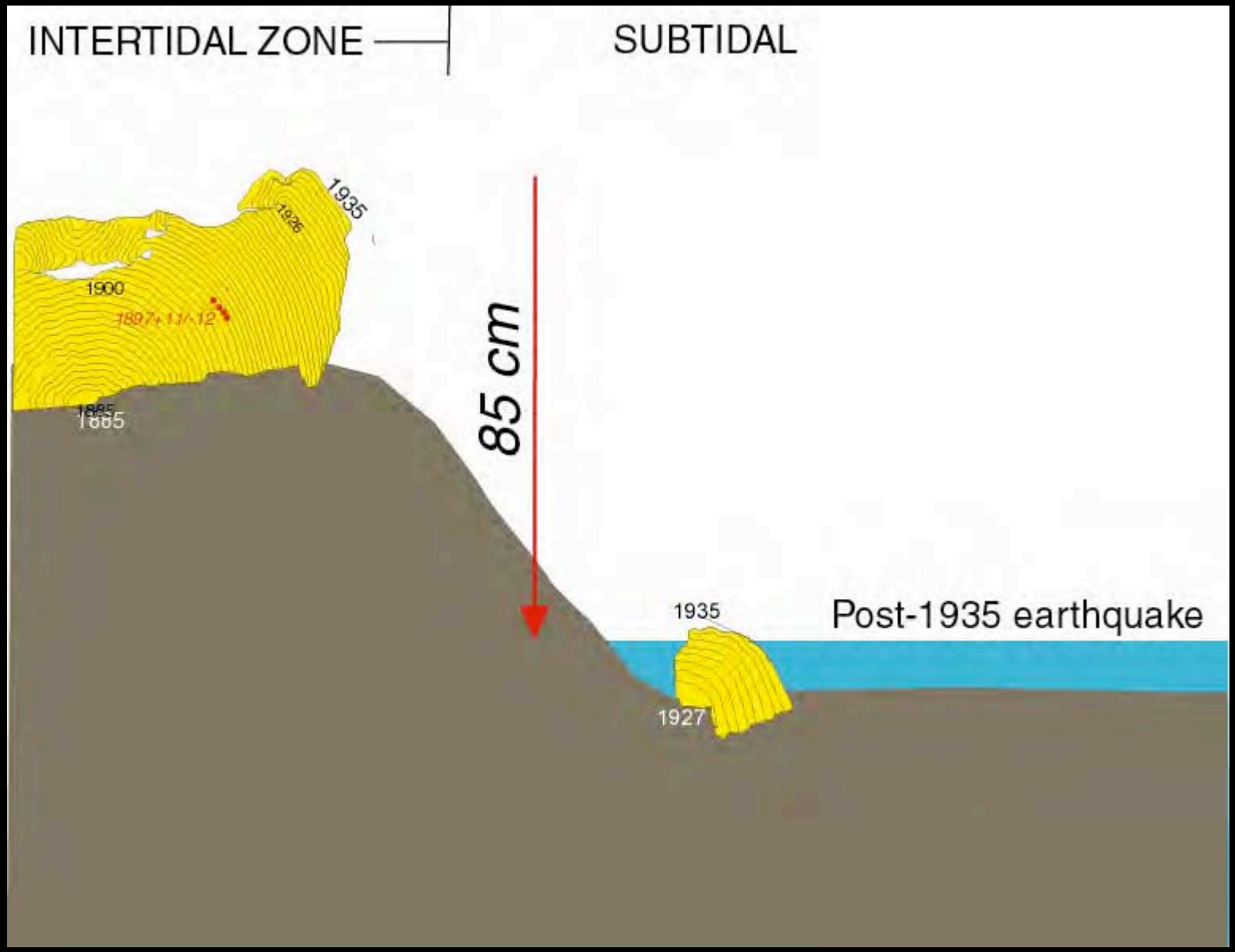

INTERTIDAL ZONE
SUBTIDAL
1928 Sea Level
1927
1900
1897+11/-12
1885
1927

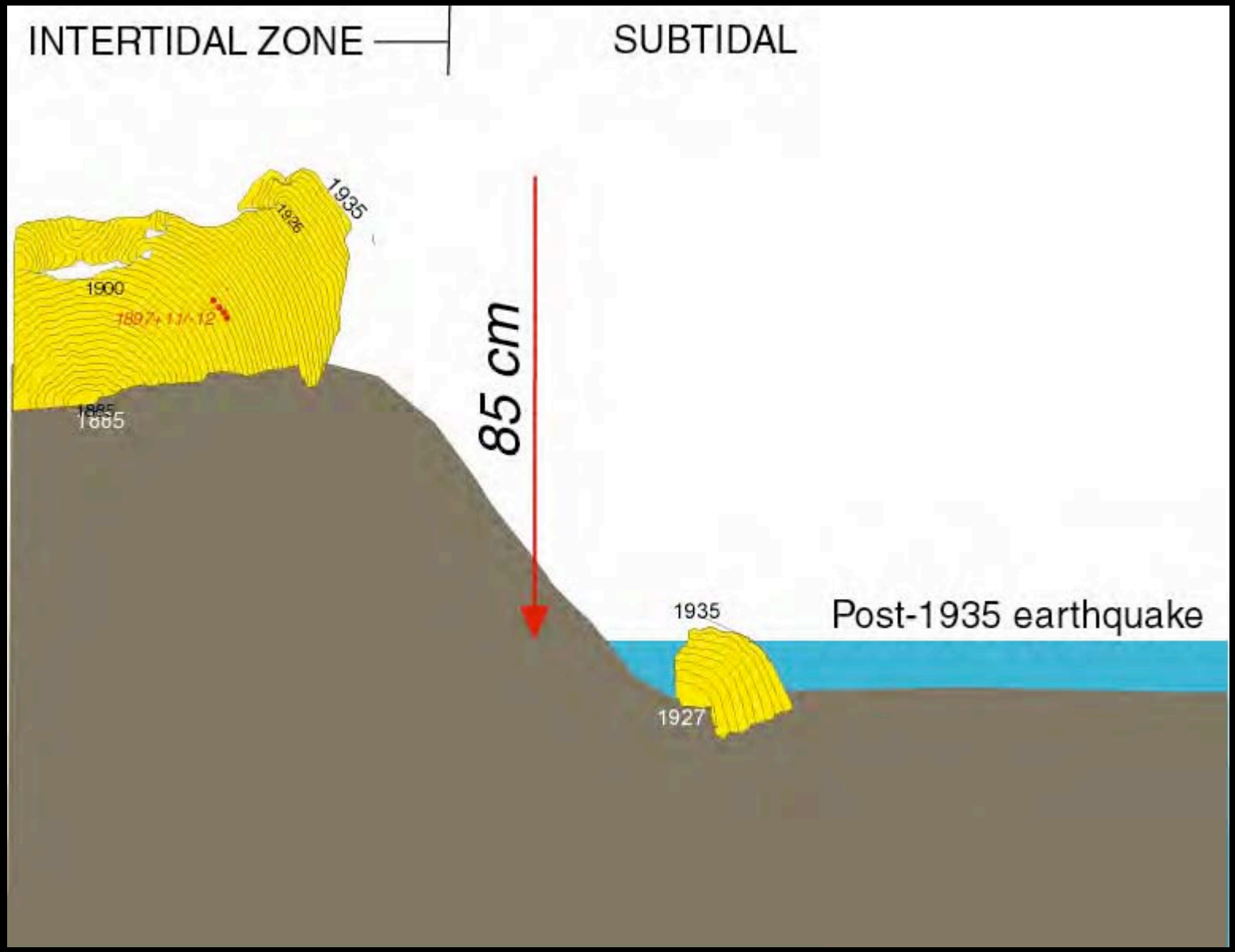

INTERTIDAL ZONE
SUBTIDAL
1929 Sea Level
1927
1900
1897+11/-12
1885
1927

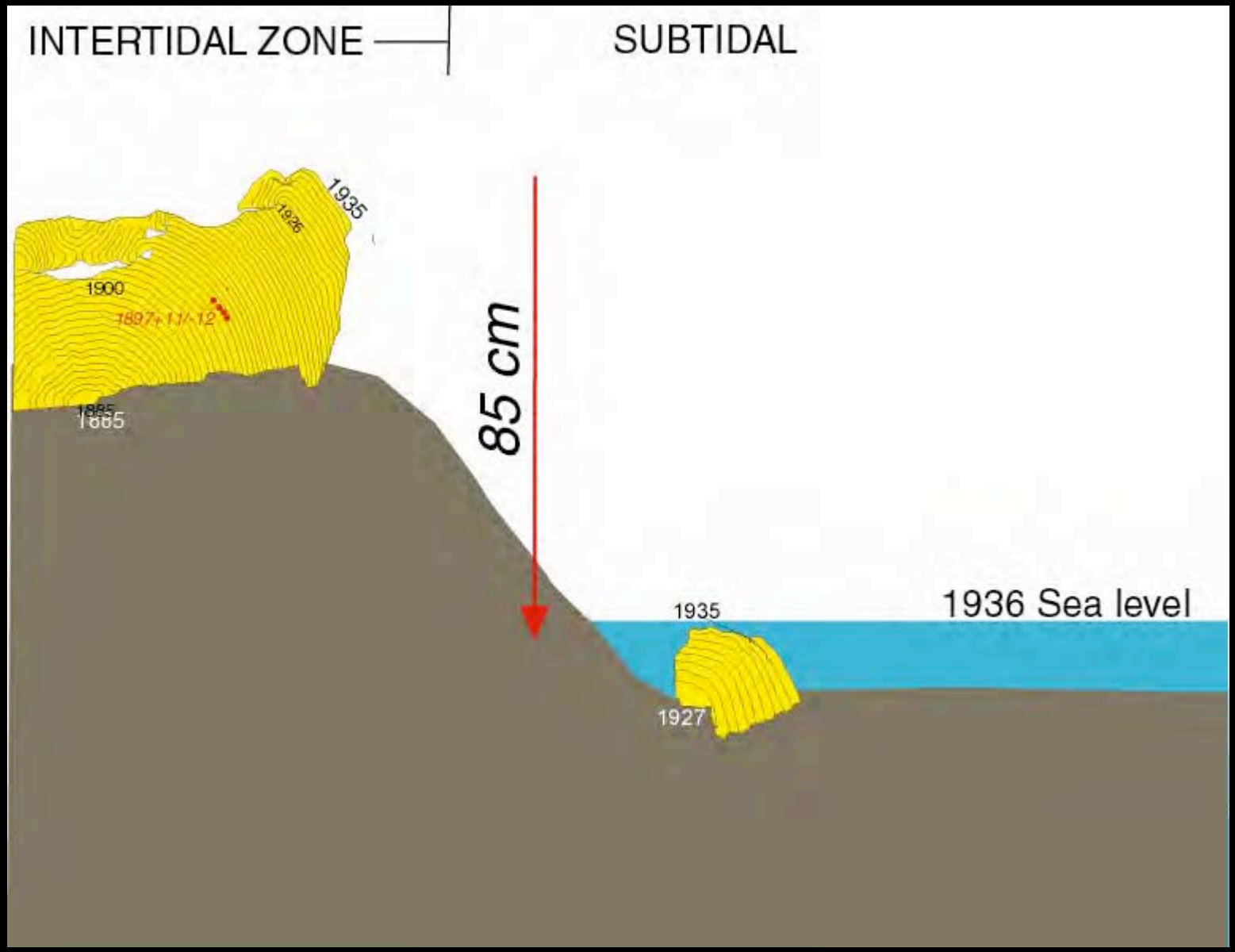

INTERTIDAL ZONE
SUBTIDAL
1931 Sea Level
1927
1900
1897+11/-12
1885
1927

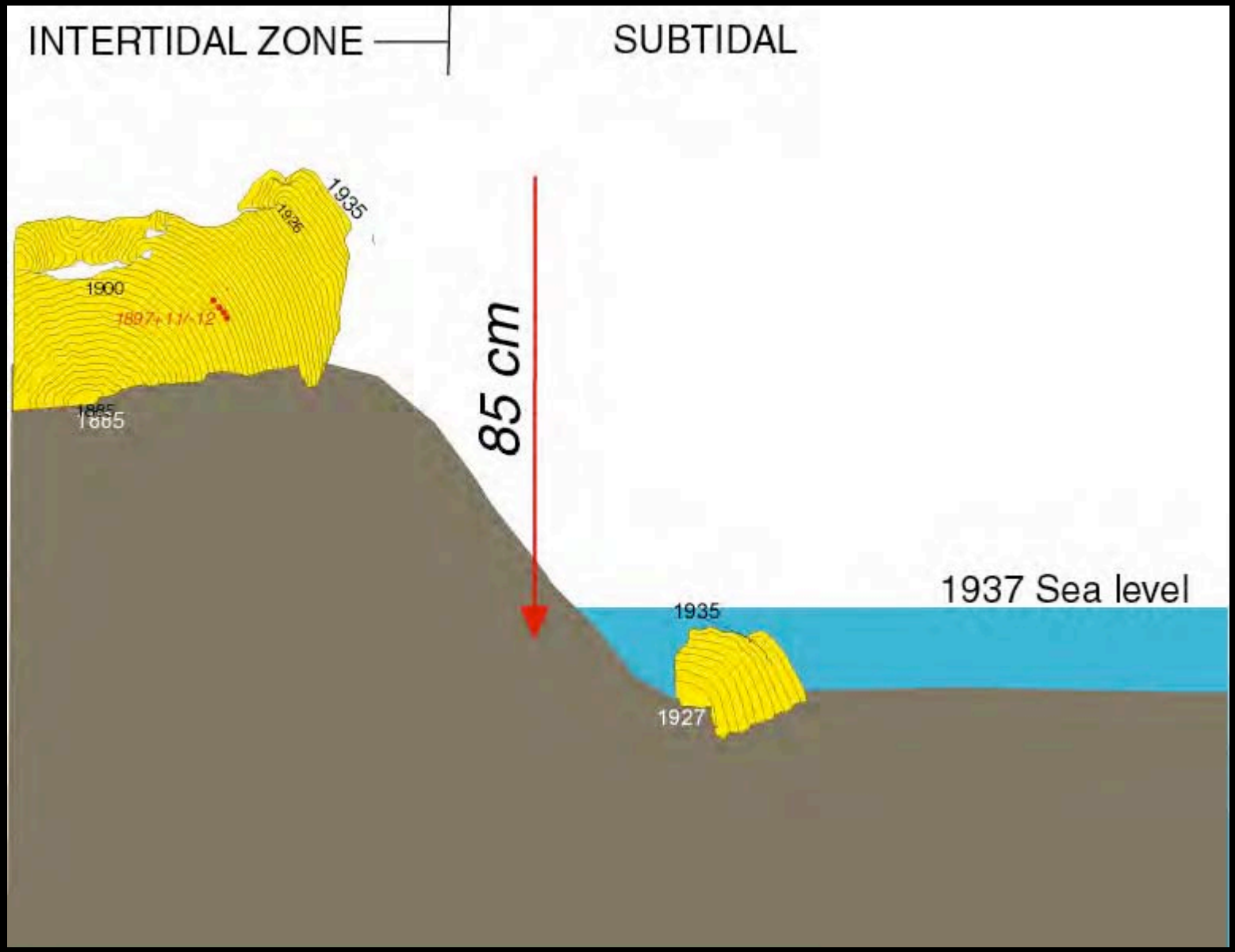

INTERTIDAL ZONE
SUBTIDAL
1934 Sea Level
1927
1900
1897+11/-12
1885
1927

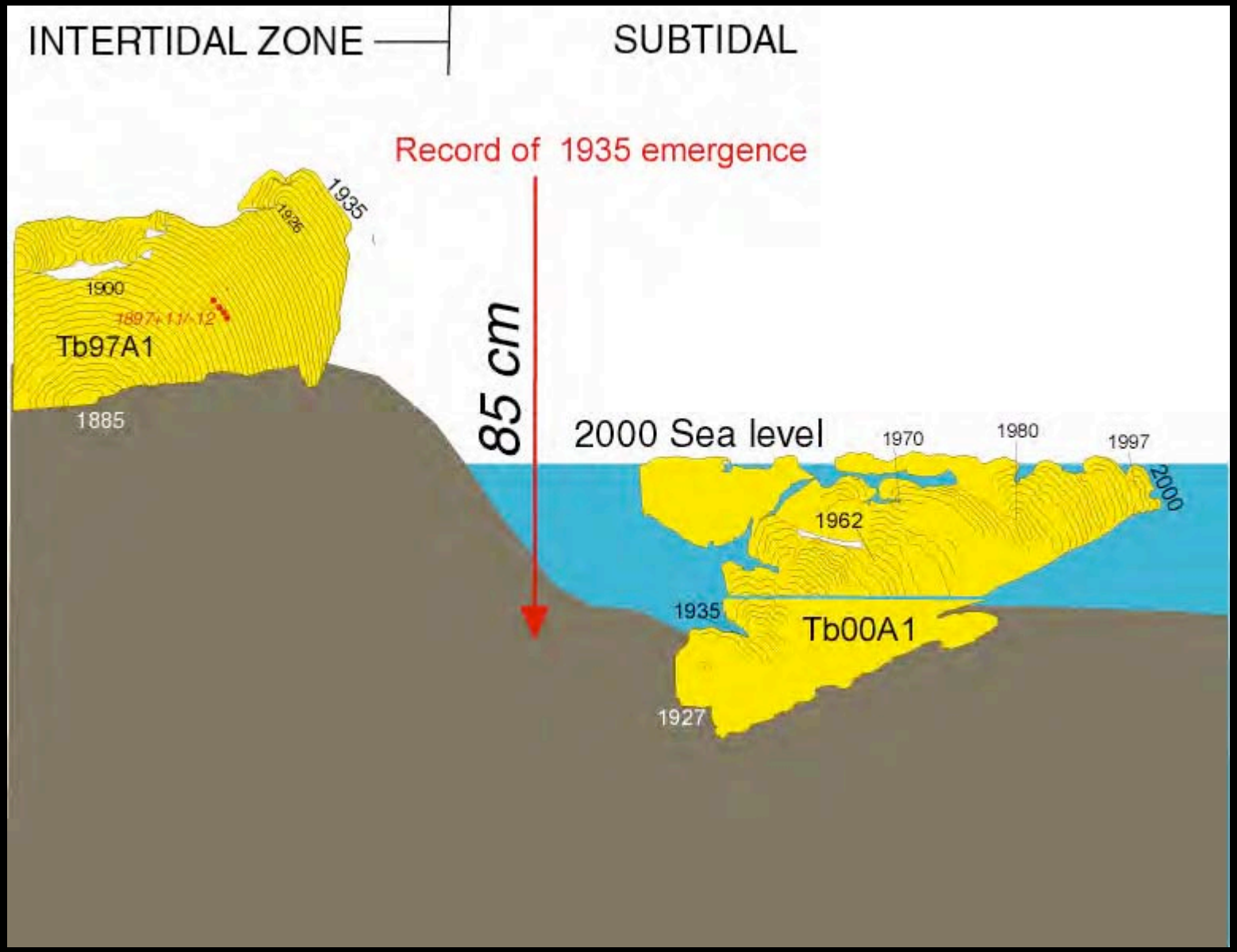

INTERTIDAL ZONE
SUBTIDAL
1935 Sea Level
1935
1926
1900
1897+11/-12
1885
1665
1935
1927

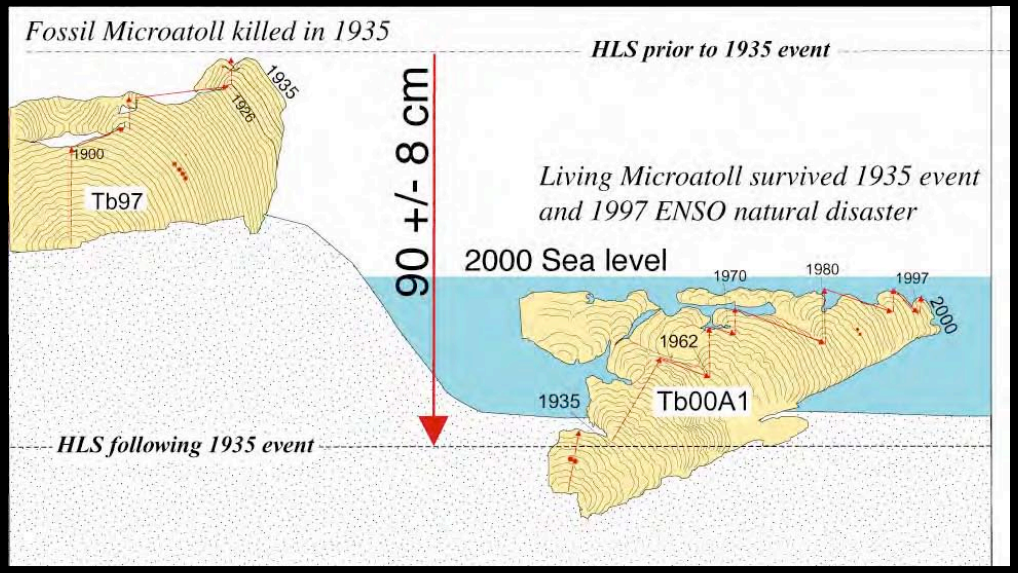

INTERTIDAL ZONE
SUBTIDAL
1935
1926
1900
1897+11/-12
1885
1885
85 cm
1935
Post-1935 earthquake
1927

