Geologic Setting of the Sacramento-San Joaquin Delta

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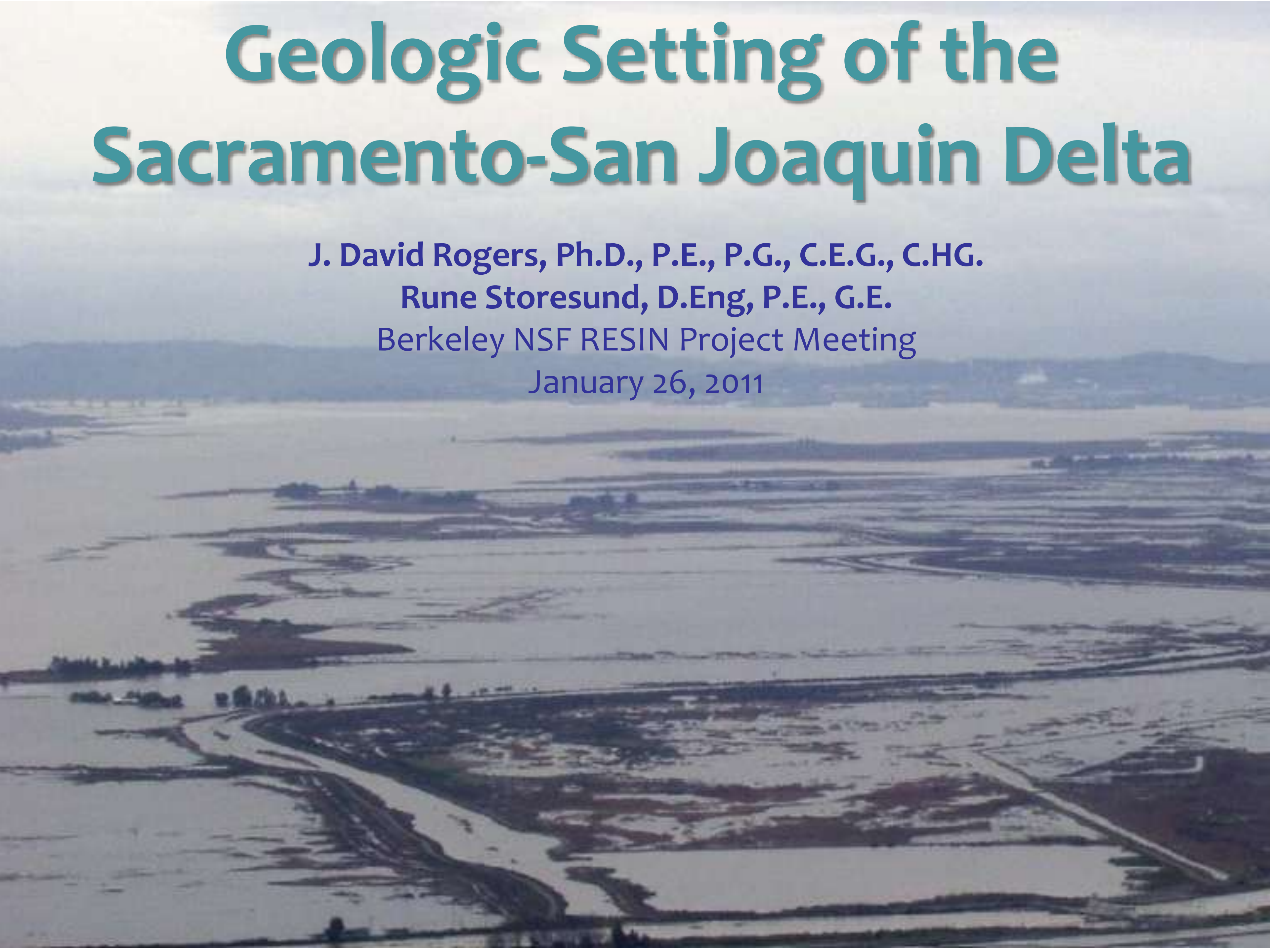


The Sacramento-San Joaquin Delta is geologically unique

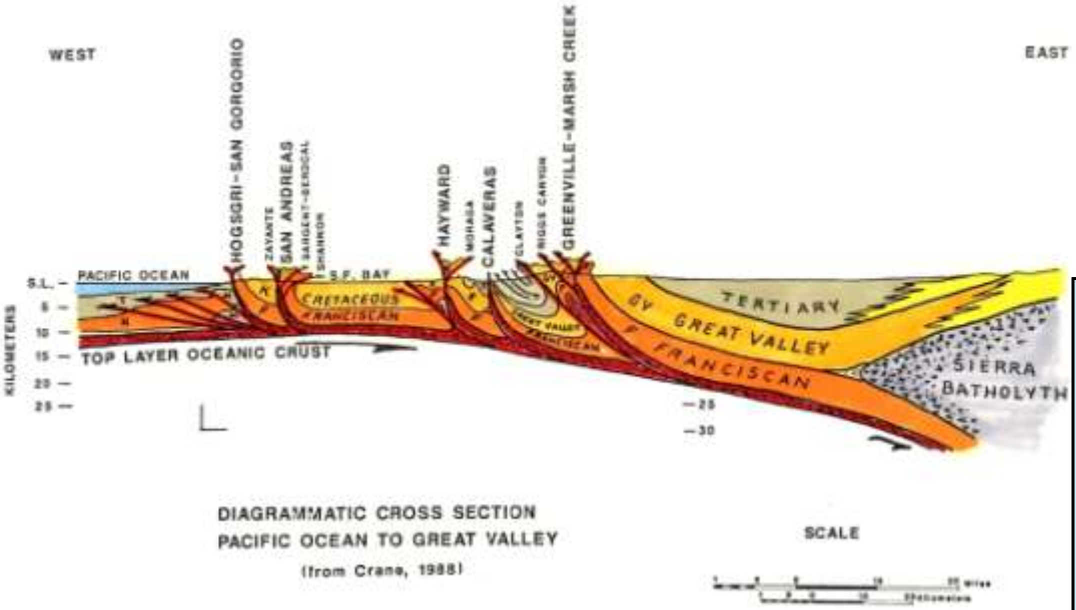
1. The depositional basin has been accumulating sediment since Cretaceous time, about **100 Ma**
2. It is one of just two tectonically-controlled ***inverse deltas*** in the world; it has grown throughout Holocene time by ***upstream migration***
3. The basin's outlet is tectonically controlled, so, absent anthroprogenic impacts, sediments are settling via ***normal compaction, isostasy***, and ***fault down-drop***

