Special issue on sediment retention in estuaries

Morphodynamics and evolution of estuaries in response to climate and anthropogenic forcing

Yoshiki Saito and co-cuthors
Geological Survey of Japan, AIST

Morphodynamics and evolution of estuaries in response to climate and anthropogenic forcing

- **Millennial time scale**

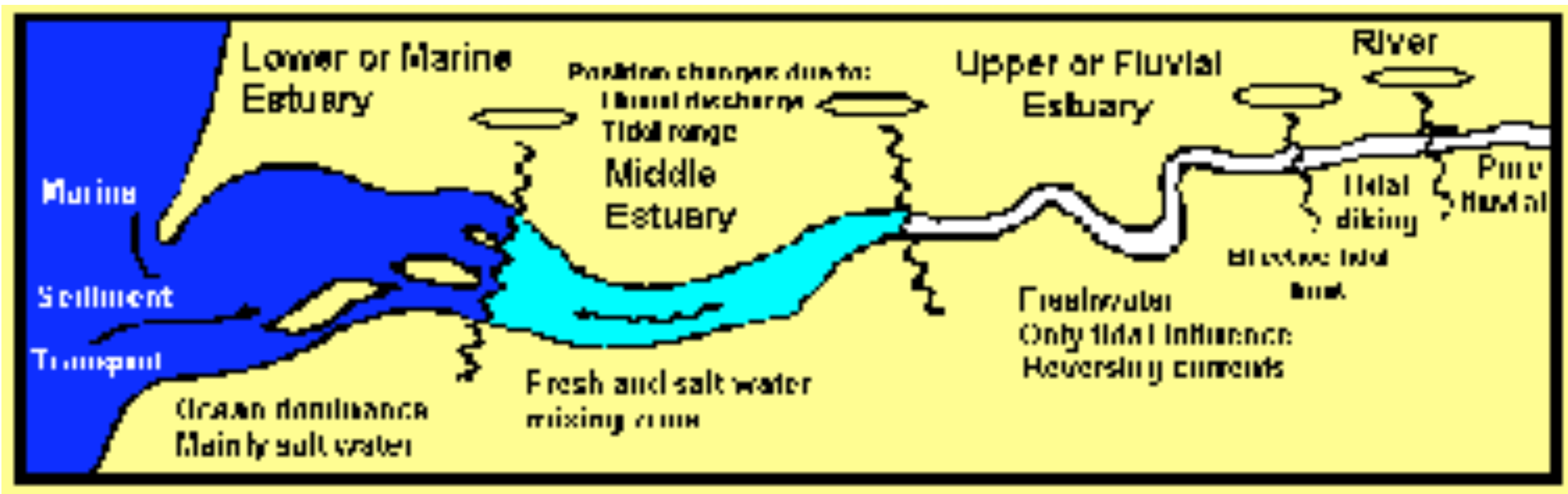
  natural, sea-level change,

  (sediment discharge)

- **Decadal time scale**

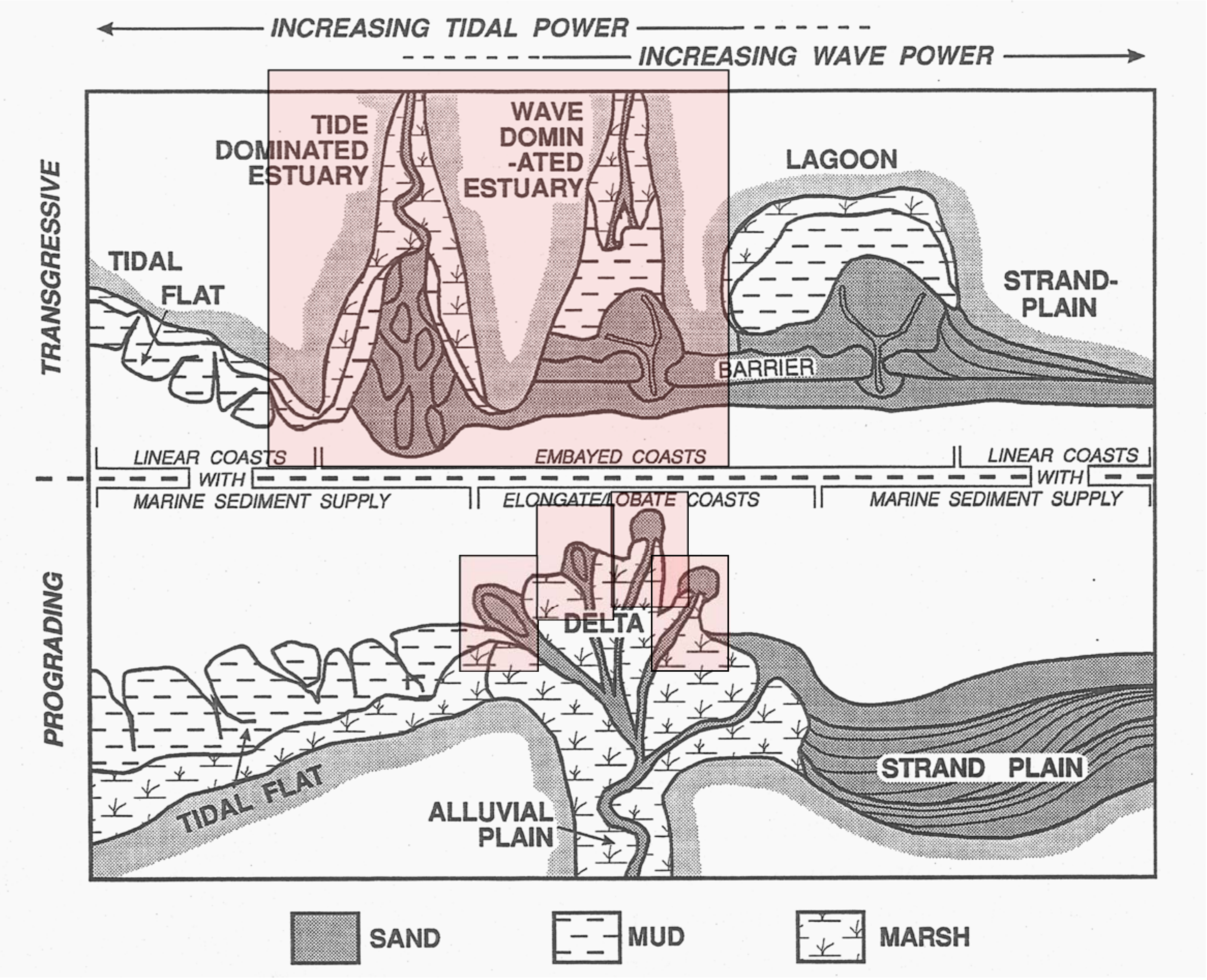
  reclamation, dykes, sea-level change, sand mining, decrease of sediment/water discharge

Estuaries



Schematic diagram of an estuary and its integration with the river. Boundaries between reaches may change in position depending on river discharge and tidal range (modified from Perillo, 1995).

Estuaries


INCREASING TIDAL POWER
INCREASING WAVE POWER
TIDE DOMINATED ESTUARY
WAVE DOMIN-ATED ESTUARY
LAGOON
TRANSGRESSIVE
TIDAL FLAT
STRAND-PLAIN
BARRIER
LINEAR COASTS
EMBAYED COASTS
LINEAR COASTS
WITH
WITH
MARINE SEDIMENT SUPPLY
ELONGATE/LOBATE COASTS
MARINE SEDIMENT SUPPLY
PROGRADING
DELTA
STRAND PLAIN
TIDAL FLAT
ALLUVIAL PLAIN
SAND
MUD
MARSH

ESTUARIES

There are many definitions of an estuary (FIGURE 31); one of the most useful and geological is that of Dalrymple et al:

> "an estuary is the seaward portion of a drowned valley system which receives sediment from both fluvial and marine sources and which contains facies influenced by both tide, wave and fluvial processes"

The phrase **drowned valley system** implies that estuaries form during **transgression.** The formation and lifespan of an estuary depends on the rate of sea level rise and the volume and rate of sediment input. A very useful classification of estuaries has been proposed by Reinson (FIGURE 32):

1. **Wave-dominated**
    - a) **lagoonal** (closed to the sea except for small tidal inlets
    - b) **partially closed** (some bars or spits across the seaward end
    - c) **open ended** (no obstruction at the seaward end)
2. **Tide-dominated** (no obstruction at the seaward end)

Definition of estuaries

An estuary is
1) a drowned valley system (used to be)
2) developing at a river mouth
3) receiving both influences of river and marine processes

Major estuaries of the world and related deltas and bays with estuaries characteristics

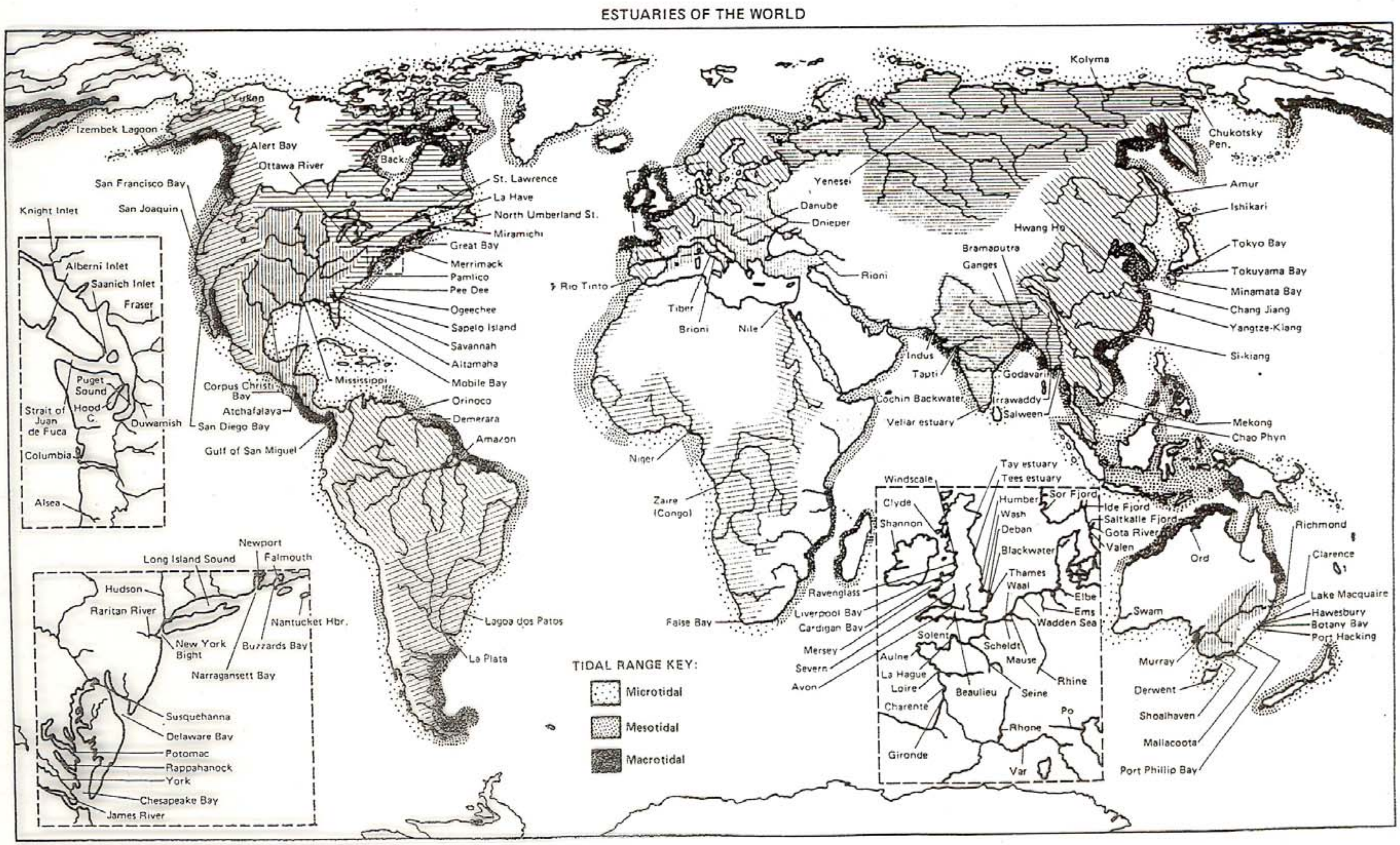


Figure 2-3. Major estuaries of the world and related deltas and bays with estuarine characteristics, (from Olausson and Cato, 1980). Hachured areas on continents represent major drainage basins. Modified and reproduced with permission of John Wiley and Sons.

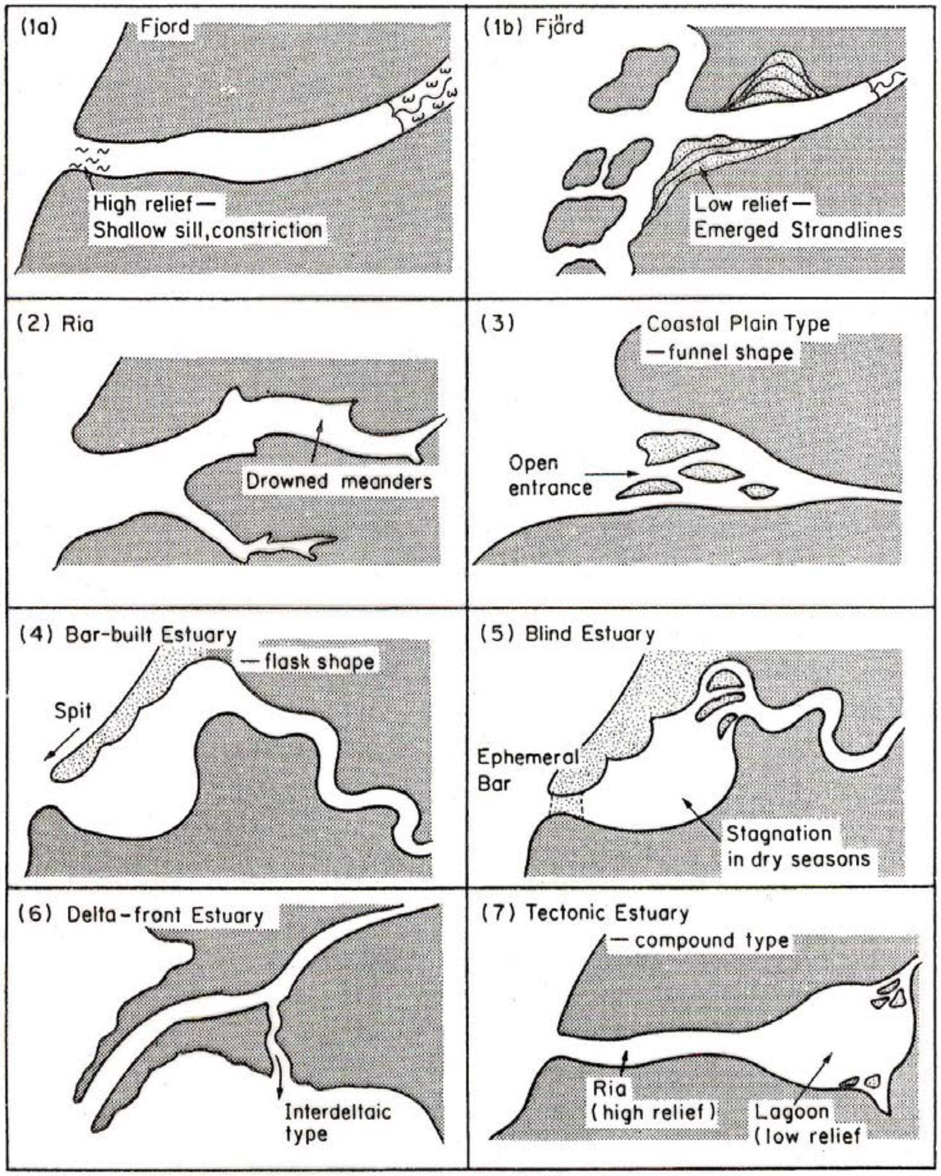


Figure 2-1. Basic estuarine physiographic types. Hydrodynamic characteristics are not considered here; discharge, tidal range, latitude (climate), and exposure all play important roles in modifying these examples, in addition to long-term secular processes such as tectonics and eustasy (schematic) (from Fairbridge, 1980).

Morphological classification

Fairbridge, 1980

By P.S. Roy

Drowned river valley estuary

1. DROWNED RIVER VALLEY ESTUARY

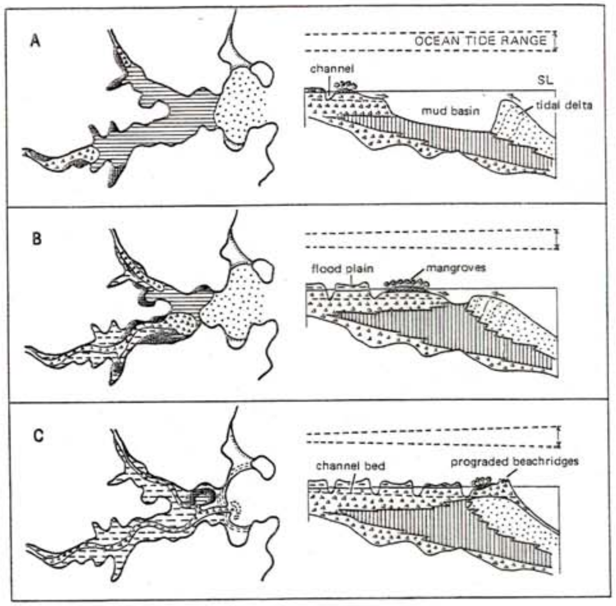


FIGURE 3. Stages of infilling in the evolution of a drowned river valley estuary. Arrows indicate direction of delta growth (sediment symbols, scales and tidal representations as for Figure 2).

Coastal lake

3. COASTAL LAKE

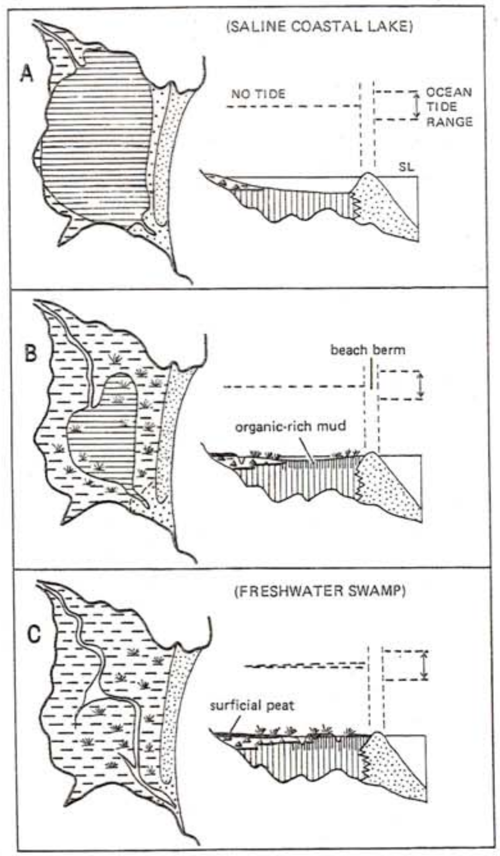


FIGURE 5. Stages of infilling in the evolution of a coastal lake (sediment symbols, scales and tidal representations as for Figure 2).

Barrier estuary

2. BARRIER ESTUARY

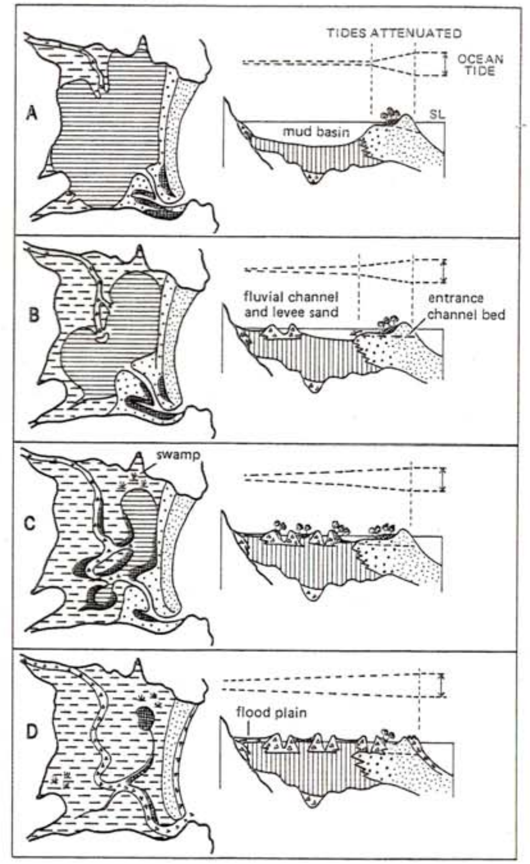


FIGURE 4. Stages of infilling in the evolution of a barrie estuary. (Sediment symbols, scales and tidal representations as for Figure 2).

B. Thom, P. Roy

Wave-dominated COASTAL - PLAIN ESTUARIES tide-dominated

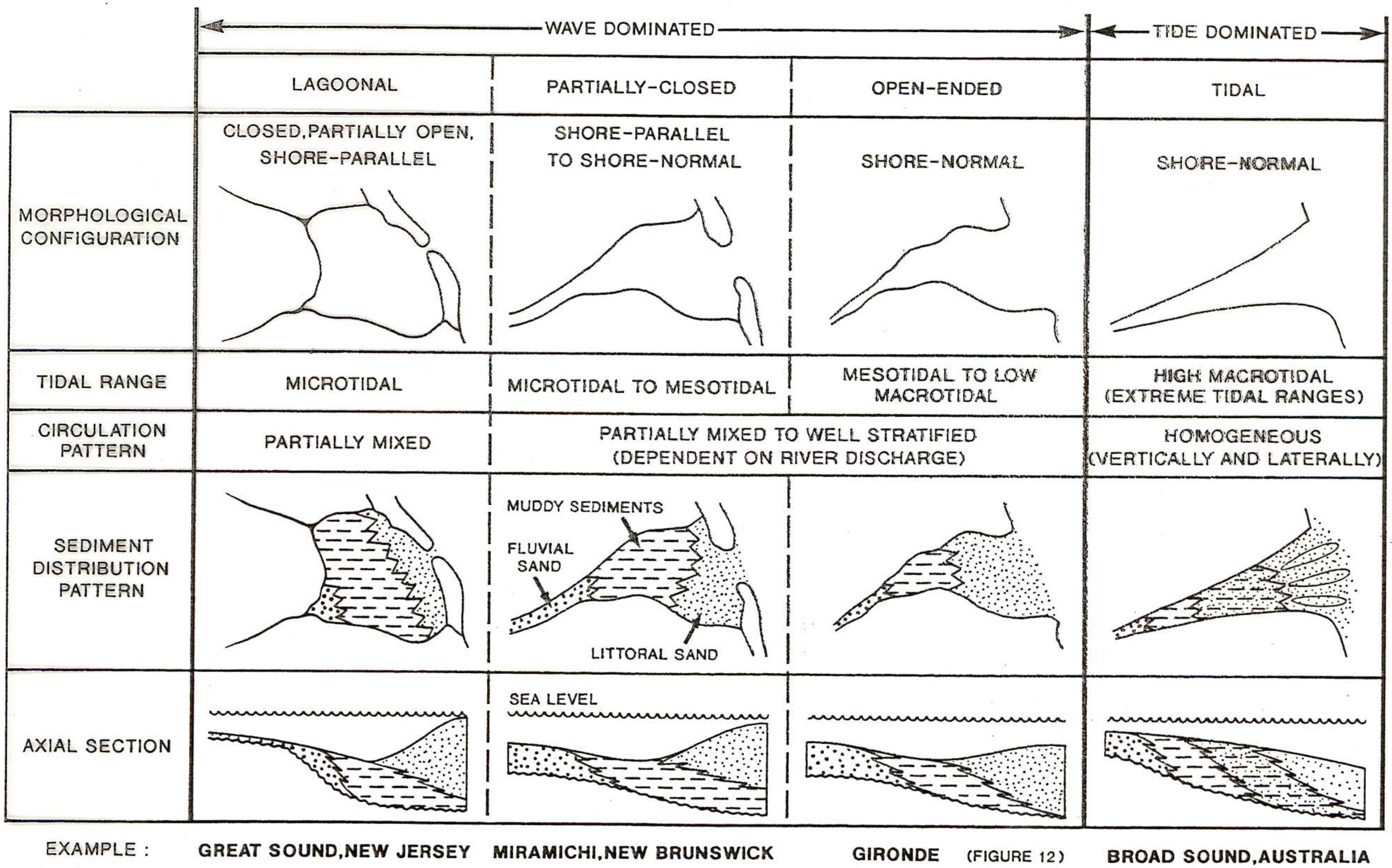


Figure 6 Classification of estuaries (based on volume of the tidal prism) illustrating morphological, oceanographic, and sedimentological characteristics of each estuary type. See Ashley (1988) and Cook and Mayo (1977) for Great Sound and Broad Sound examples, respectively.

Classification of estuaries based on volume of the Tidal prism

Wave-dominated

Tide-dominated

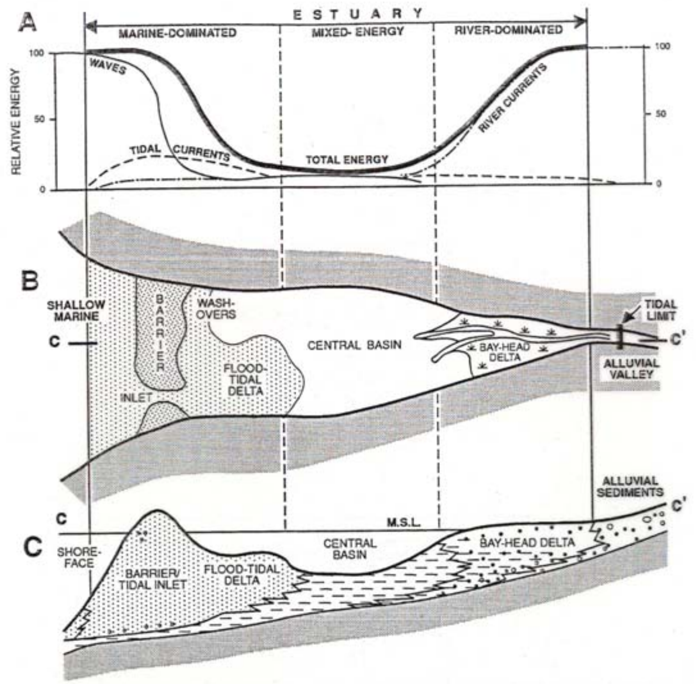


Fig. 4.—Distribution of A) energy types, B) morphological components in plan view, and C) sedimentary facies in longitudinal section within an idealized wave-dominated estuary. Note that the shape of the estuary is schematic. The barrier/sand plug is shown here as headland attached, but on low-gradient coasts it may not be connected to the local interfluves and is separated from the mainland by a lagoon. The section in C represents the onset of estuary filling following a period of transgression.