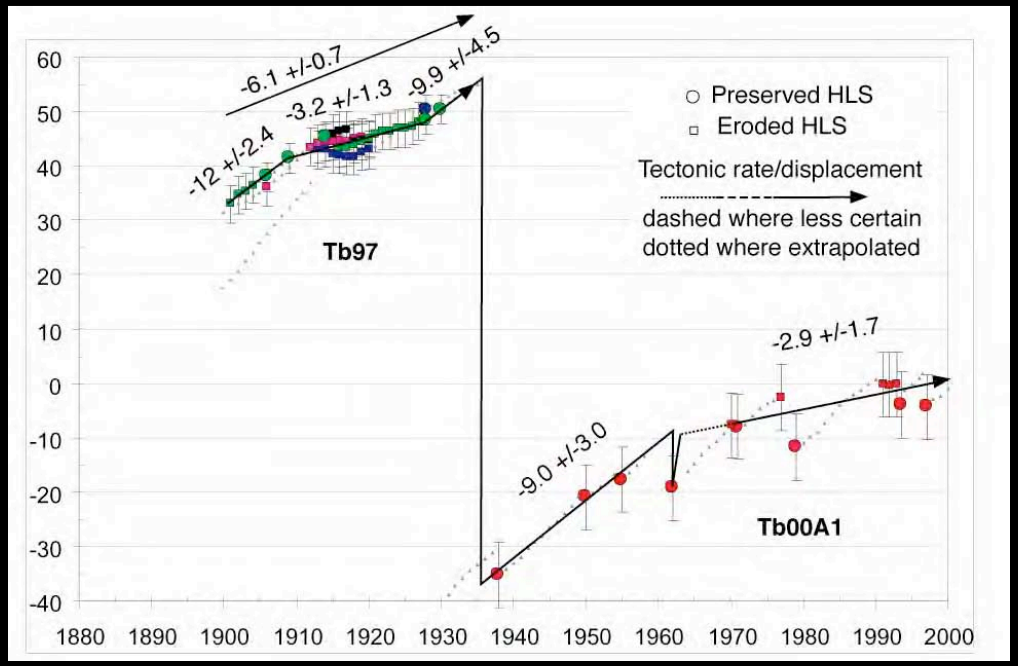

INTERTIDAL ZONE
SUBTIDAL
1935
1926
1900
1897+11/-12
1885
1885
85 cm
1935
Post-1935 earthquake
1927

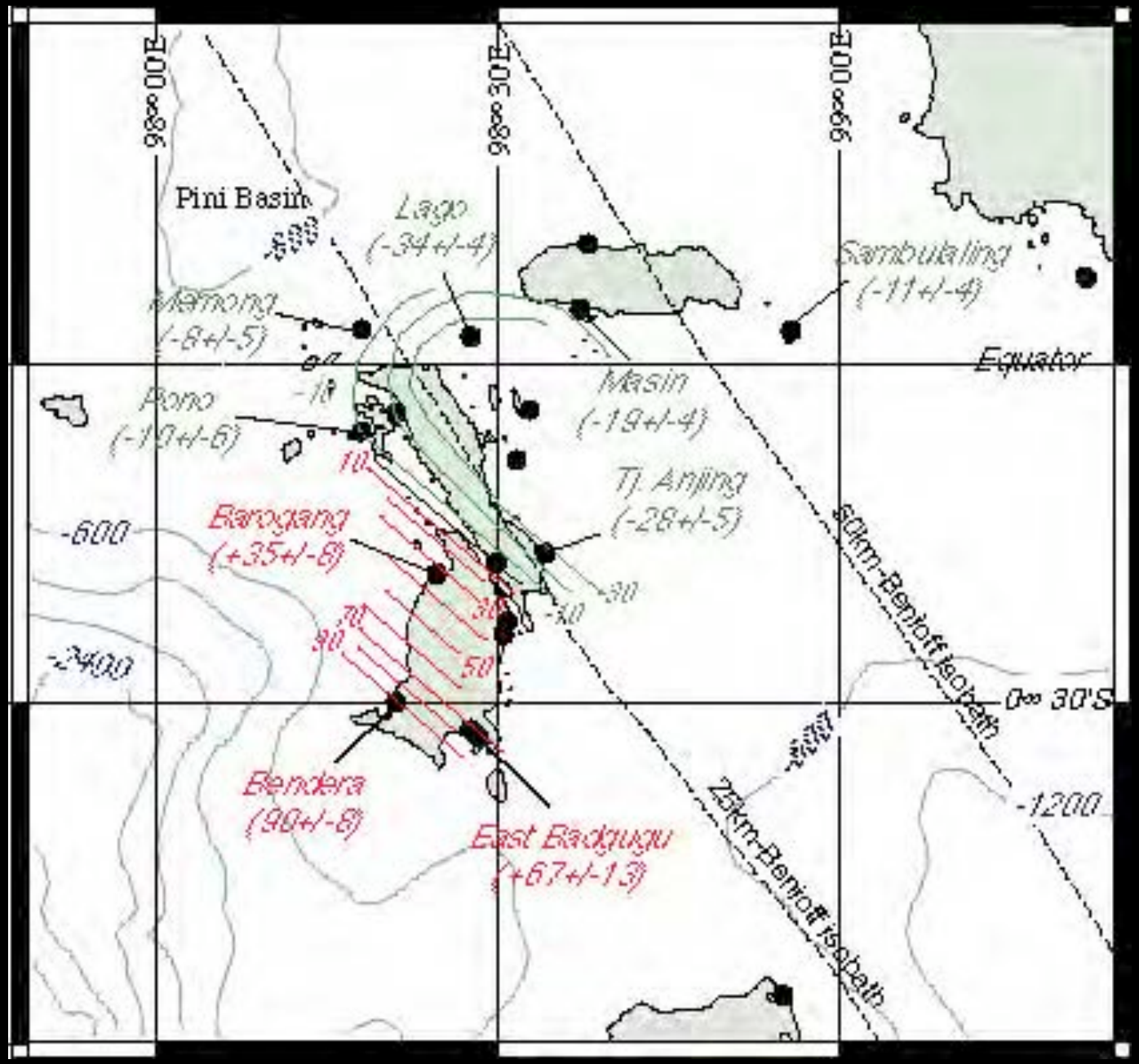

INTERTIDAL ZONE
SUBTIDAL
1935
1926
1900
1897+11/-12
1885
1665
85 cm
1936 Sea level
1935
1927

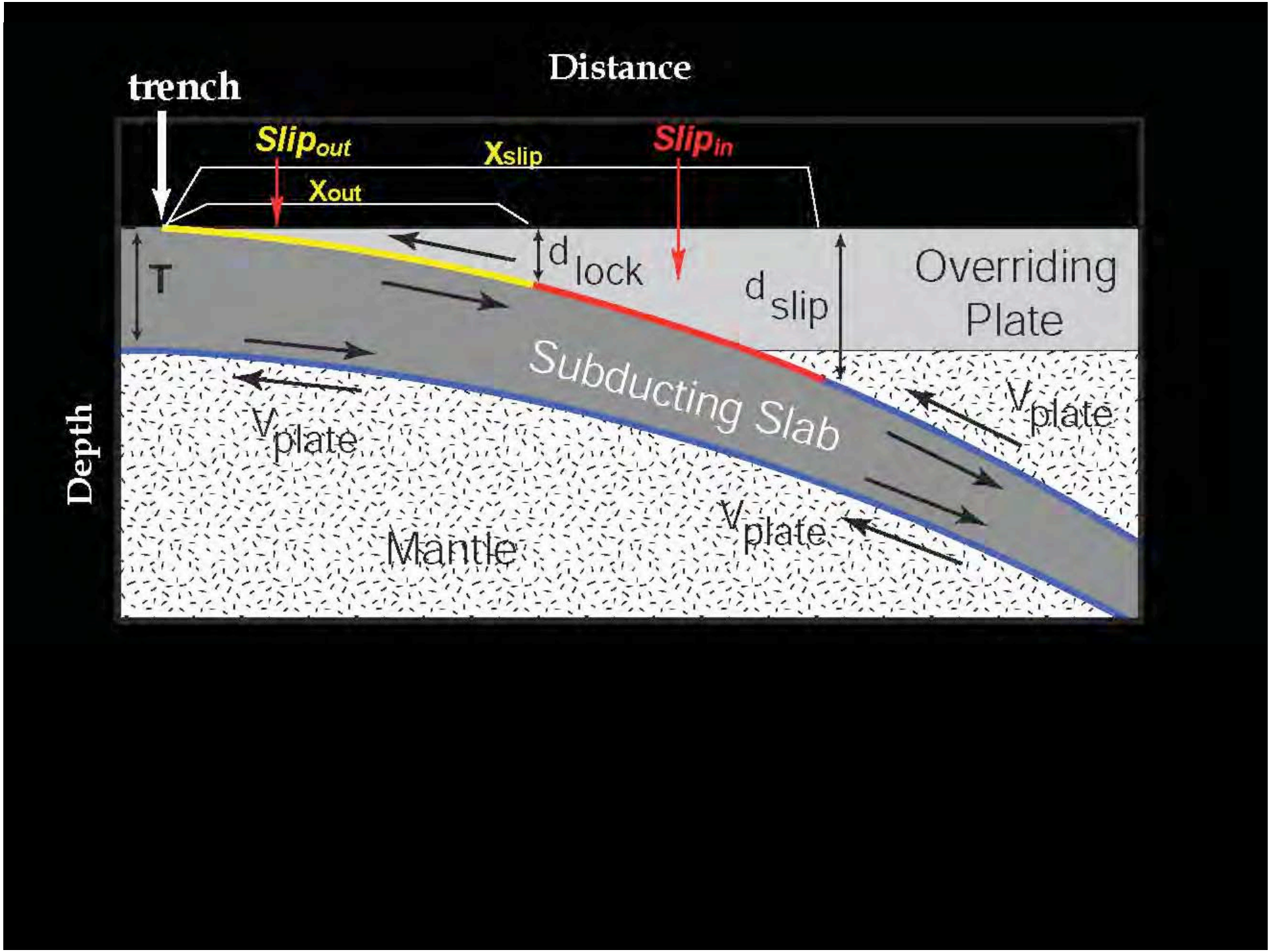

INTERTIDAL ZONE
SUBTIDAL
1935
1926
1900
1897+11/-12
1885
1865
85 cm
1937 Sea level
1935
1927

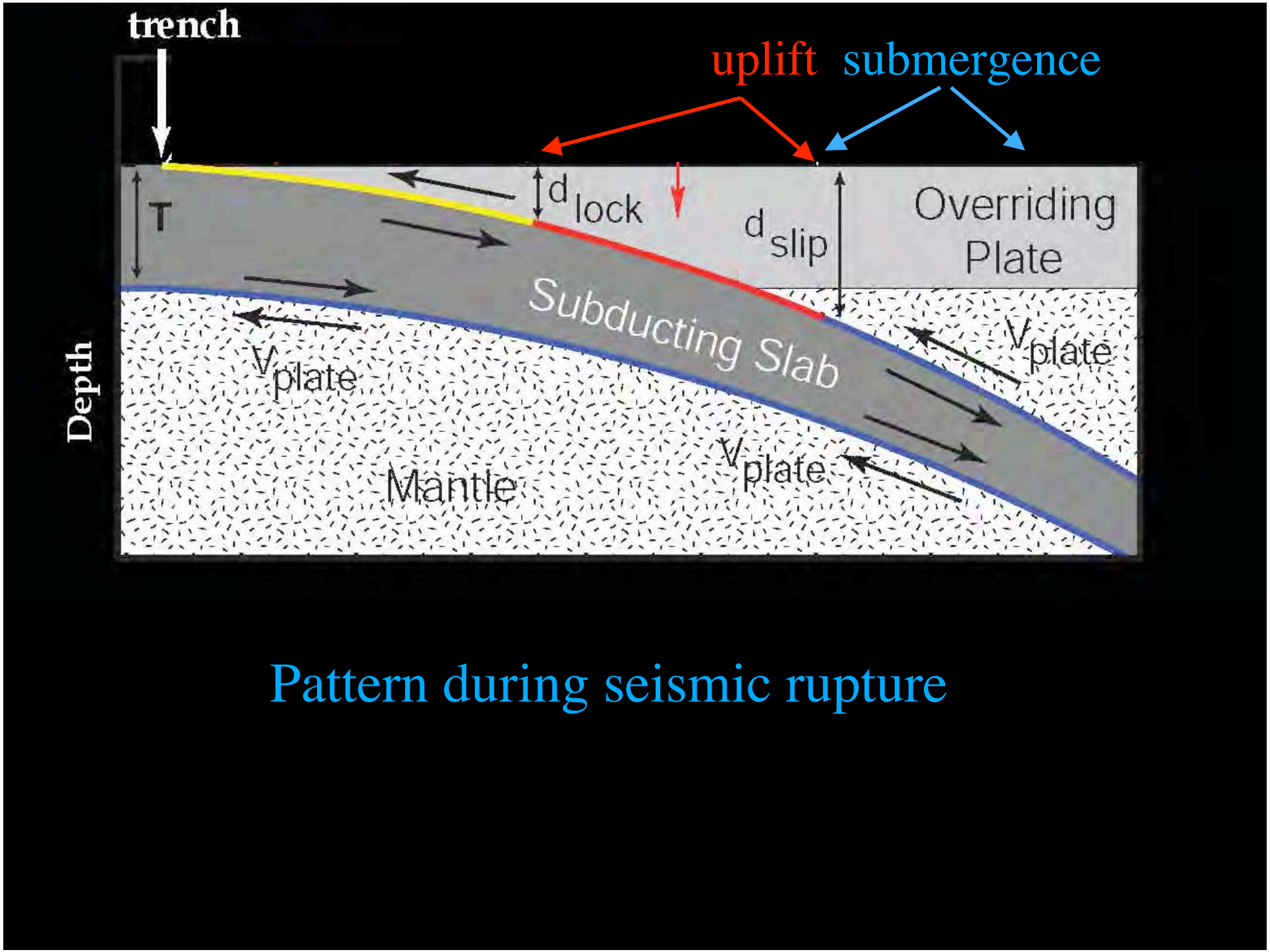

INTERTIDAL ZONE
SUBTIDAL
Record of 1935 emergence
85 cm
1935
1926
1900
1897+11/-12
Tb97A1
1885
2000 Sea level
1970
1980
1997
2000
1962
1935
Tb00A1
1927


Fossil Microatoll killed in 1935
HLS prior to 1935 event
1935
1926
1900
Tb97
90 +/- 8 cm
Living Microatoll survived 1935 event
and 1997 ENSO natural disaster
2000 Sea level
1970
1980
1997
2000
1962
1935
Tb00A1
HLS following 1935 event

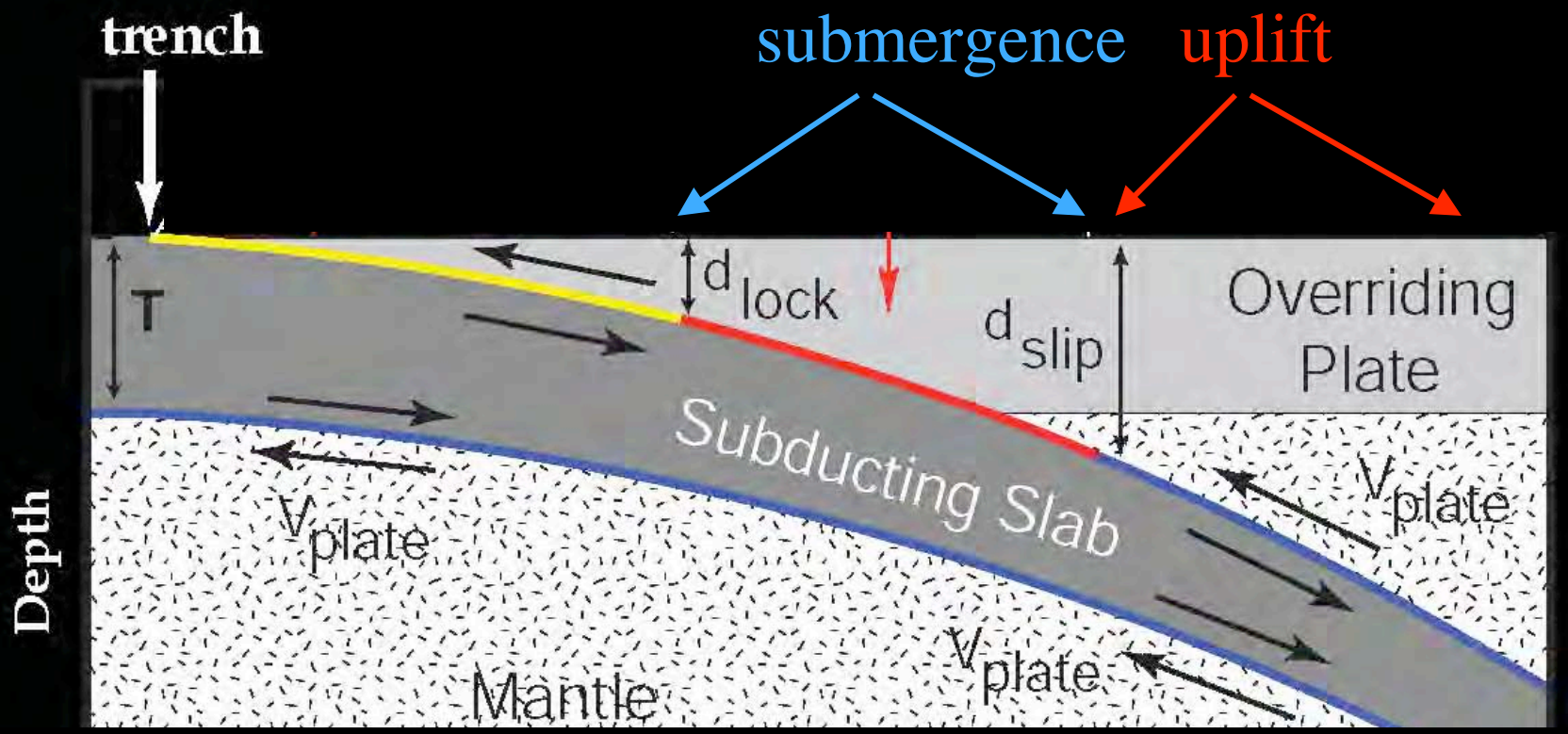

-6.1 +/-0.7
-3.2 +/-1.3
-9.9 +/-4.5
-12 +/-2.4
Tb97
Preserved HLS
Eroded HLS
Tectonic rate/displacement
dashed where less certain
dotted where extrapolated
-2.9 +/-1.7
-9.0 +/-3.0
Tb00A1
60
50
40
30
20
10
0
-10
-20
-30
-40
1880
1890
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000


98°00'E
98°30'E
99°00'E
Pini Basin
Lagu
(-34+/-4)
Sambutaling
(-11+/-4)
Mentawai
(-8+/-5)
Equator
Pono
(-19+/-6)
Masin
(-19+/-4)
Tj. Anjing
(-28+/-5)
Barogang
(+35+/-8)
-600
-2400
50km-Benioff isobath
0°30'S
75km-Benioff isobath
-1200
Bendera
(90+/-8)
East Badguguru
(+67+/-13)

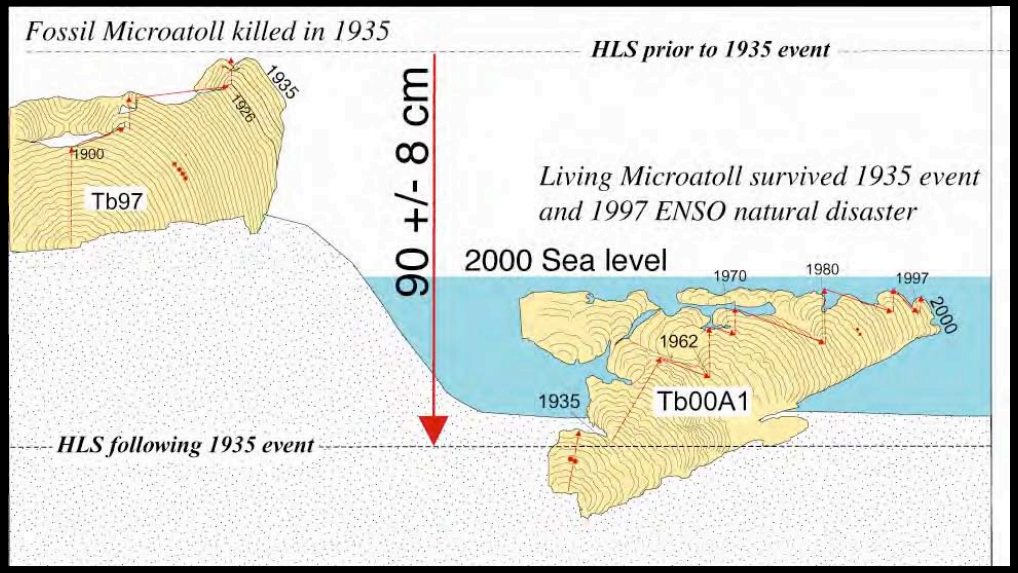

Distance
trench
Slip out
Xslip
Slip in
Xout
T
d lock
d slip
Overriding Plate
Subducting Slab
V plate
V plate
V plate
Mantle
Depth