Presentation Overview

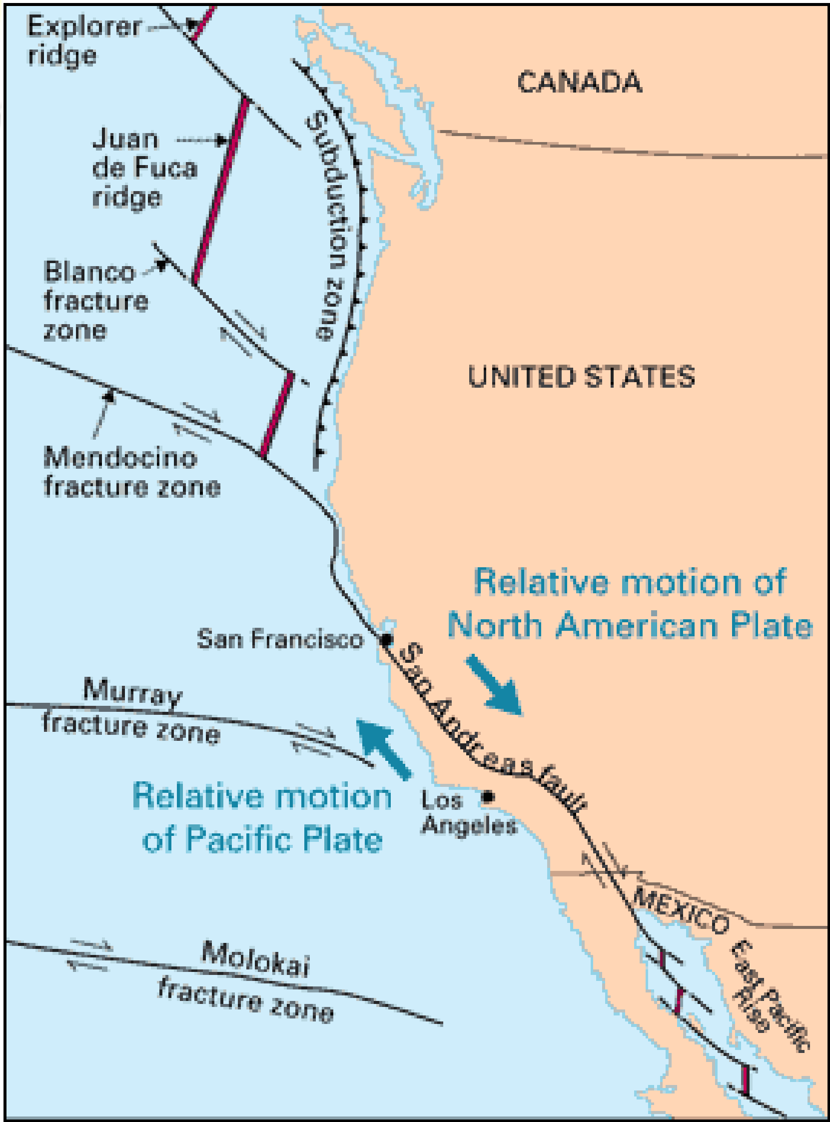
- Tectonic Setting
- Rapid growth of the delta during the Holocene Epoch
- Variable foundation conditions tied to deltaic stratigraphy
- Anthropogenic impacts since 1850
- Peat CO2 flux & subsidence
- Site characterization issues in the delta
- Preferential seepage paths
- Case studies of levee failures

THE TECTONIC SETTING OF THE DELTA

The tectonic setting controls the geography

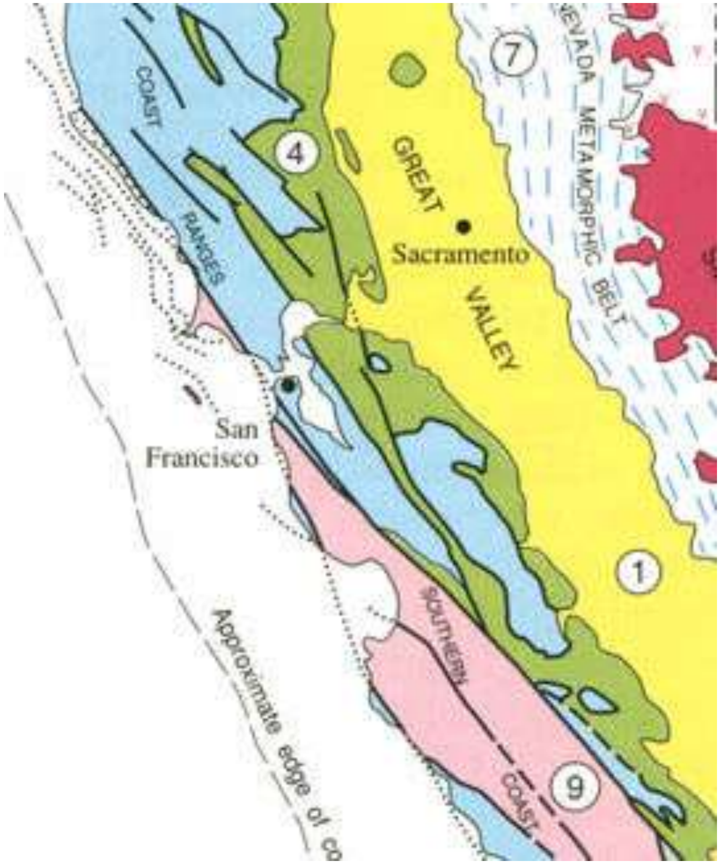


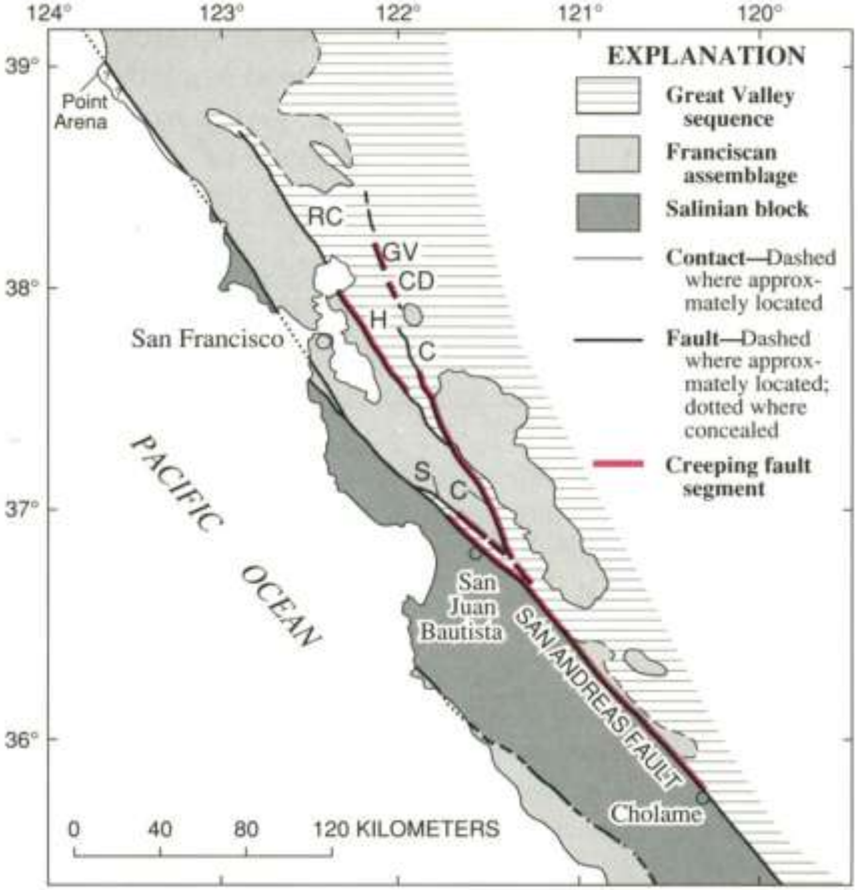
DIAGRAMMATIC CROSS SECTION
PACIFIC OCEAN TO GREAT VALLEY
(from Crane, 1988)