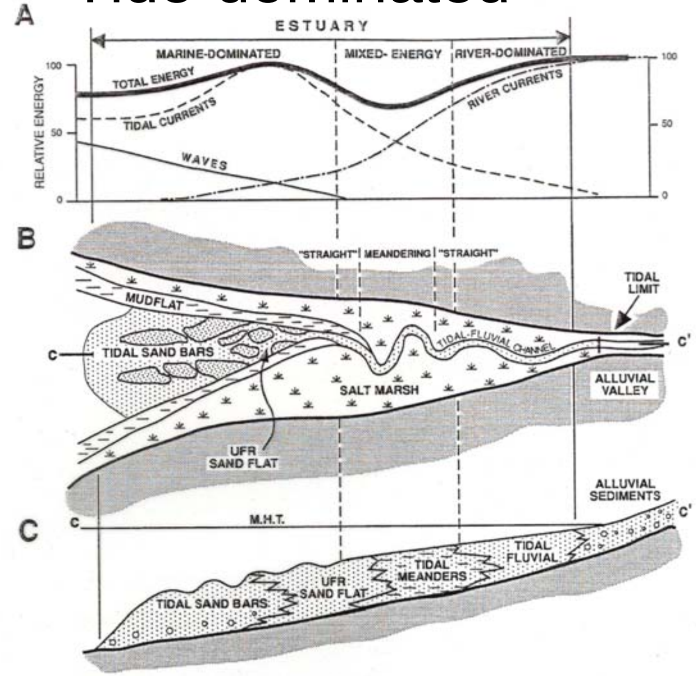


Fig. 7.—Distribution of A) energy types, B) morphological elements in plan view, and C) sedimentary facies in longitudinal section within an idealized tide-dominated estuary. URF = upper flow regime; M.H.T. = mean high tide. The section in C is taken along the axis of the channel and does not show the marginal mudflat and salt marsh facies; it illustrates the onset of progradation following transgression, the full extent of which is not shown.

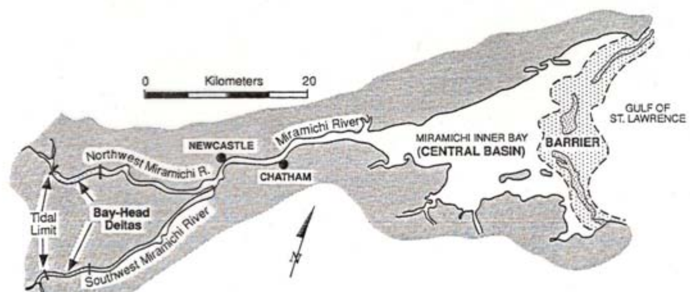


Fig. 6.—Facies map of the wave-dominated, Miramichi River estuary (12 in Fig. 3 and Table 1). Due to the large tidal prism, three tidal inlets dissect the barrier sand body. The bay-head deltas are small because of the low sediment yield. They do not show a birdsfoot morphology because the incised valleys are too narrow.

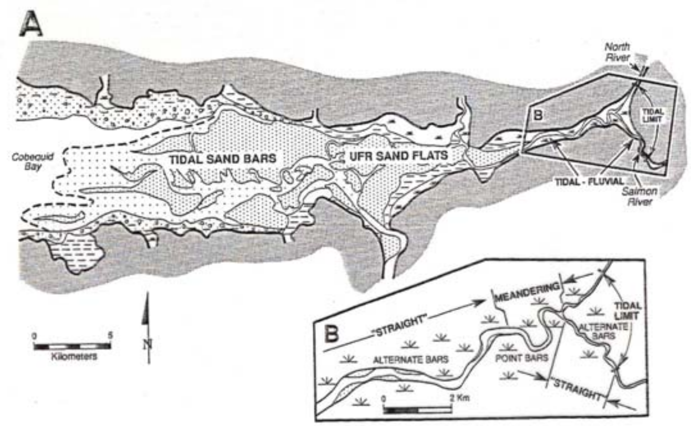


Fig. 8.—A) Facies zonation in the tide-dominated, Cobequid Bay-Salmon River estuary (33; Dalrymple et al. 1990). The dashed line in Cobequid Bay marks the outer limit of the estuarine sand body. B) Enlargement of the inner portion of the estuary showing the longitudinal changes in channel morphology and bar type.

Posamentier, Dalrymple, Boyd

Holocene evolution of

Drowned river valley estuary

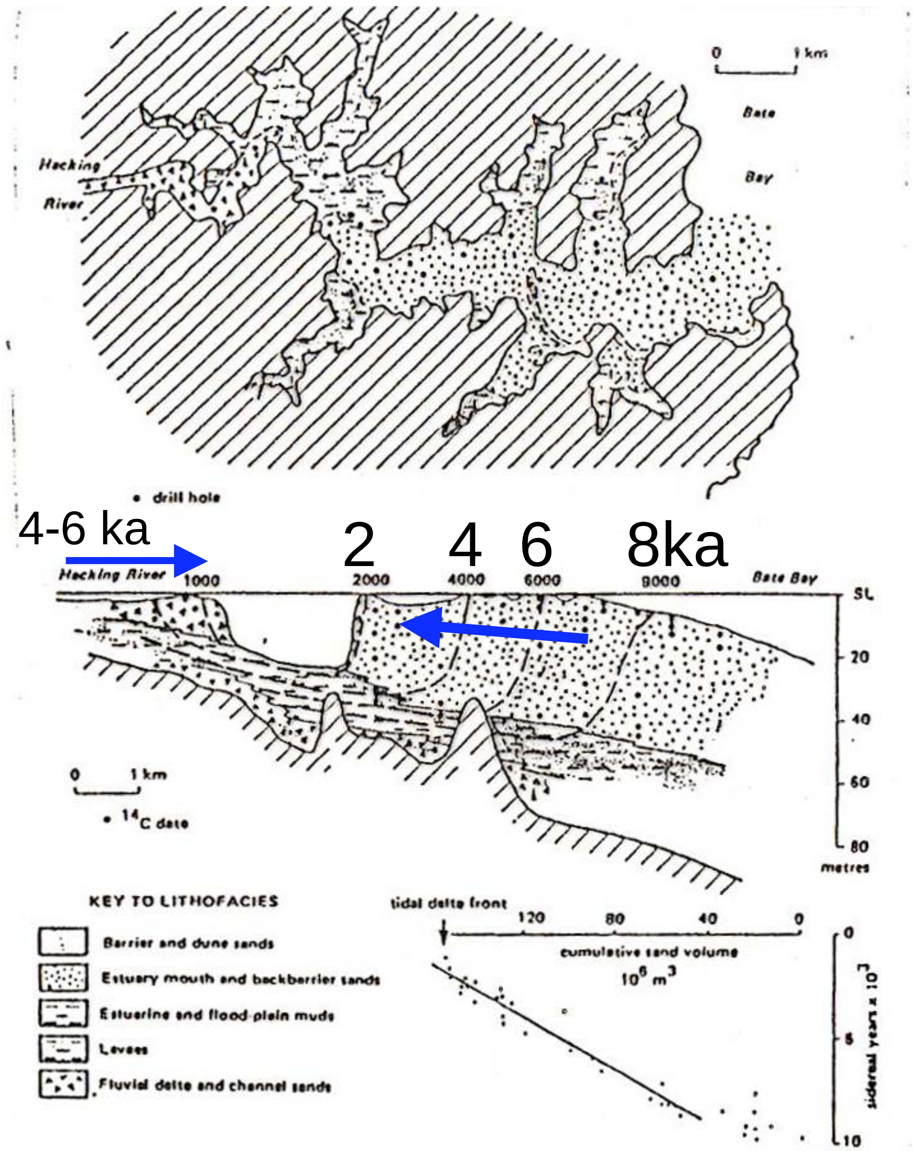


FIG. 5.—Drowned river valley at Port Hacking near Sydney (see Fig. 3 for location). Distribution and sectional geometry of lithofacies are shown together with time lines based on radiocarbon dates. Tidal delta growth is indicated for the last 10,000 years.

THOM and ROY 1985

Estuary evolution: estuary filling

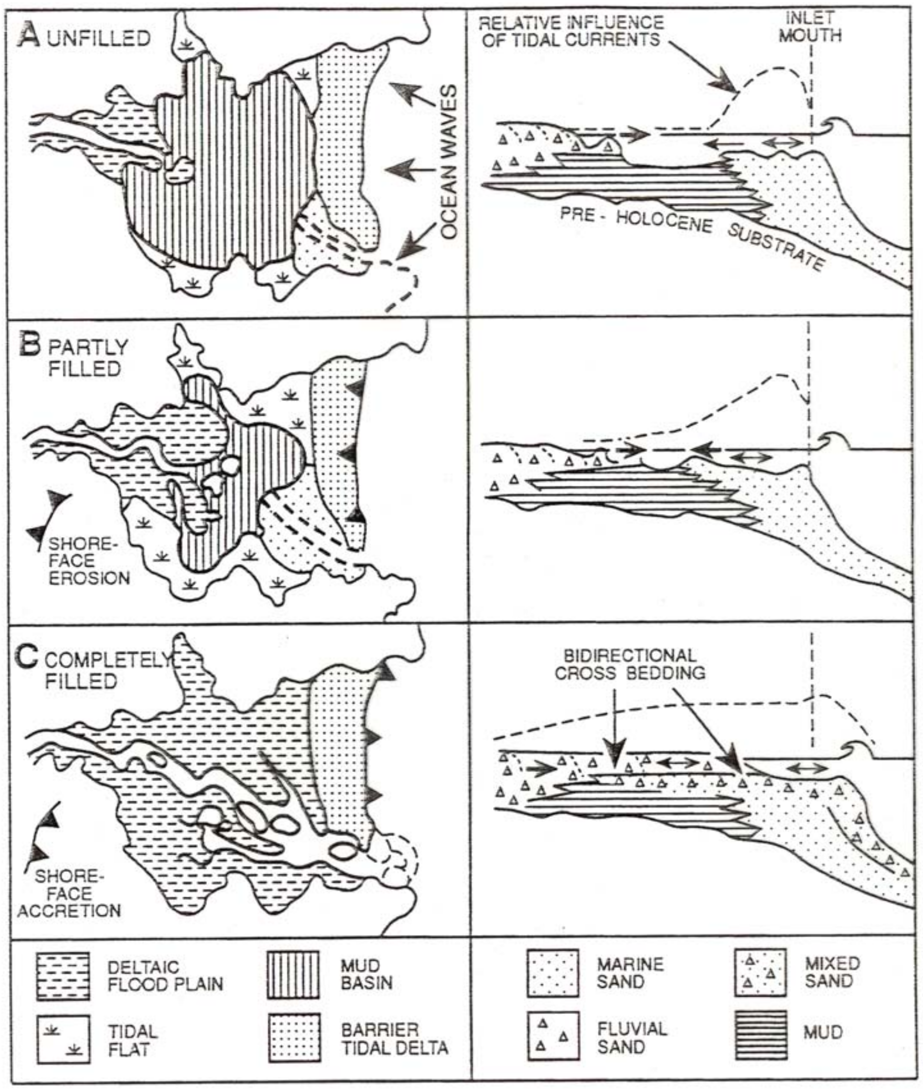


FIG. 11.—Stages in the filling of a wave-dominated estuary (after Roy et al. 1980). Note that the relative influence of tidal currents increases as the estuary fills. The mud basin is equivalent to the central basin described in this paper. Stage C is considered here to be a delta because fluvial sediment is accumulating on the shoreface.

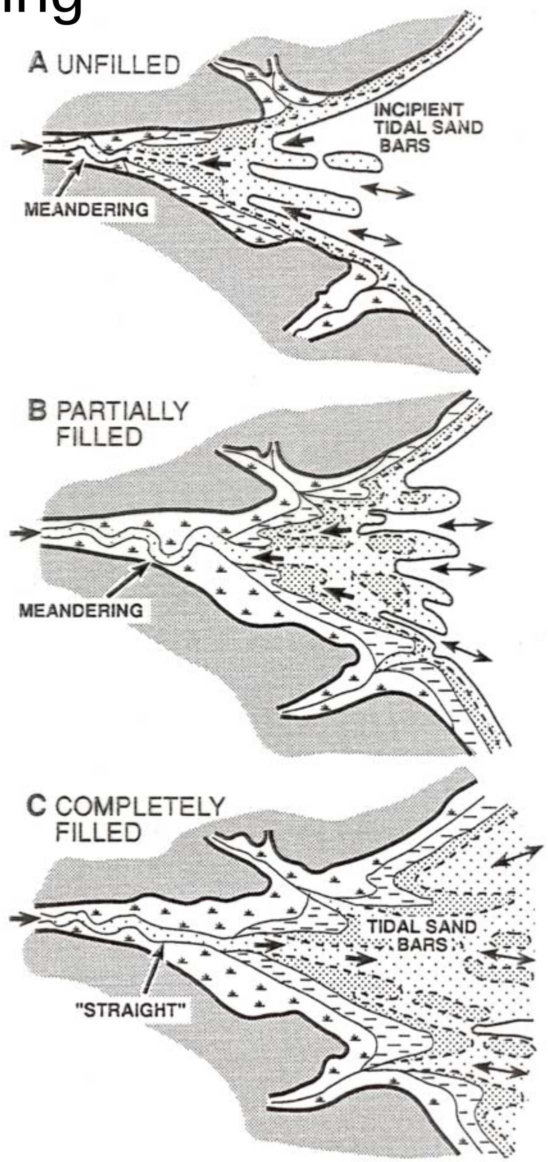
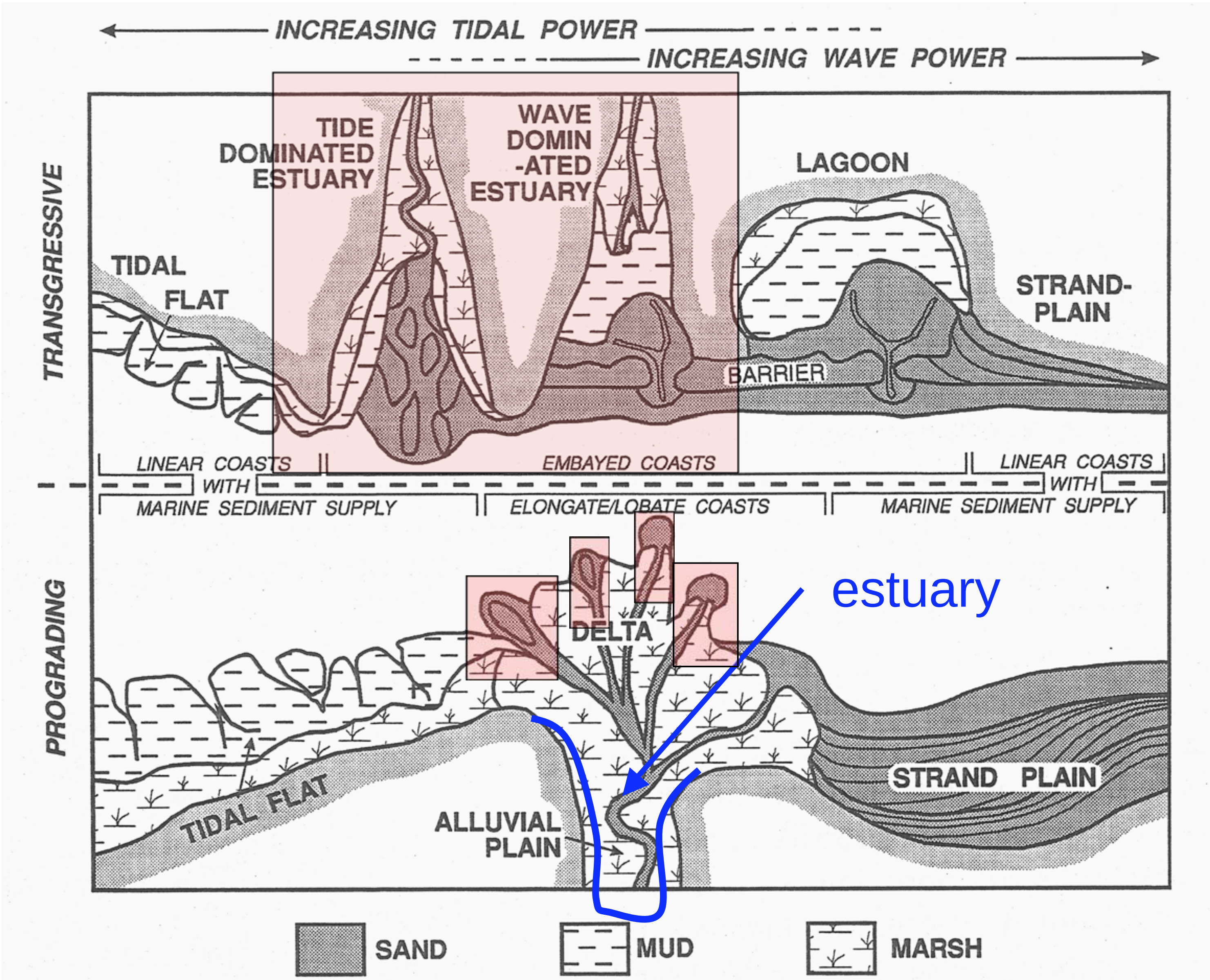
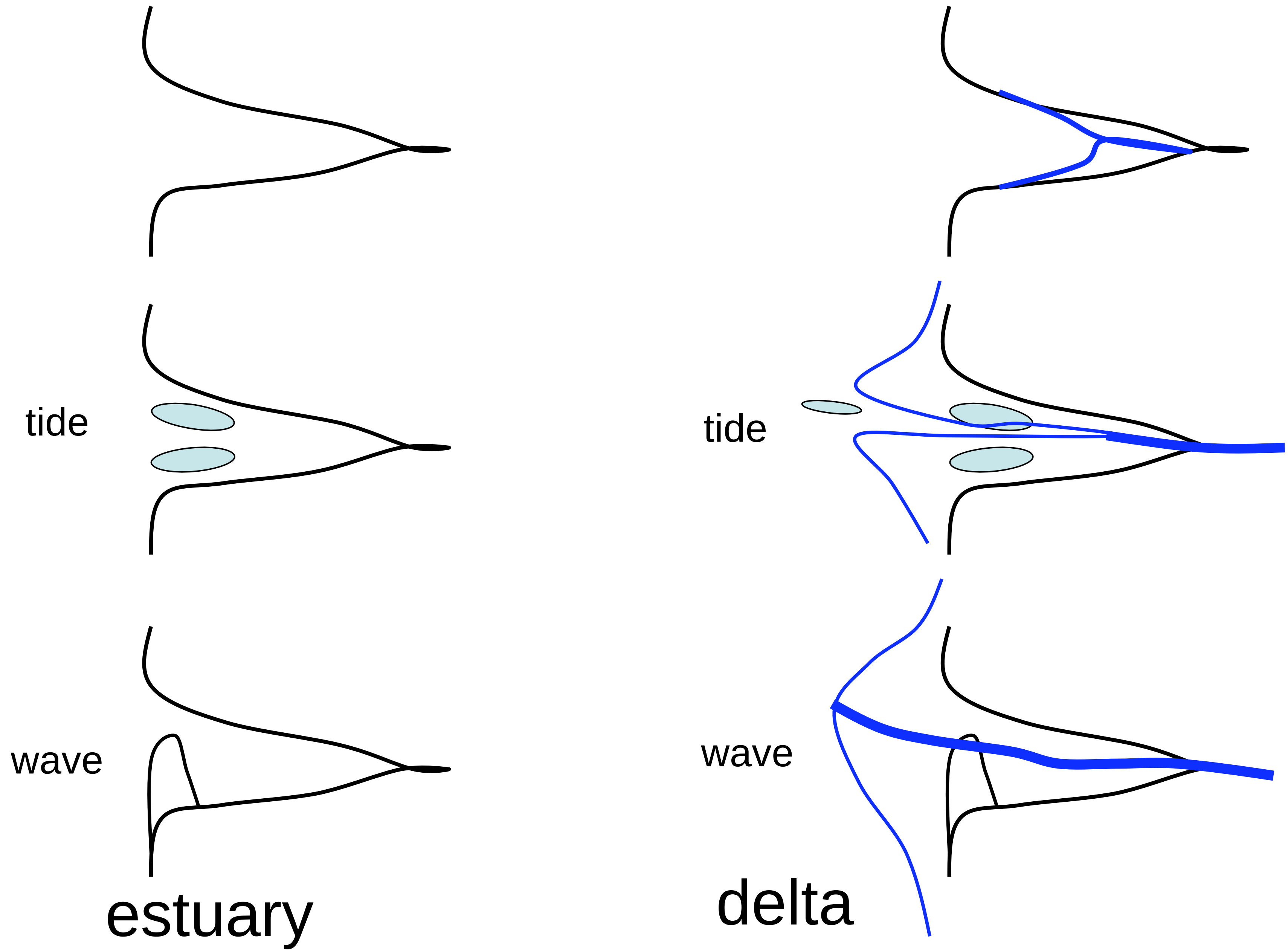


FIG. 12.—Stages in the filling of a tide-dominated estuary (based partially on Harris 1988), showing the expansion and shallowing of the sand bars, and the seaward movement of the meandering zone. When the meandering zone disappears (C), the system is considered to be a delta.

Estuaries


INCREASING TIDAL POWER
INCREASING WAVE POWER
TRANSGRESSIVE
TIDE DOMINATED ESTUARY
WAVE DOMIN -ATED ESTUARY
LAGOON
TIDAL FLAT
STRAND-PLAIN
BARRIER
LINEAR COASTS WITH MARINE SEDIMENT SUPPLY
EMBAYED COASTS
ELONGATE/LOBATE COASTS
LINEAR COASTS WITH MARINE SEDIMENT SUPPLY
PROGRADING
DELTA
estuary
STRAND PLAIN
TIDAL FLAT
ALLUVIAL PLAIN
SAND
MUD
MARSH


tide
wave
estuary
tide
wave
delta

Yangtze (Changjiang) example

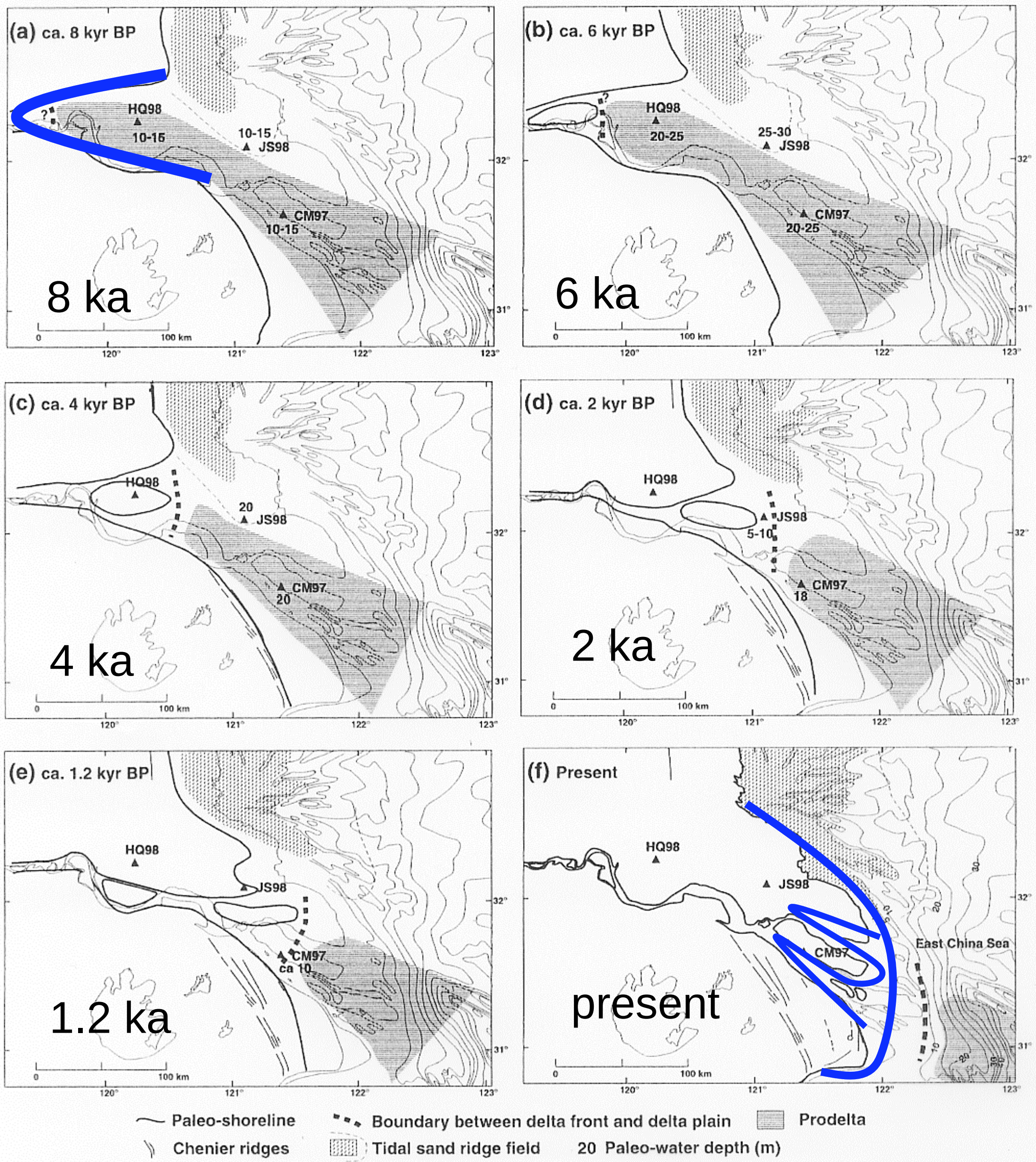


Fig. 9. Paleogeographic map illustrating the evolution of the Changjiang delta and the surrounding area. The distribution of tidal sand ridges with shaded tone shows the only shallow part, which is less than about 10 m water depth. Paleoshorelines are from Wang et al. (1981), Chen (1998). Paleo-water depth is estimated from Fig. 6.