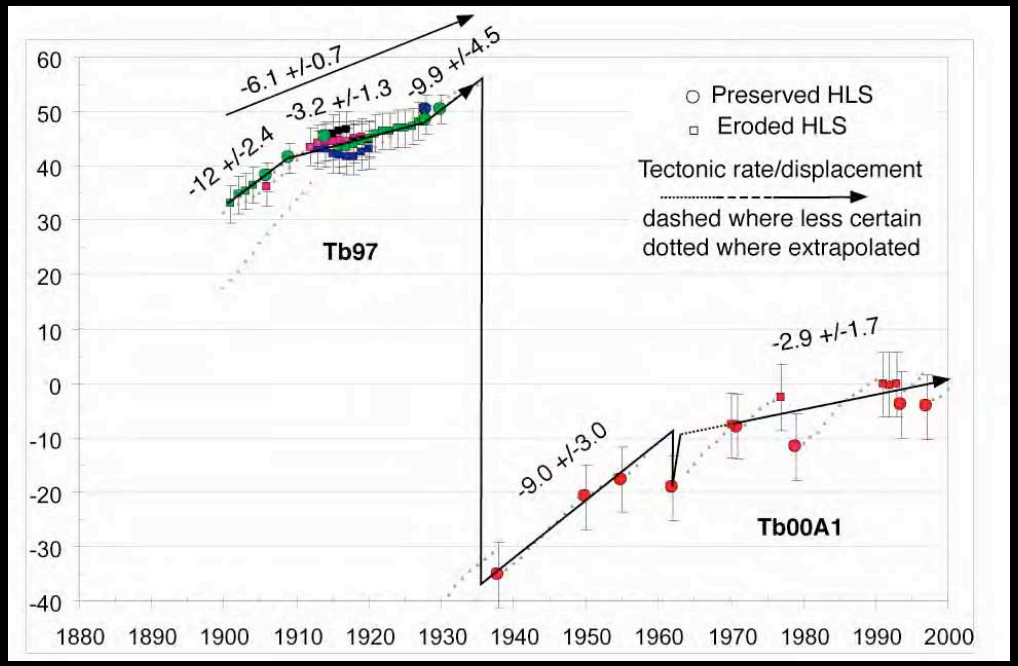


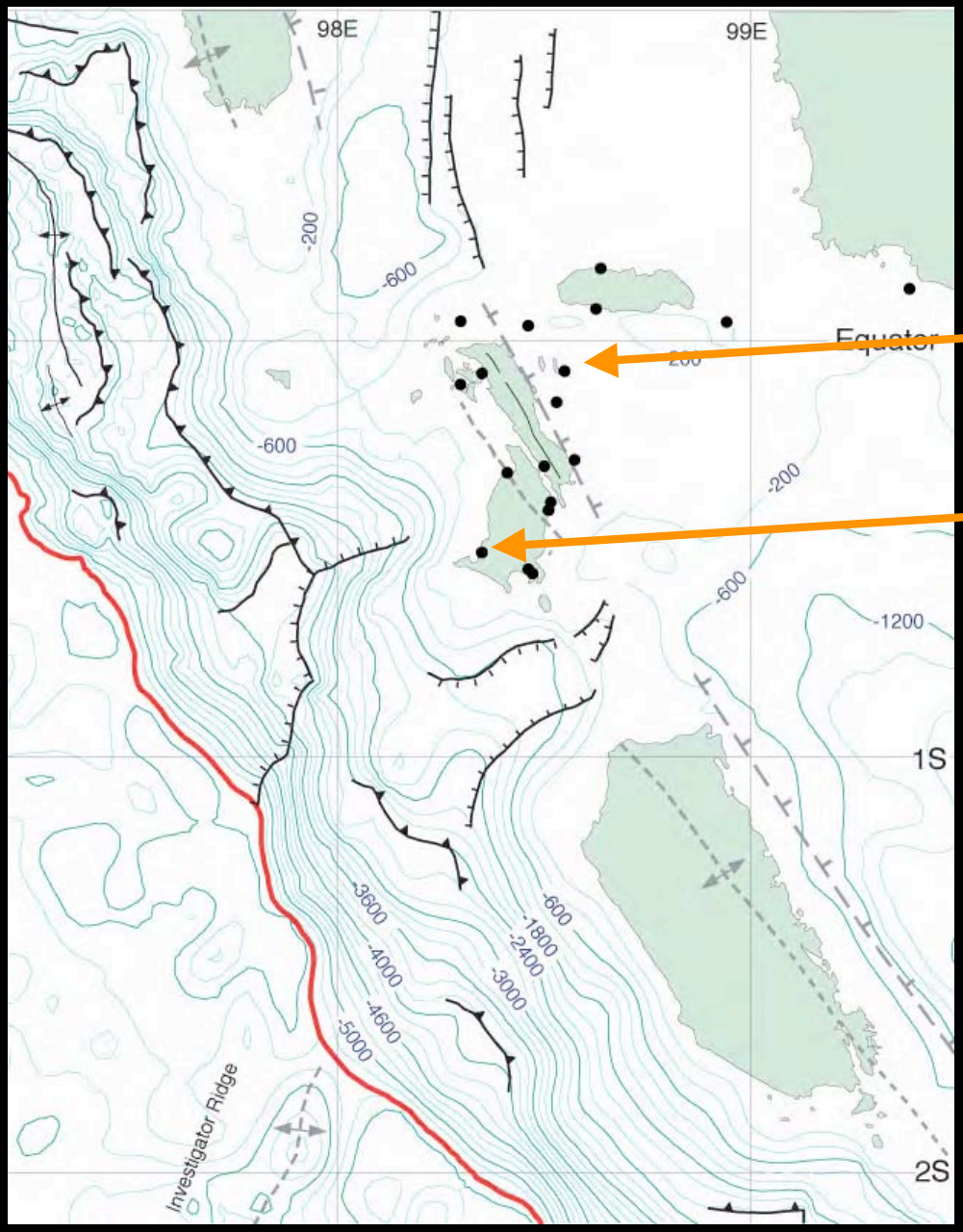
Pattern during seismic rupture

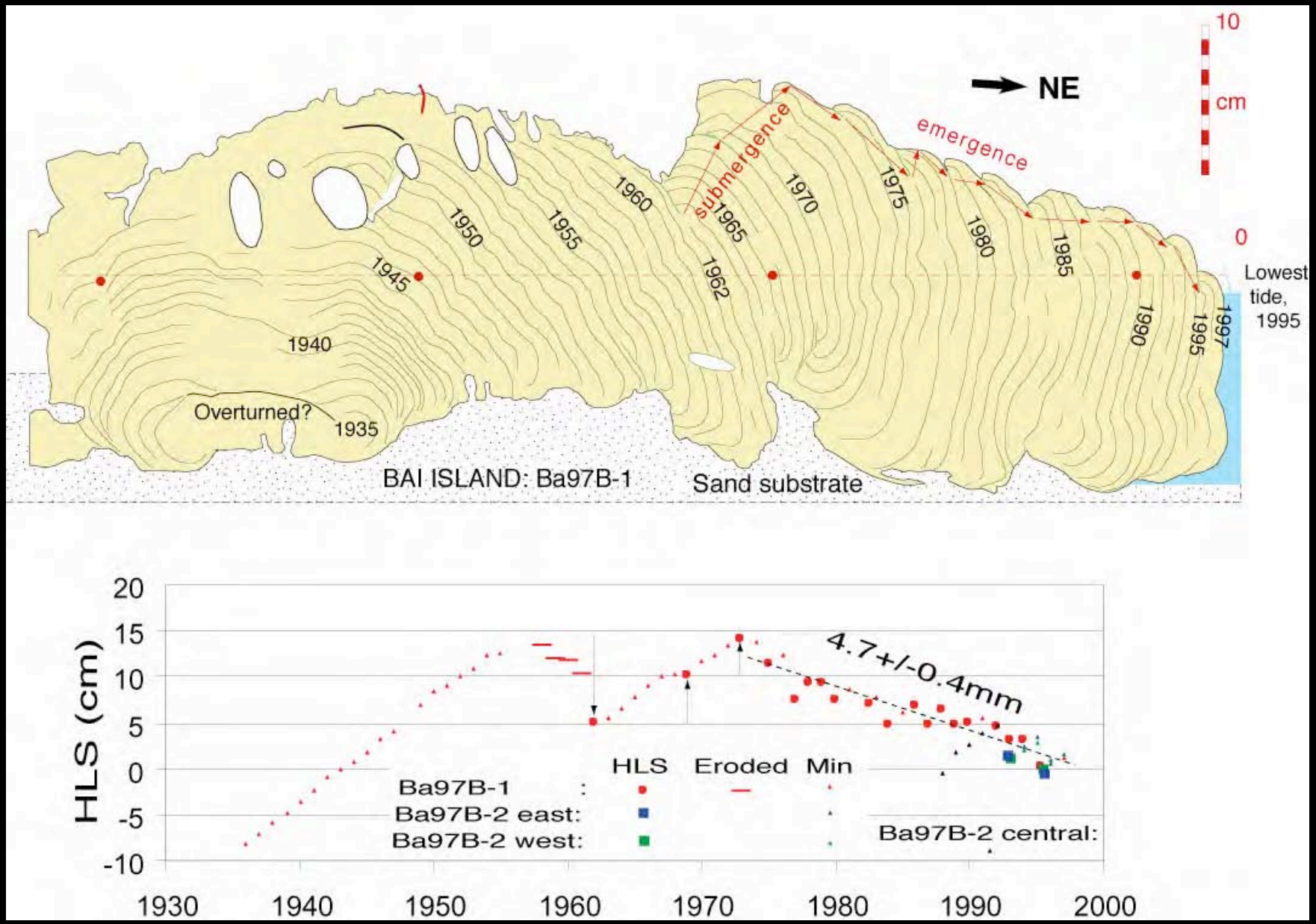


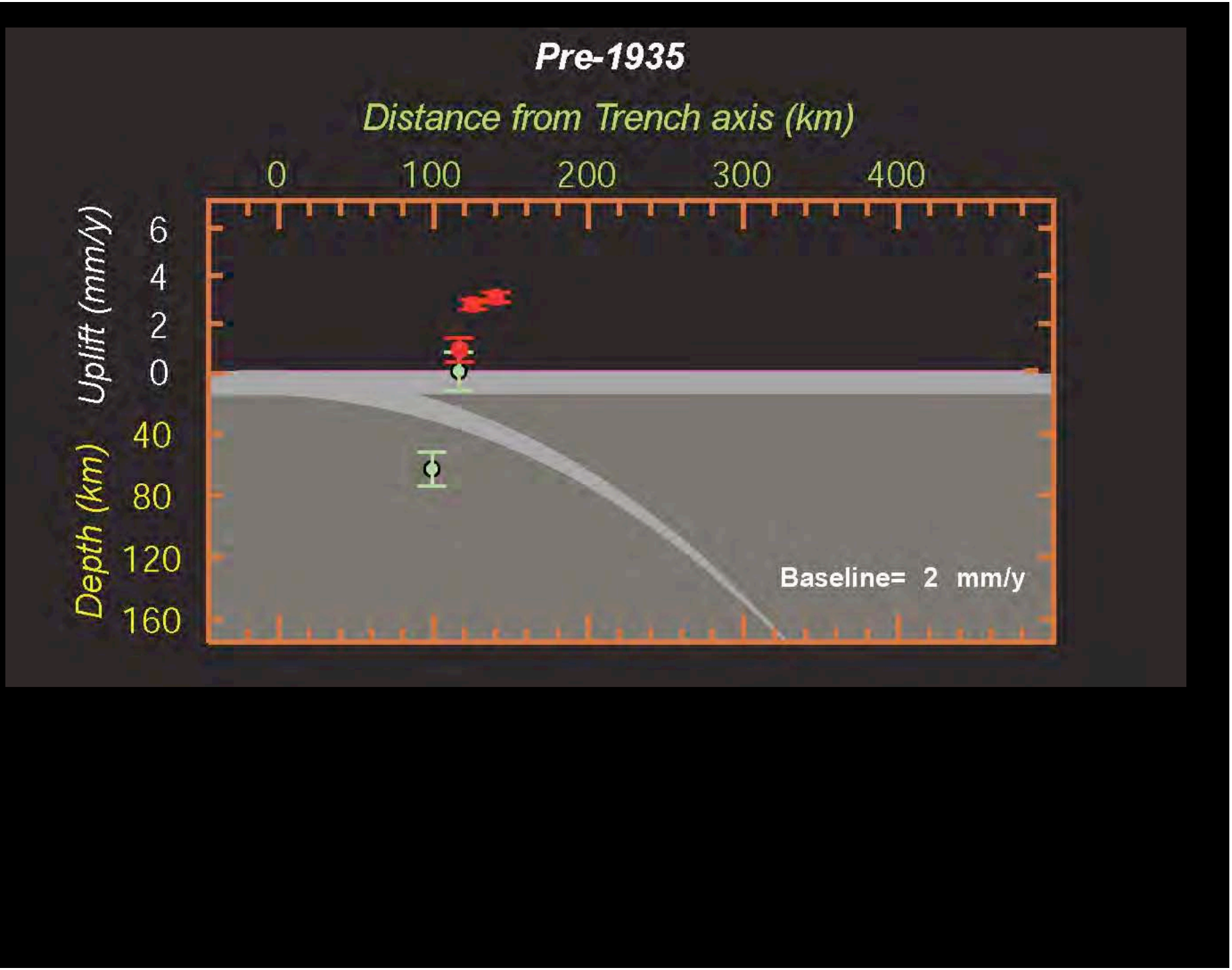
Basic pattern during interseismic period

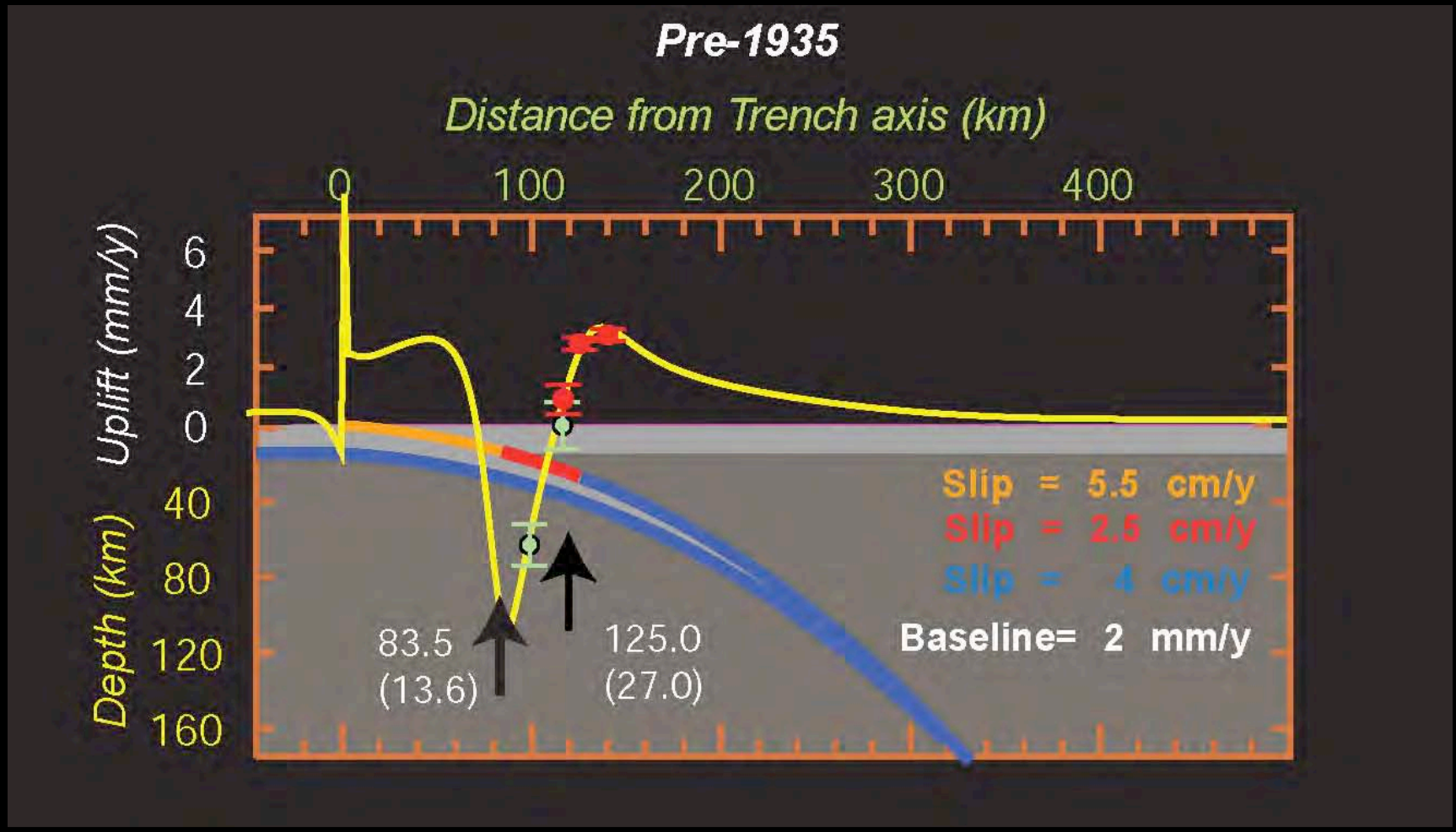

Fossil Microatoll killed in 1935
HLS prior to 1935 event
1935
1926
1900
Tb97
90 +/- 8 cm
Living Microatoll survived 1935 event
and 1997 ENSO natural disaster
2000 Sea level
1970
1980
1997
2000
1962
1935
Tb00A1
HLS following 1935 event

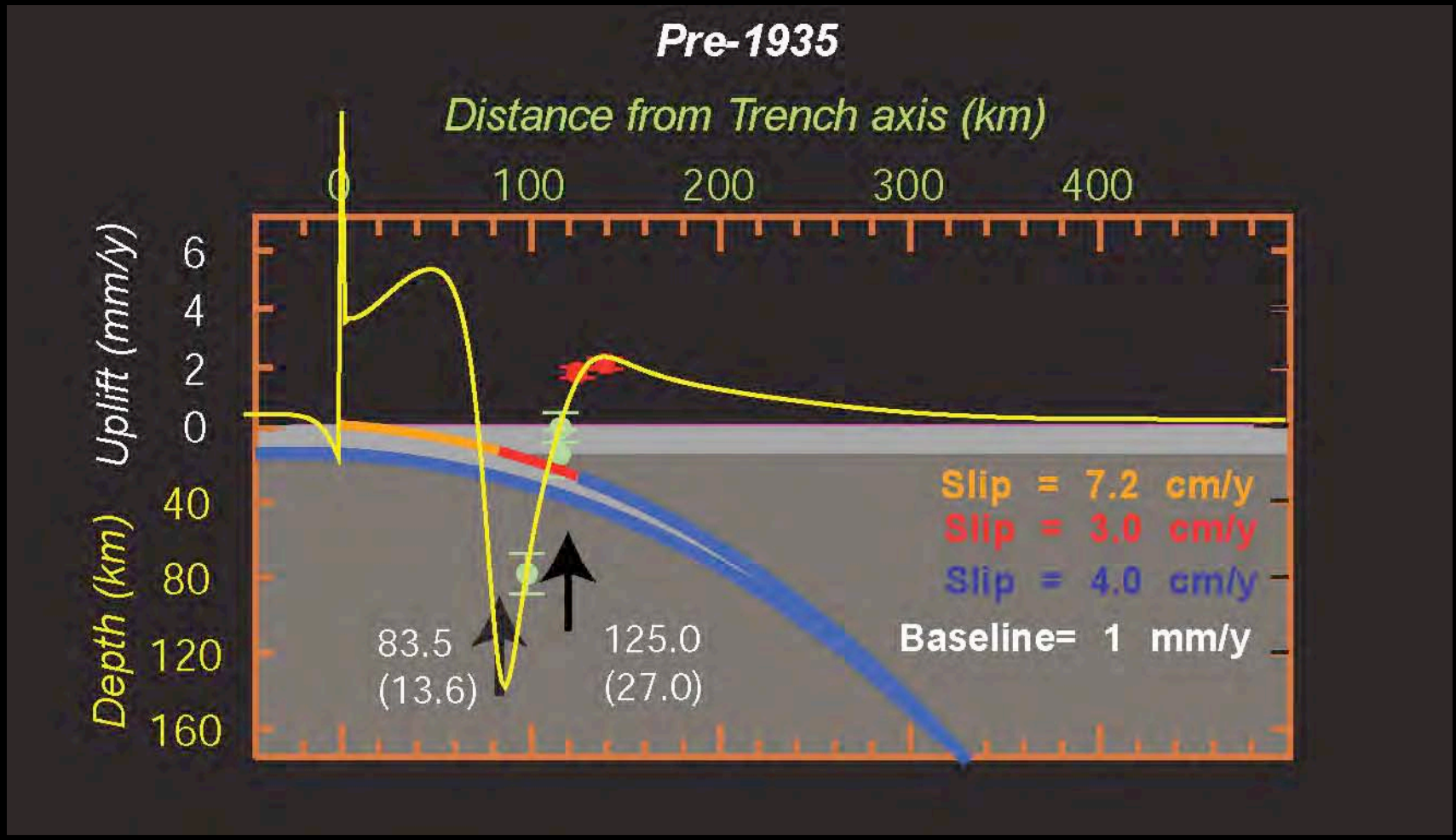

-6.1 +/-0.7
-3.2 +/-1.3
-9.9 +/-4.5
-12 +/-2.4
Tb97
Preserved HLS
Eroded HLS
Tectonic rate/displacement
dashed where less certain
dotted where extrapolated
-2.9 +/-1.7
-9.0 +/-3.0
Tb00A1
60
50
40
30
20
10
0
-10
-20
-30
-40
1880
1890
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000