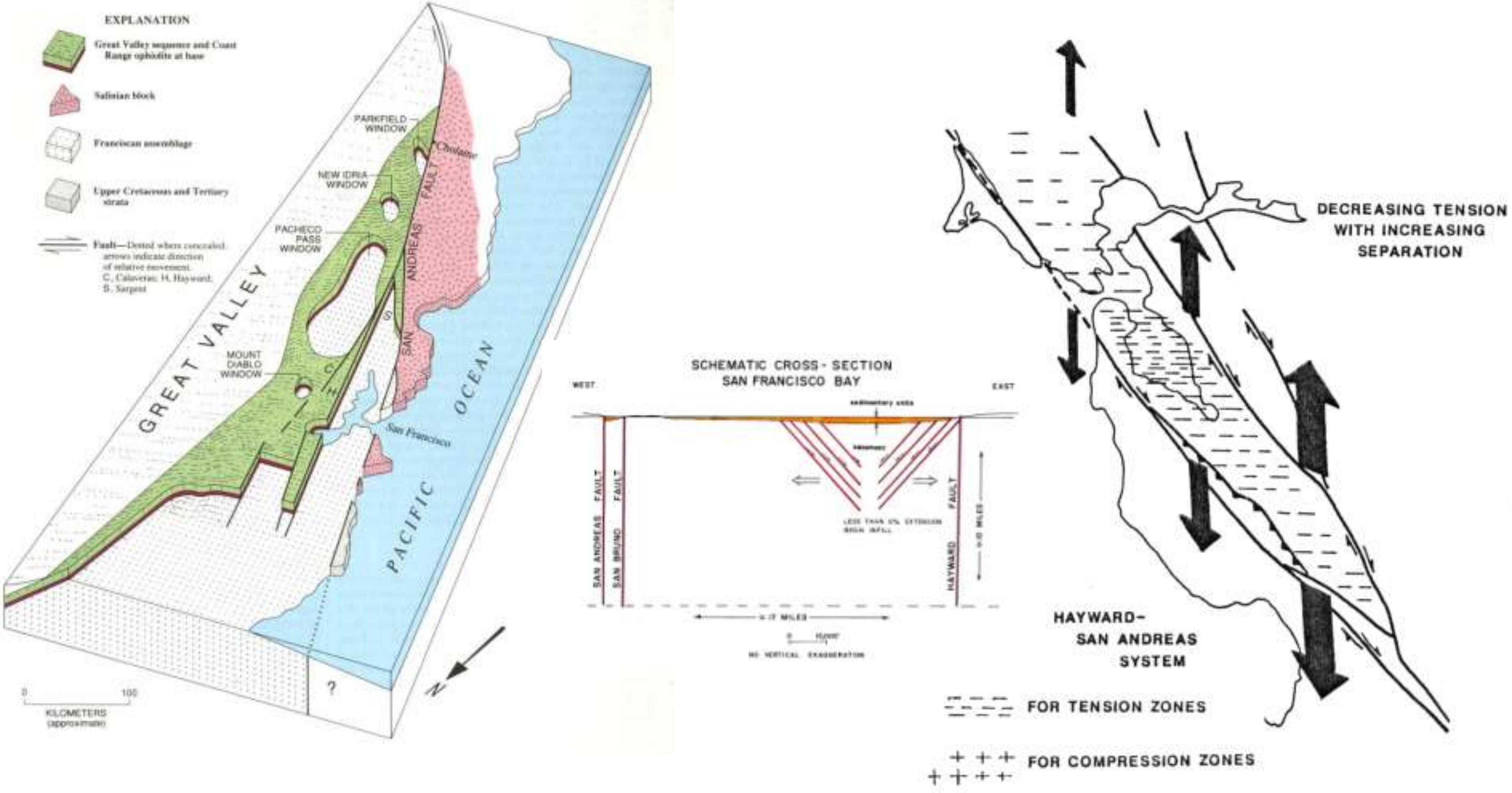
California lies on the margins of one of the world's most tectonically active sutures, a transform fault system between the East Mexico Rise and the Gorda Ridge. The rate of lateral offset has averaged about 22.5 mm/yr over the past 200 ka; of which about half (22 mm/yr) is taken up by the san Andreas fault.

Note how SHALLOW the Earth's crust is beneath the Coast Ranges bounding the San Francisco Bay, deepening to the east.





- **The central California coastline is structurally controlled by a series of northwest-trending strike slip faults, with decreasing rates of movement proceeding inland. This is because the faults become deeper, moving inland, and greater strain energy is accumulated between rupture events.**