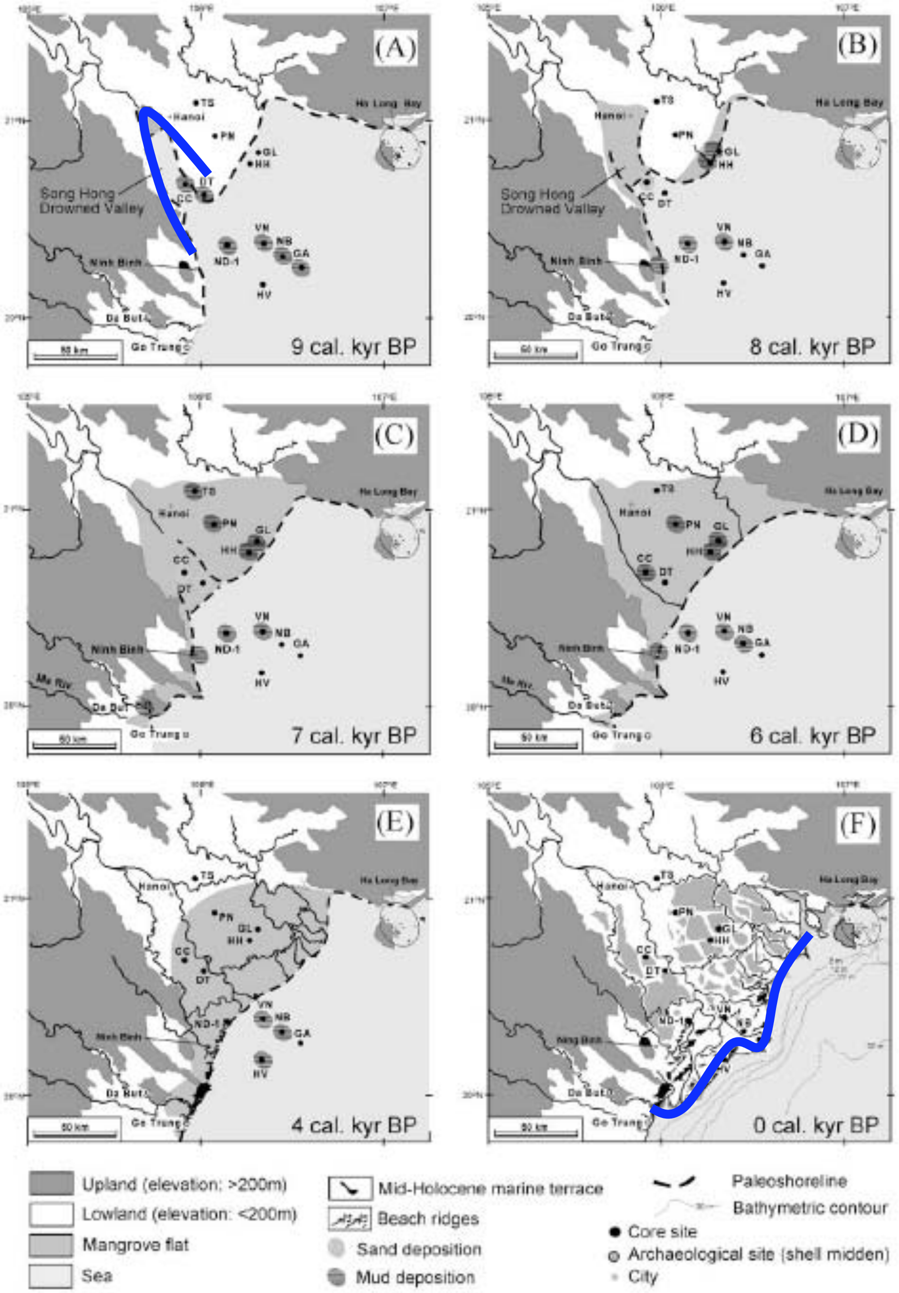


Fig. 10. Paleogeographic map illustrating the evolution of the Song Hong delta during the past 9 kyr. Modified after Tanabe et al. (2003b) using newly collected data.

Red River (Song Hong) example

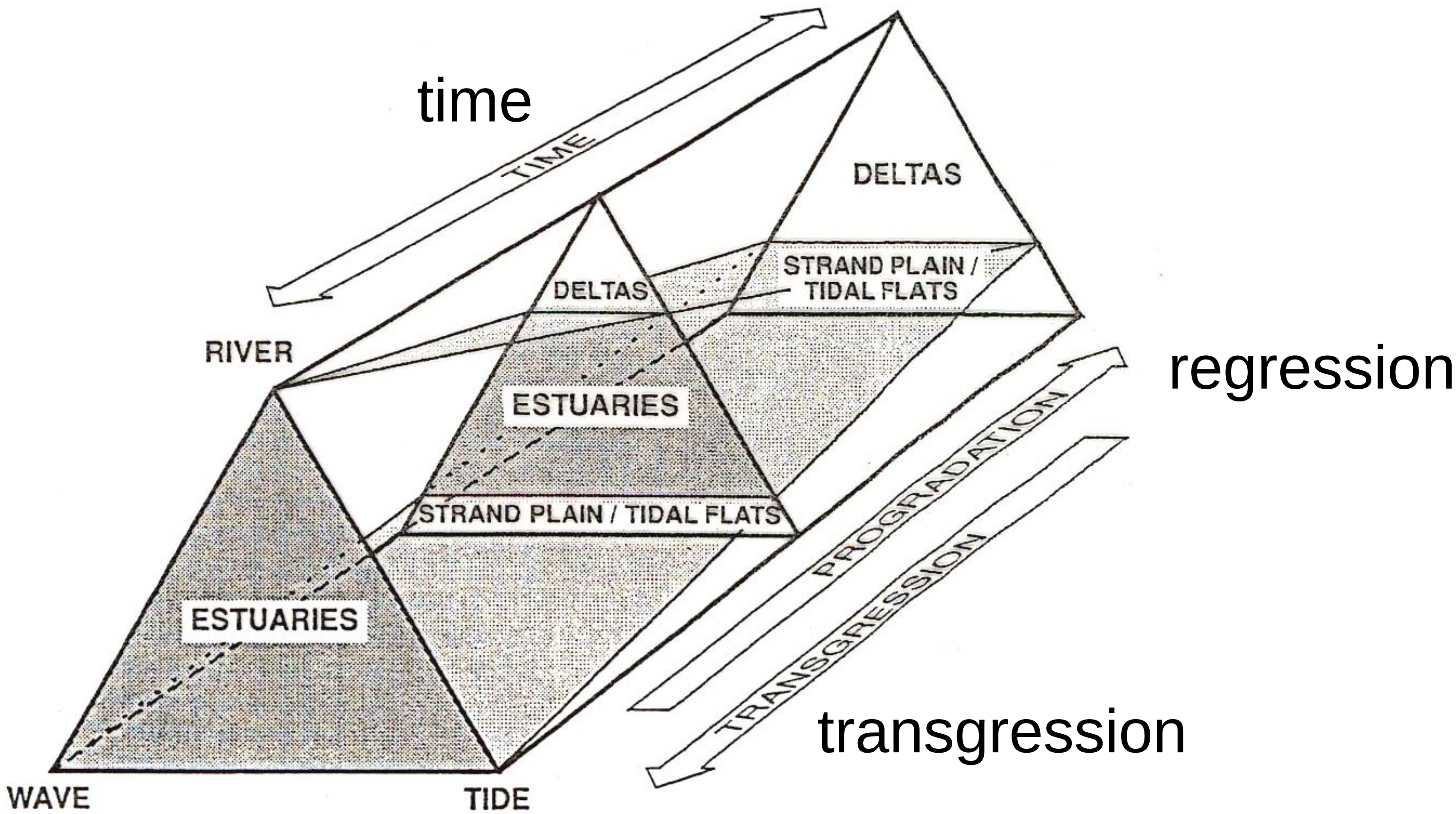
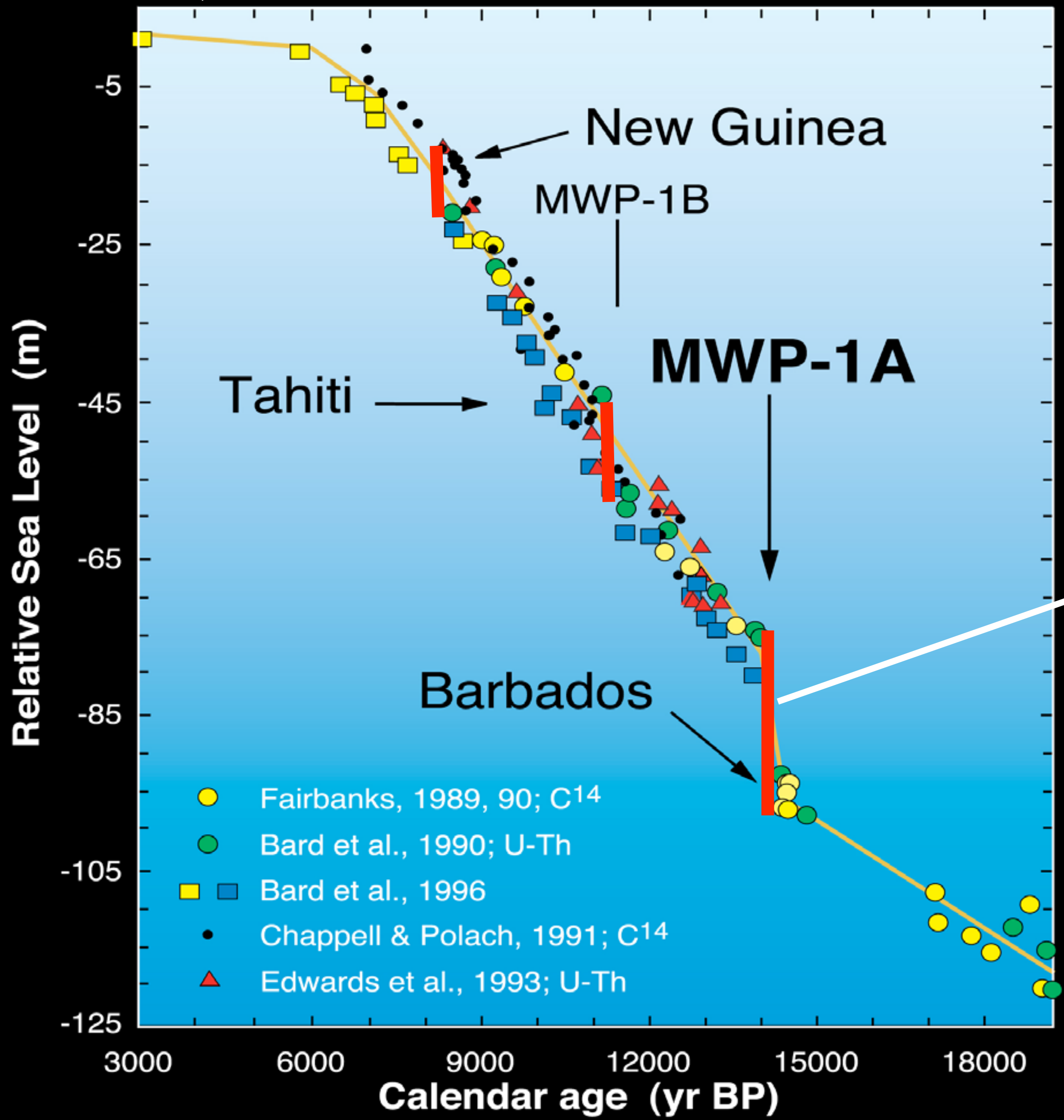


FIG. 2.—Evolutionary classification of coastal environments. The long axis of the three-dimensional prism represents relative time with reference to changes in relative sea level and sediment supply (i.e., transgression and progradation). The three edges of the prism correspond to conditions dominated by fluvial, wave and tidal processes. Deltas occupy the uppermost area; the intermediate, wedge-shaped space contains all estuaries; and the bottom wedge represents non-deltaic, prograding coasts. Transgressive, barrier-lagoon systems which form along coasts without incised valleys occupy part of the estuary field. During a sea-level cycle, a coastal area will track forward and backward through the prism at a rate, and by an amount, determined by the rate of sea-level change, the sedimentation rate and basin size.

Delta system



Sea-level changes for the last 20 ka

Sea-level jump

Relative sea-level changes

Eustasy (seawater volume)