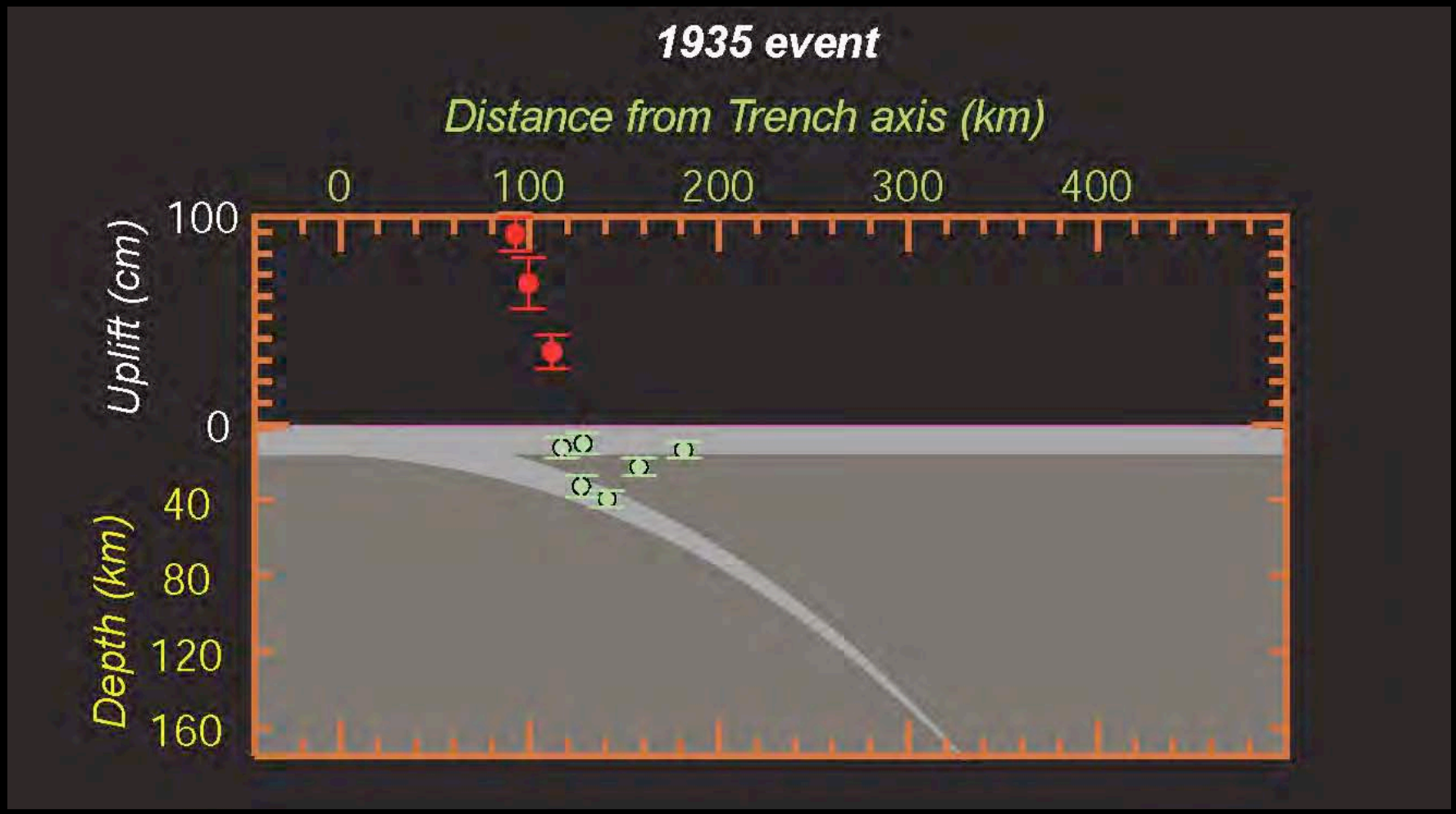

98E
99E
Equator
1S
2S
-200
-600
-1200
-1800
-2400
-3000
-3600
-4000
-4600
-5000
Investigator Ridge
Bai
Bendera

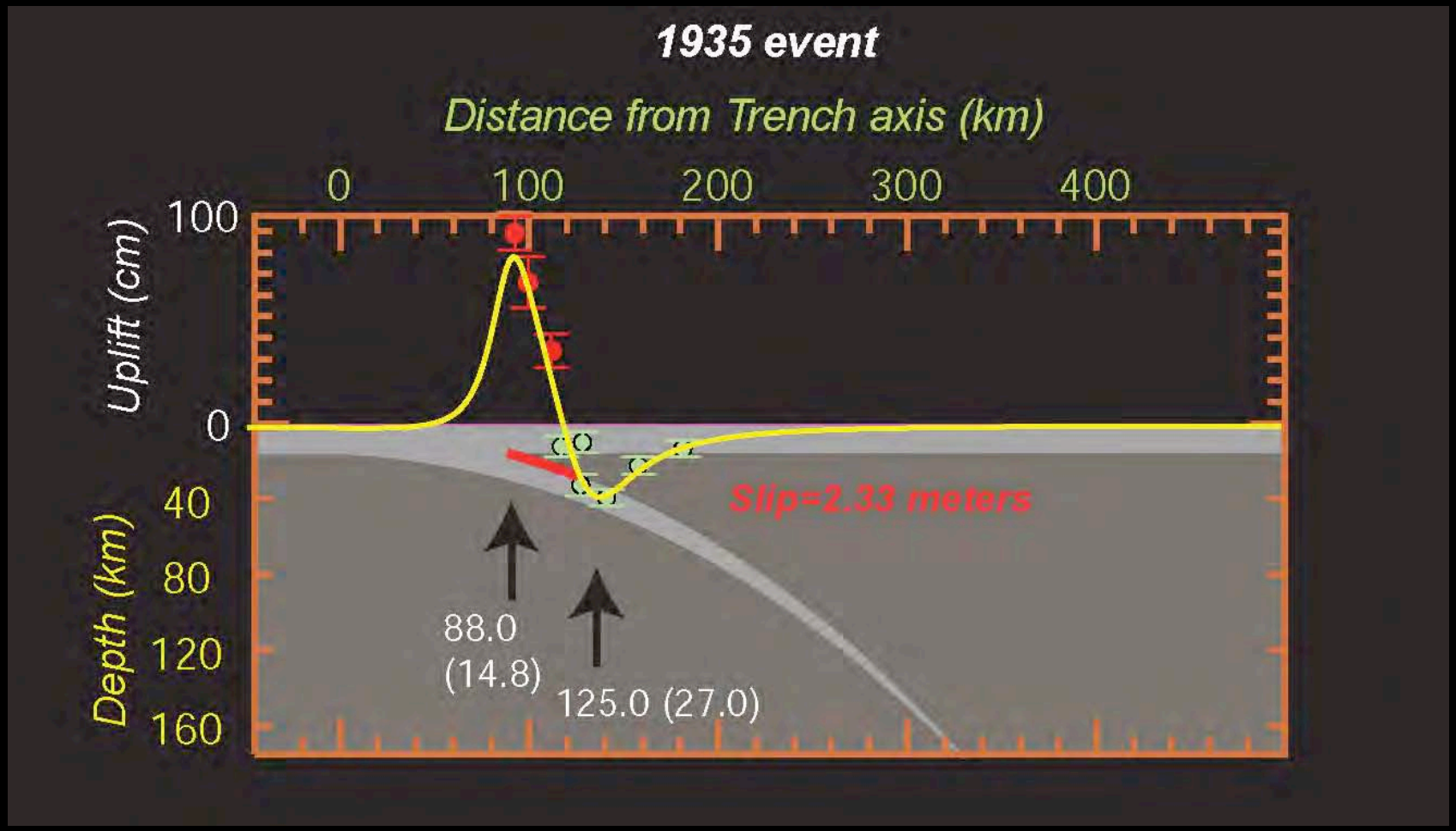

10
cm
0
NE
submergence
emergence
1940
1945
1950
1955
1960
1962
1965
1970
1975
1980
1985
1990
1995
1997
Lowest tide, 1995
Overturned?
1935
BAI ISLAND: Ba97B-1
Sand substrate
HLS (cm)
20
15
10
5
0
-5
-10
1930
1940
1950
1960
1970
1980
1990
2000
4.7+/-0.4mm
HLS
Eroded
Min
Ba97B-1 :
Ba97B-2 east:
Ba97B-2 west:
Ba97B-2 central:

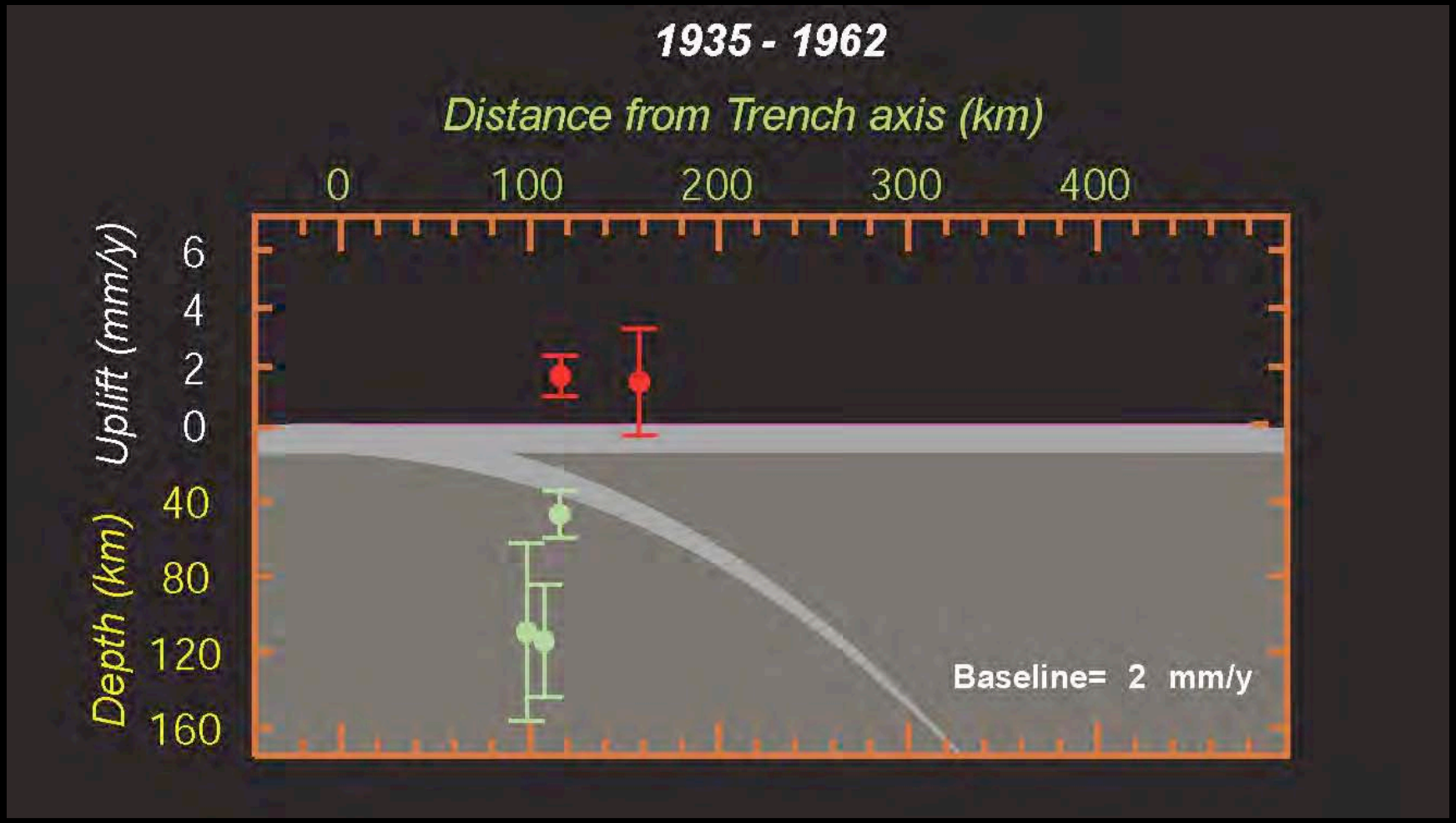

Pre-1935
Distance from Trench axis (km)
0
100
200
300
400
Uplift (mm/y)
6
4
2
0
Depth (km)
40
80
120
160
Baseline= 2 mm/y

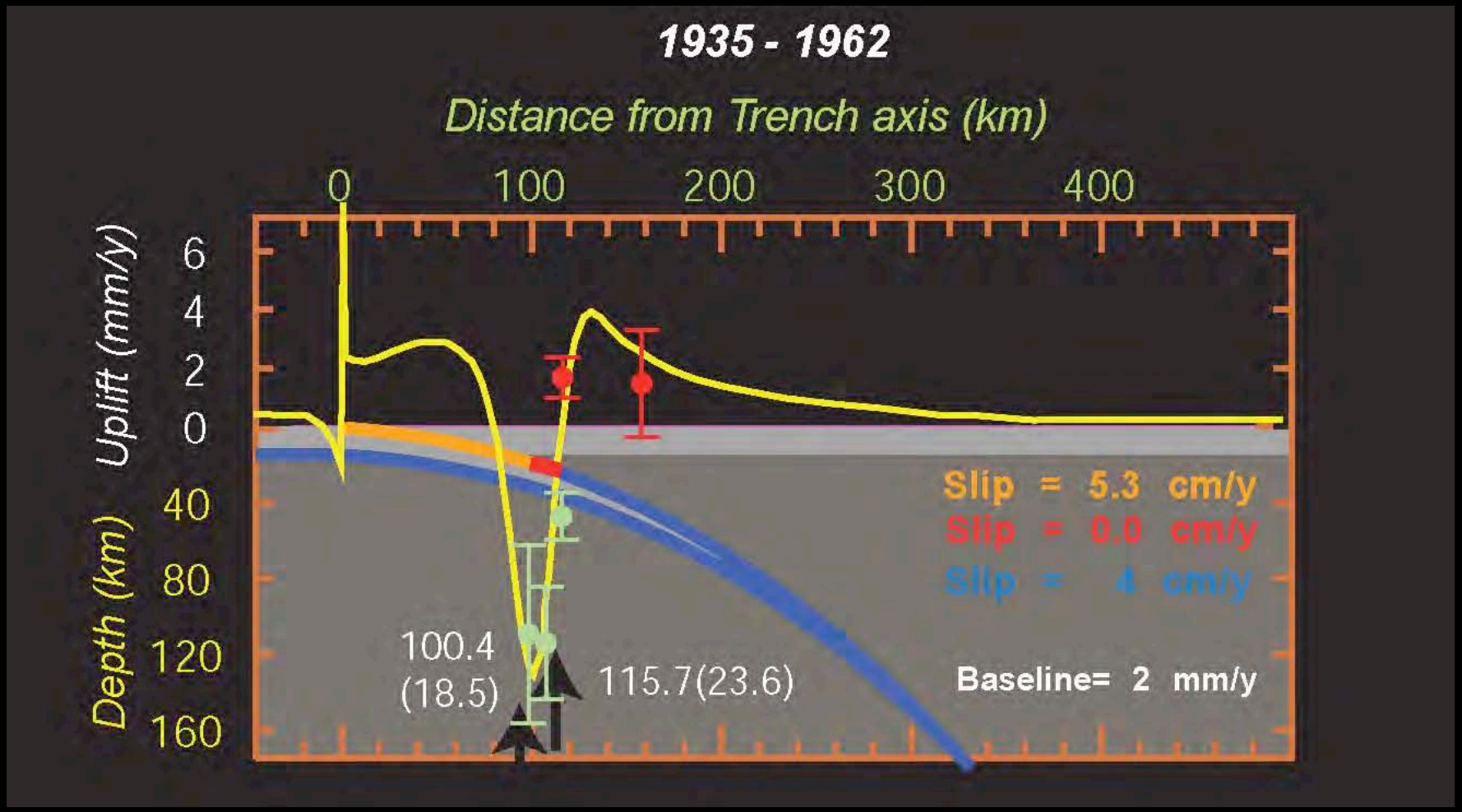

Pre-1935
Distance from Trench axis (km)
0
100
200
300
400
Uplift (mm/y)
6
4
2
0
Depth (km)
40
80
120
160
Slip = 5.5 cm/y
Slip = 2.5 cm/y
Slip = 4 cm/y
Baseline= 2 mm/y
83.5
(13.6)
125.0
(27.0)

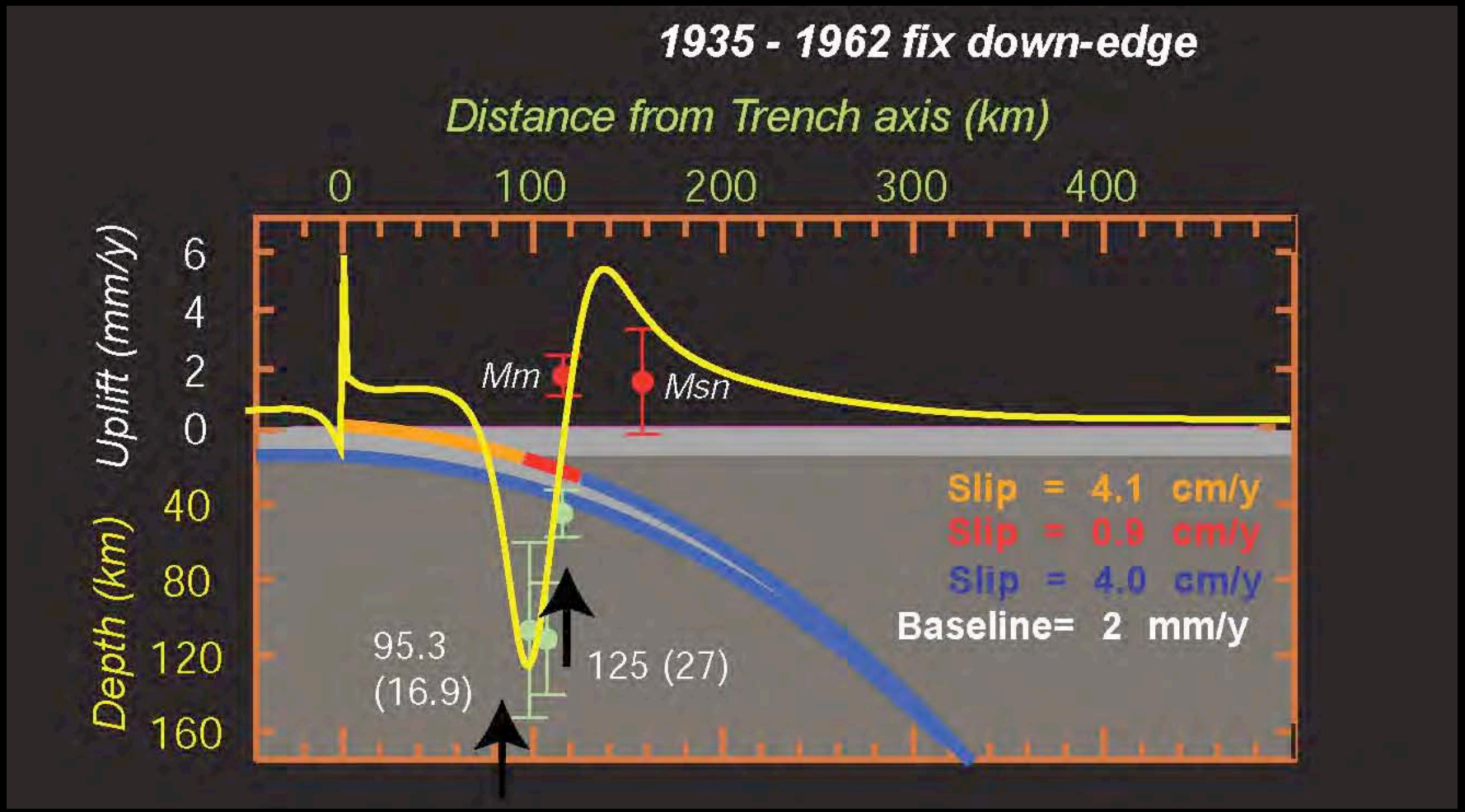

Pre-1935
Distance from Trench axis (km)
0
100
200
300
400
Uplift (mm/y)
6
4
2
0
Depth (km)
40
80
120
160
Slip = 7.2 cm/y
Slip = 3.0 cm/y
Slip = 4.0 cm/y
Baseline= 1 mm/y
83.5
(13.6)
125.0
(27.0)