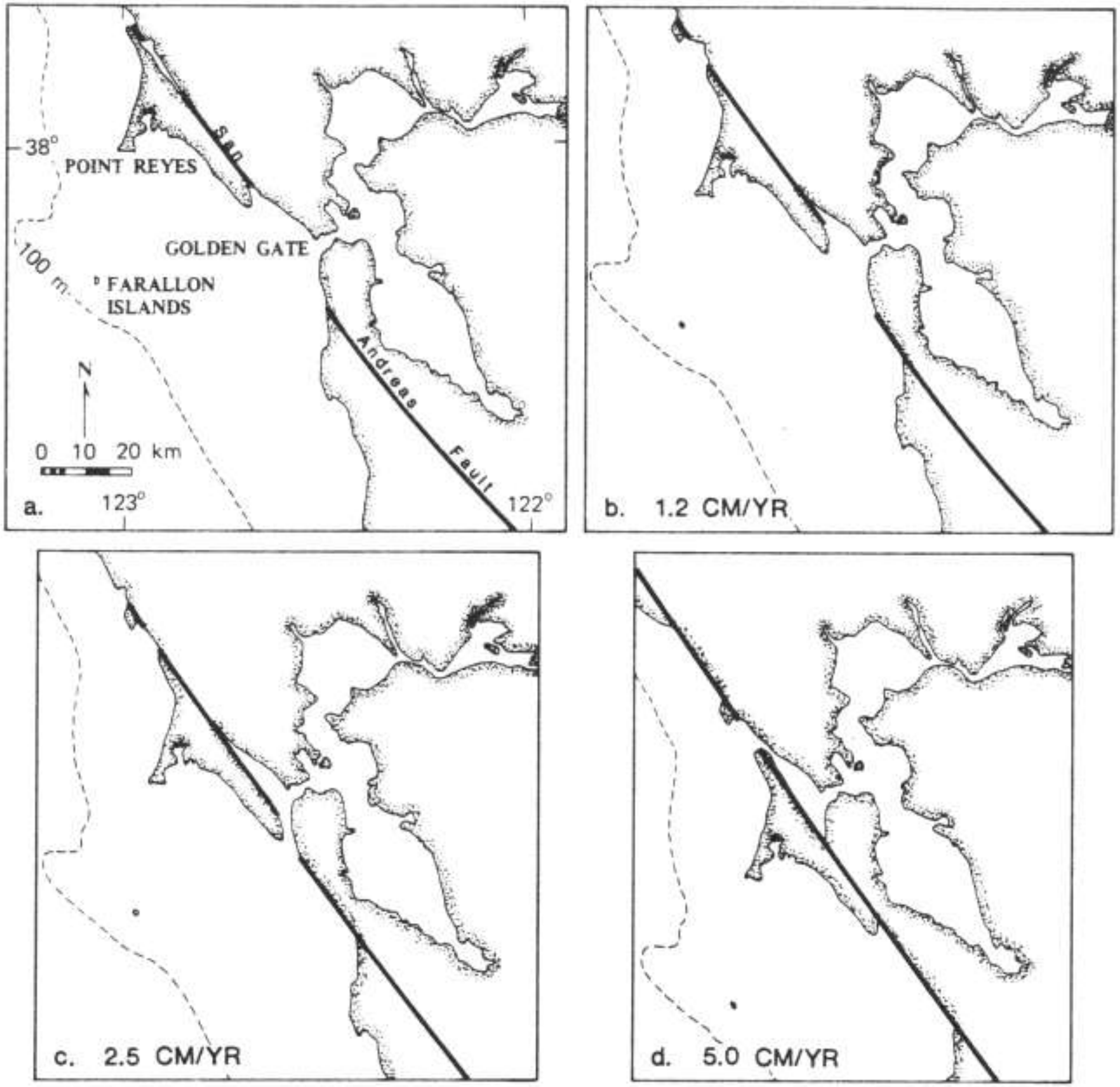
A right-stepping series of right-lateral faults creates *down-dropped basins* that tend to fill with sediment. This is termed fault segmentation. These ridges and valleys restrict drainage from the Great Central Valley structural depression.

Visualizing the SF Bay Area 1 million years ago

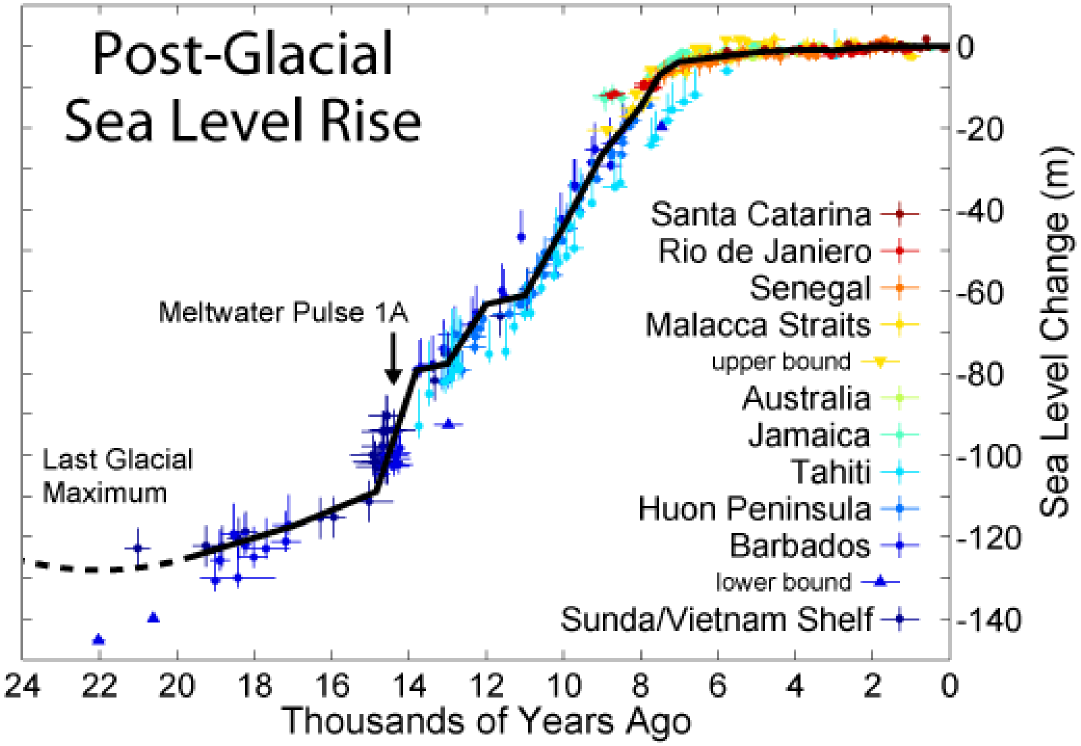
In 1979 Brian Atwater of the USGS theorized about what the drainage outlet to the Pacific Ocean may have looked like, assuming various average rates of right-lateral offset for the San Andreas fault.

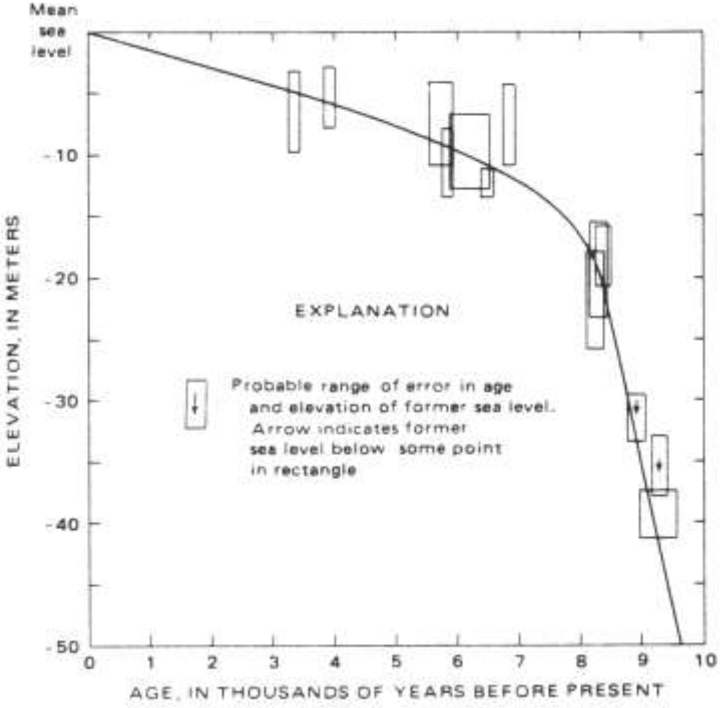
Over the last 200 ka the actual value has been about 2.2 cm/yr, close to Example C, at lower left.