Glacial isostasy

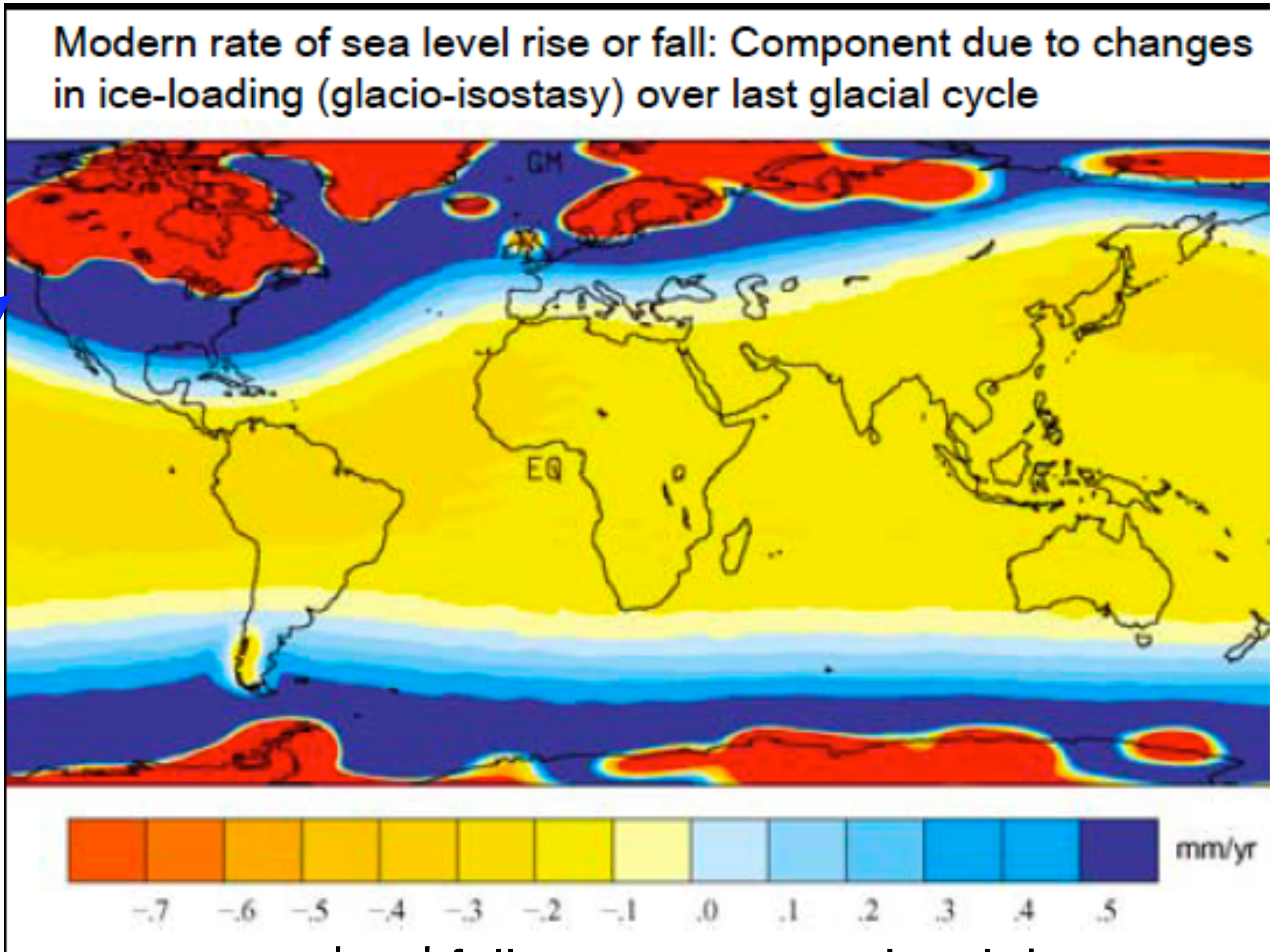
Hydro-isostasy

Local tectonics

Glacio-isostasy

uplift

subsidence



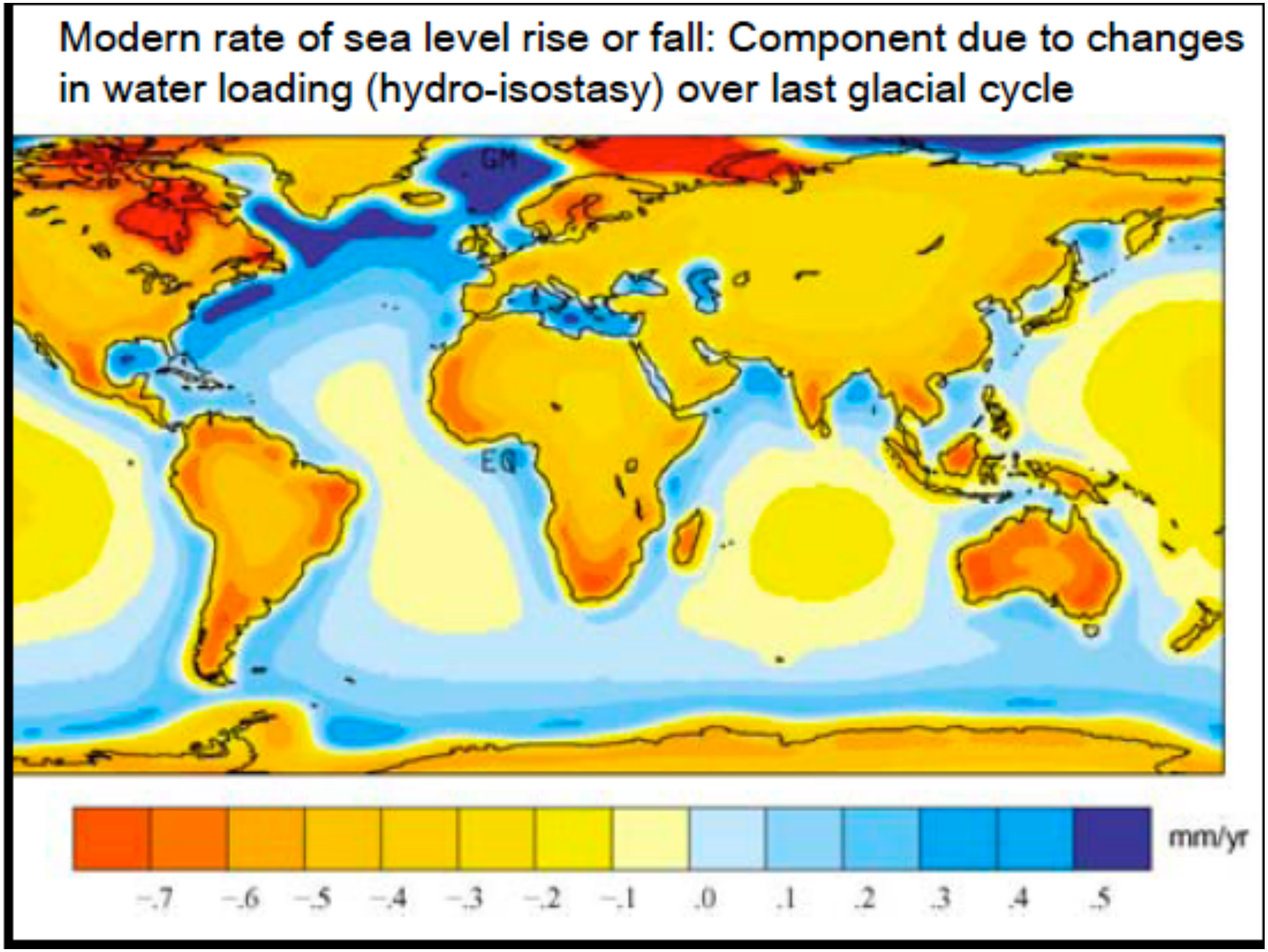
sea-level fall

sea-level rise

Hydro-isostasy

uplift

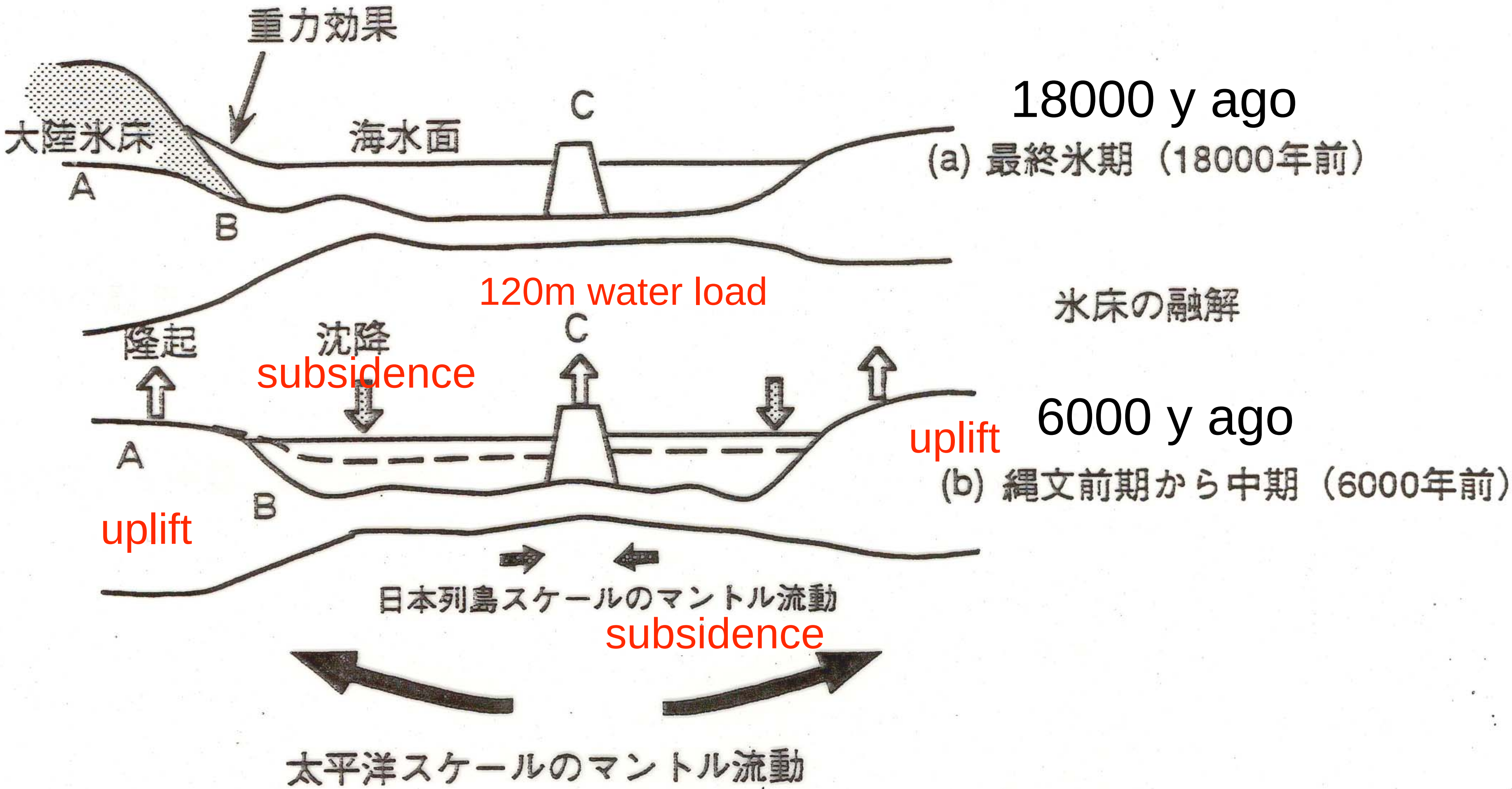
subsidence



sea- level fall

sea-level rise

Hydro-isostasy



Ocean scale

Paired sea level curves
Seaward vs landward

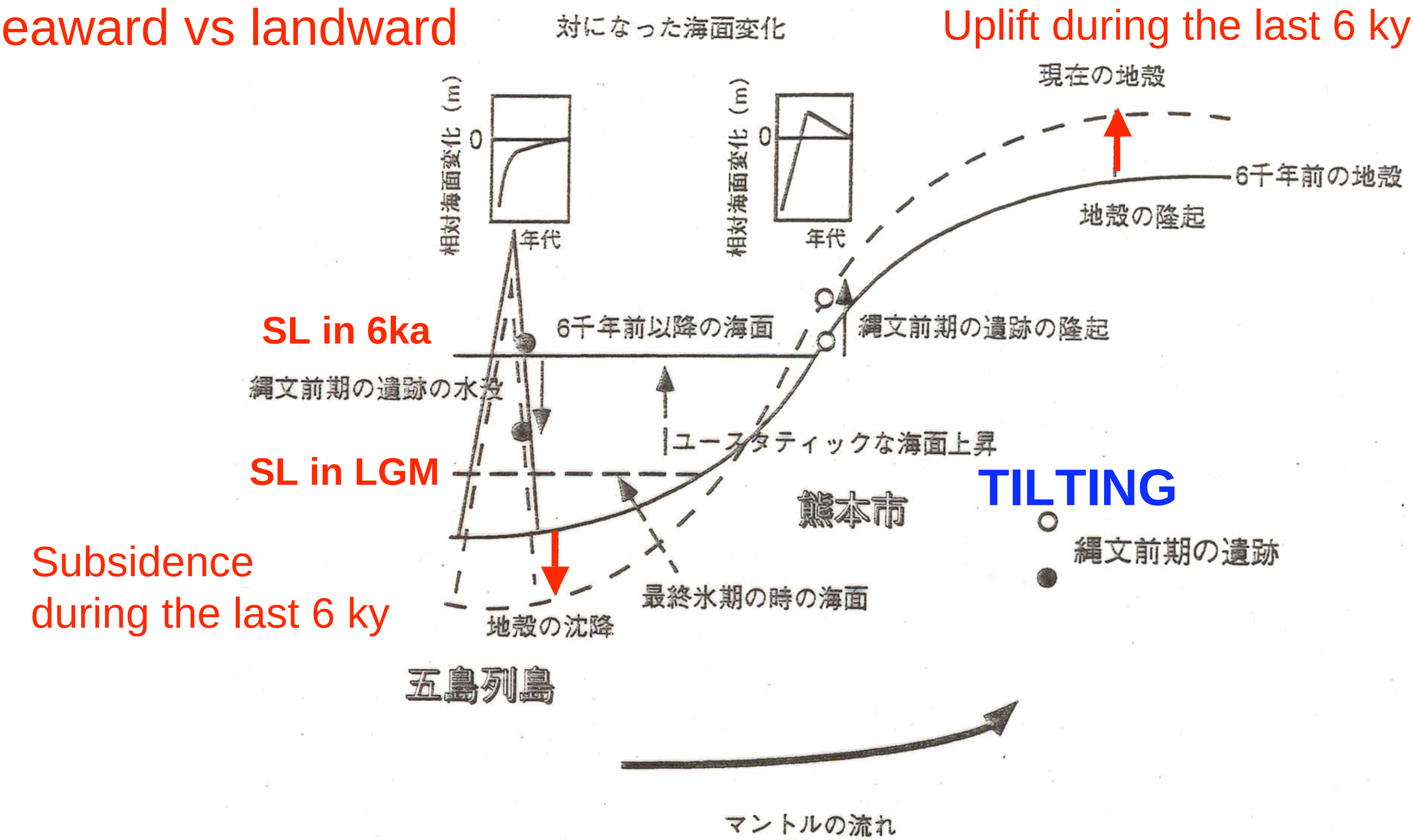


図7　熊本市から五島列島地域のハイドロアイソスタシーの概念図と縄文遺跡の関係

Island/coast scale

Present level of
6 ka sea level

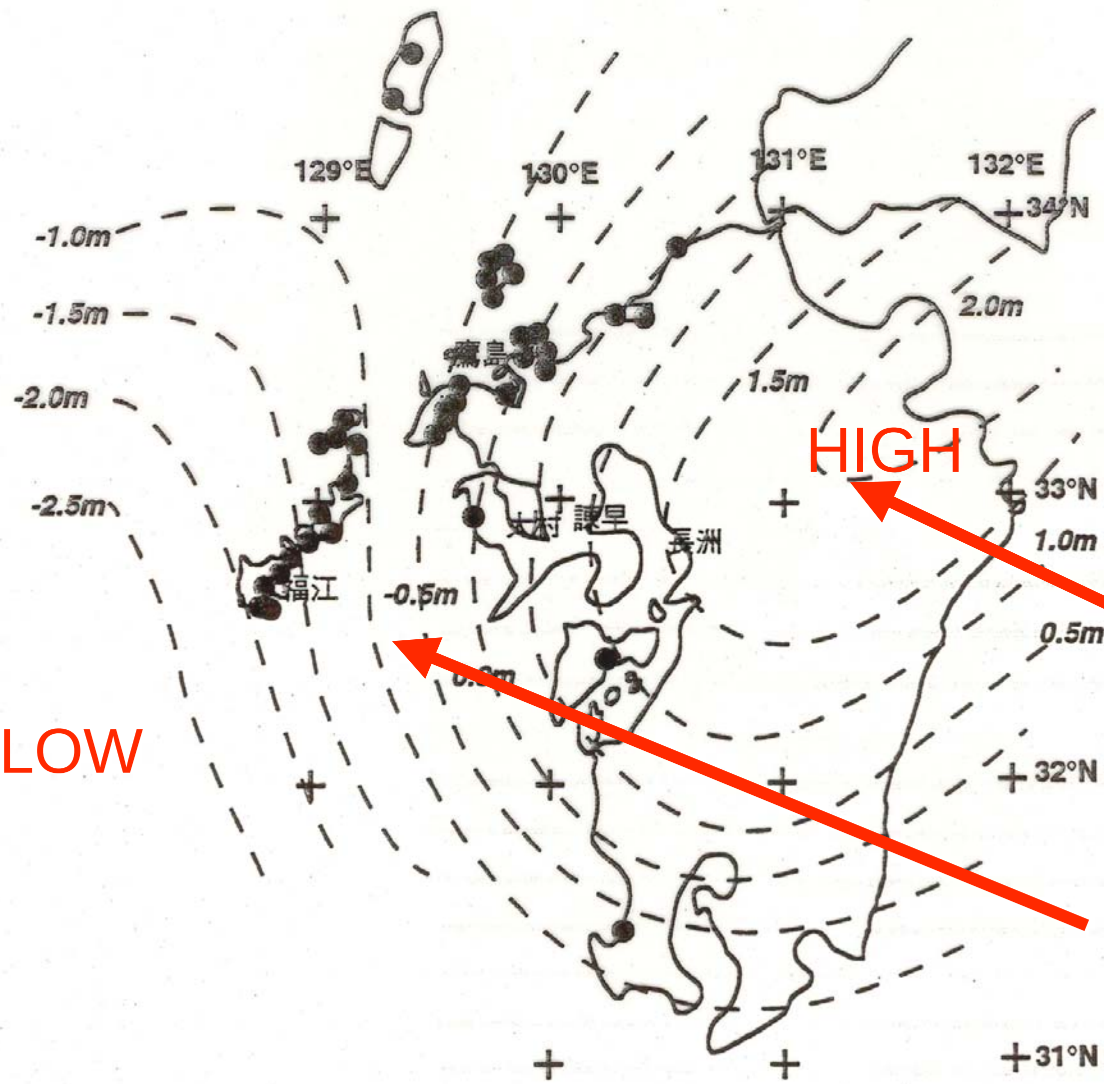


図５　九州における現海面に対する６千年前の海面高度の計算値（単位：m）と水中遺跡の分布

この計算に用いられた氷床モデルはARC3＋ANT4B。粘弾性地球モデルは図８のA。水中遺跡は６千年前の海面が現海面より低い位置に集中的に分布しているのが特徴的である。

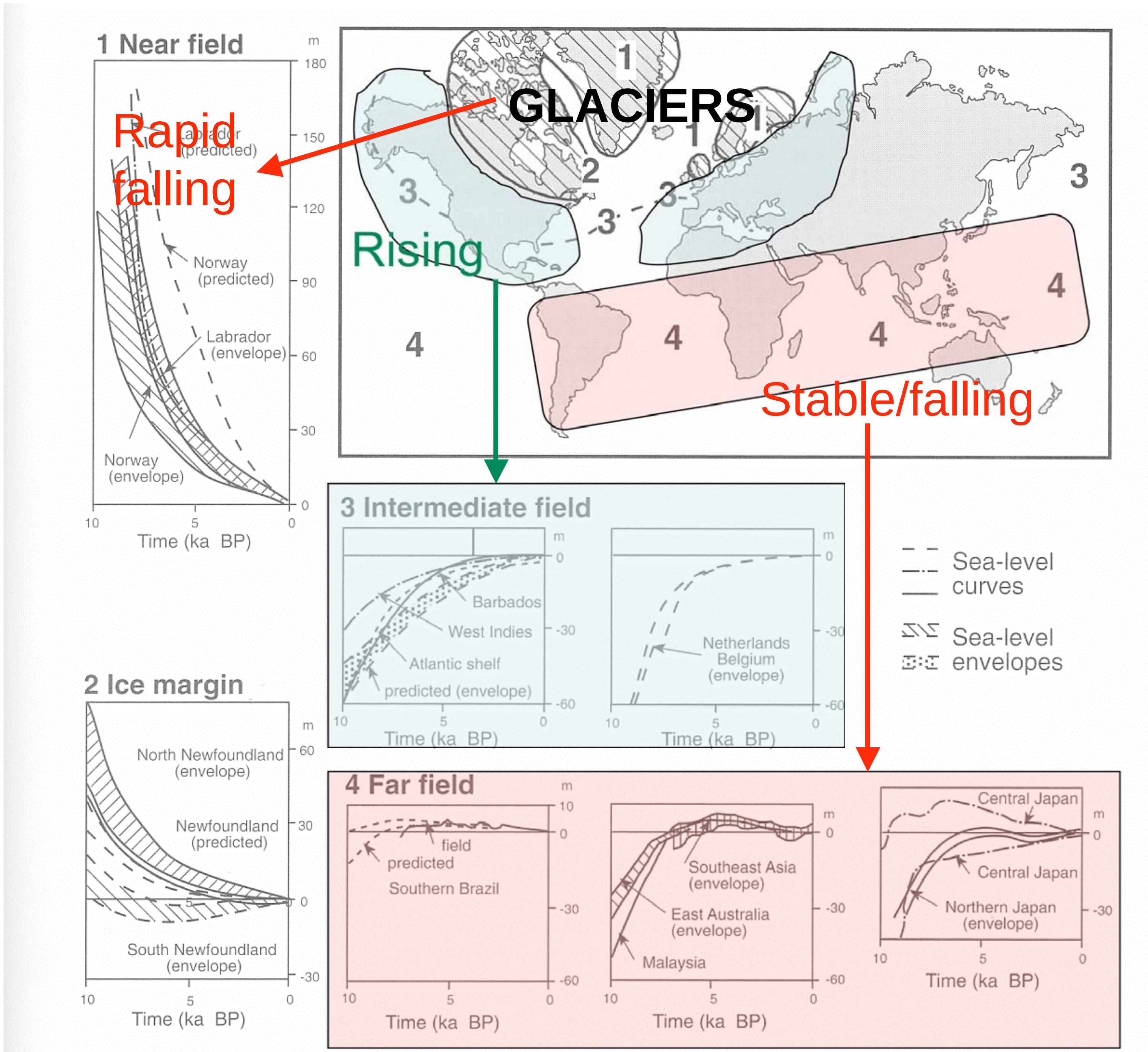
Highstand of sea level In the middle Holocene

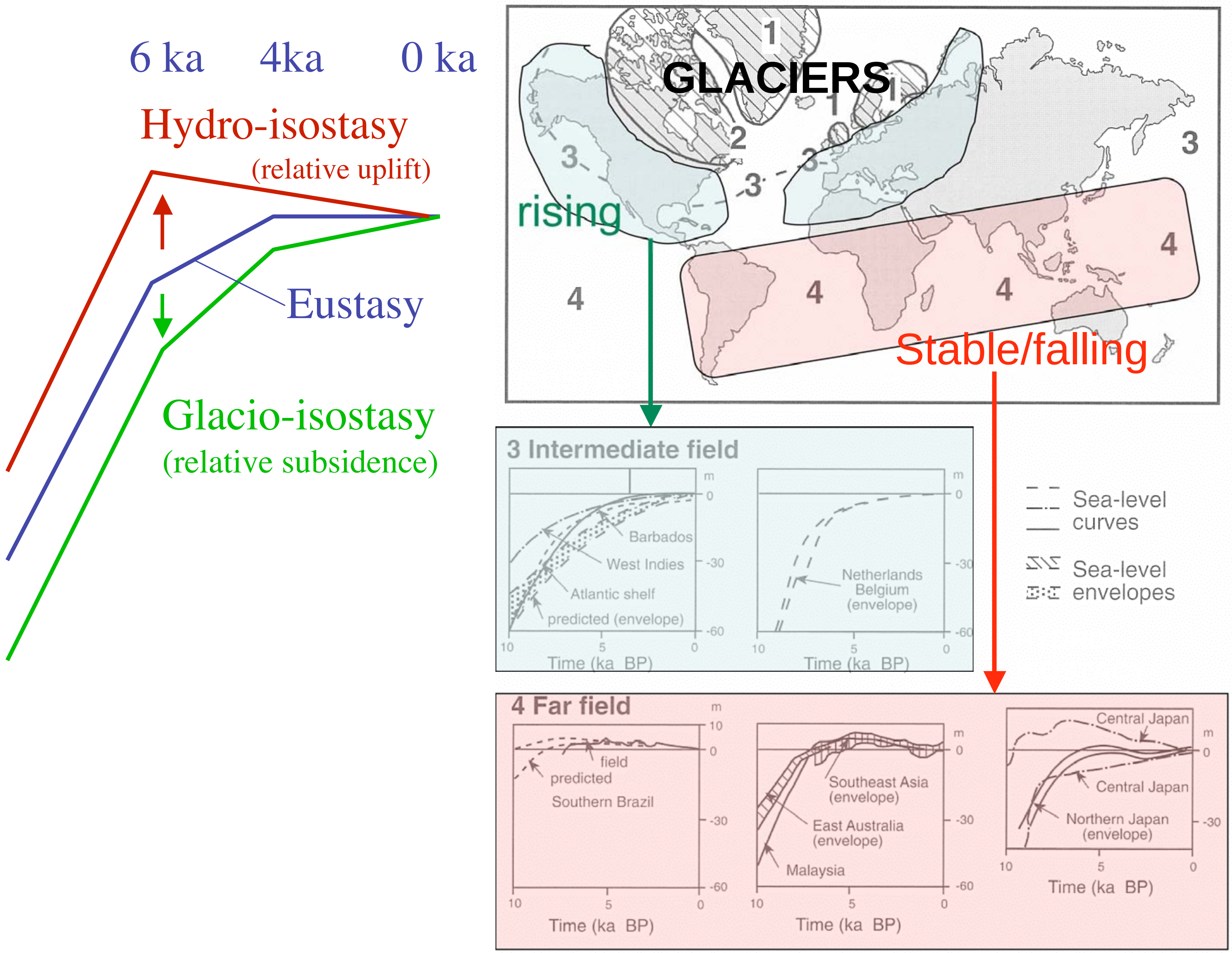
Present sea level is relatively highest in the Holocene

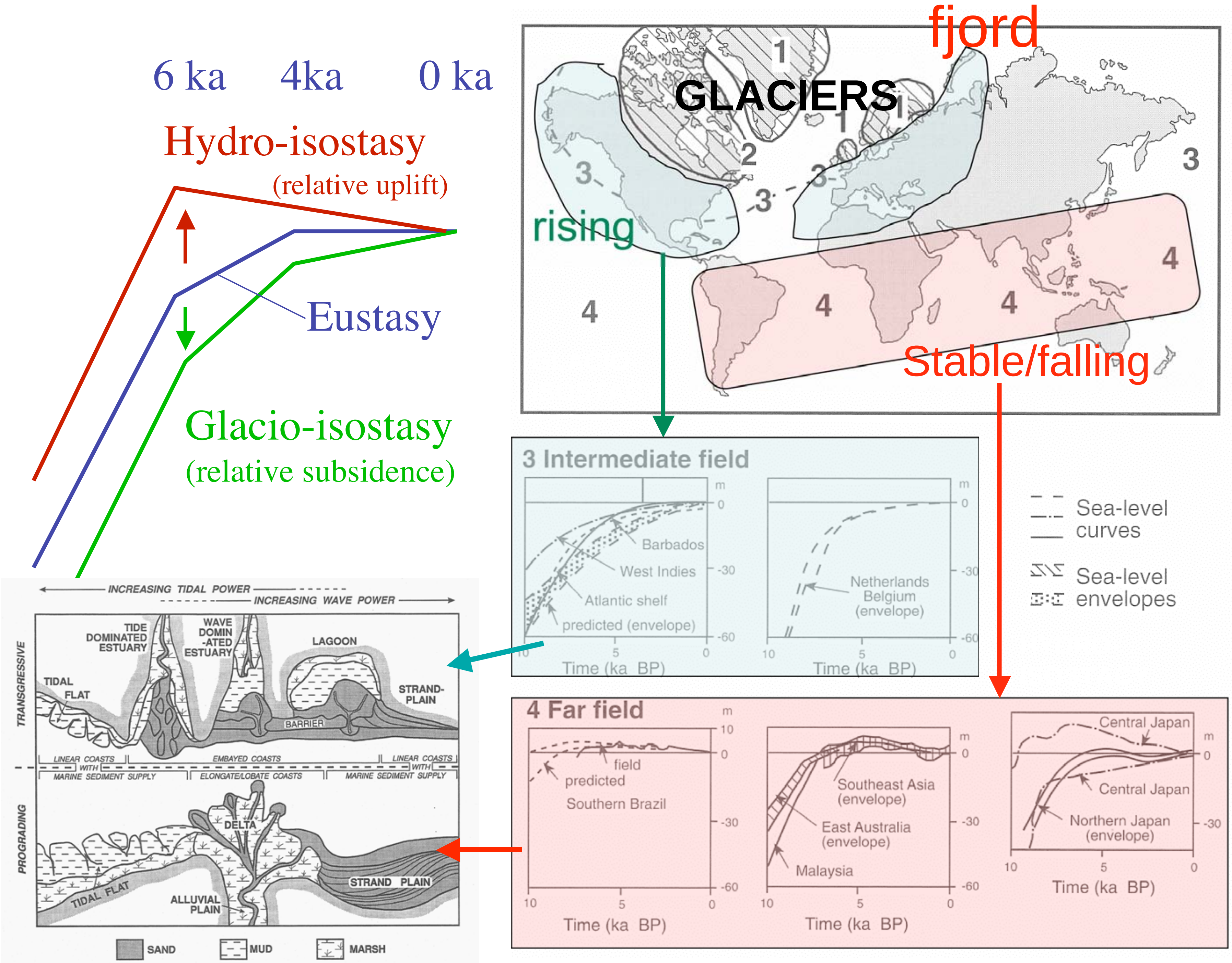
Holocene Sea-level Changes are controlled by

1) Eustatic SLC
2) Glacio-
3) Hydro-isostasy, Globally

4) Tectonics Locally

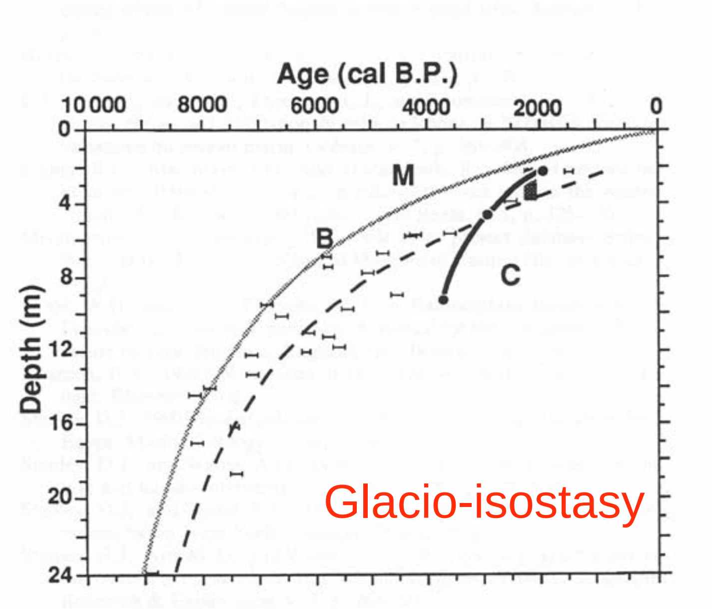


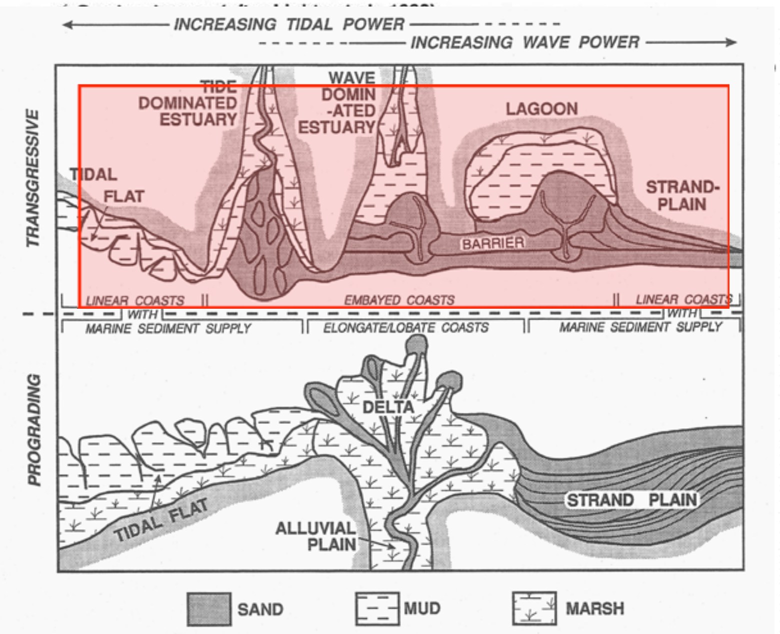

6 ka
4ka
0 ka
Hydro-isostasy
(relative uplift)
Eustasy
Glacio-isostasy
(relative subsidence)
GLACIERS
1
2
3
4
rising
Stable/falling
3 Intermediate field
Barbados
West Indies
Atlantic shelf
predicted (envelope)
Netherlands
Belgium
(envelope)
Time (ka BP)
m
0
-30
-60
10
5
Sea-level
curves
Sea-level
envelopes
4 Far field
field
predicted
Southern Brazil
Southeast Asia
(envelope)
East Australia
(envelope)
Malaysia
Central Japan
Central Japan
Northern Japan
(envelope)

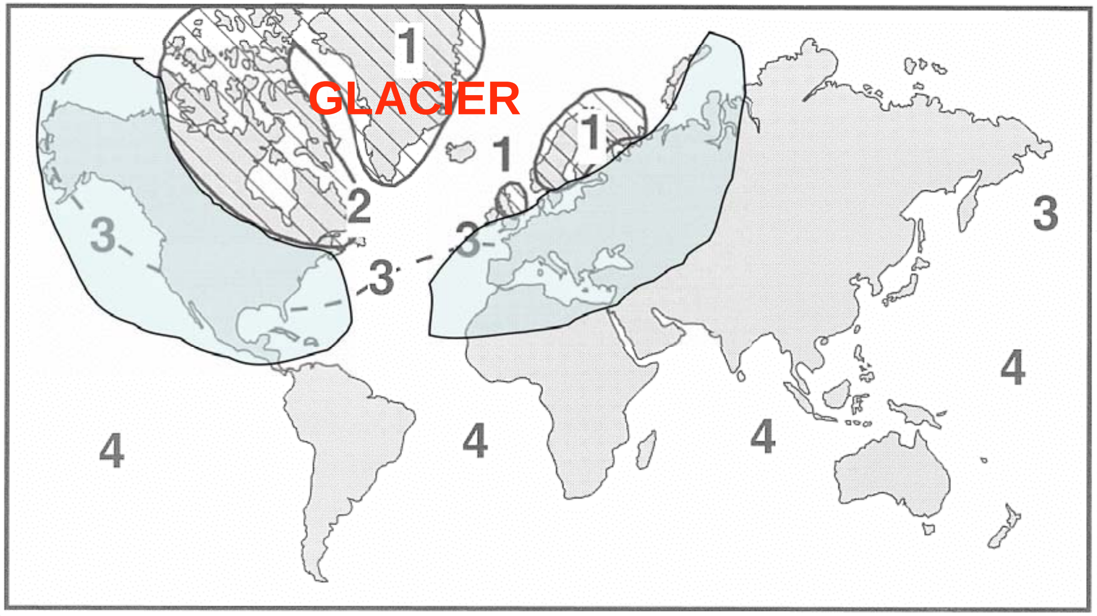


6 ka
4ka
0 ka
Hydro-isostasy
(relative uplift)
Eustasy
Glacio-isostasy
(relative subsidence)
fjord
GLACIERS
rising
Stable/falling
1
2
3
4
3 Intermediate field
Barbados
West Indies
Atlantic shelf
predicted (envelope)
Netherlands
Belgium
(envelope)
Time (ka BP)
Sea-level
curves
Sea-level
envelopes
4 Far field
field
predicted
Southern Brazil
Southeast Asia
(envelope)
East Australia
(envelope)
Malaysia
Central Japan
Central Japan
Northern Japan
(envelope)
Time (ka BP)
INCREASING TIDAL POWER
INCREASING WAVE POWER
TRANSGRESSIVE
TIDE DOMINATED ESTUARY
WAVE DOMIN-ATED ESTUARY
LAGOON
TIDAL FLAT
STRAND-PLAIN
BARRIER
LINEAR COASTS WITH MARINE SEDIMENT SUPPLY
EMBAYED COASTS
ELONGATE/LOBATE COASTS
LINEAR COASTS WITH MARINE SEDIMENT SUPPLY
PROGRADING
DELTA
TIDAL FLAT
ALLUVIAL PLAIN
STRAND PLAIN
SAND
MUD
MARSH