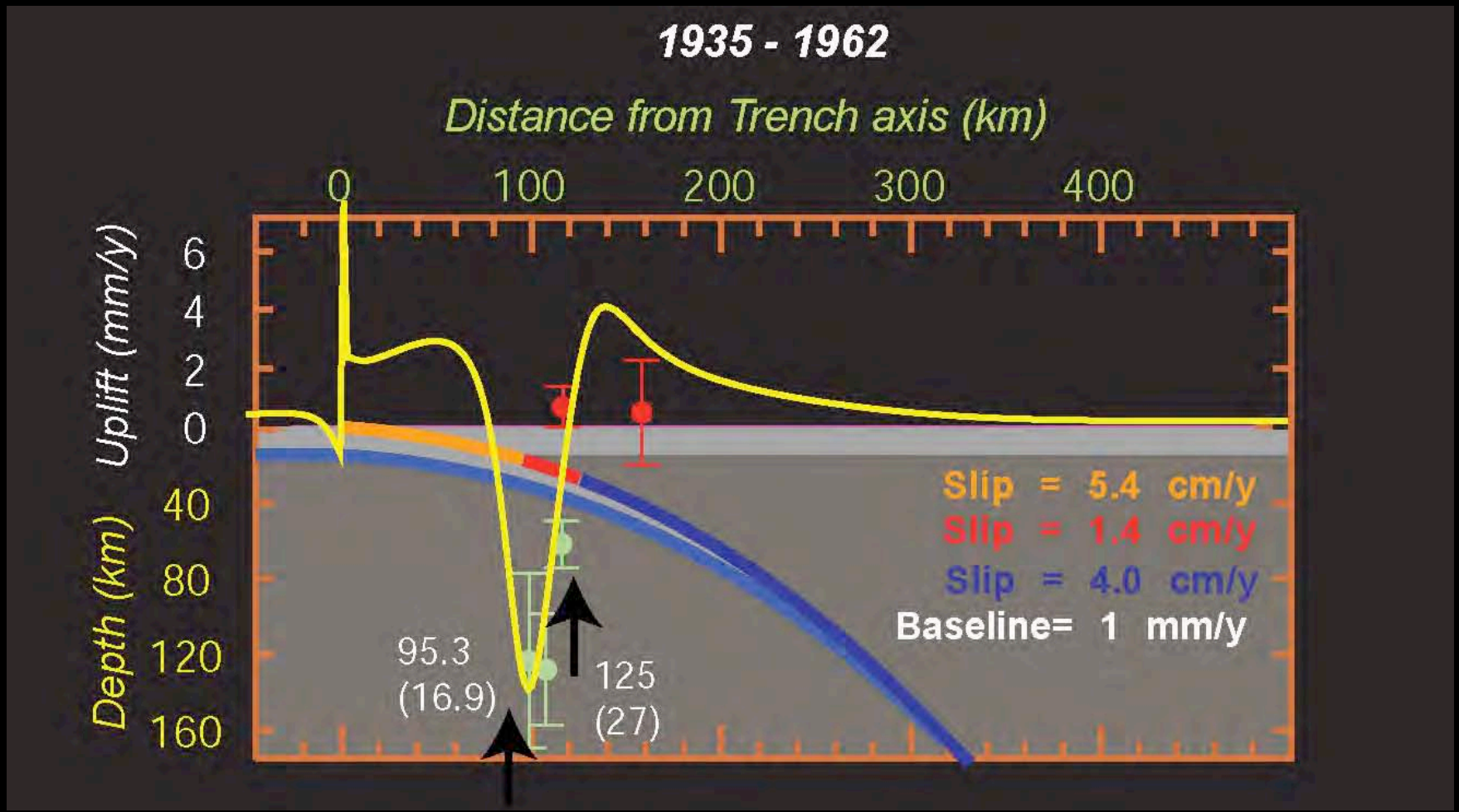

1935 event
Distance from Trench axis (km)
0
100
200
300
400
Uplift (cm)
100
0
Depth (km)
40
80
120
160

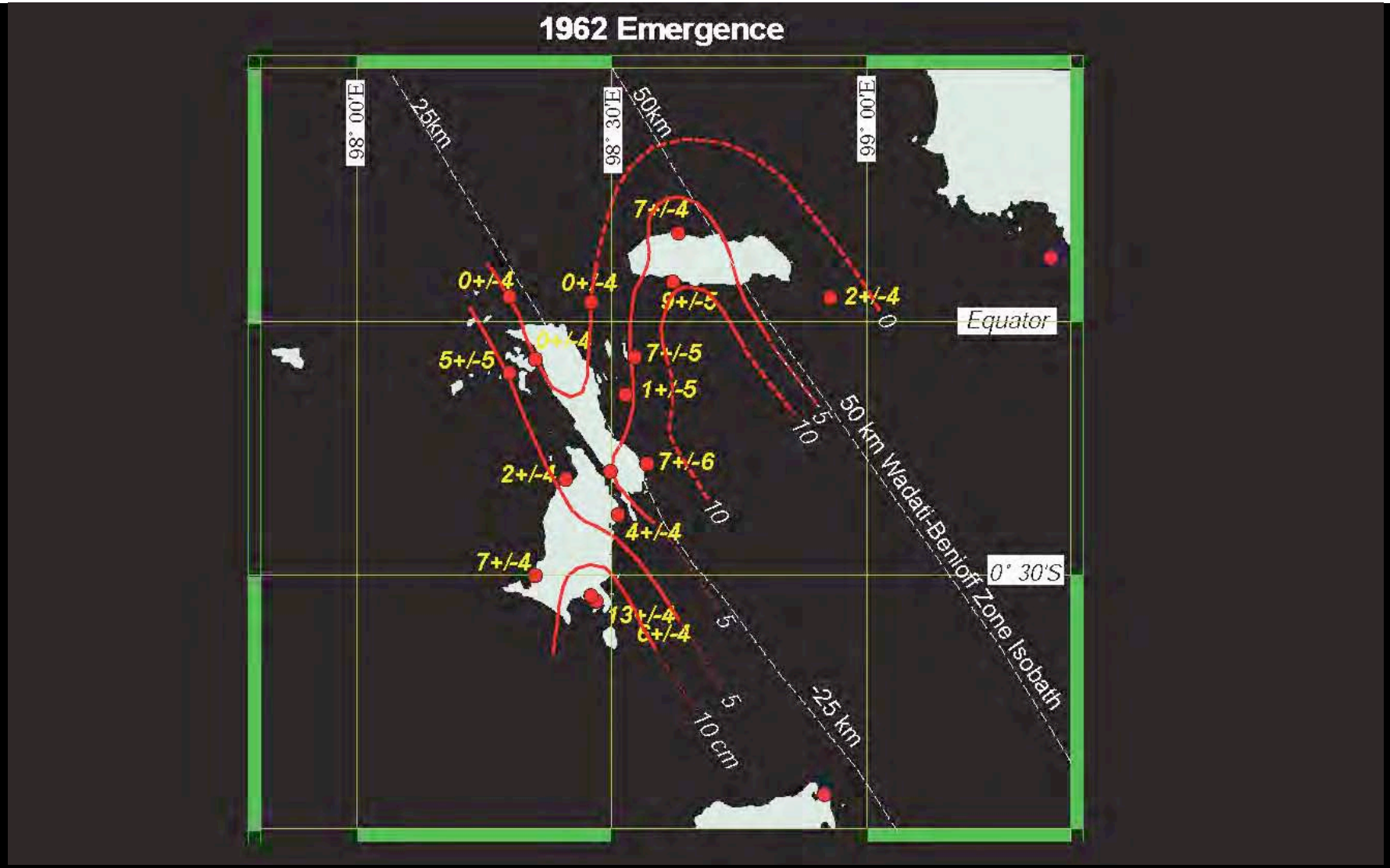

1935 event
Distance from Trench axis (km)
0
100
200
300
400
100
0
Uplift (cm)
40
80
120
160
Depth (km)
Slip=2.33 meters
88.0
(14.8)
125.0 (27.0)

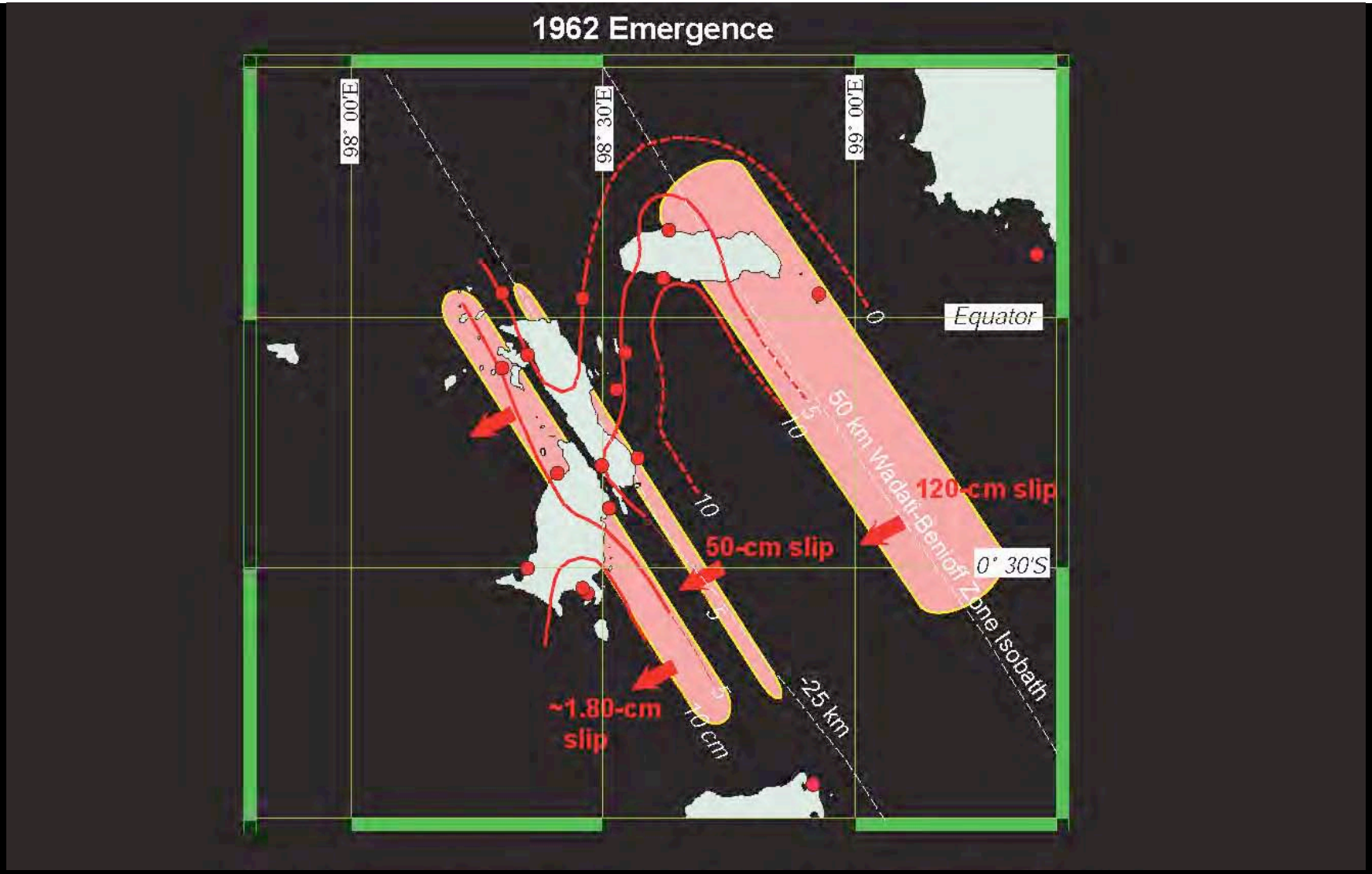

1935 - 1962
Distance from Trench axis (km)
0
100
200
300
400
Uplift (mm/y)
6
4
2
0
Depth (km)
40
80
120
160
Baseline= 2 mm/y

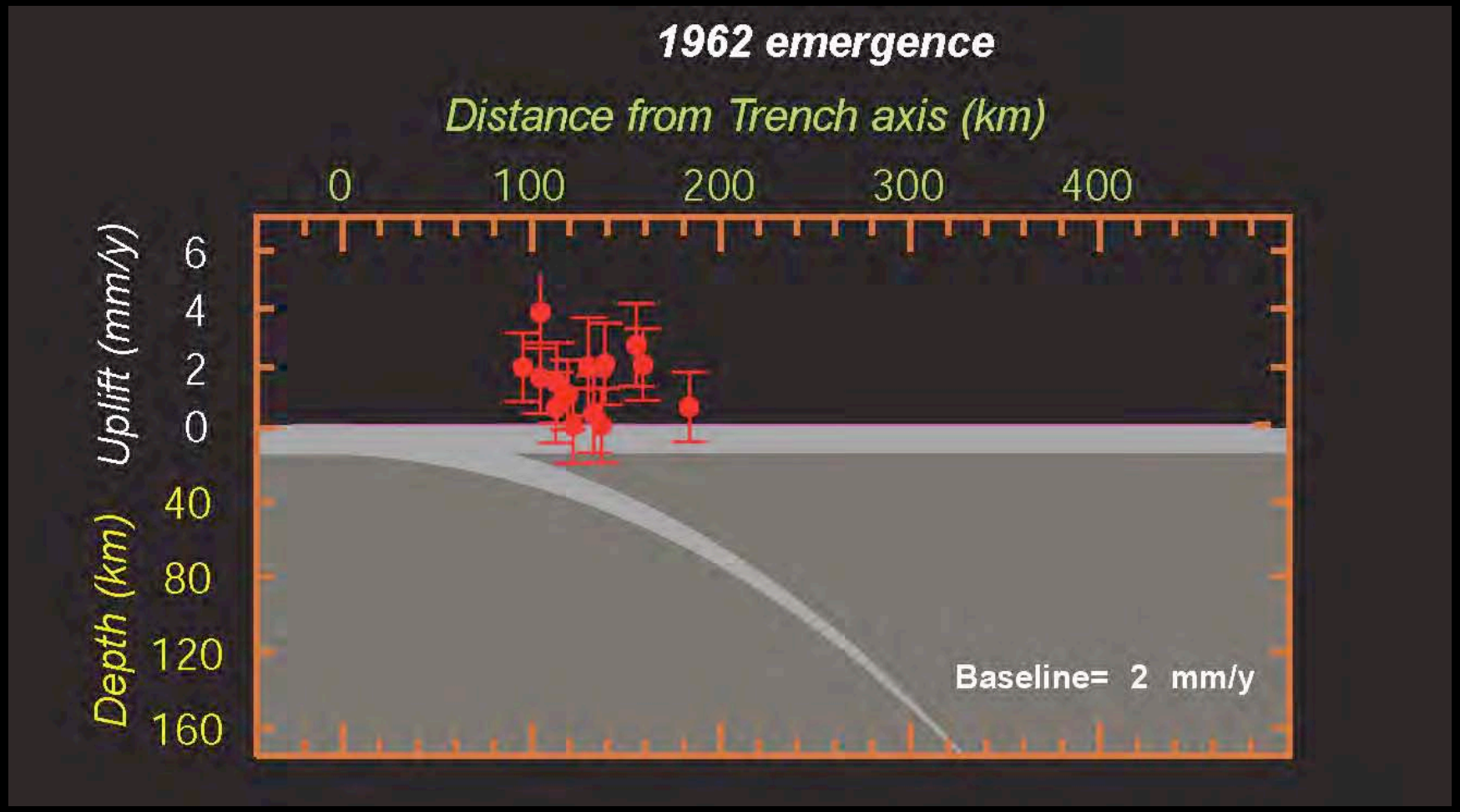

1935 - 1962
Distance from Trench axis (km)
0
100
200
300
400
Uplift (mm/y)
6
4
2
0
Depth (km)
40
80
120
160
Slip = 5.3 cm/y
Slip = 0.0 cm/y
Slip = 4 cm/y
100.4
(18.5)
115.7(23.6)
Baseline= 2 mm/y

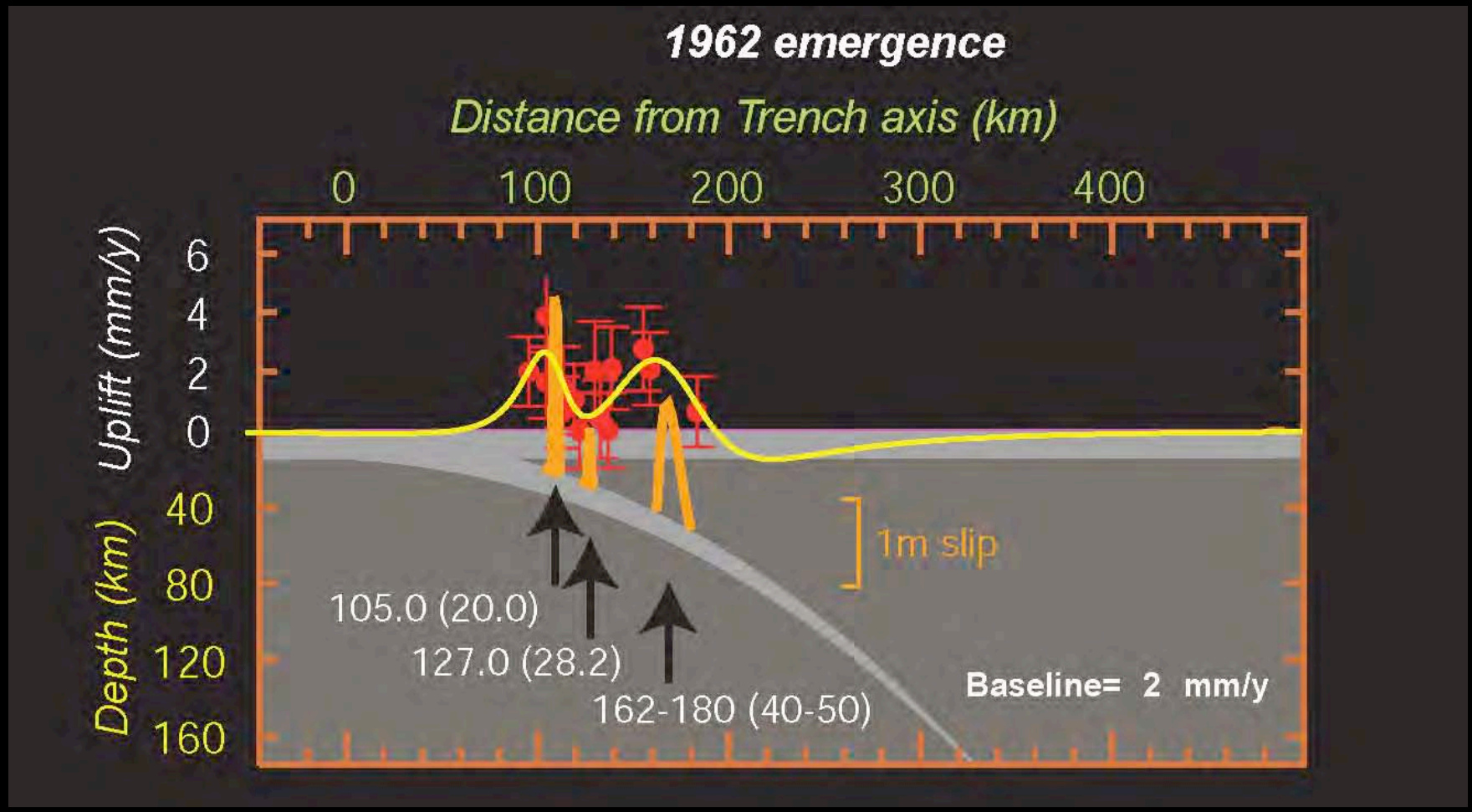

1935 - 1962 fix down-edge
Distance from Trench axis (km)
0
100
200
300
400
Uplift (mm/y)
6
4
2
0
Depth (km)
40
80
120
160
Mm
Msn
Slip = 4.1 cm/y
Slip = 0.9 cm/y
Slip = 4.0 cm/y
Baseline= 2 mm/y
95.3
(16.9)
125 (27)

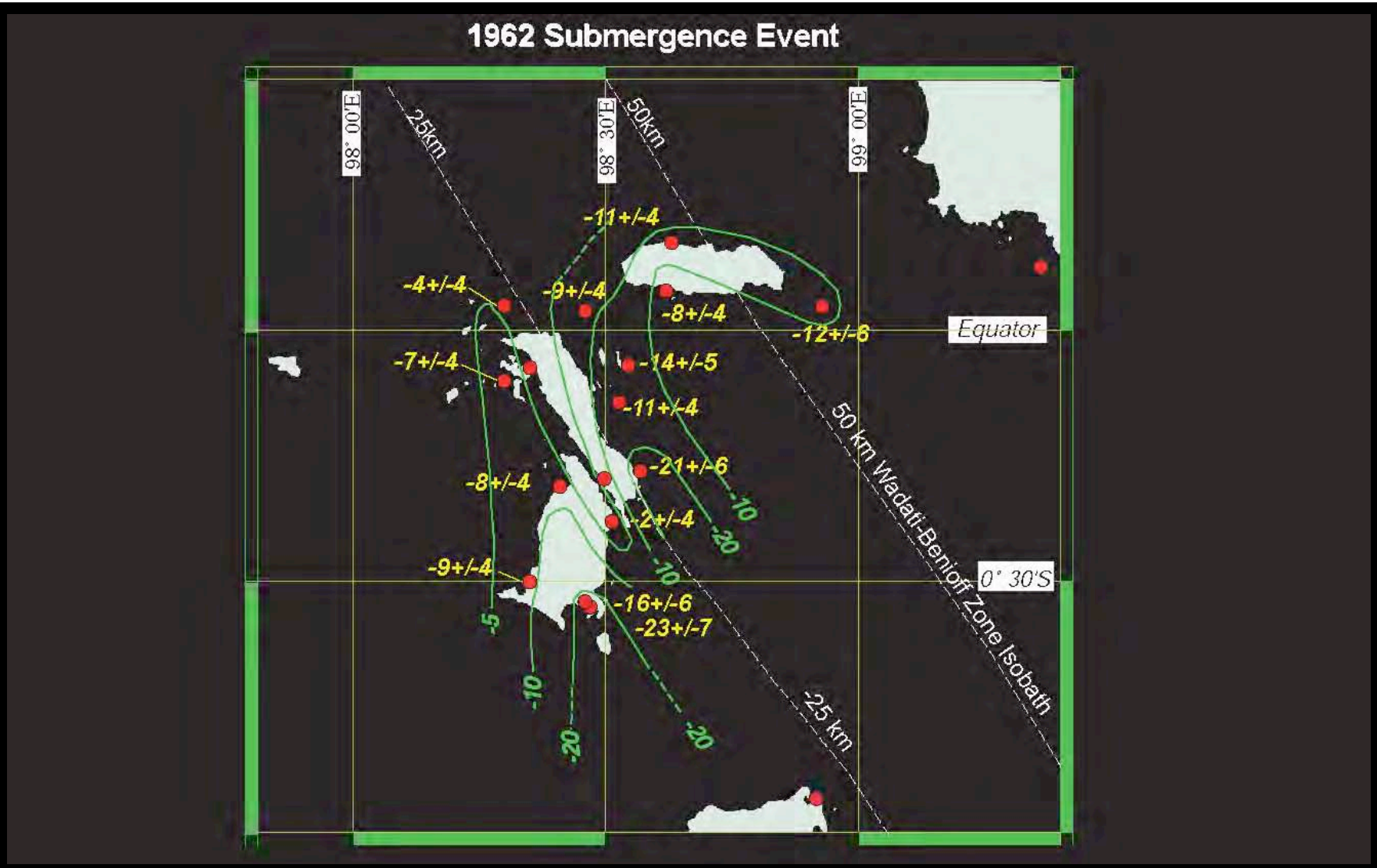

1935 - 1962
Distance from Trench axis (km)
0
100
200
300
400
Uplift (mm/y)
6
4
2
0
Depth (km)
40
80
120
160
Slip = 5.4 cm/y
Slip = 1.4 cm/y
Slip = 4.0 cm/y
Baseline= 1 mm/y
95.3
(16.9)
125
(27)