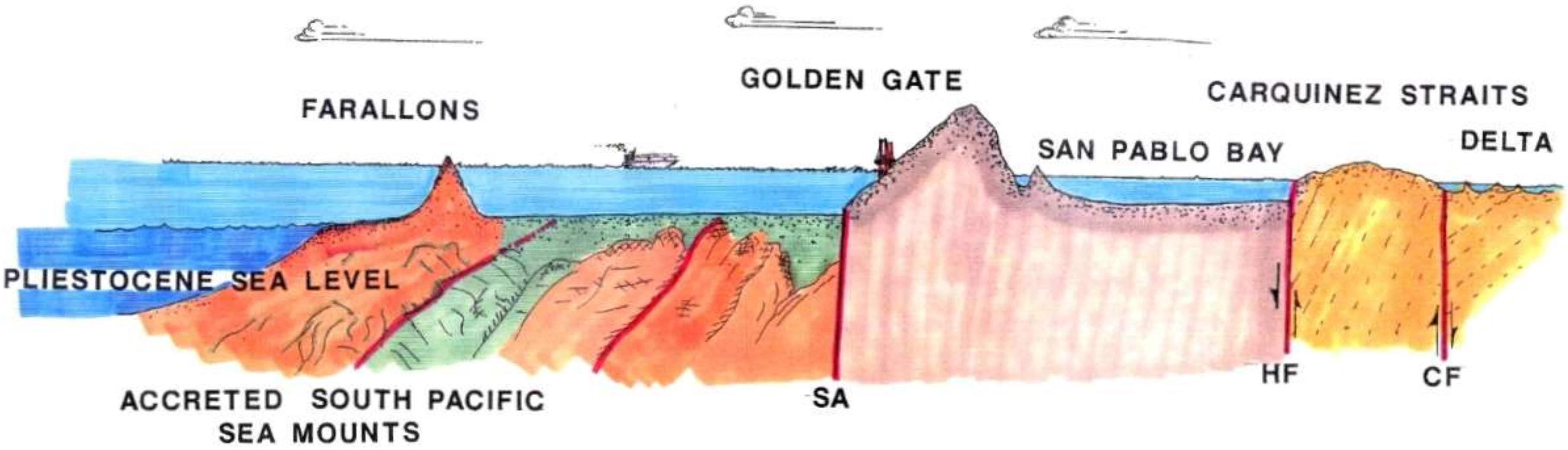
This offset has been accompanied by a vertical component of 0.05 cm/yr, or about 5 m per millennium. The river system must excavate the uplifted blocks at a rate greater than 0.05 cm/yr to keep pace with the uplift.




18.0 ka

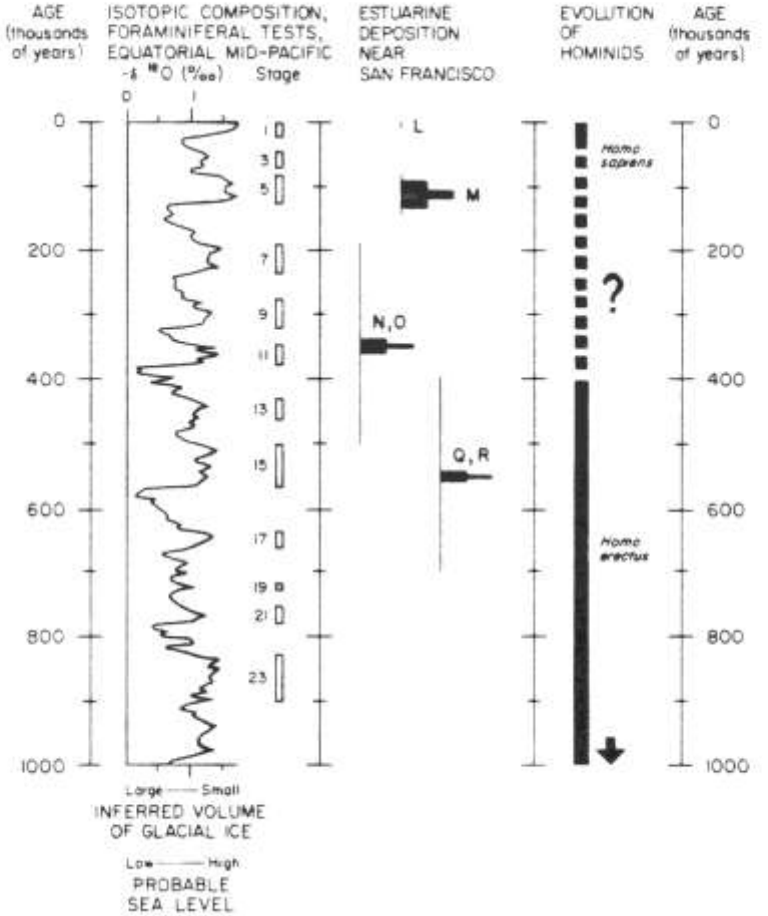


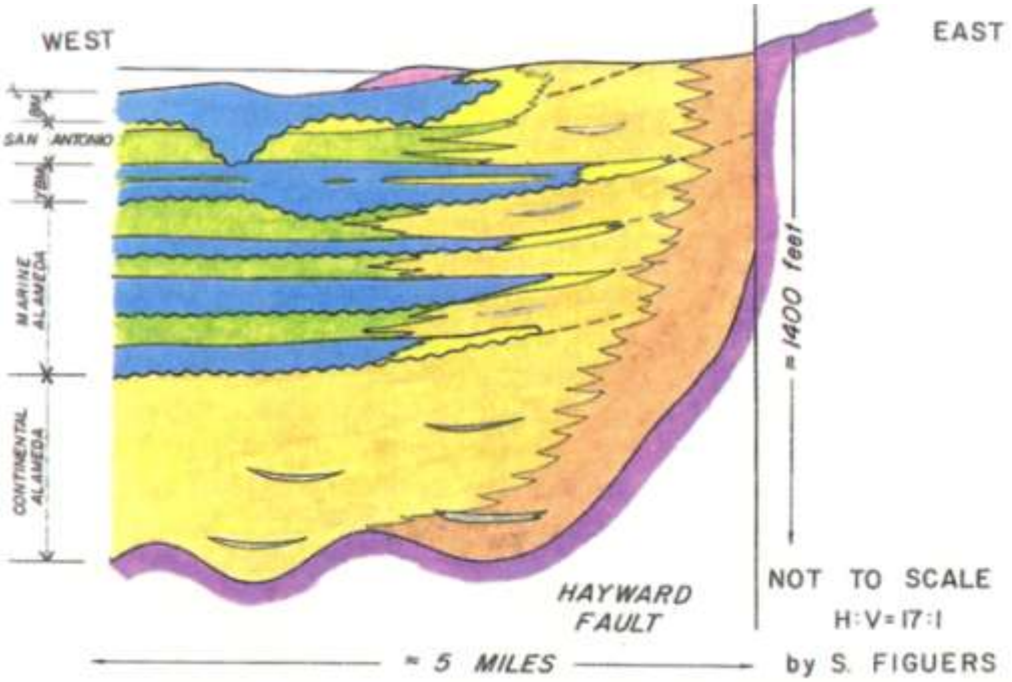




About 14.5 ka, sea level began rising markedly, world-wide.