Transgressive depositional systems

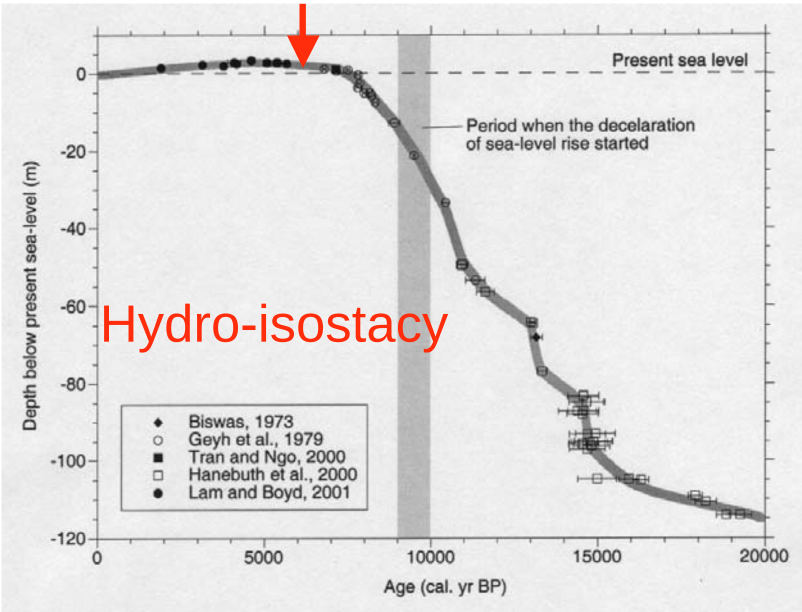


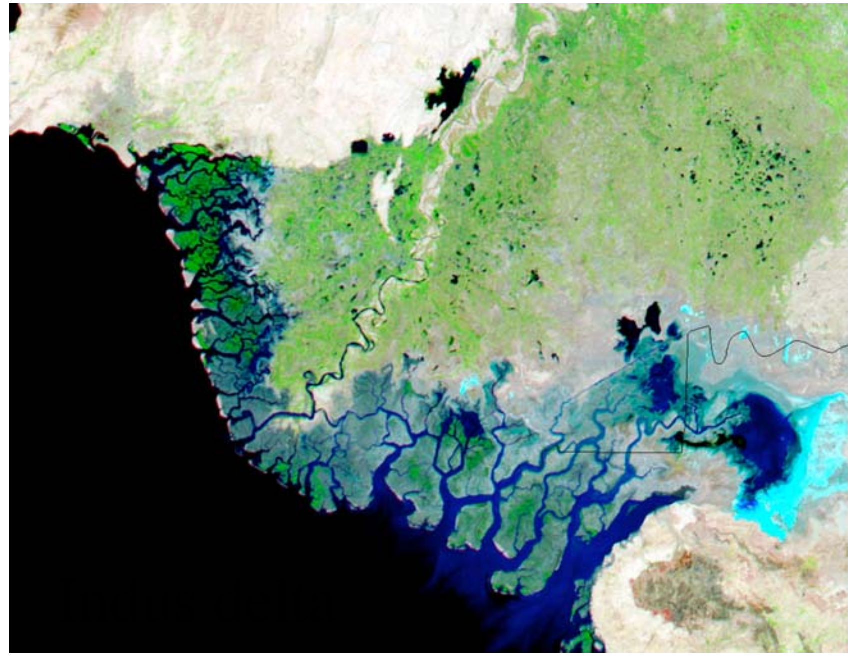


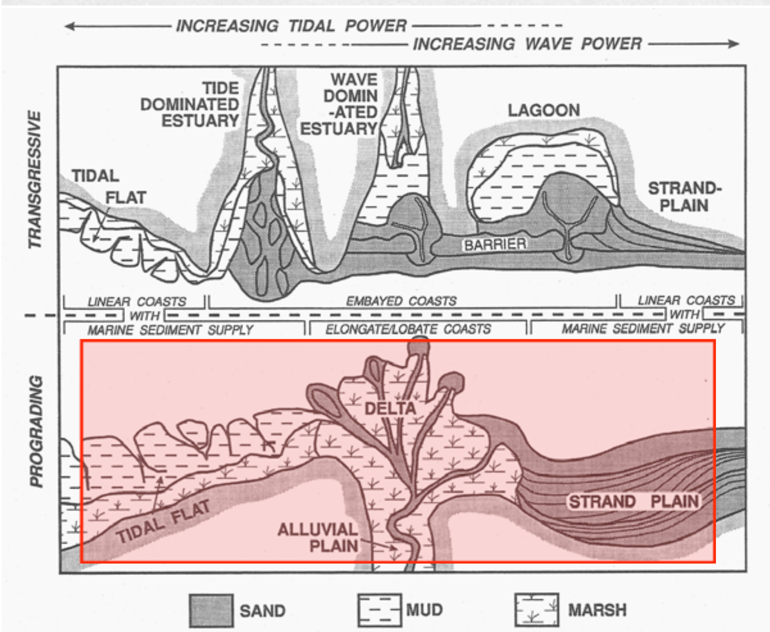


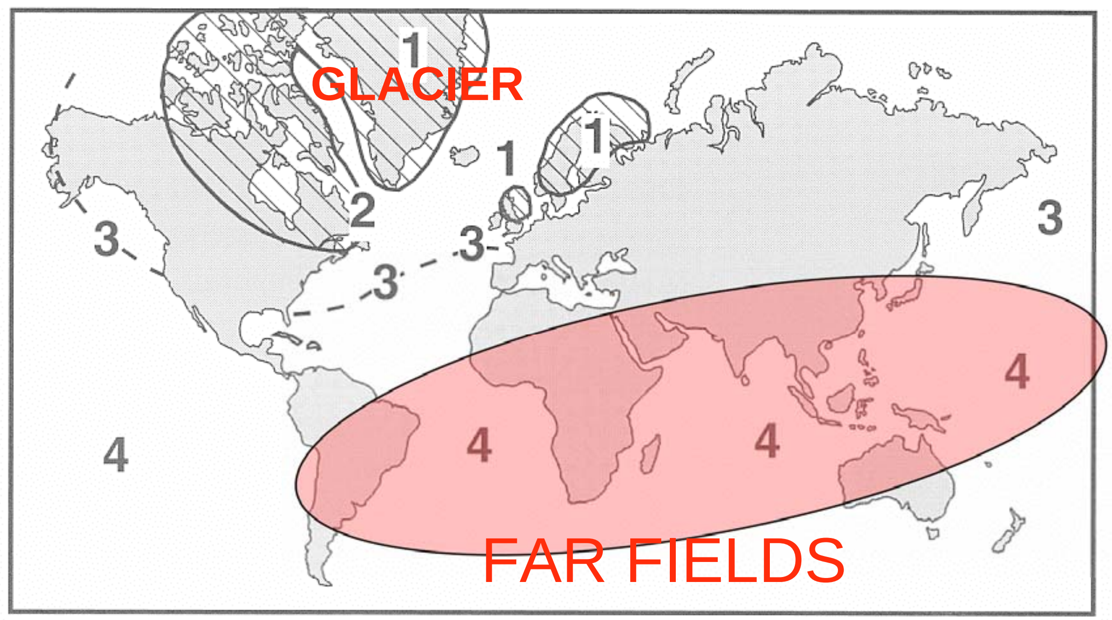
regressive depositional systems

High sea-levels at 6-7 ka









Yangtze

convex < concave

Estuary morphology

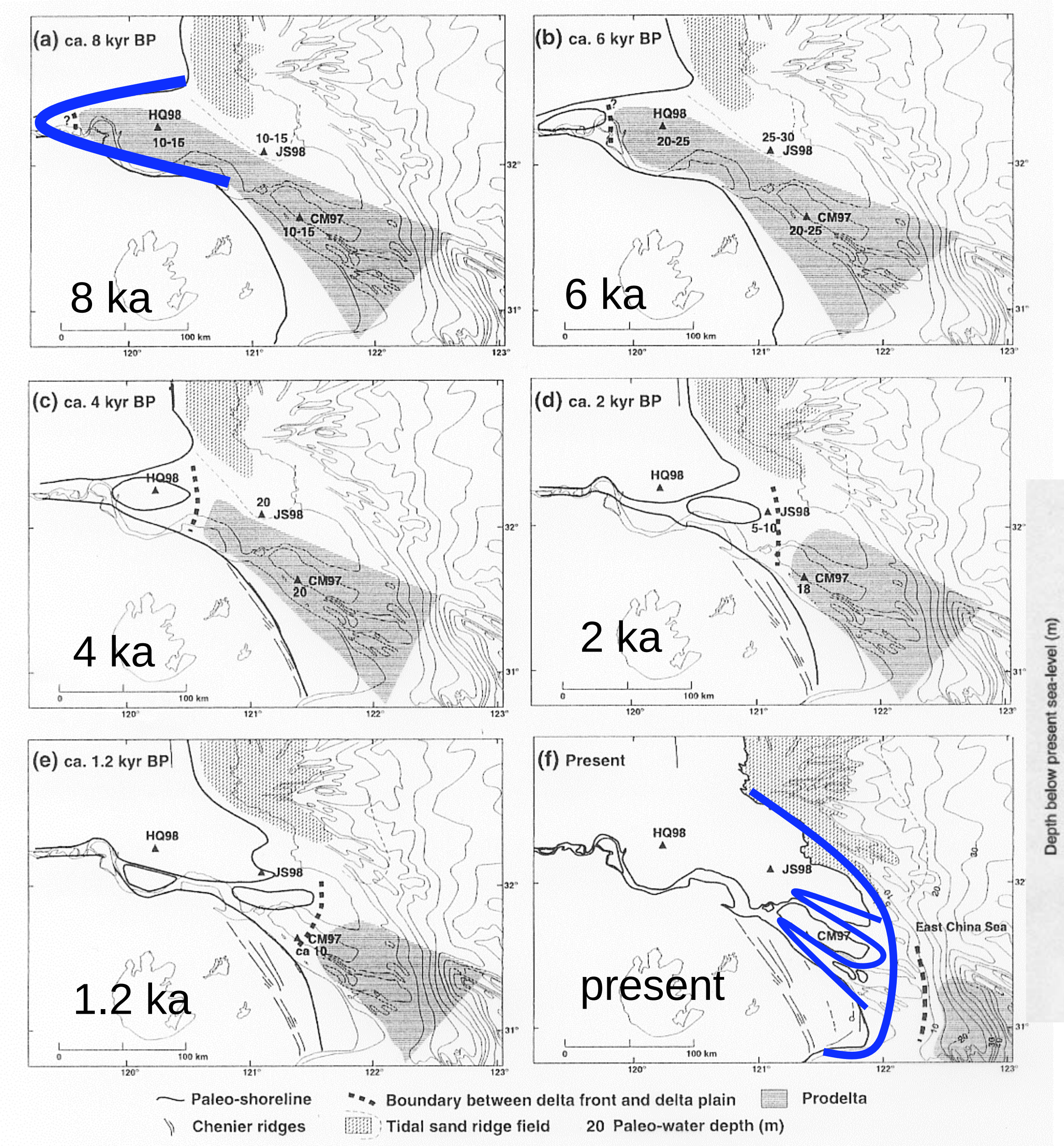
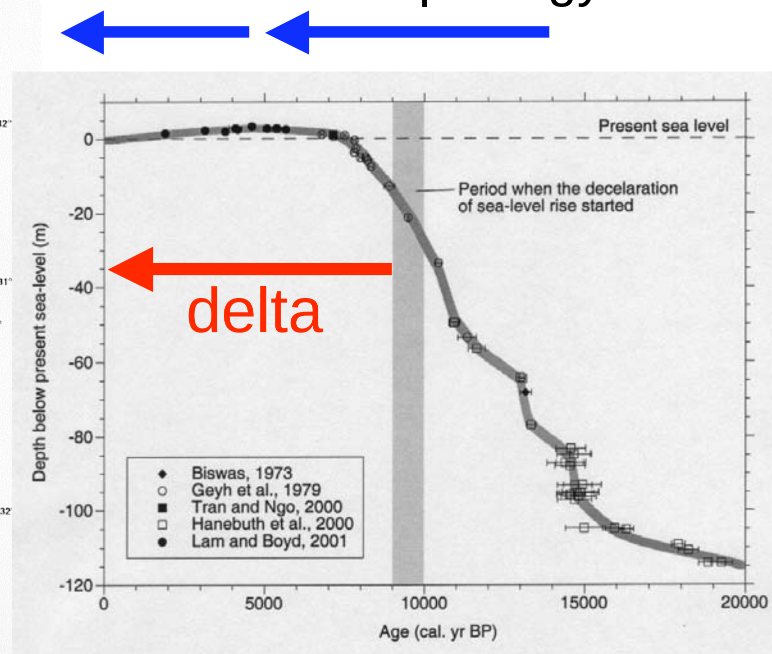


Fig. 9. Paleogeographic map illustrating the evolution of the Changjiang delta and the surrounding area. The distribution of tidal sand ridges with shaded tone shows the only shallow part, which is less than about 10 m water depth. Paleoshorelines are from Wang et al. (1981), Chen (1998). Paleo-water depth is estimated from Fig. 6.



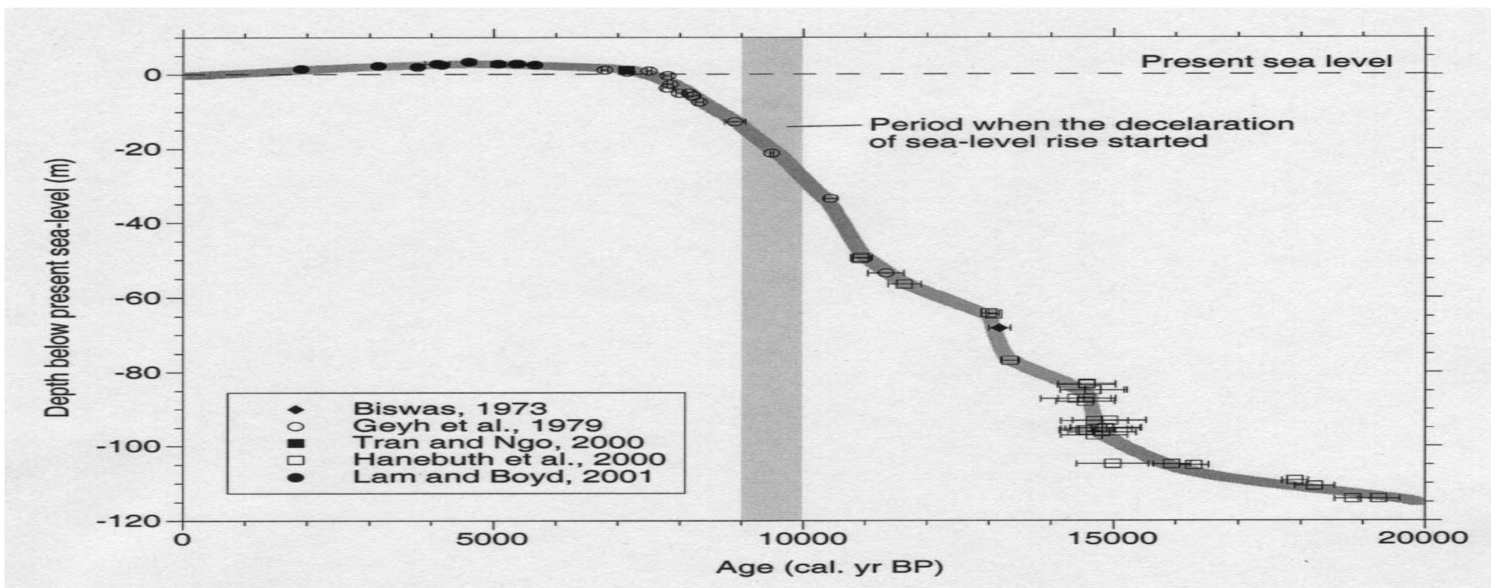
Estuary morphology

Sediment discharge
Incised valley morphology

Australian River

Yangtze

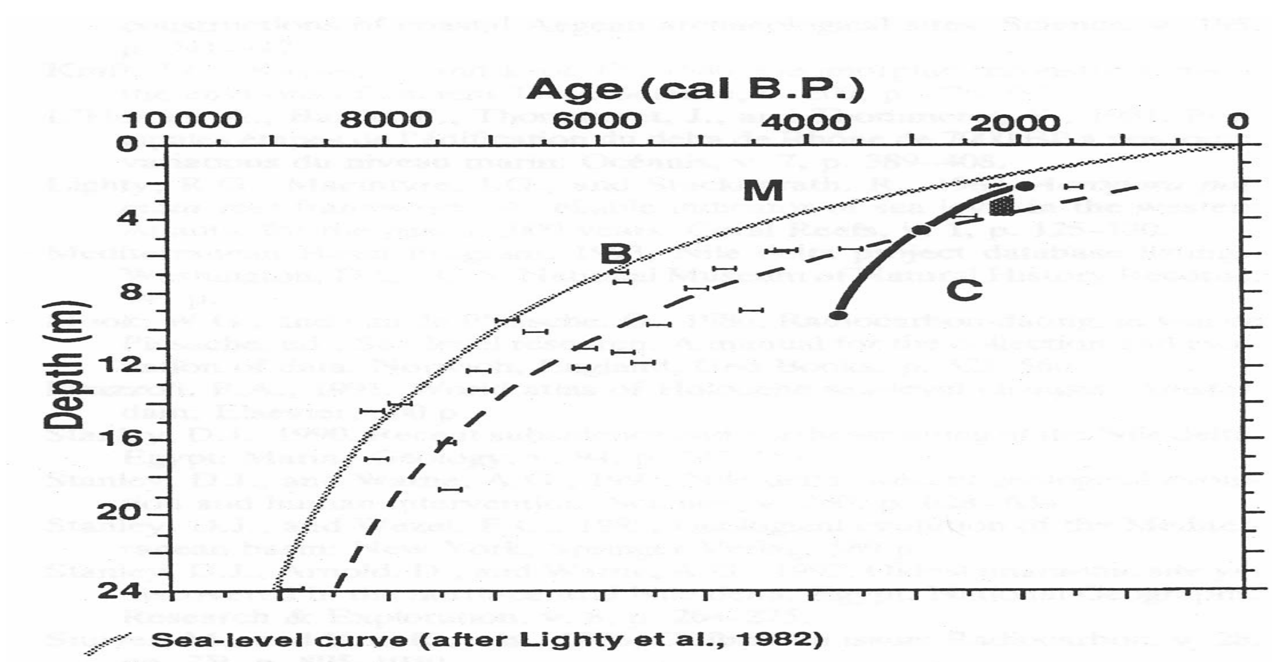
Red River



Estuary morphology

Sediment discharge
Incised valley morphology

Modern estuary
Po river
Rhine River



Millennial scale evolution

Concave estuary morphology

↓

Convex deltaic morphology

Controlling factors

Relative sea-level change

Sediment supply

Incised-valley morphology

Morphodynamics and evolution of estuaries in response to climate and anthropogenic forcing

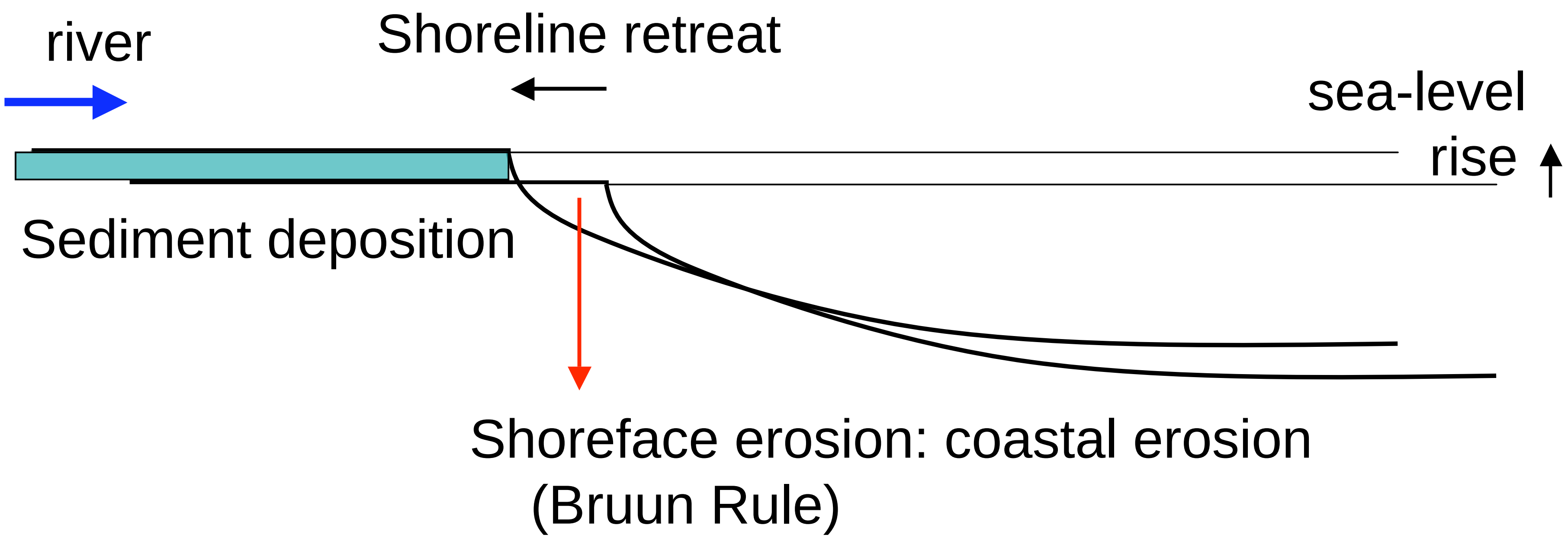
- **Millennial time scale**
  natural, sea-level change,
  (sediment discharge)

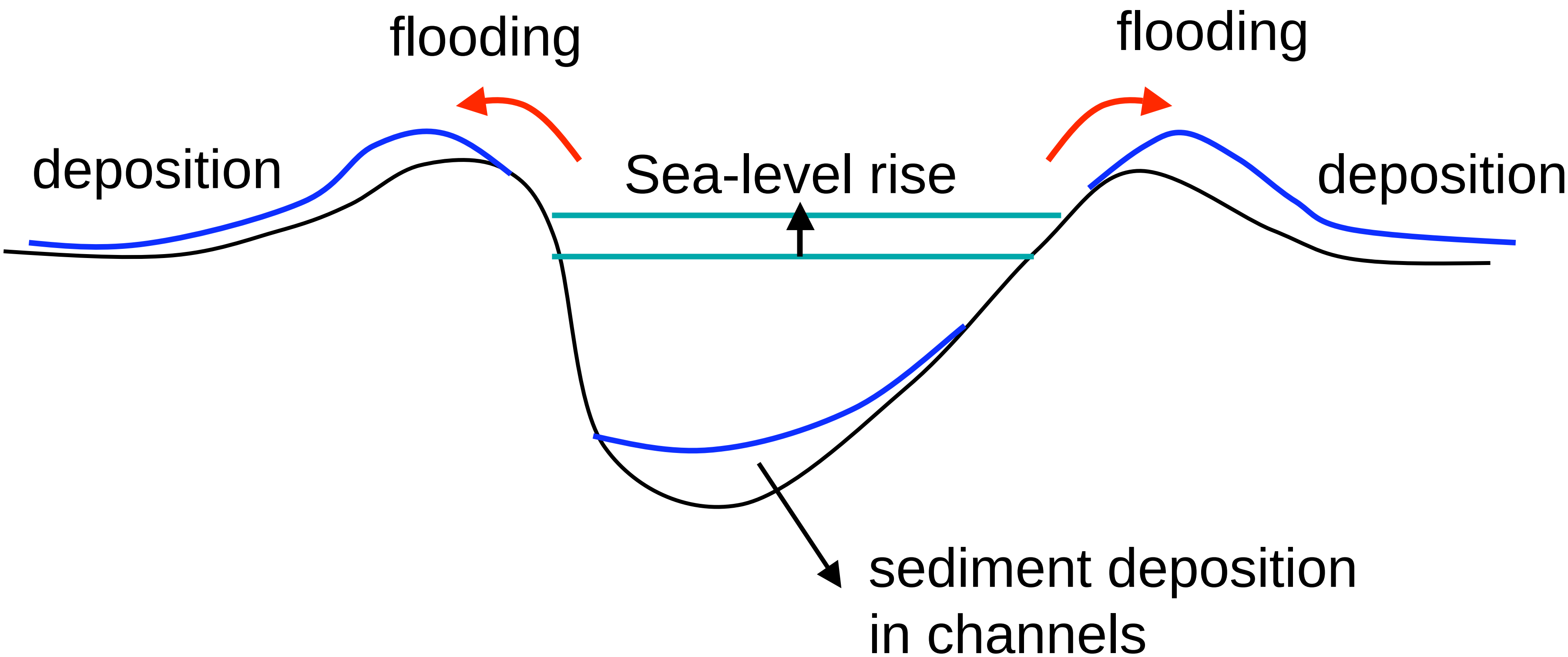
- **Decadal time scale**
  reclamation, dykes, sea-level change, sand mining,
  decrease of sediment/water discharge

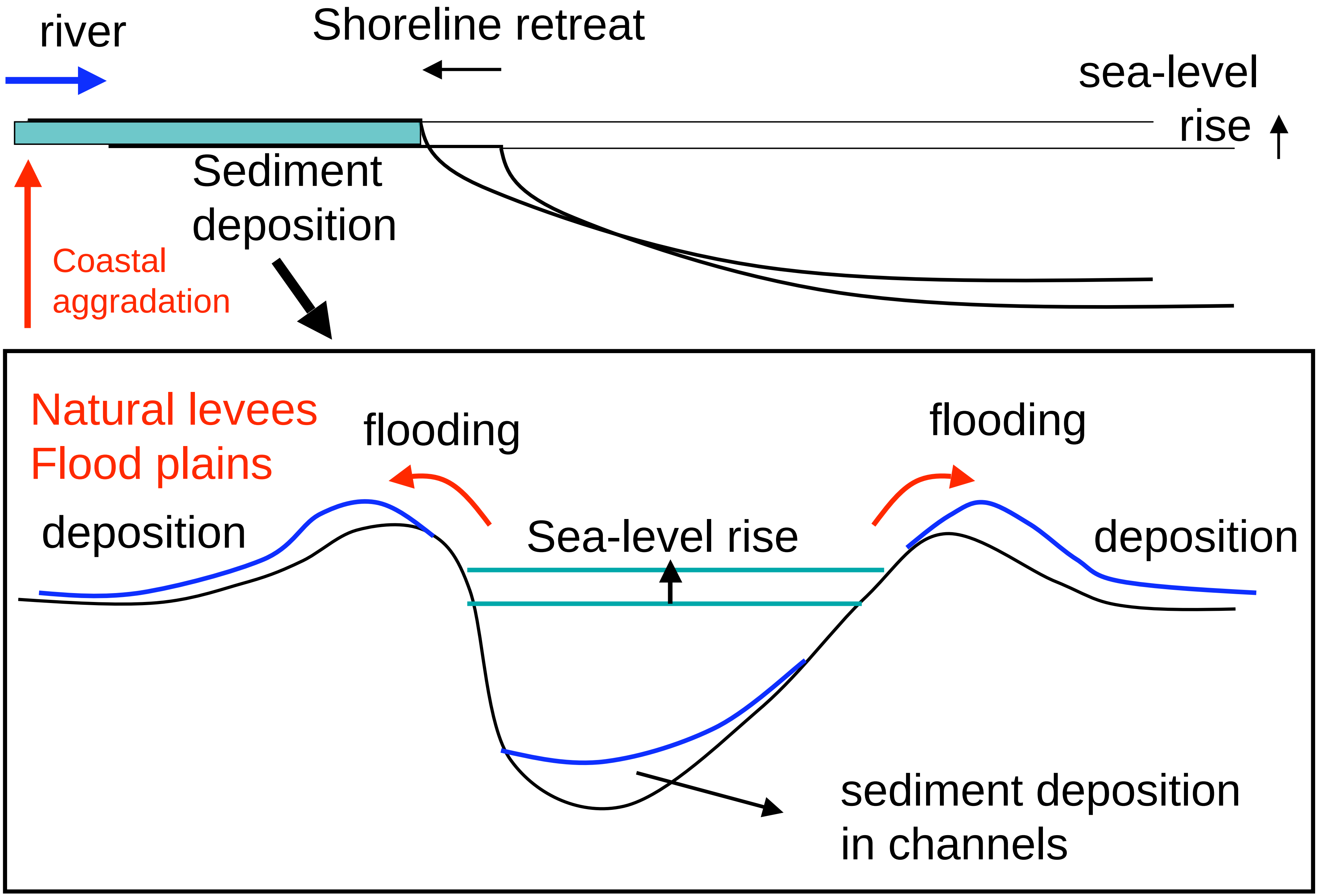
Impacts of sea-level rise on estuarine sedimentation/morphology