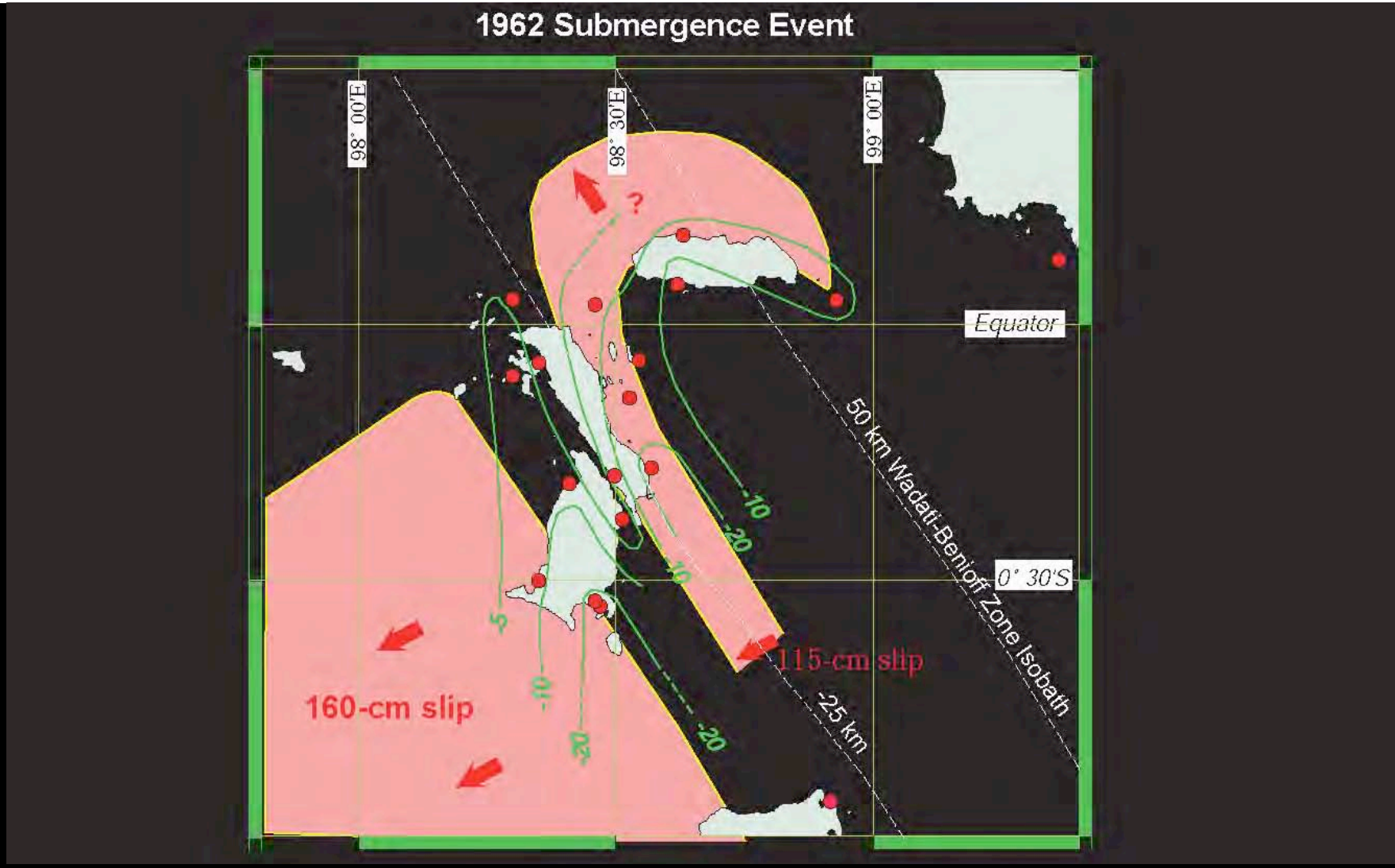

1962 Emergence
98° 00'E
98° 30'E
99° 00'E
25km
50km
7+/-4
0+/-4
0+/-4
9+/-5
2+/-4
Equator
0+/-4
5+/-5
7+/-5
1+/-5
5
10
50 km Wadati-Benioff Zone Isobath
7+/-6
2+/-4
10
4+/-4
7+/-4
0° 30'S
13+/-4
6+/-4
5
5
10 cm
-25 km

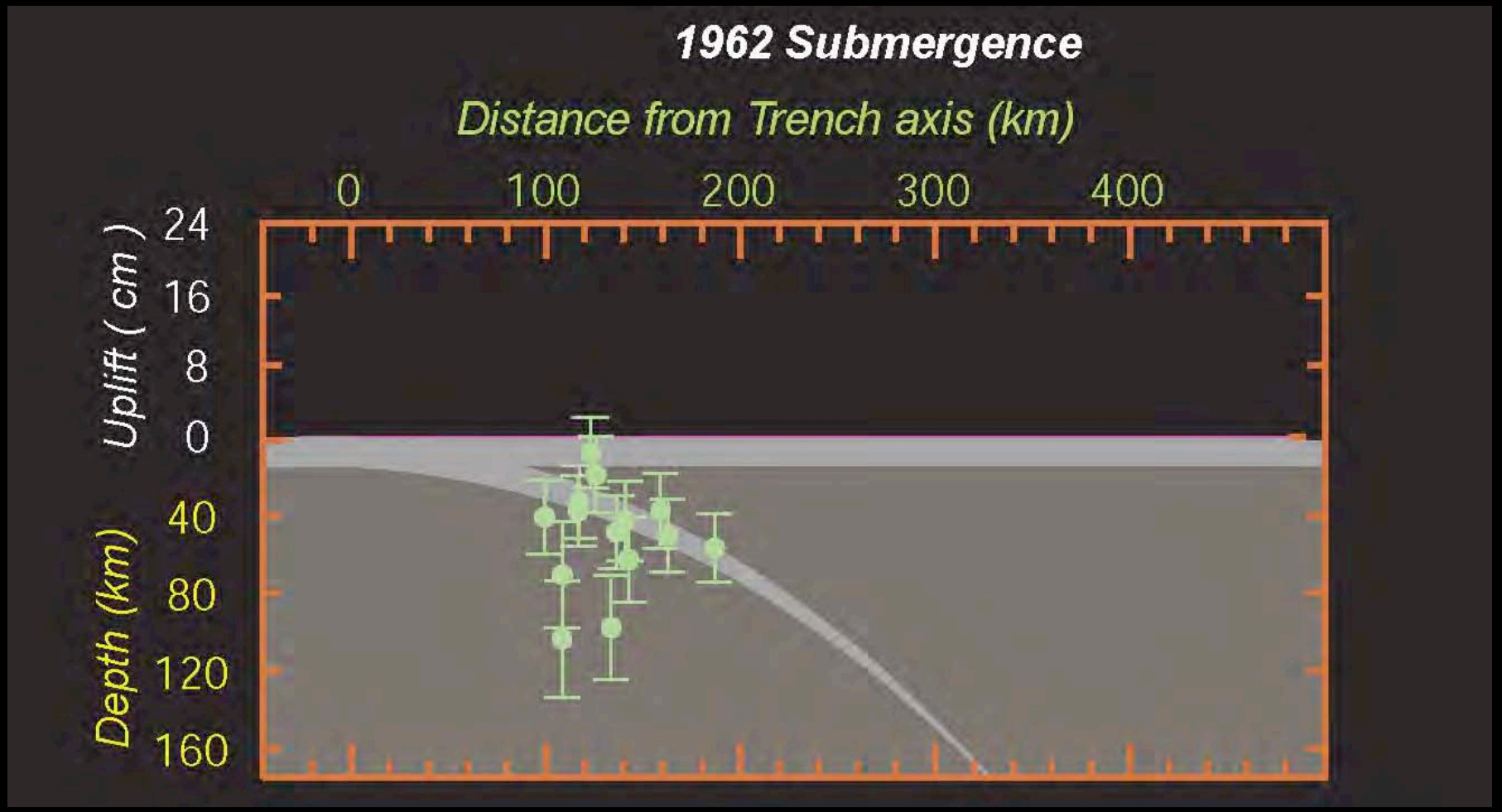

1962 Emergence
98° 00'E
98° 30'E
99° 00'E
Equator
0° 30'S
0
5
10
50 km Wadati-Benioff Zone Isobath
120-cm slip
50-cm slip
~1.80-cm slip
25 km
10 cm

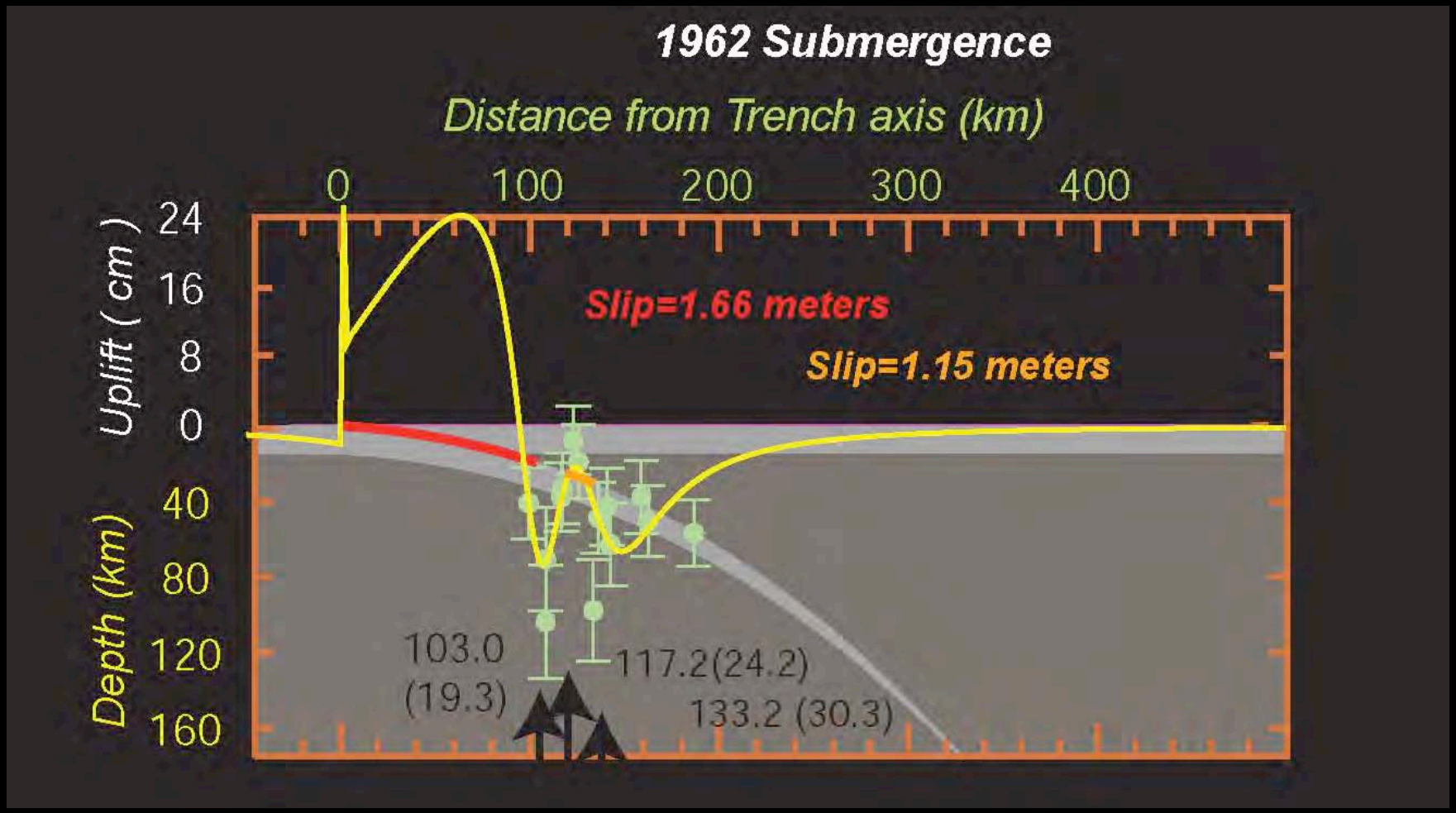

1962 emergence
Distance from Trench axis (km)
0
100
200
300
400
Uplift (mm/y)
6
4
2
0
Depth (km)
40
80
120
160
Baseline= 2 mm/y

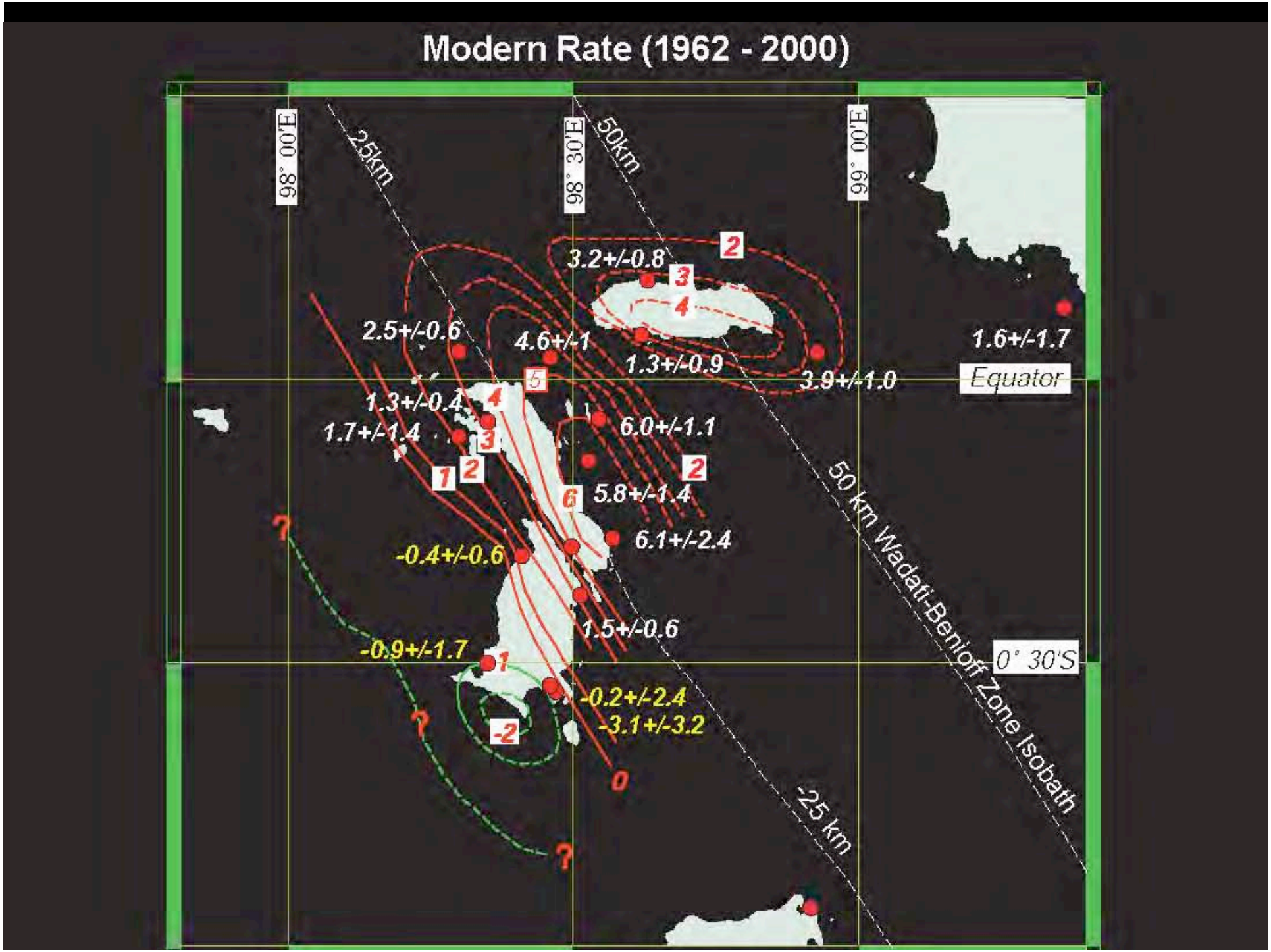

1962 emergence
Distance from Trench axis (km)
0
100
200
300
400
Uplift (mm/y)
6
4
2
0
Depth (km)
40
80
120
160
1m slip
105.0 (20.0)
127.0 (28.2)
162-180 (40-50)
Baseline= 2 mm/y


1962 Submergence Event
98° 00'E
98° 30'E
99° 00'E
25km
50km
-11+/-4
-4+/-4
-9+/-4
-8+/-4
-12+/-6
Equator
-7+/-4
-14+/-5
-11+/-4
-21+/-6
-8+/-4
-2+/-4
-10
-20
-9+/-4
-10
0° 30'S
-16+/-6
-23+/-7
-5
-10
-20
-20
50 km Wadati-Benioff Zone Isobath
-25 km

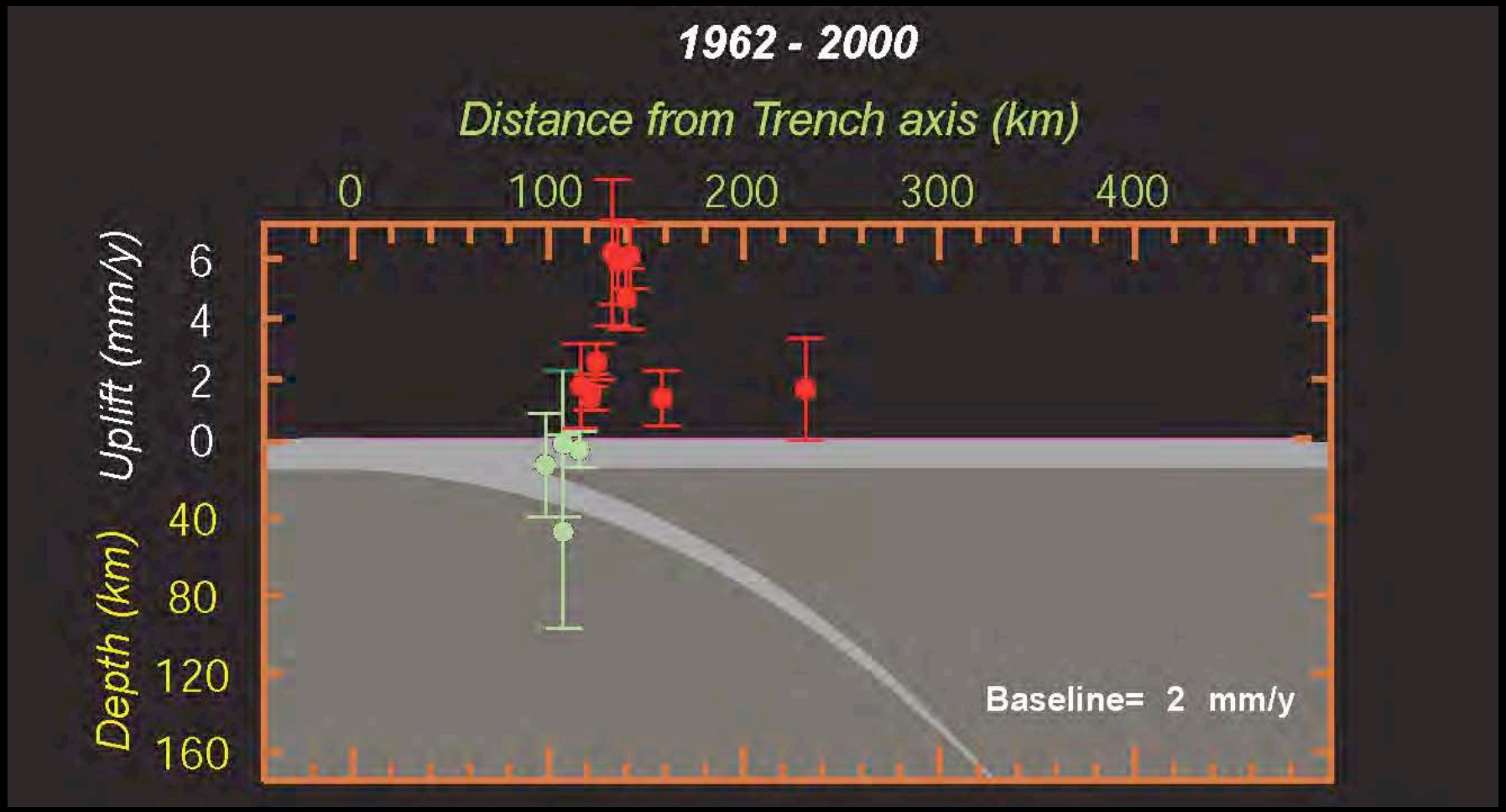

1962 Submergence Event
98° 00'E
98° 30'E
99° 00'E
Equator
0° 30'S
50 km Wadati-Benioff Zone Isobath
?
-10
-20
-10
-5
-10
-20
-20
-25 km
115-cm slip
160-cm slip