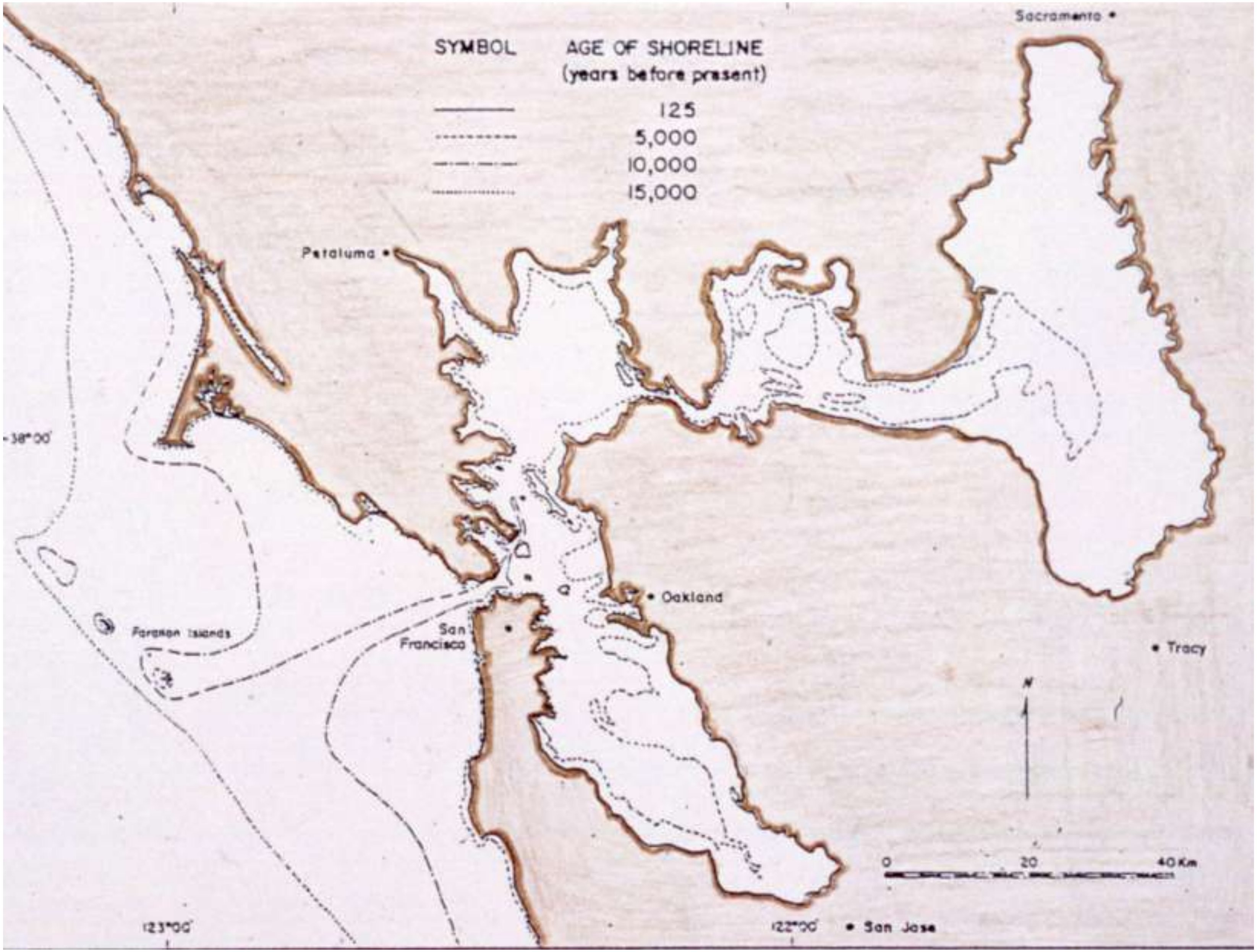
Esturarine clays correspond with repeated sequences of sea level rise in the San Francisco Bay region





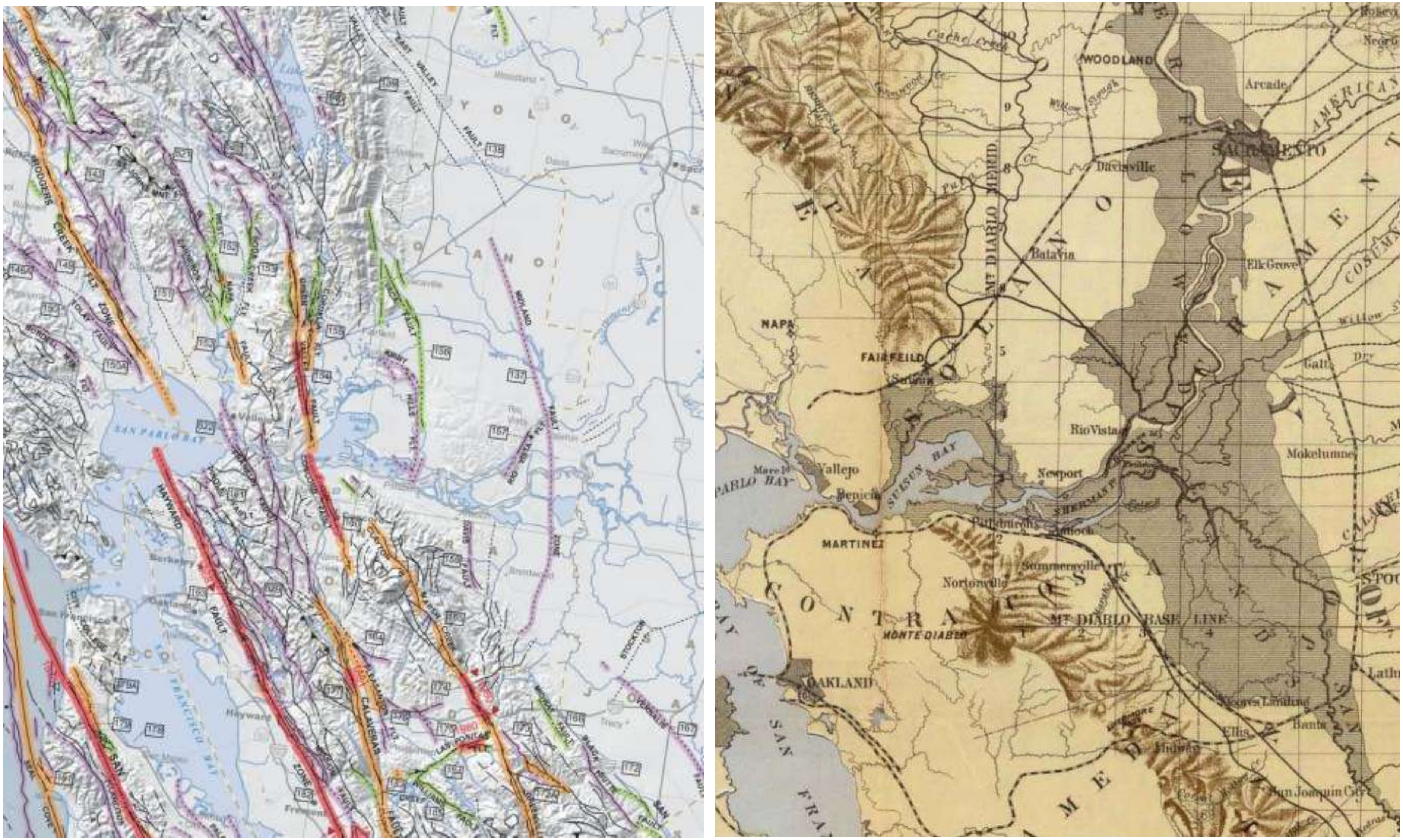
Sediments lying beneath the eastern San Francisco Bay record five major sequences of sea level rise, spaced about 100 ka apart, dating back 500 ka. The sea stand at Isotope Stage 5e (116 to 126 ka) was about 22.5 ft higher than present. These marine incursions are underlain by continental sediments of the Alameda Group.