Sea-level rise

1) Eustasy (global warming)
2) Glacio-& hydro-isostasy
3) Tectonics
4) Subsidence (extraction of subsurface materials)


river
Shoreline retreat
sea-level
rise
Sediment deposition
Shoreface erosion: coastal erosion
(Bruun Rule)


flooding
flooding
deposition
Sea-level rise
deposition
sediment deposition
in channels



river
Shoreline retreat
sea-level
rise
Sediment
deposition
Coastal
aggradation
Natural levees
Flood plains
flooding
flooding
deposition
Sea-level rise
deposition
sediment deposition
in channels

examples

1) Po river delta (Syvitski et al. 2005)

Riverine sediments trapped in channels

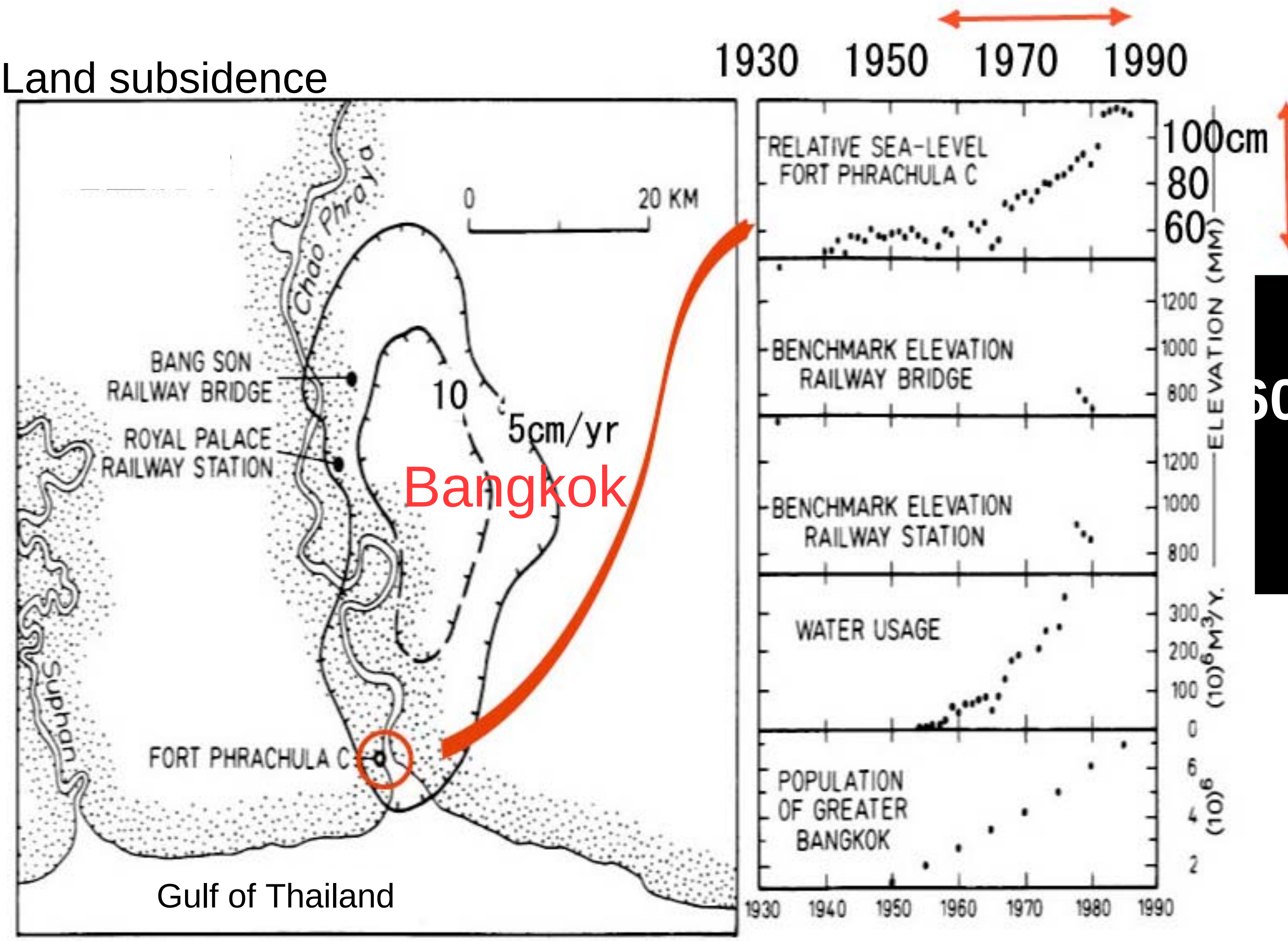
2) Chao Phraya (Saito et al, 2007)

rapid sediment accumulation in the intertidal zone related to 1m relative sea-level rise due to ground water pumping

3) Ganges Brahmaputra system (Goodbred)

30 % deposition on coastal plains/ sea-level rise on millennial scale

Land subsidence



0 cm rise in SL
1960-1990

Land subsidence
During 1992-2000

>20 cm/ 8 years

More than 1m
Sea-level rise
For the last 50 y

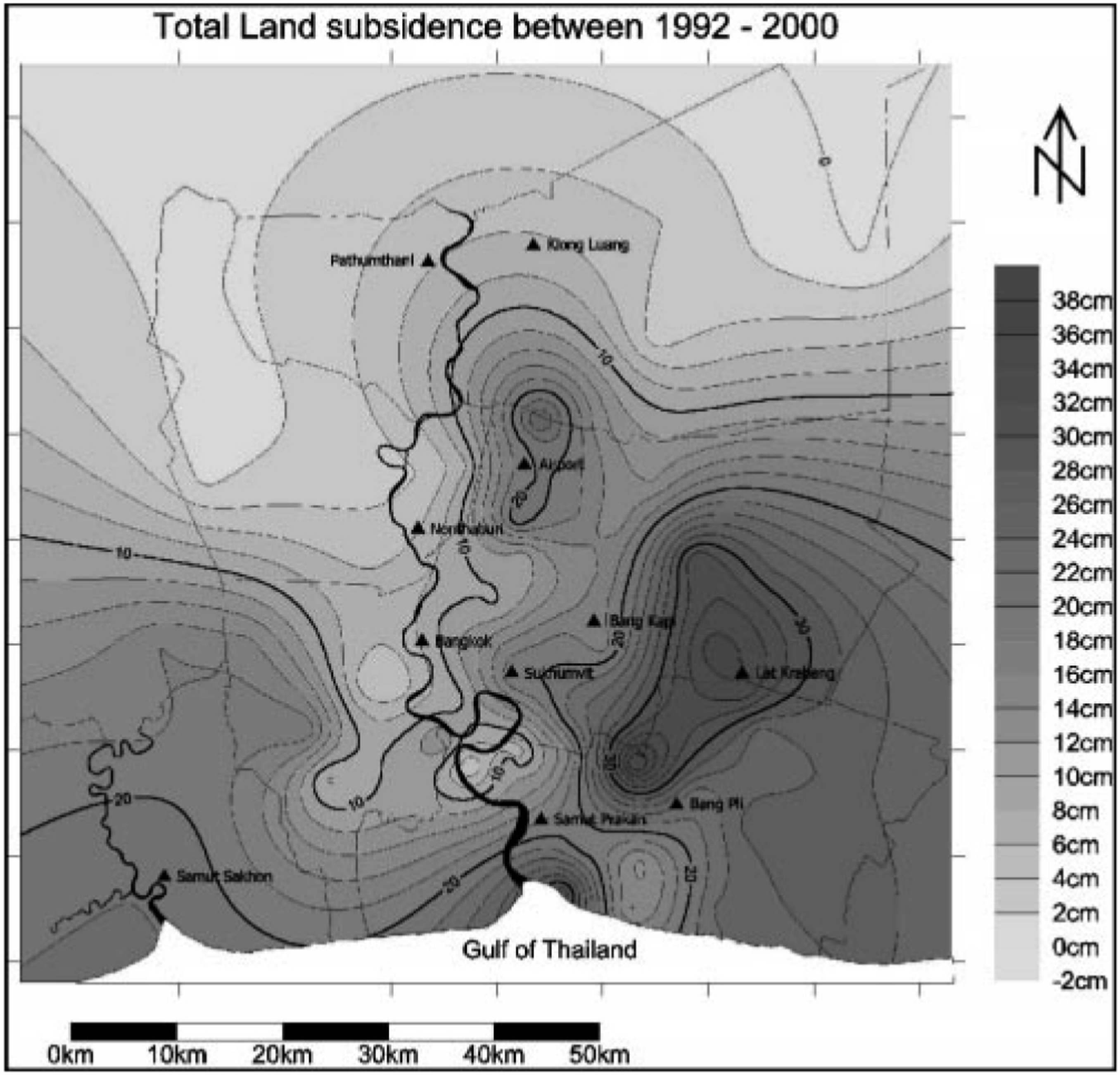
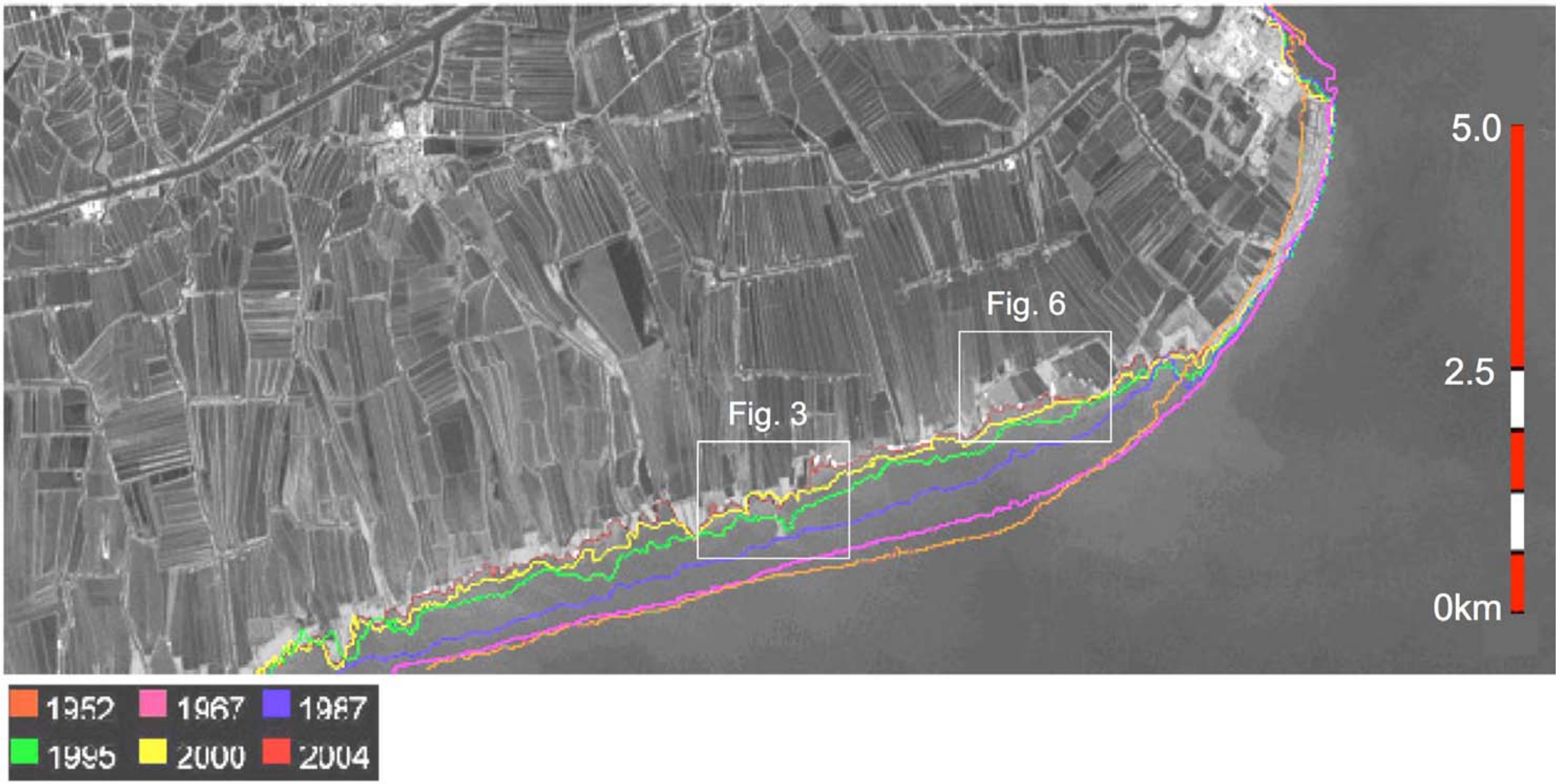


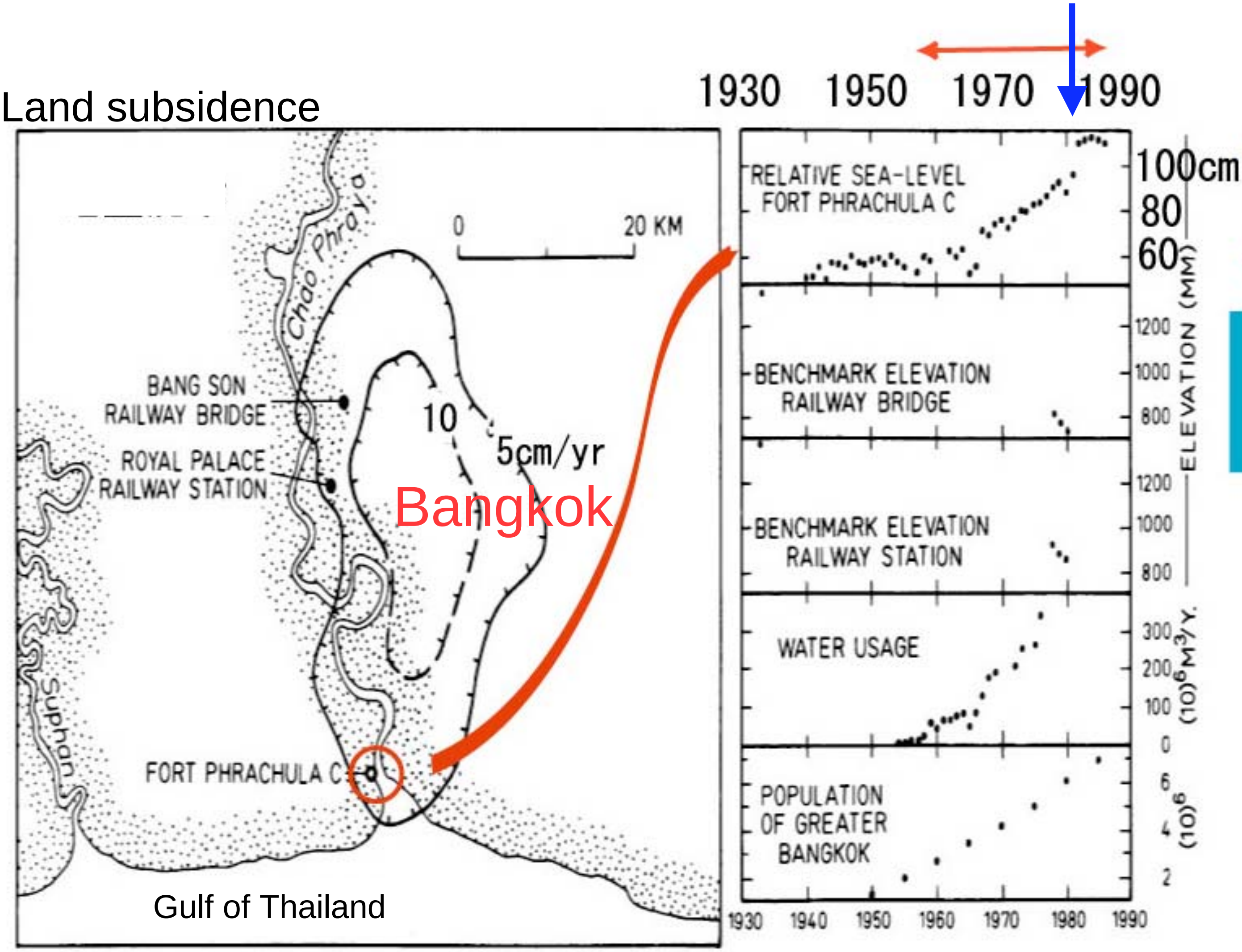
Figure 4. Measured land subsidence in the period 1992–2000.

1 km shoreline retreat at the river mouth of the Chao Phraya



During 1969–1976, accretion: 8.9 km^2, erosion: 4.5 km^2 net accretion rate: 0.62 km^2/y;
During 1976–1987, accretion 4.9 km^2, erosion 10.3 km^2, net accretion rate: –0.49 km^2/y
During 1987–1997, accretion 7.4 km^2 , erosion 4.5 km^2, net accretion rate 0.25 km^2/y

Land subsidence



約30年間に
60cmの海面上昇

examples

1) Po river delta (Syvitski et al. 2005)

Riverine sediments trapped in channels

2) Chao Phraya (Saito et al, 2007)

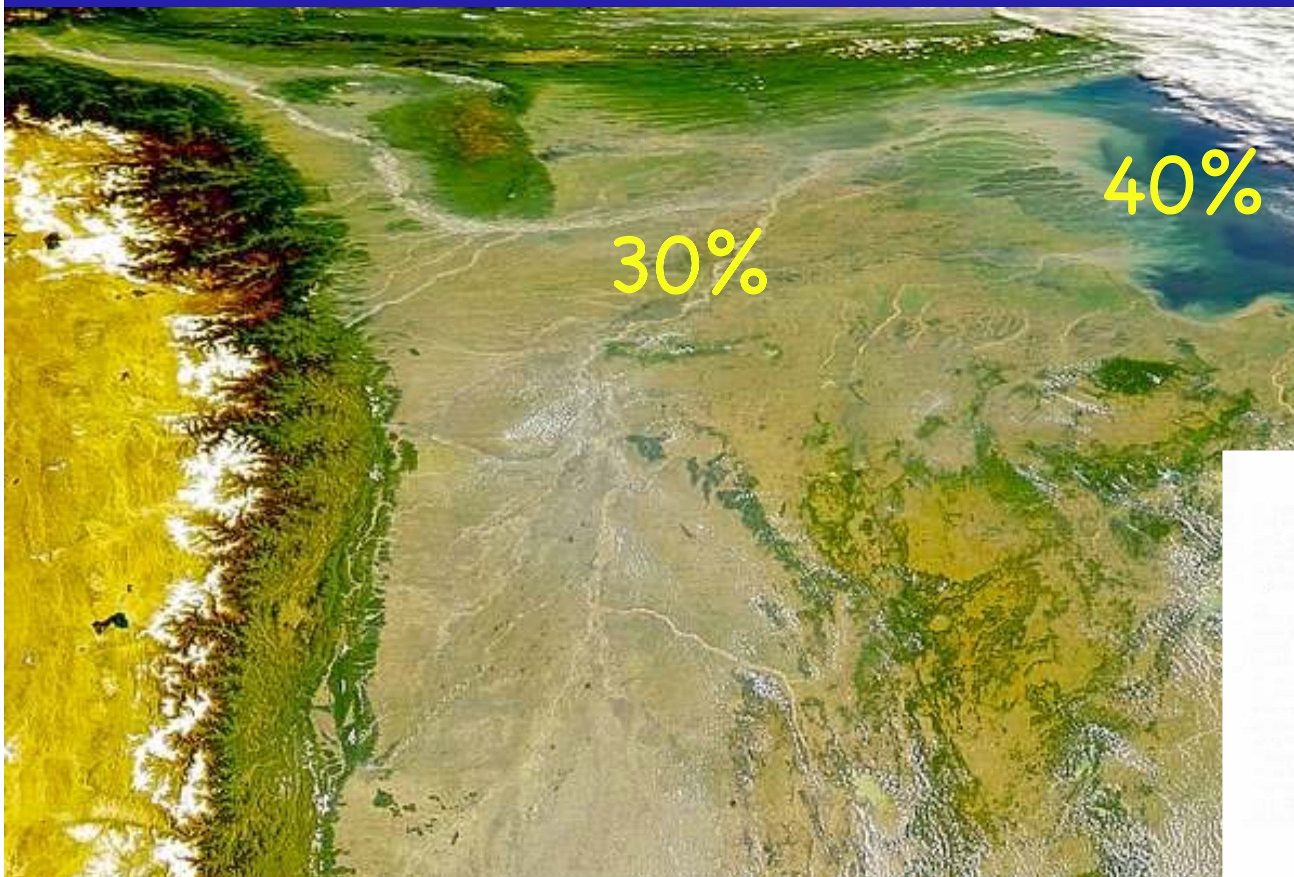
rapid sediment accumulation in the intertidal zone related to 1m relative sea-level rise due to ground water pumping

3) Ganges Brahmaputra system (Goodbred)

30 % deposition on coastal plains/ sea-level rise on millennial scale

sediment partitioning of Ganges-Brahmaputra delta

Delta plain | subaqueous delta | deep-sea fan



30%

Sea-level curve

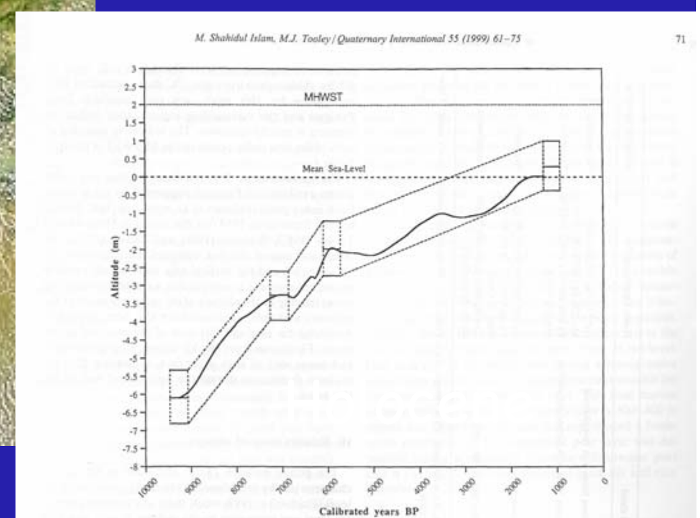


Fig. 5. A sea-level curve from Panigati based on the age and altitude of 4 radiocarbon dated samples, for which error margins are given. Within the sea-level band, variations of the curve are derived from a consideration of changes in the bio- and lithostratigraphy.