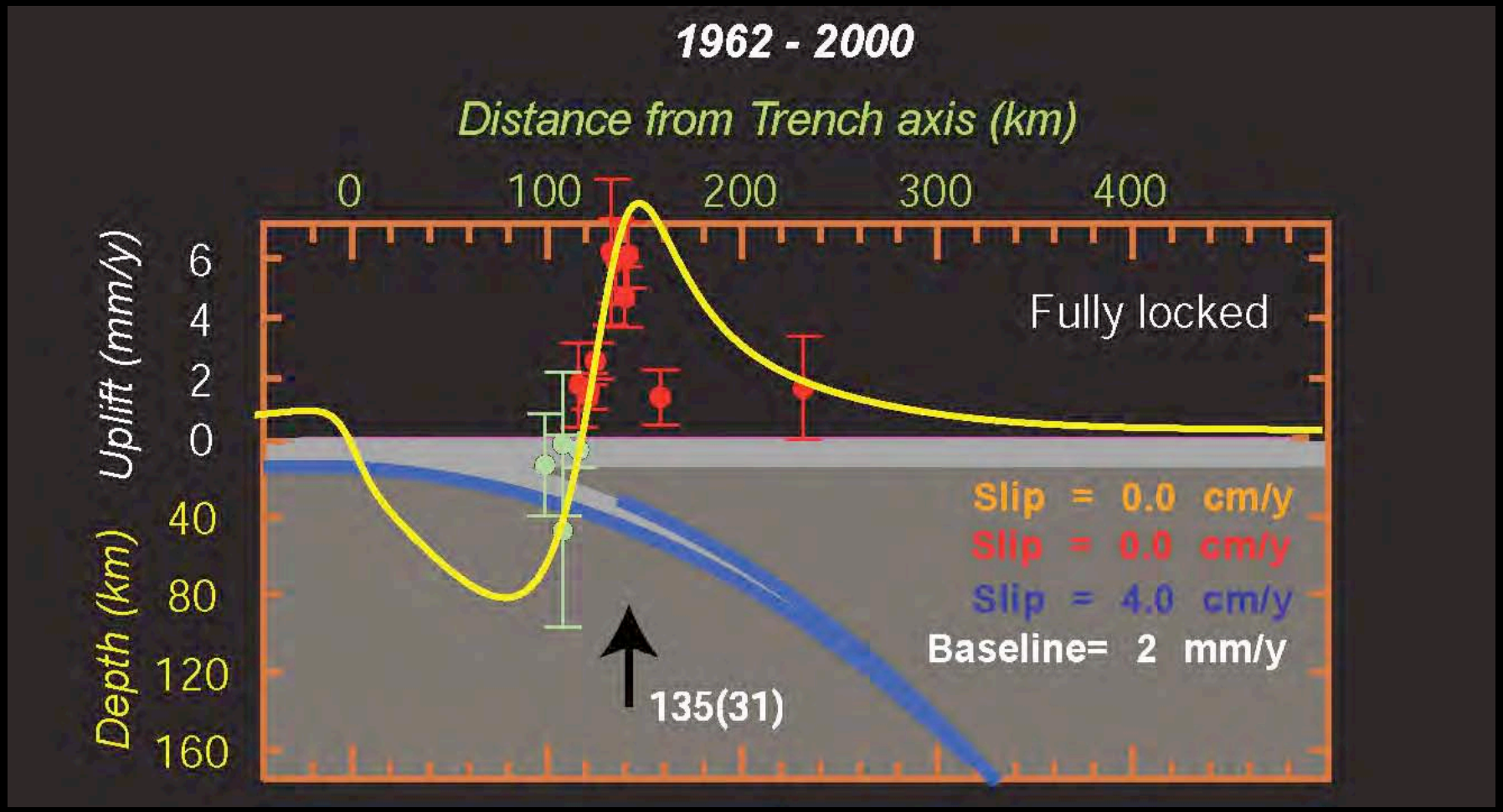

1962 Submergence
Distance from Trench axis (km)
0
100
200
300
400
Uplift (cm)
24
16
8
0
Depth (km)
40
80
120
160

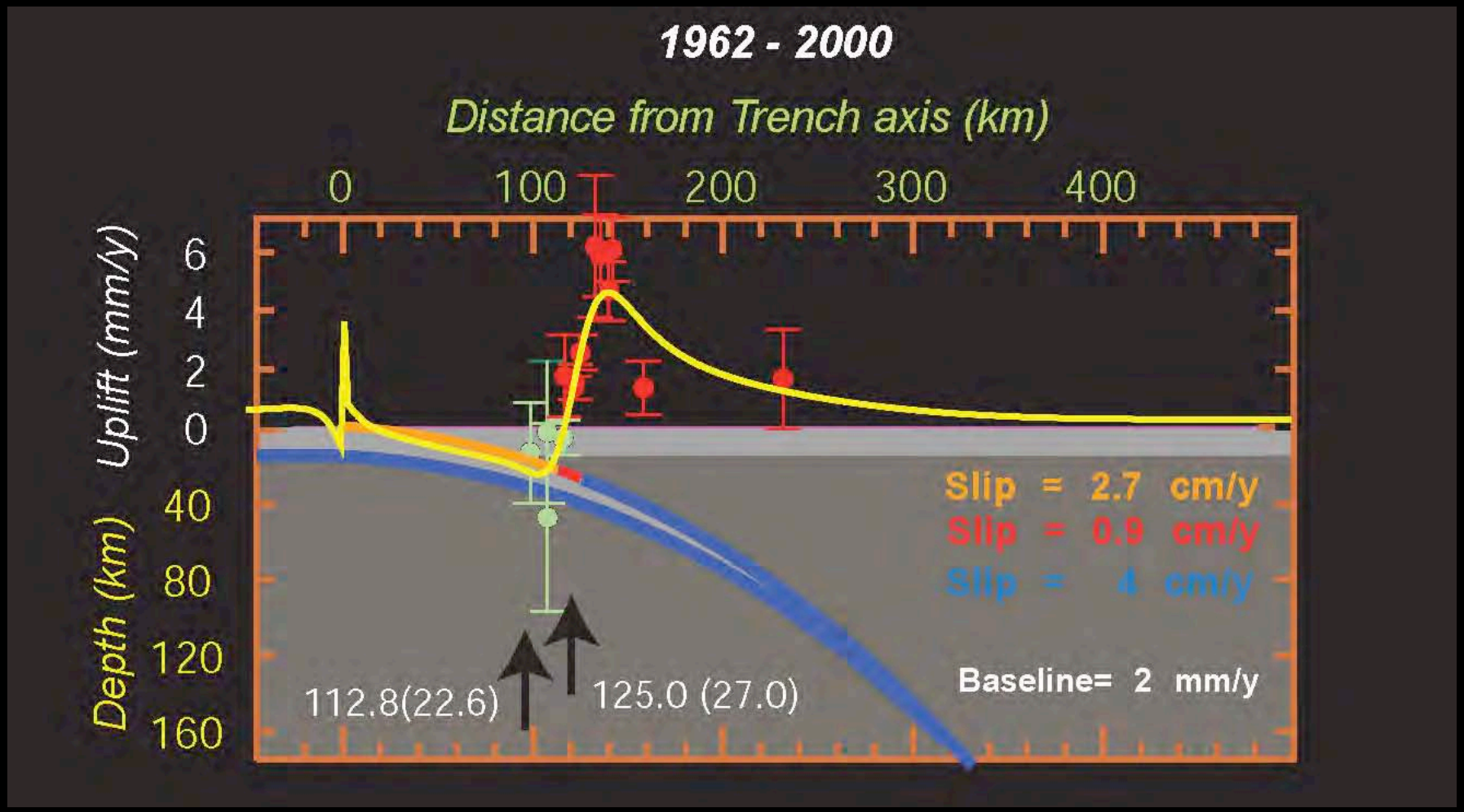

1962 Submergence
Distance from Trench axis (km)
0
100
200
300
400
Uplift (cm)
24
16
8
0
Depth (km)
40
80
120
160
Slip=1.66 meters
Slip=1.15 meters
103.0
(19.3)
117.2(24.2)
133.2 (30.3)

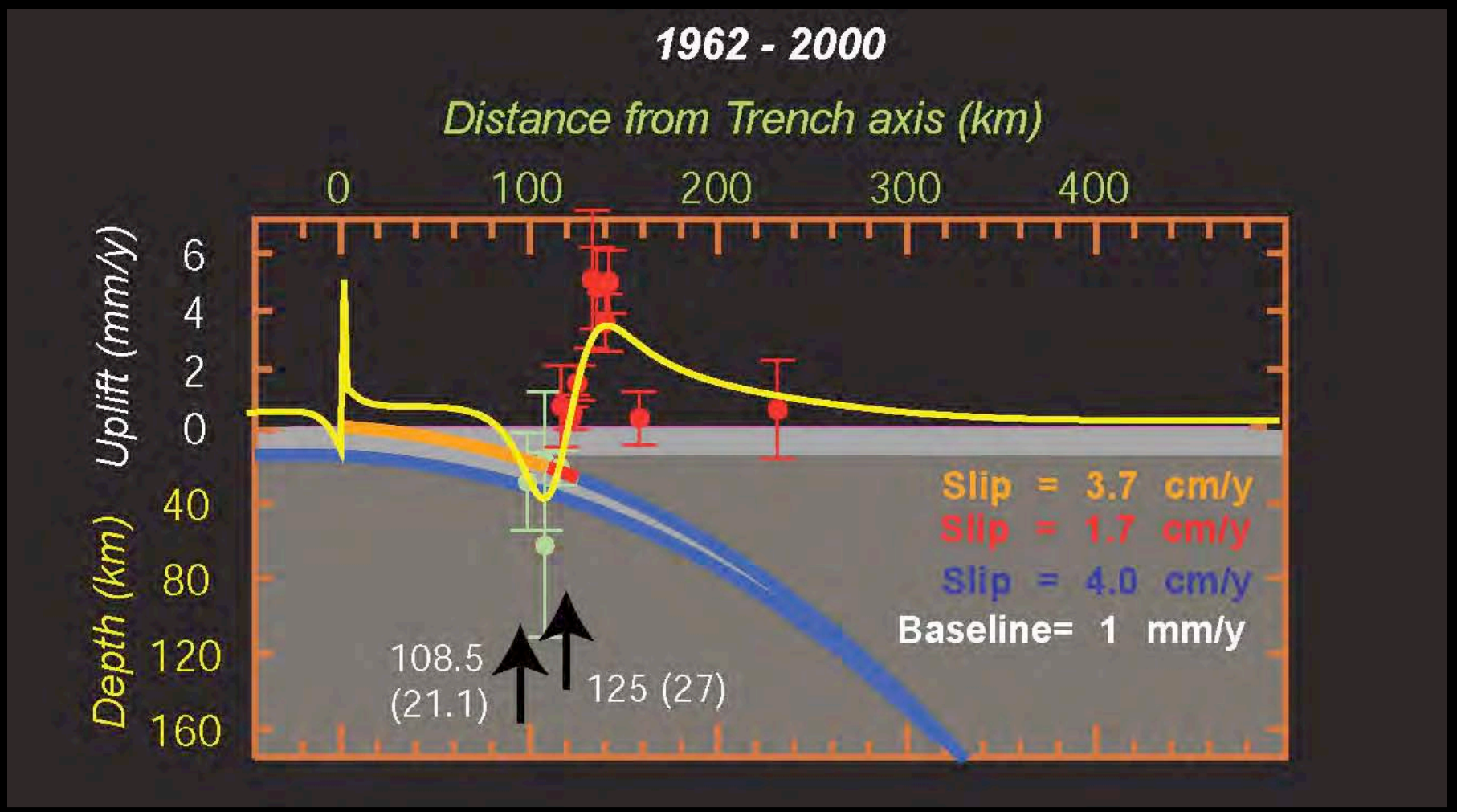

Modern Rate (1962 - 2000)
98° 00'E
98° 30'E
99° 00'E
25km
50km
3.2+/-0.8
2.5+/-0.6
4.6+/-1
1.3+/-0.9
3.9+/-1.0
1.6+/-1.7
Equator
1.3+/-0.4
1.7+/-1.4
6.0+/-1.1
5.8+/-1.4
6.1+/-2.4
-0.4+/-0.6
1.5+/-0.6
-0.9+/-1.7
-0.2+/-2.4
-3.1+/-3.2
50 km Wadati-Benioff Zone Isobath
0° 30'S
25 km

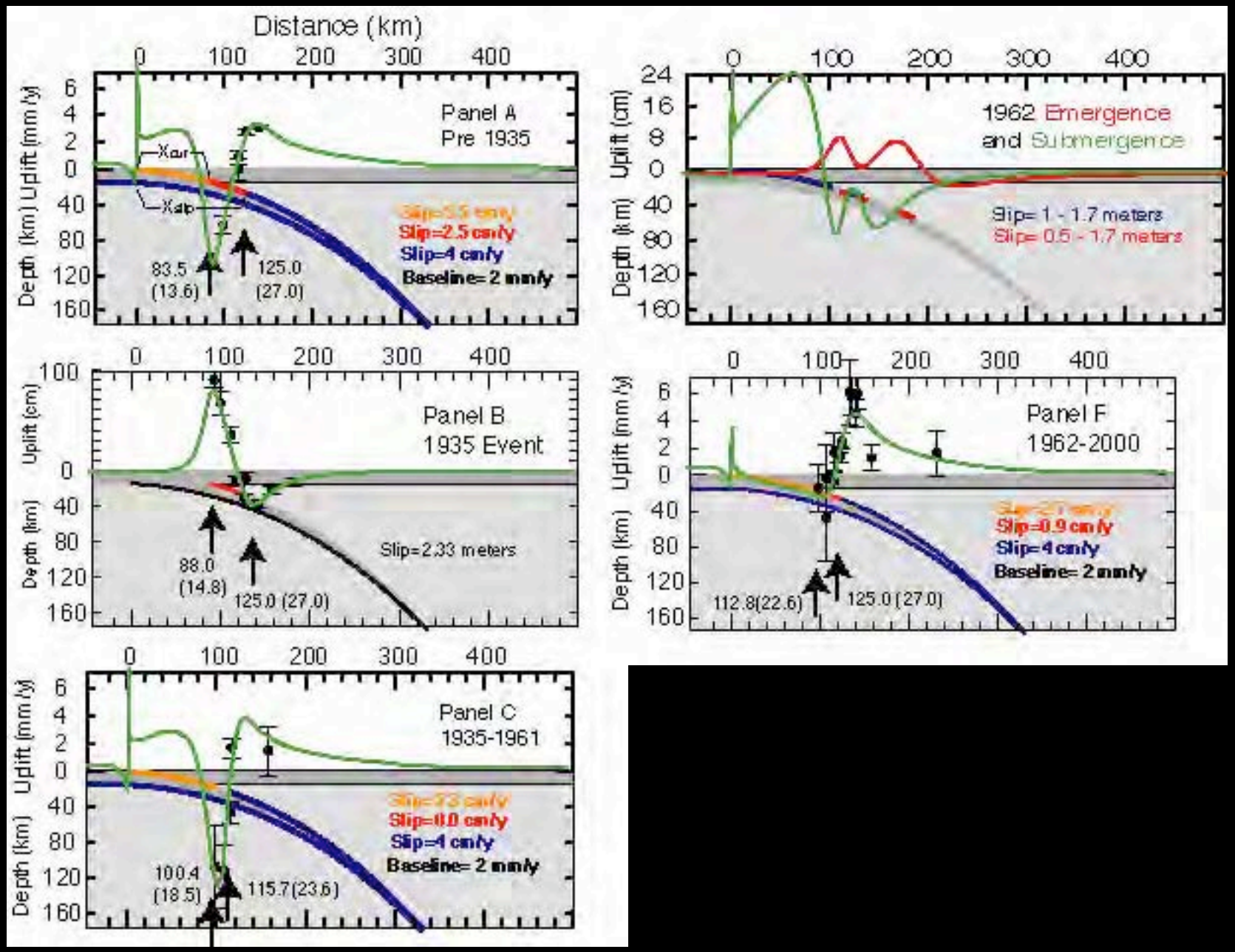

Modern Locked patch
98° 00'E
98° 30'E
99° 00'E
Eq Equator
0° 30'S
50 km Wadati-Benioff Zone Isobath
25 km
40 mm/yr
27 mm/yr
9 mm/yr
?
?
?
2
3
4
5
4
3
2
1
2
6
1
-2
0

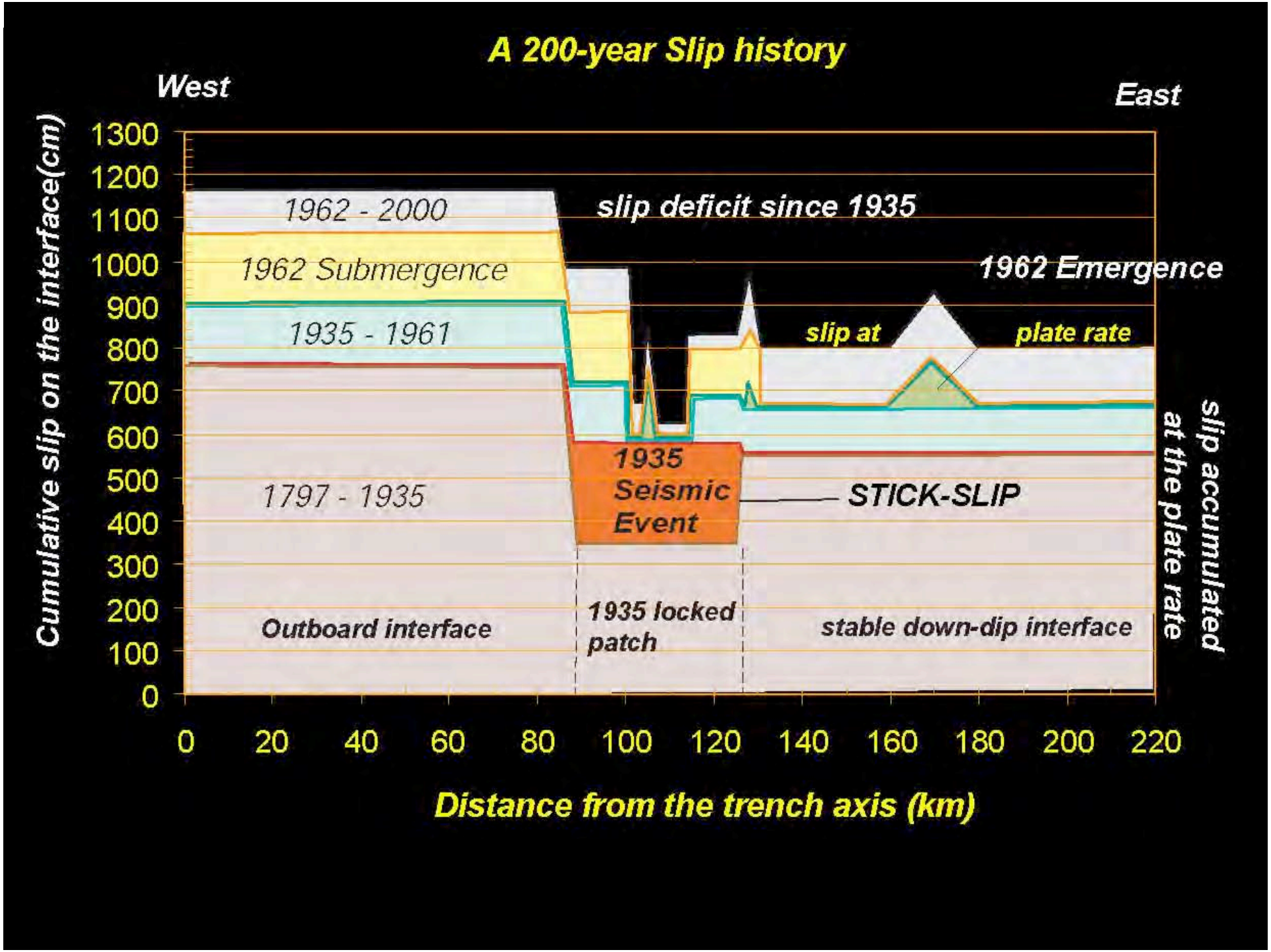

1962 - 2000
Distance from Trench axis (km)
0
100
200
300
400
Uplift (mm/y)
6
4
2
0
Depth (km)
40
80
120
160
Baseline= 2 mm/y


1962 - 2000
Distance from Trench axis (km)
0
100
200
300
400
Uplift (mm/y)
6
4
2
0
Depth (km)
40
80
120
160
Fully locked
Slip = 0.0 cm/y
Slip = 0.0 cm/y
Slip = 4.0 cm/y
Baseline= 2 mm/y
135(31)

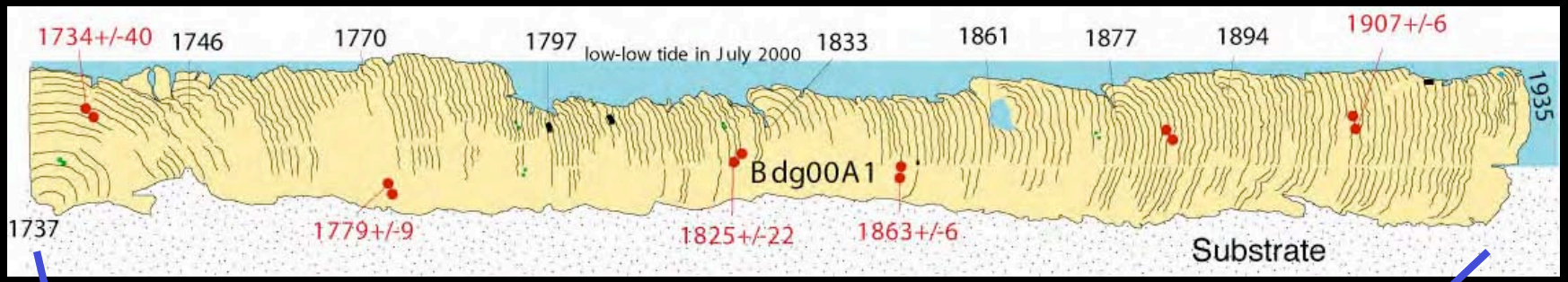

1962 - 2000
Distance from Trench axis (km)
0
100
200
300
400
Uplift (mm/y)
6
4
2
0
Depth (km)
40
80
120
160
Slip = 2.7 cm/y
Slip = 0.9 cm/y
Slip = 4 cm/y
Baseline= 2 mm/y
112.8(22.6)
125.0 (27.0)