Rising sea level drowns the river valleys




2.0 ka

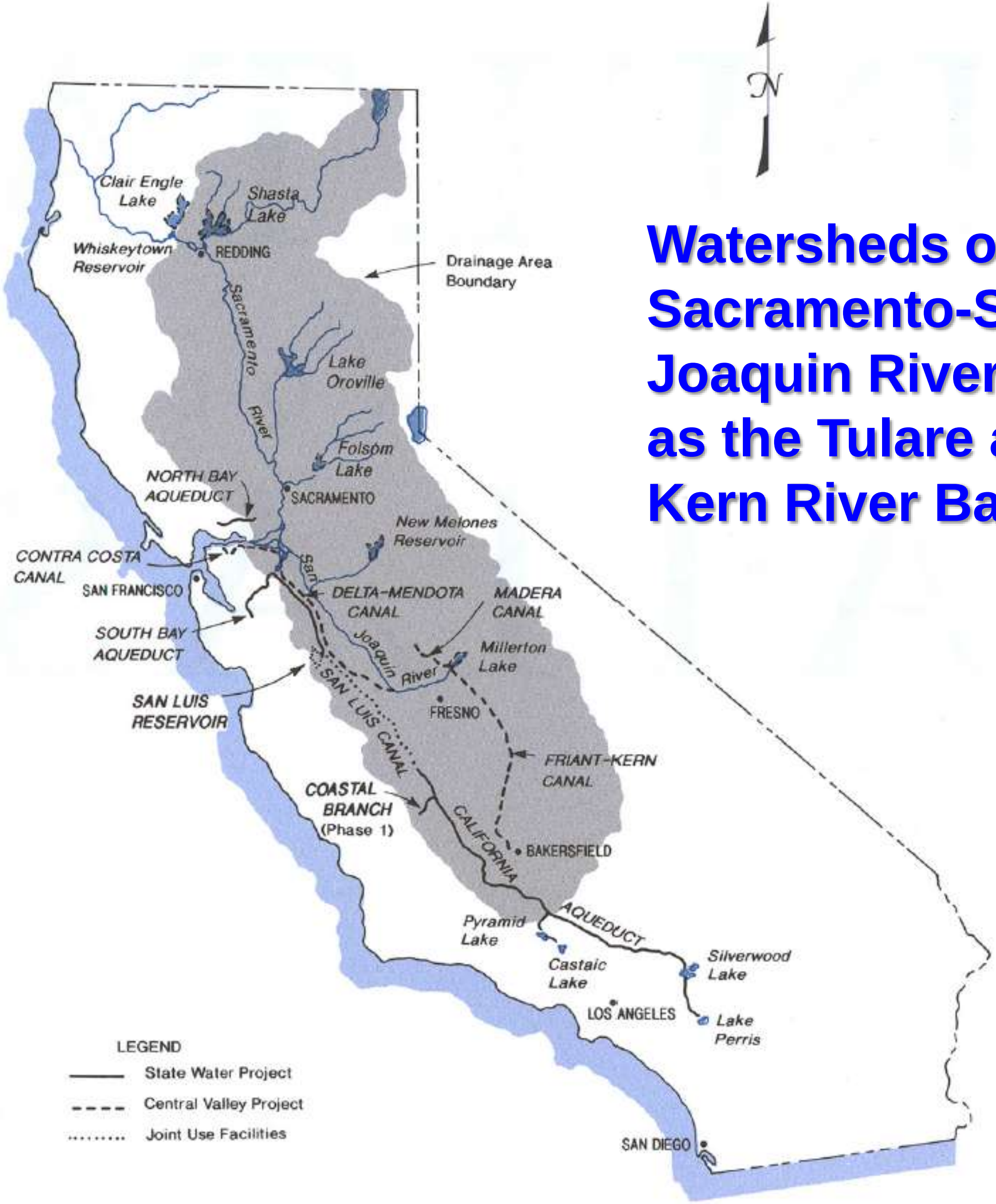
Present

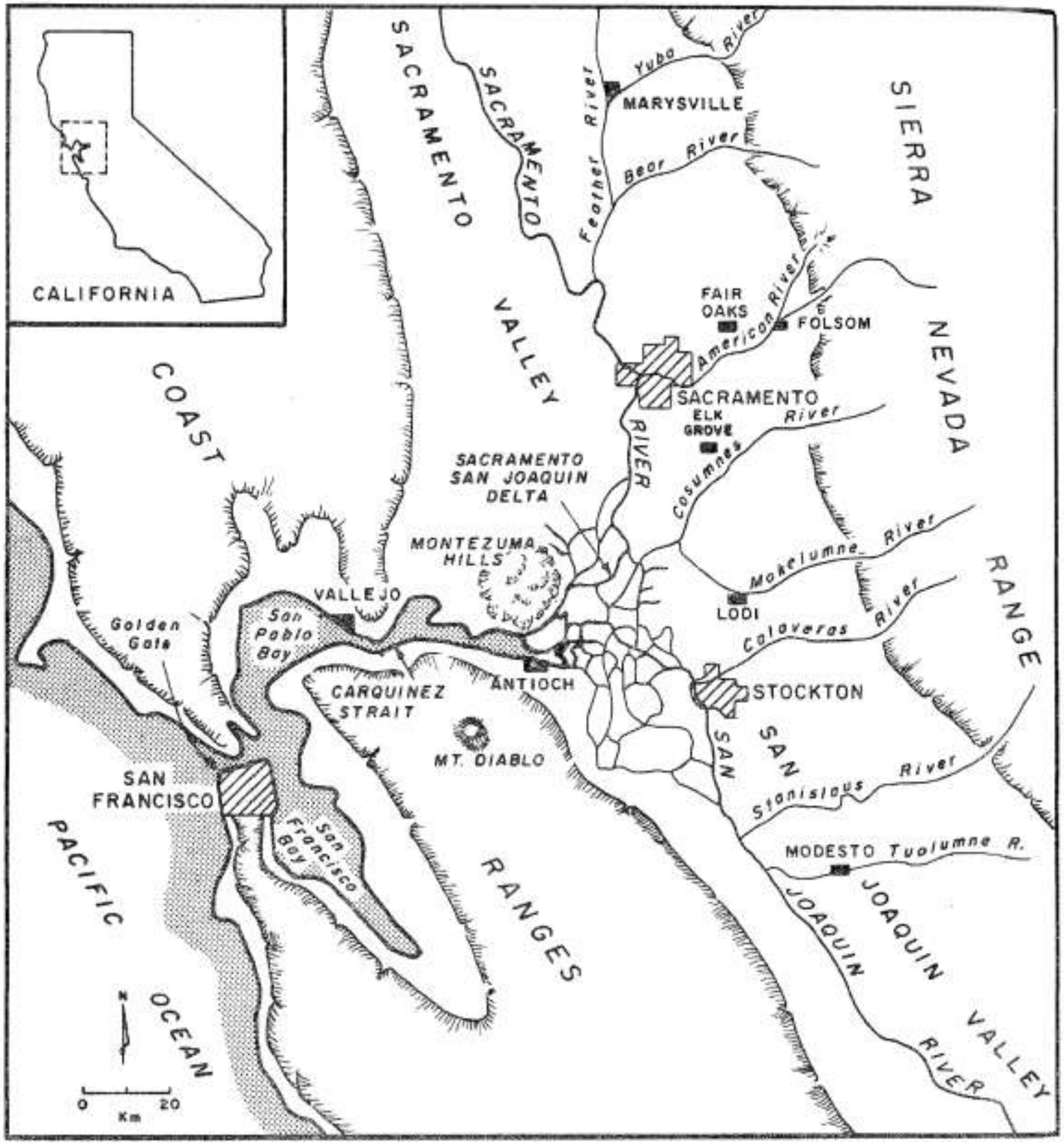


The historic Sacramento-San Joaquin Delta, under tidal influx and filled with tules and bull rushes, is shown at right