TECTONIC SUBSIDENCE

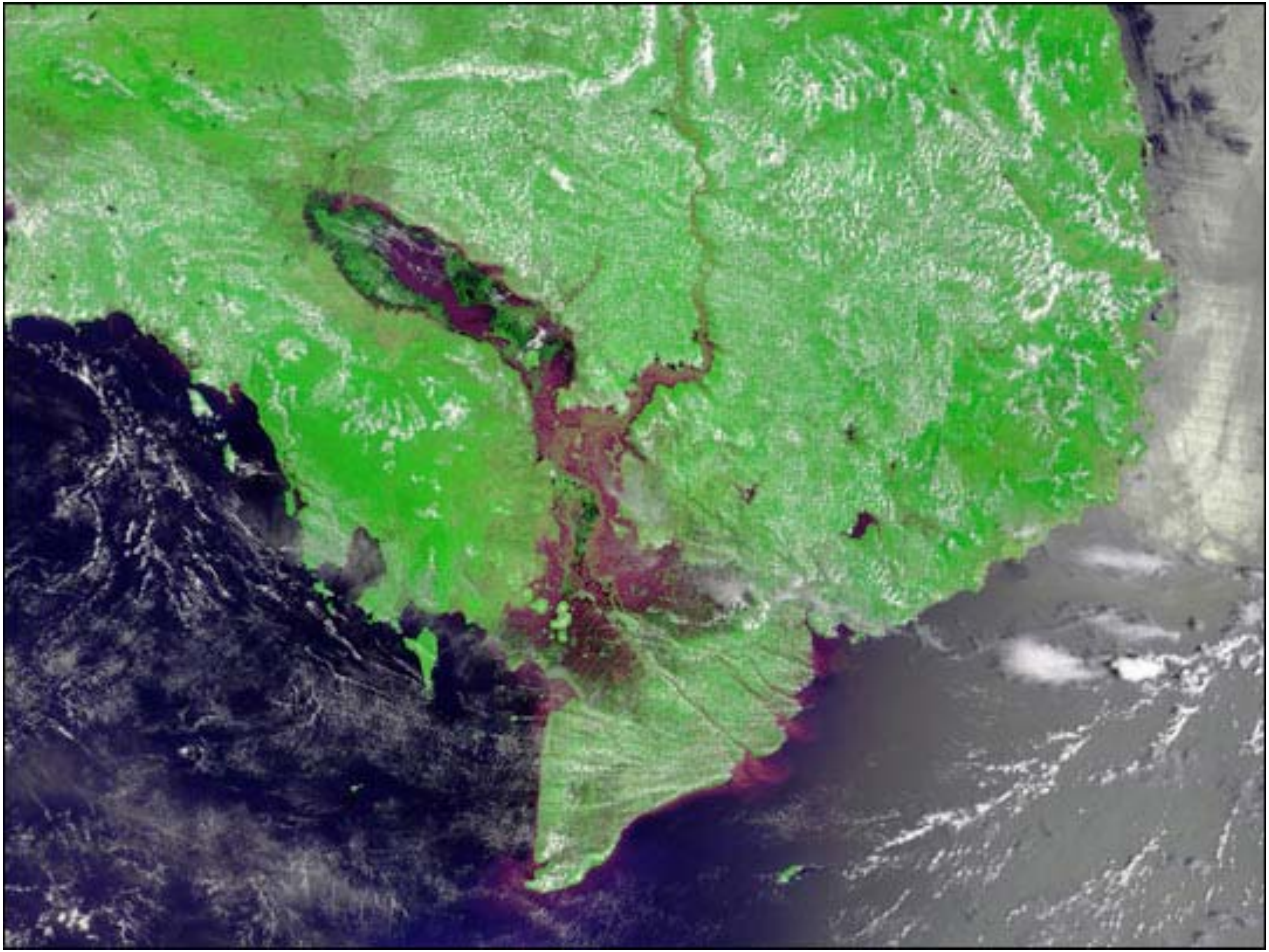
Rising sea level during the Holocene

Islam & Tooley, 1999

coastal/flood plain sedimentation related to extreme flood events

1998 Yangtze flood: half of sediments are deposited on the flood plain

Thick floodplain sediments (~7 m for 5 ky) in the Mekong



Impacts of reclamation on estuarine sedimentation/morphology

Reduction of estuary area

↓

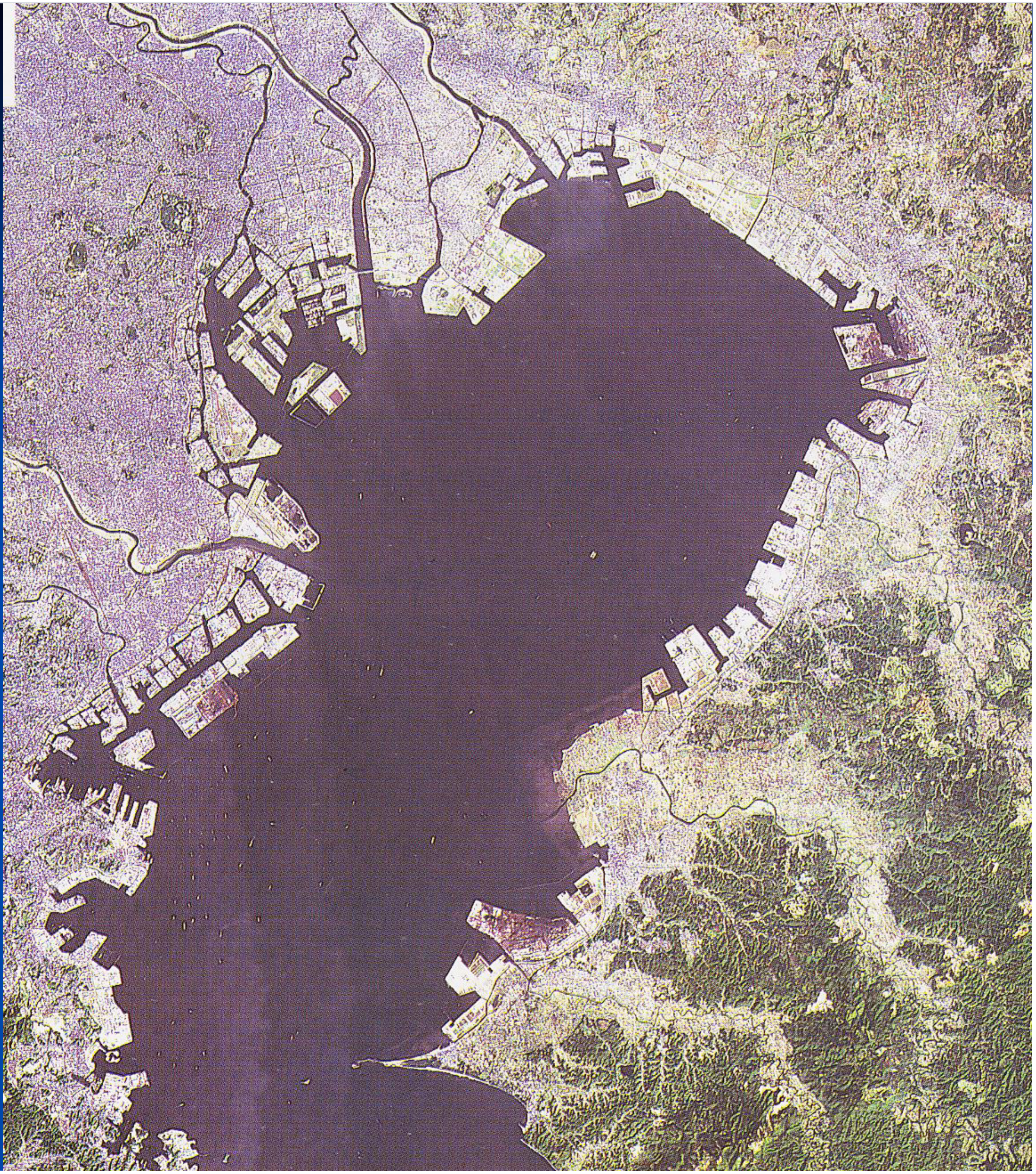
Decrease of tidal amplitude

tidal prism

↓

Sedimentation

Tokyo Bay



Tokyo Bay

1960年代の半ばごろまで，東京湾の湾奥のあちらこちらで潮干狩りがおこなわれていた。しかし1960年代の高度経済成長によって，図にしめされるように東京湾岸の埋め立てが急激に進行し，潮干狩りのできる場所は東京湾の奥からほとんど姿をけした。埋め立て地は，かつては工業用地としての利用が多かったが，現在では多様な目的に利用されるようになってきている

Yanagi and Ohnishi, 1999

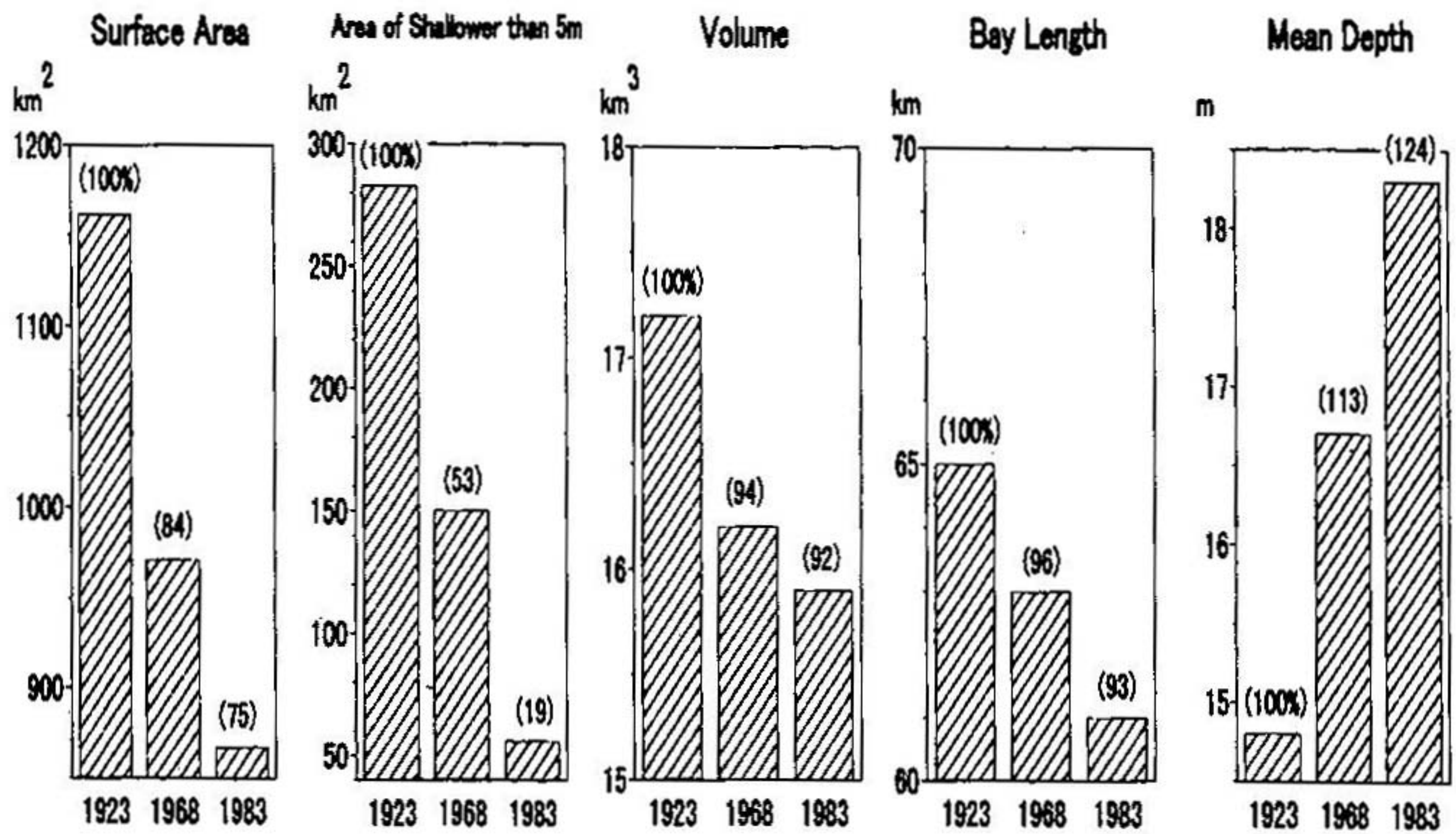


Fig. 2. Changes of sea surface area, area with depths shallower than 5 m, volume, bay length, and mean depth of Tokyo Bay from 1923 to 1983.

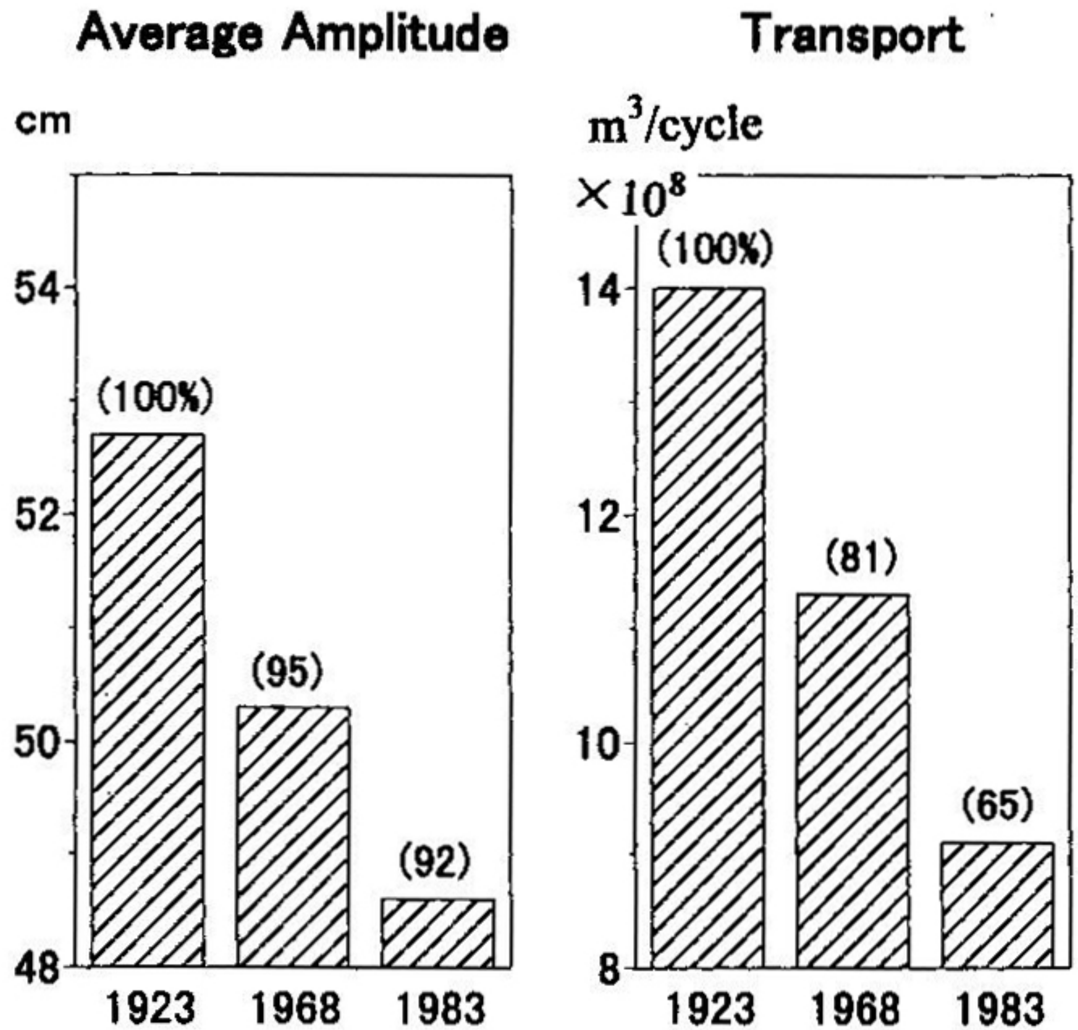


Fig. 5. Changes of average amplitude of M_2 tide and water exchange volume by M_2 tidal current across the bay mouth in Tokyo Bay from 1923 to 1983.

Yanagi & Ohnishi, 1999

)

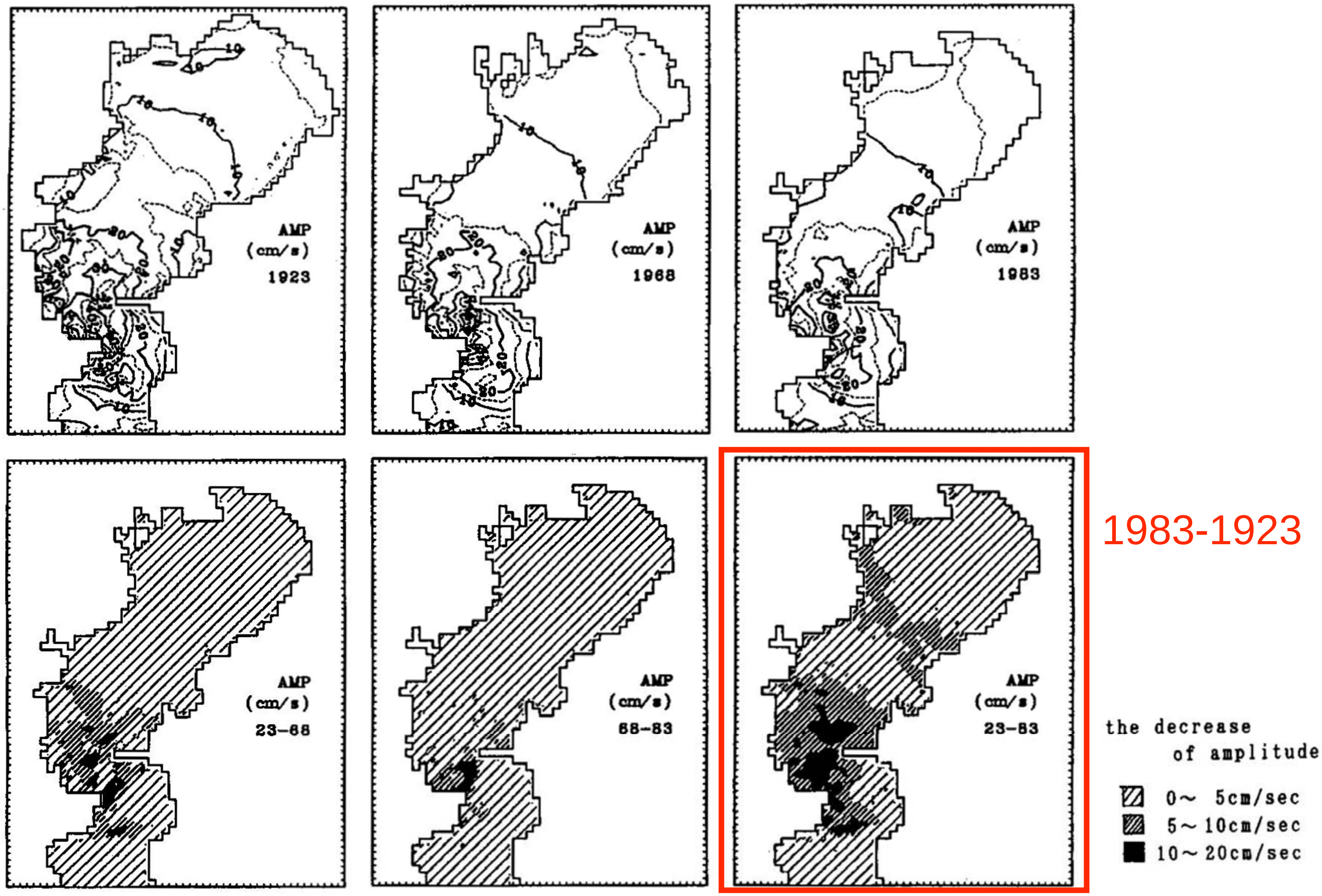


Fig. 6. M_2 tidal current amplitude in Tokyo Bay in 1923, 1968, and 1983 (upper) and the difference of M_2 tidal current amplitude between 1923 and 1968 (lower left), 1968 and 1983 (lower center), and 1923 and 1983 (lower right).

Bottom sediment of Tokyo Bay

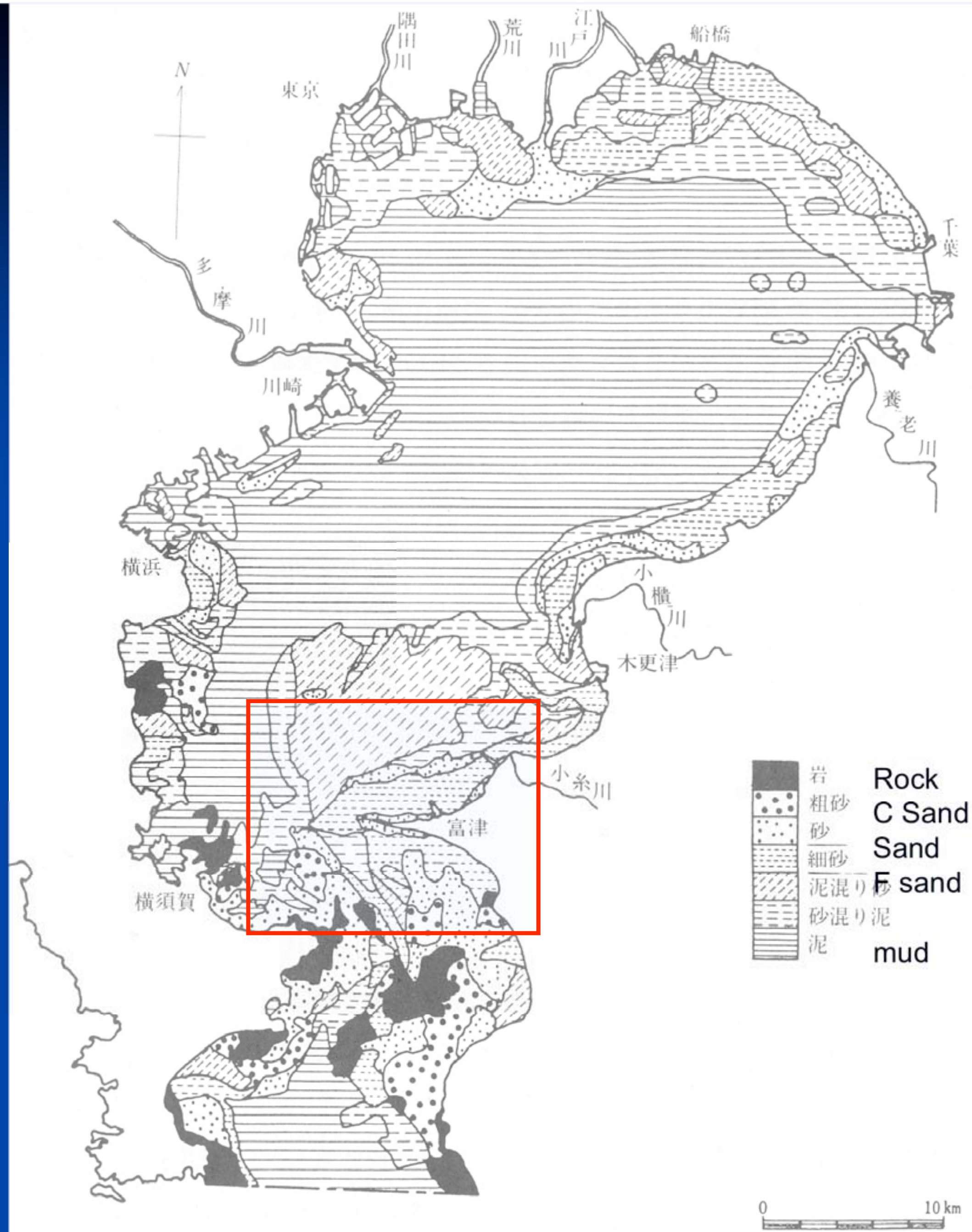
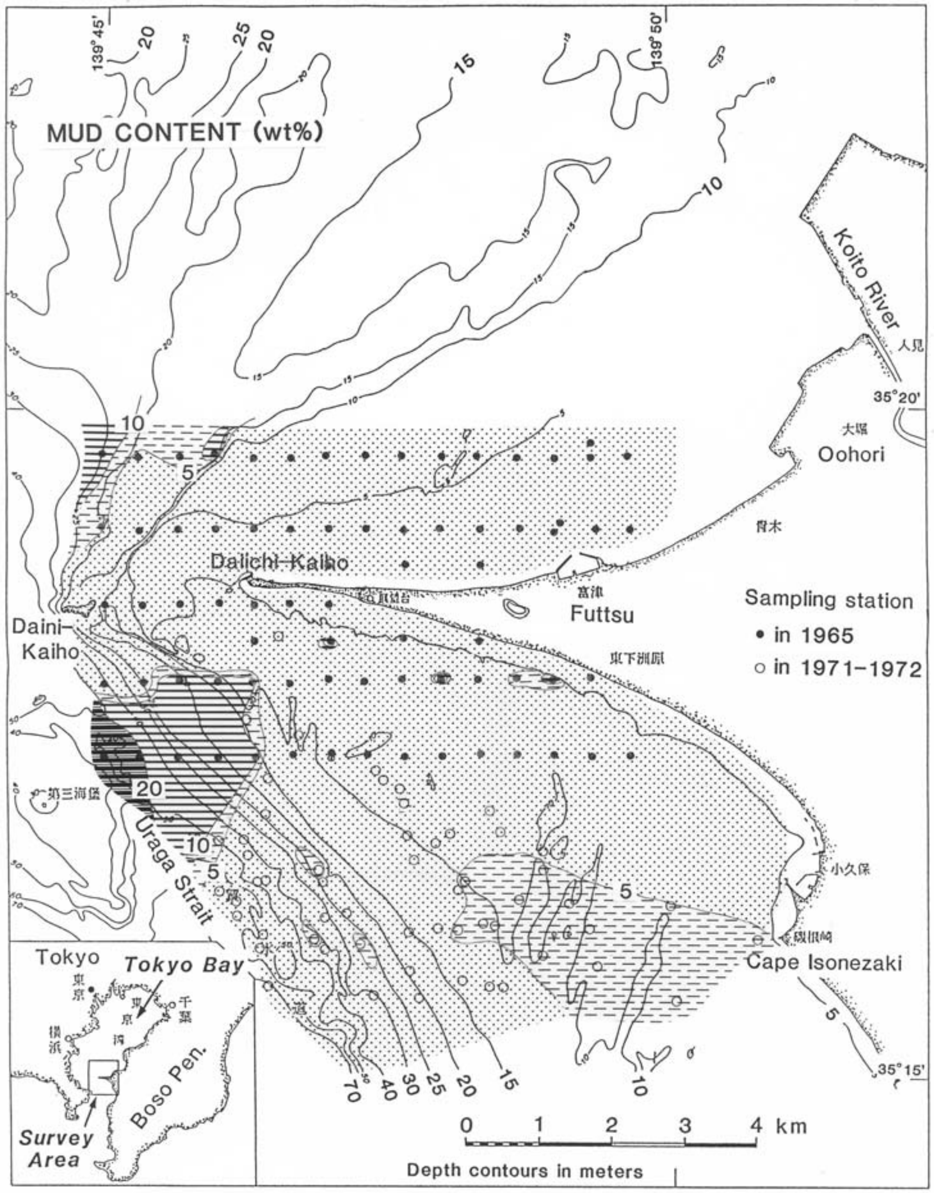


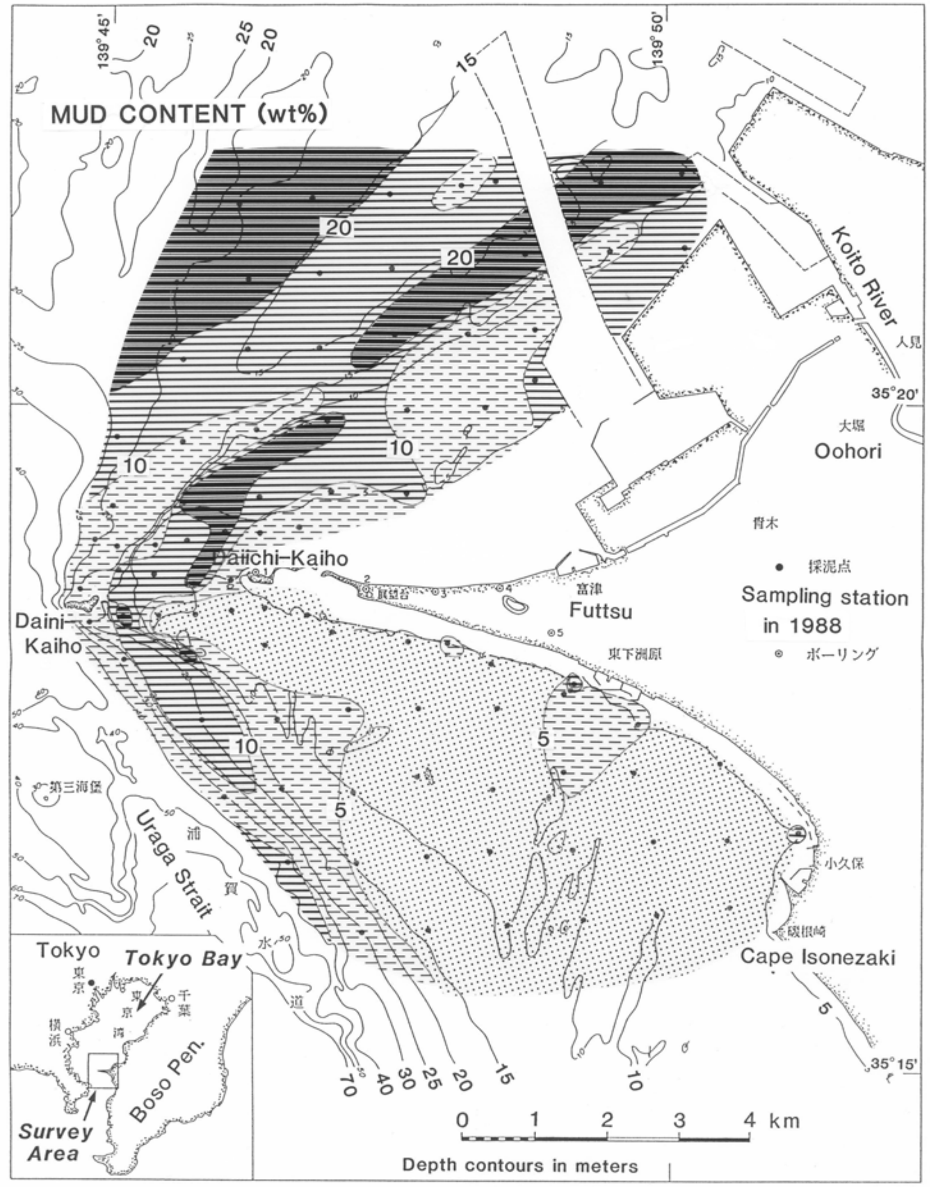
図 1-2　東京湾の底質
原図は 5 万分の 1 東京湾底質図（3 葉，首都圏整備委員会事務局，1959～61 年刊）