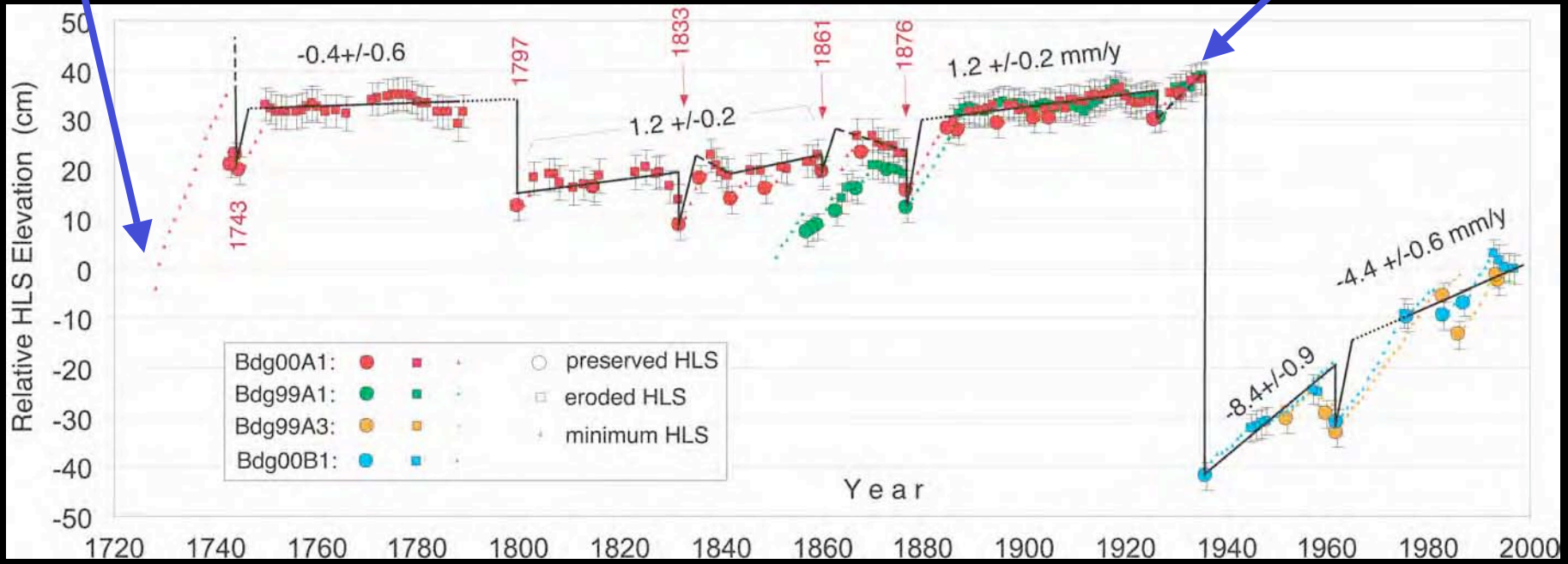

1962 - 2000
Distance from Trench axis (km)
0
100
200
300
400
Uplift (mm/y)
6
4
2
0
Depth (km)
40
80
120
160
Slip = 3.7 cm/y
Slip = 1.7 cm/y
Slip = 4.0 cm/y
Baseline= 1 mm/y
108.5
(21.1)
125 (27)


Distance (km)
0
100
200
300
400
Panel A
Pre 1935
Xcur
Xslip
Slip=2.5 cm/y
Slip=4 cm/y
Baseline= 2 mm/y
83.5
(13.6)
125.0
(27.0)
Depth (km) Uplift (mm/y)
Panel B
1935 Event
Uplift (cm)
Depth (km)
Slip=2.33 meters
88.0
(14.8)
125.0 (27.0)
Panel C
1935-1961
Slip=0.0 cm/y
Slip=4 cm/y
Baseline= 2 mm/y
100.4
(18.5)
115.7(23.6)
1962 Emergence
and Submergence
Slip= 1 - 1.7 meters
Slip= 0.5 - 1.7 meters
Panel F
1962-2000
Slip=0.9 cm/y
Slip=4 cm/y
Baseline= 2 mm/y
112.8(22.6)
125.0 (27.0)


A 200-year Slip history
West
East
Cumulative slip on the interface(cm)
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
1962 - 2000
slip deficit since 1935
1962 Submergence
1962 Emergence
1935 - 1961
slip at
plate rate
1935
Seismic
Event
1797 - 1935
STICK-SLIP
Outboard interface
1935 locked
patch
stable down-dip interface
slip accumulated
at the plate rate
0
20
40
60
80
100
120
140
160
180
200
220
Distance from the trench axis (km)

What about longer-term behavior?

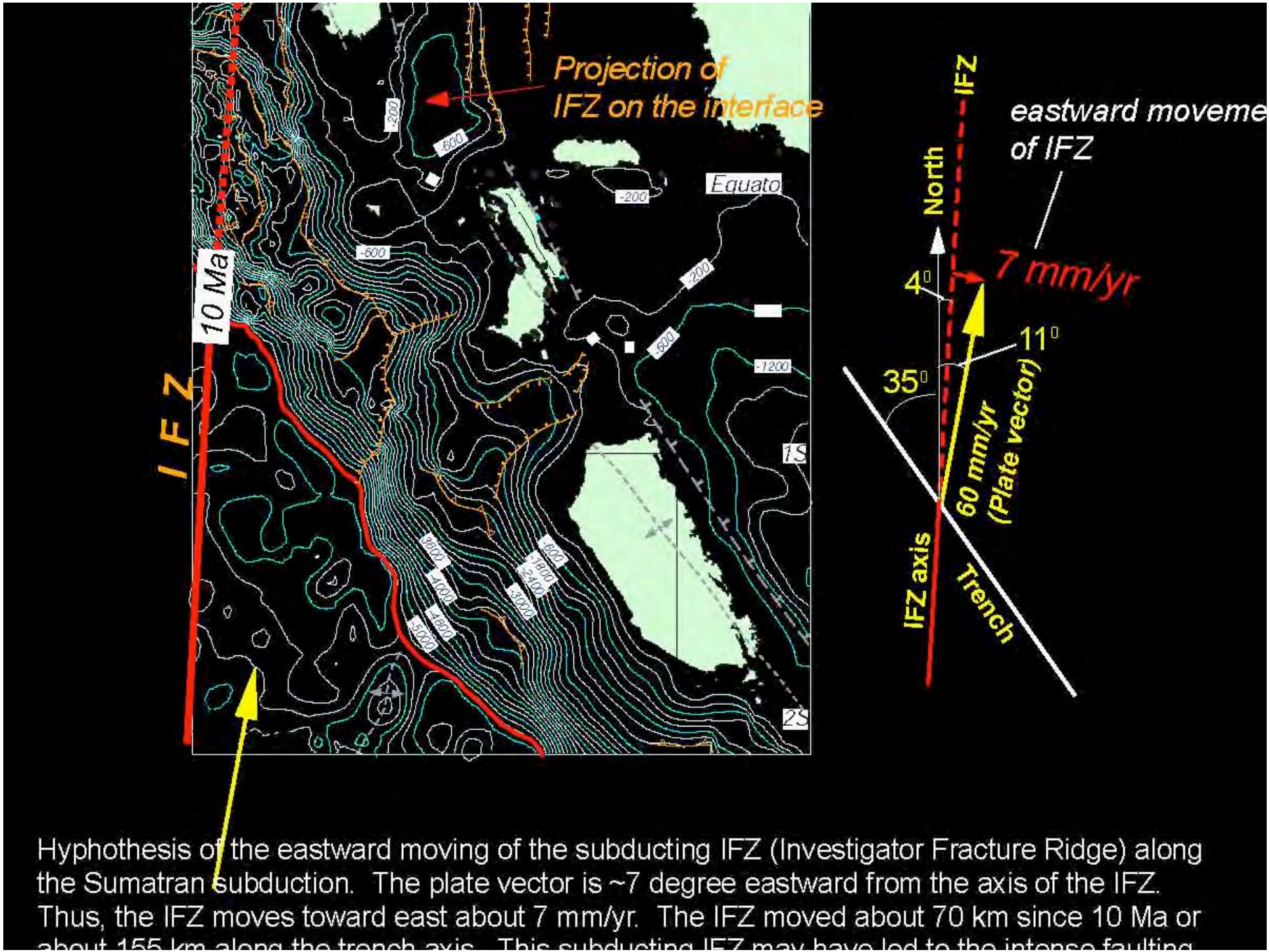

1734+/-40
1746
1770
1797
low-low tide in July 2000
1833
1861
1877
1894
1907+/-6
1935
Bdg00A1
1737
1779+/-9
1825+/-22
1863+/-6
Substrate


Relative HLS Elevation (cm)
50
40
30
20
10
0
-10
-20
-30
-40
-50
1720
1740
1760
1780
1800
1820
1840
1860
1880
1900
1920
1940
1960
1980
2000
Year
1743
-0.4+/-0.6
1797
1833
1861
1876
1.2 +/-0.2
1.2 +/-0.2 mm/y
-8.4+/-0.9
-4.4 +/-0.6 mm/y
Bdg00A1:
Bdg99A1:
Bdg99A3:
Bdg00B1:
preserved HLS
eroded HLS
minimum HLS

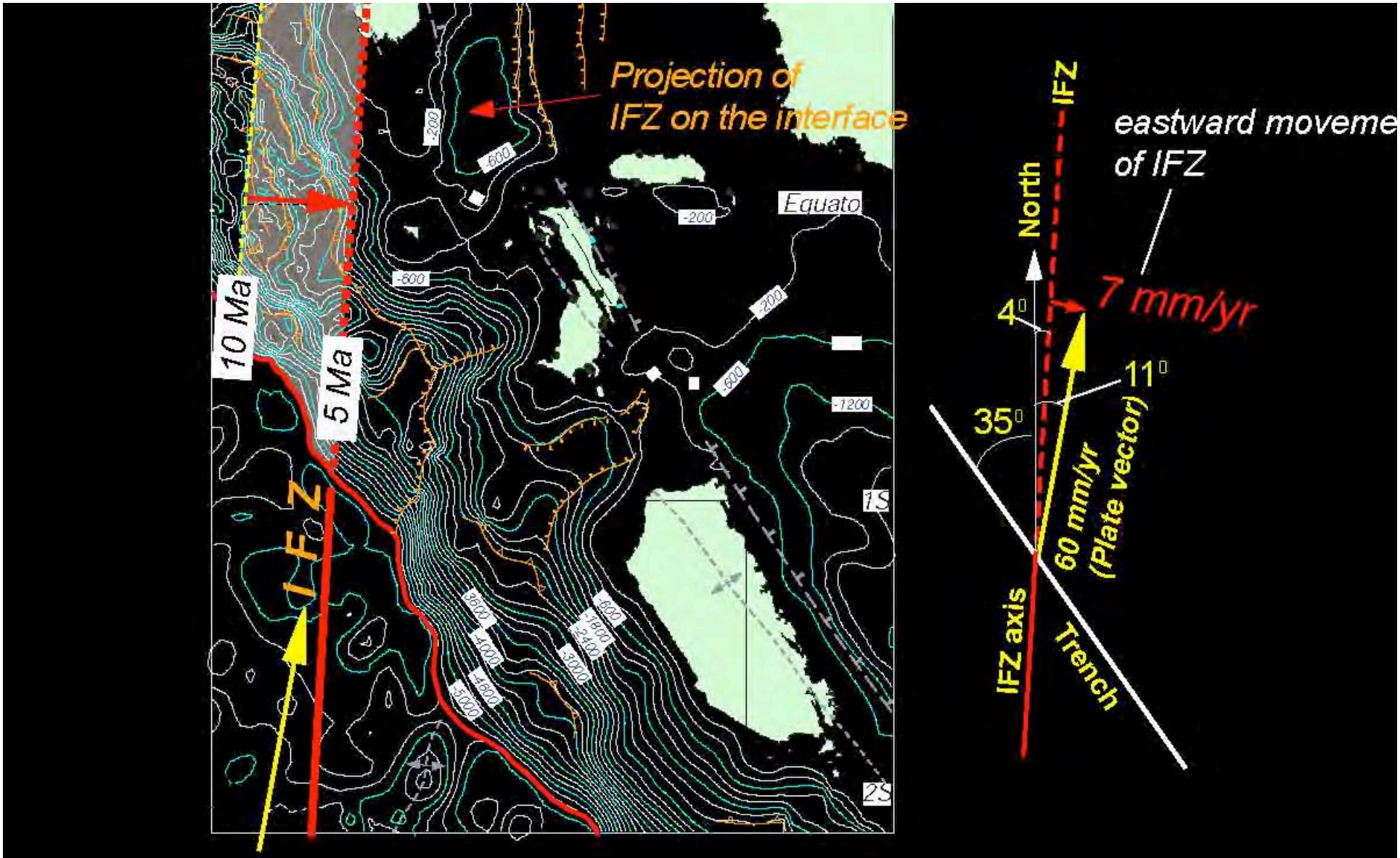
Low seismic rate, moderate events

High seismic rate, very large events

Why?



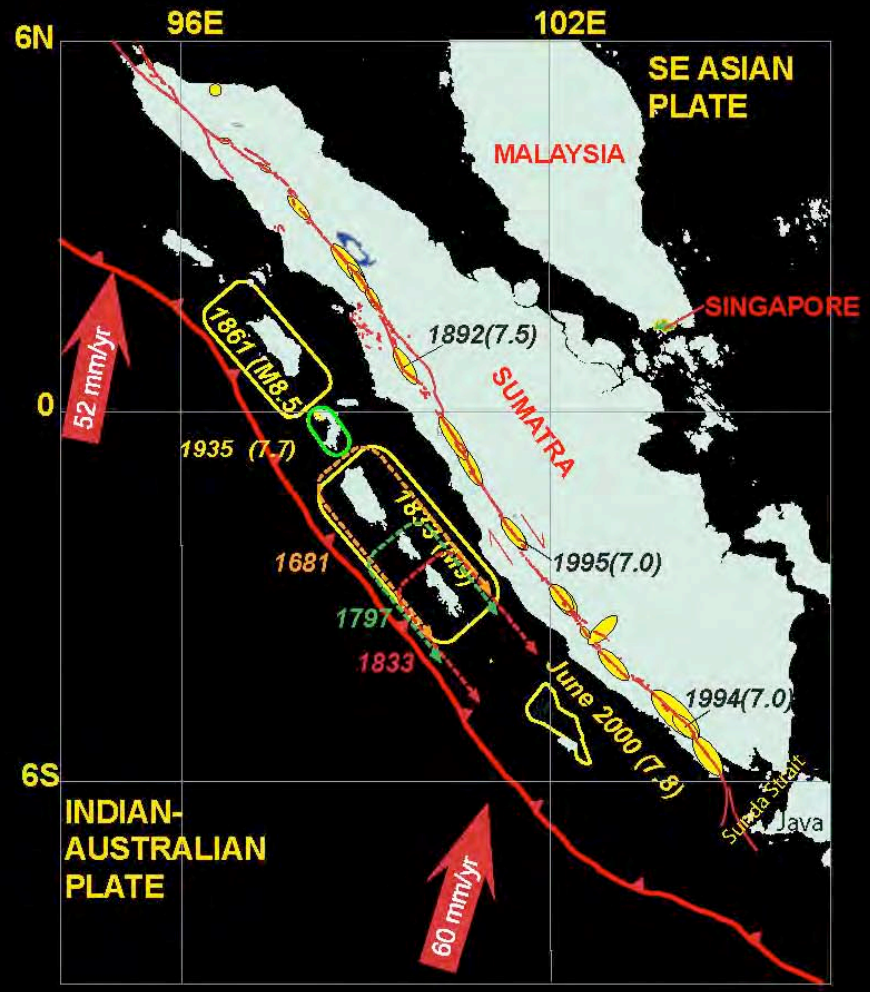
Hyphothesis of the eastward moving of the subducting IFZ (Investigator Fracture Ridge) along the Sumatran subduction. The plate vector is ~7 degree eastward from the axis of the IFZ. Thus, the IFZ moves toward east about 7 mm/yr. The IFZ moved about 70 km since 10 Ma or about 155 km along the trench axis. This subducting IFZ may have led to the intense faulting



Hyphothesis of the eastward moving of the subducting IFZ (Investigator Fracture Ridge) along the Sumatran subduction. The plate vector is ~7 degree eastward from the axis of the IFZ. Thus, the IFZ moves toward east about 7 mm/yr. The IFZ moved about 70 km since 10 Ma or about 155 km along the trench axis. This subducting IFZ may have led to the intense faulting

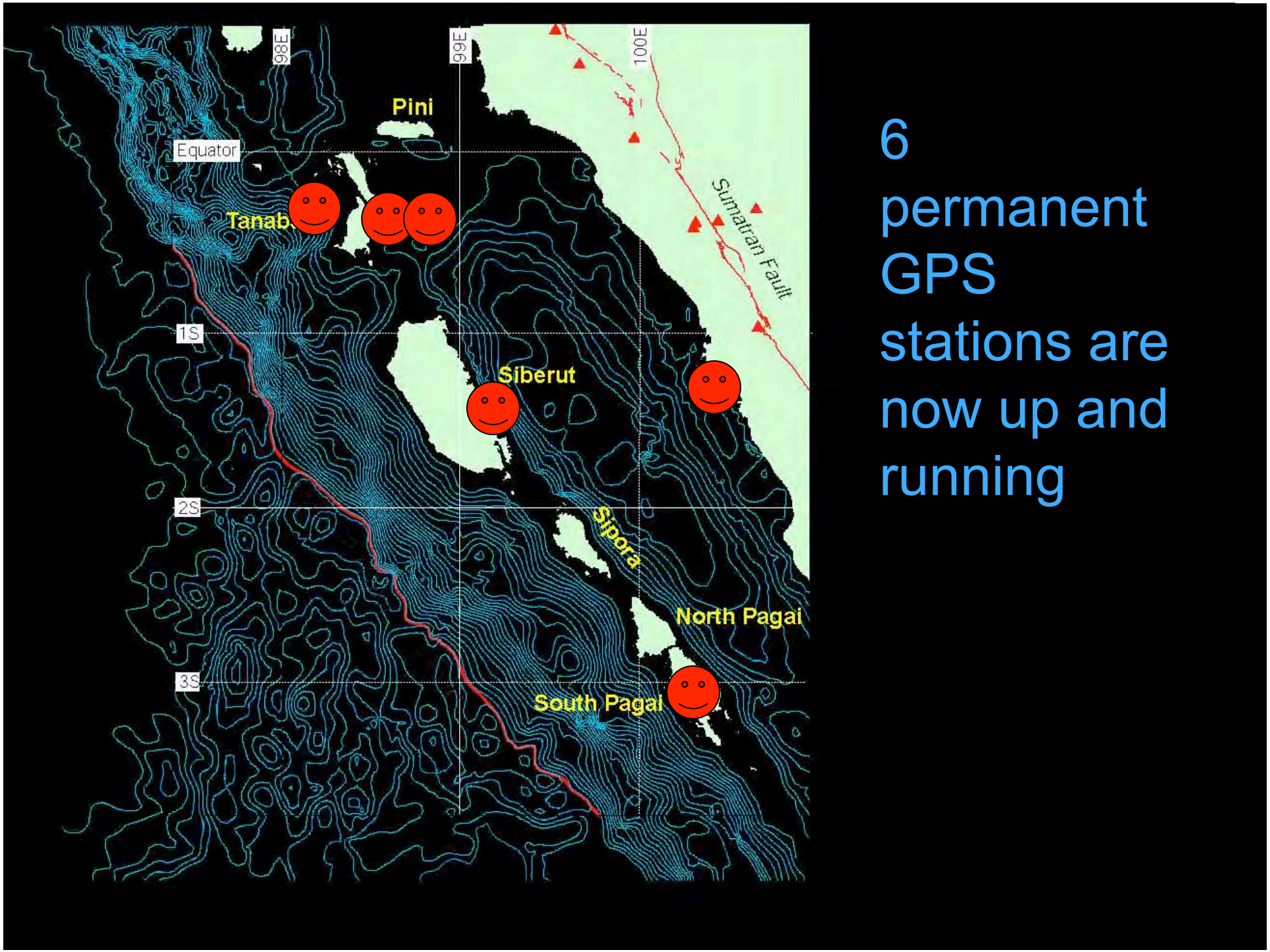
Conclusions

- Behavior is localized geographically
  - One region is predominantly aseismic
  - An adjacent region is predominantly seismic
- These behavioral patterns persist over centuries
- Giant earthquakes occur in clusters with overlapping sources?



Work in progress

- **Paleogeodetic studies south of the Equator:**
  - **modern rate variations along strike, rapid aseismic geodetic events, giant earthquakes**
  - **5 cycles of steady aseismic submergence and uplift during large earthquakes**



6 permanent GPS stations are now up and running