Mud content of bottom sediments

1970

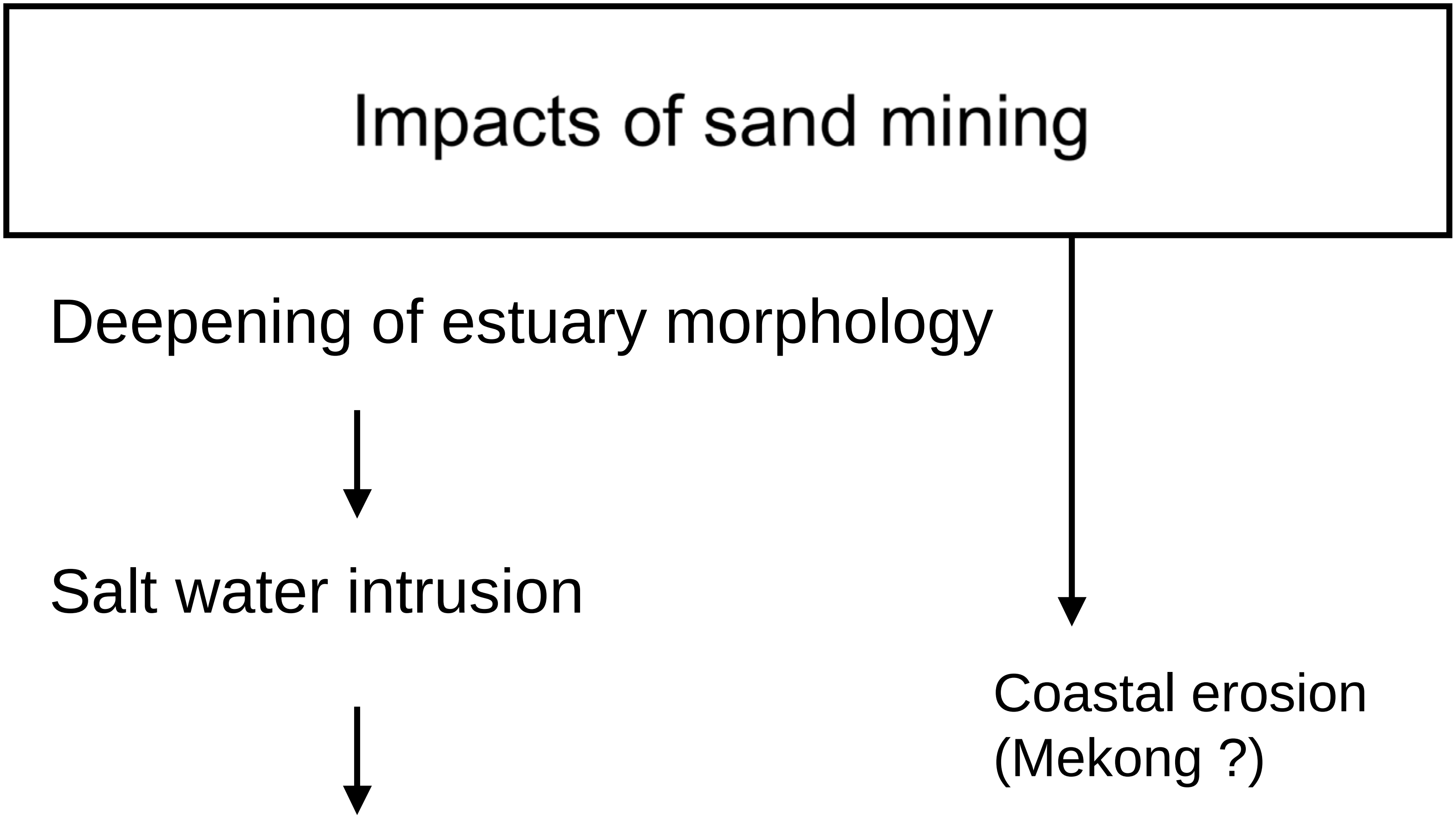


1988



Tidal amplitude decrease (tidal gauge data)

- Tokyo Bay
- Nagoya Bay
- Osaka Bay
- Ariake Bay


Impacts of sand mining
Deepening of estuary morphology
Salt water intrusion
Turbidity maximum change?
Coastal erosion
(Mekong ?)

Pearl River (Zhujiang) example

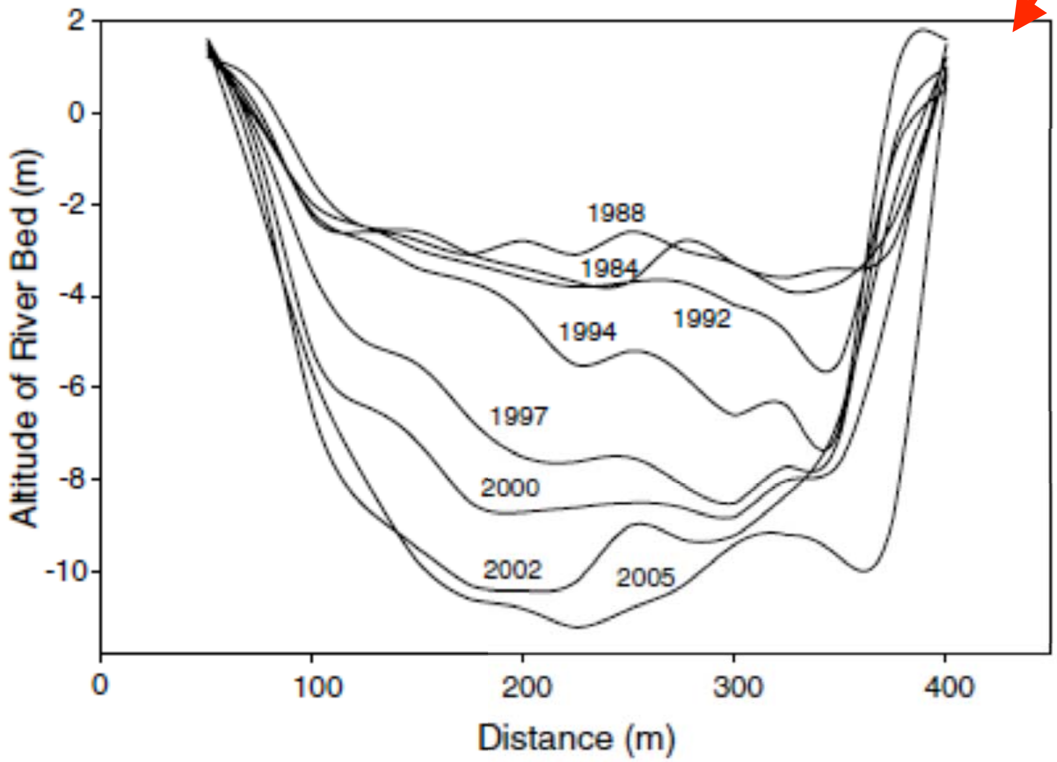
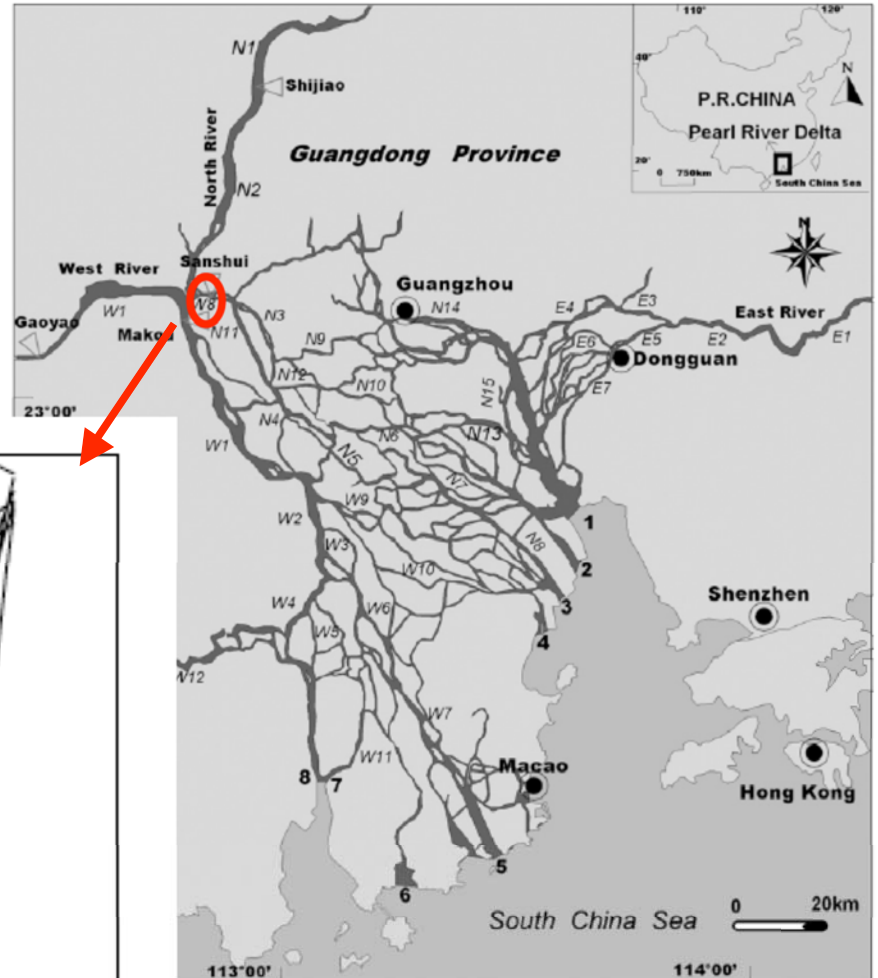


Figure 4 Temporal changes of the cross section at the Sanshui station (Fig. 1). The data in the figure were provided by the Sanshui Hydrologic State.



and its river network. N1—N15, W1—W12, and E1—E7 are the cha
, and East River network, respectively; Numbers 1—8 indicate the e
South China Sea, include Humen, Jiaomen, Hongqimen, Hengme
to west. The triangle symbols represent the locations of the hydro

>8.7x108 m3 sand/22 years
>4 x 107 m3 sand/year
8 x 107 t/y (ss): 1 x 107 m3 sand

Luo et a

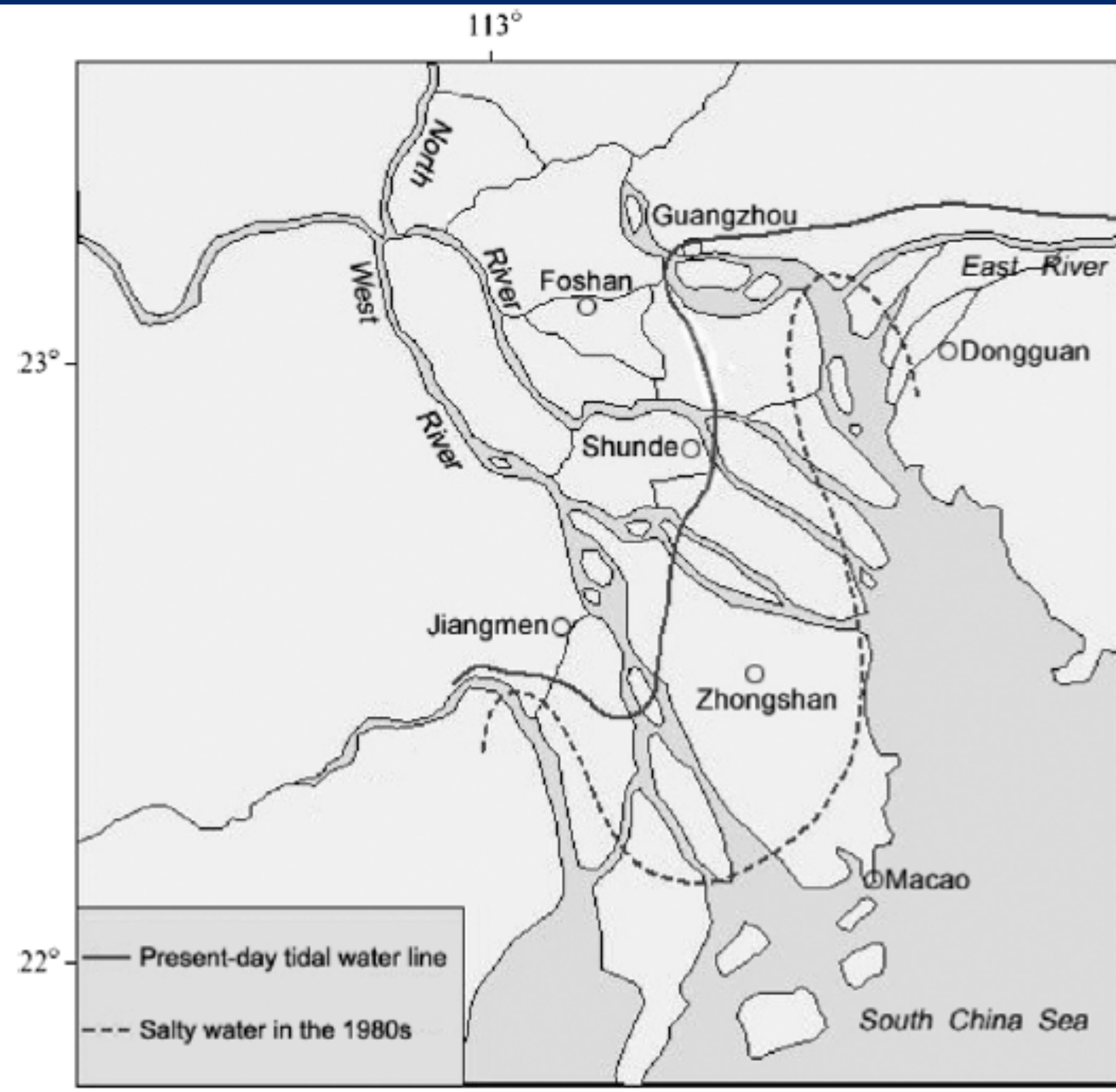
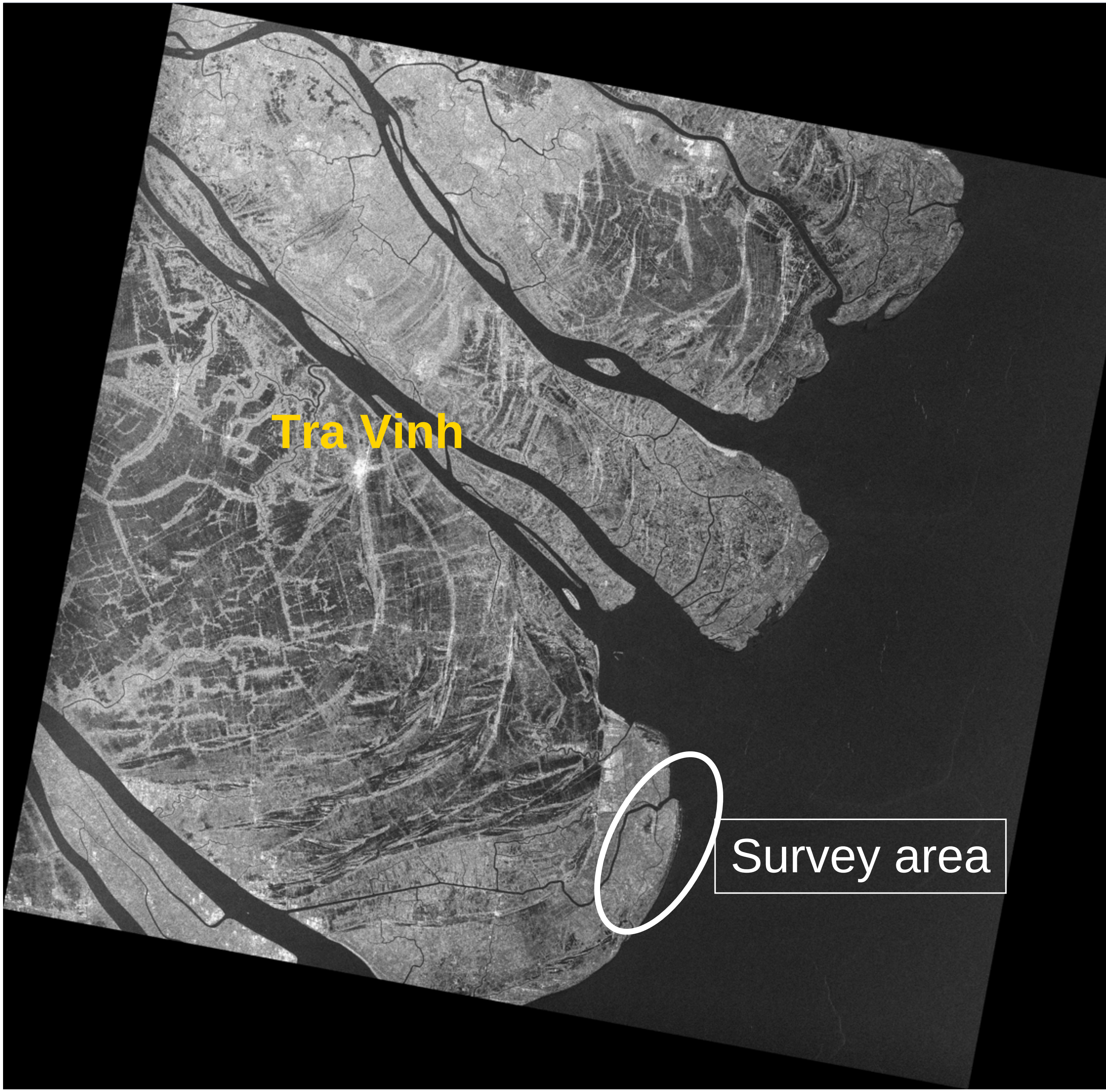
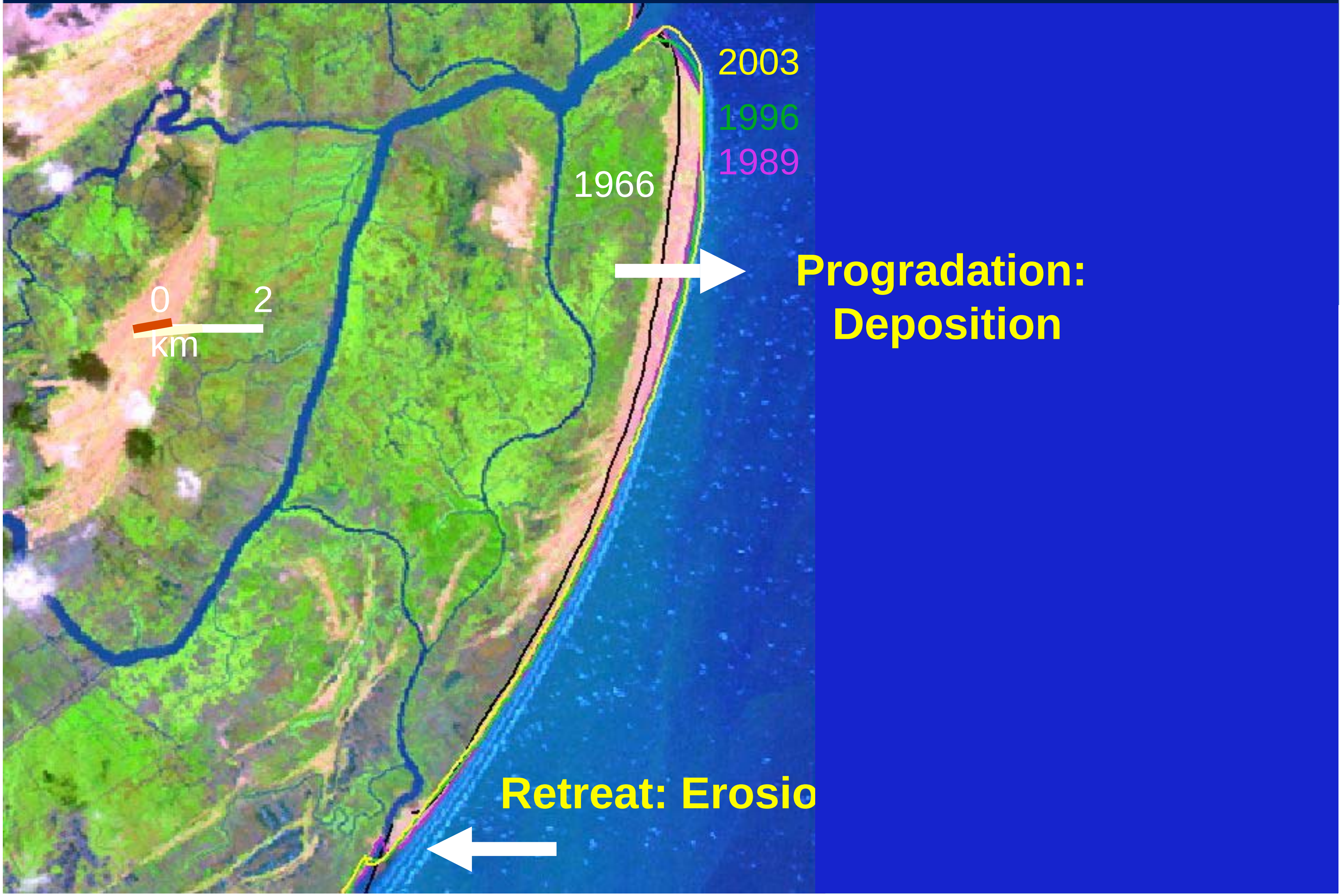


Figure 7 Brackish-water intrusion ranges in the 1980s and the present days within the Pearl River Delta.


Tra Vinh
Survey area

Shoreline changes in Tra Vinh area



Impacts of decrease in sediment/water discharge on estuarine sedimentation/morphology

Sediment decrease
- sediment distribution
- accumulation rate
- coastal erosion

Water decrease
- more marine influence
- tidal pumping effect

Seasonal change

Morphodynamics and evolution of estuaries in response to climate and anthropogenic forcing

- **Millennial time scale**

  natural, sea-level change,

  (sediment discharge)
- **Decadal time scale**

  reclamation, dykes, sea-level change, sand mining, decrease of sediment/water discharge

Rate of sea-level changes: natural ~5cm/y   anthropogenic ~10 cm/y

Sediment discharge: 10-folded increase and 1/10-folded decrease

Reclamation: 10 to 100-folded faster than natural progradation

Sand mining: several times larger than natural sand supply

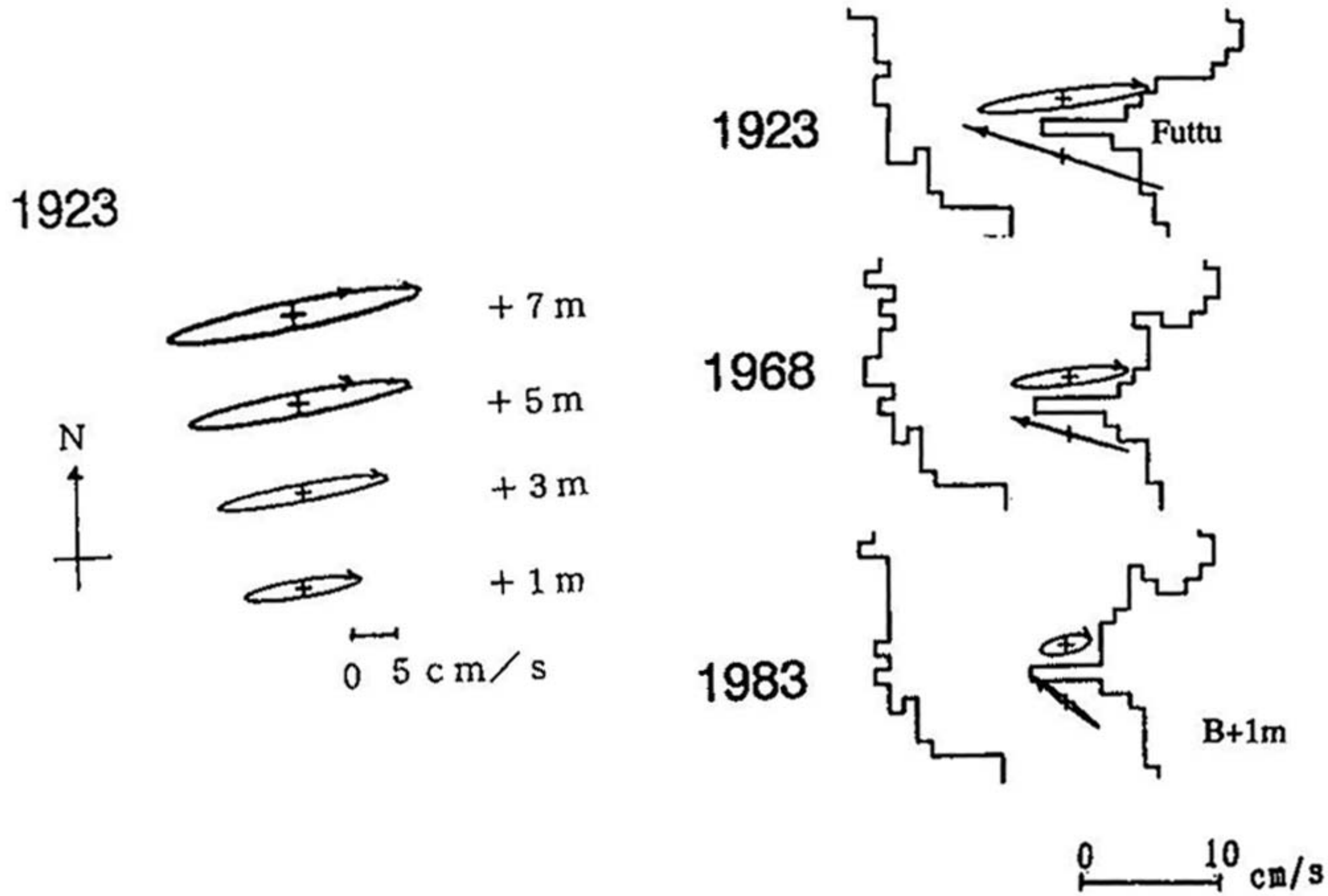


Fig. 7. Vertical distribution of M_2 tidal current ellipses at the station with the depth of 8 m north of Futtu point (left). M_2 tidal current ellipses 1 m above the sea bottom near Futtu point in Tokyo Bay in 1923, 1968, and 1983 (right).