in 1855. The map at left shows active faults in this same map area.

RAPID GROWTH OF THE DELTA DURING THE LAST 11,000 YEARS

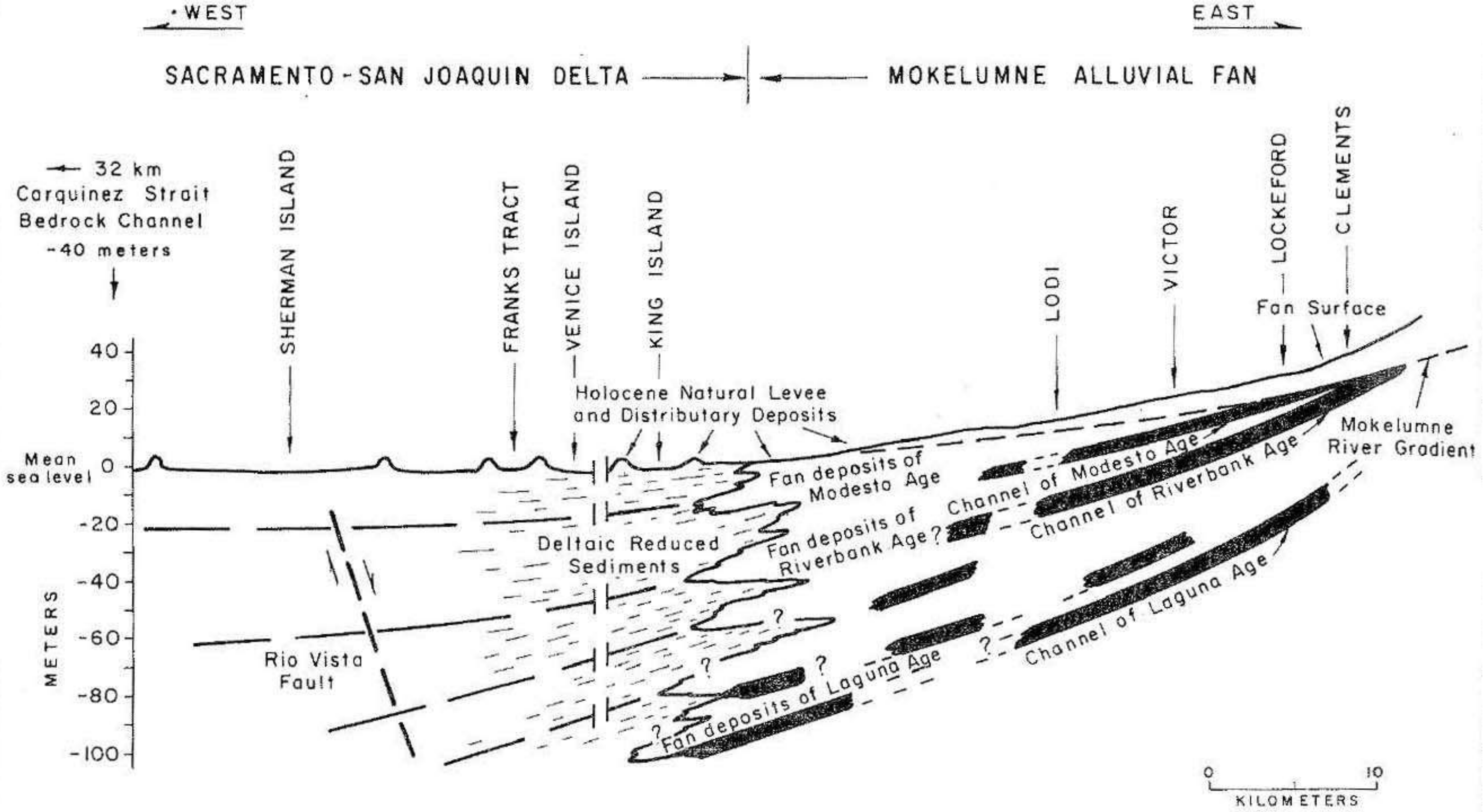
Watersheds of the Sacramento-San Joaquin River, as well as the Tulare and Kern River Basins





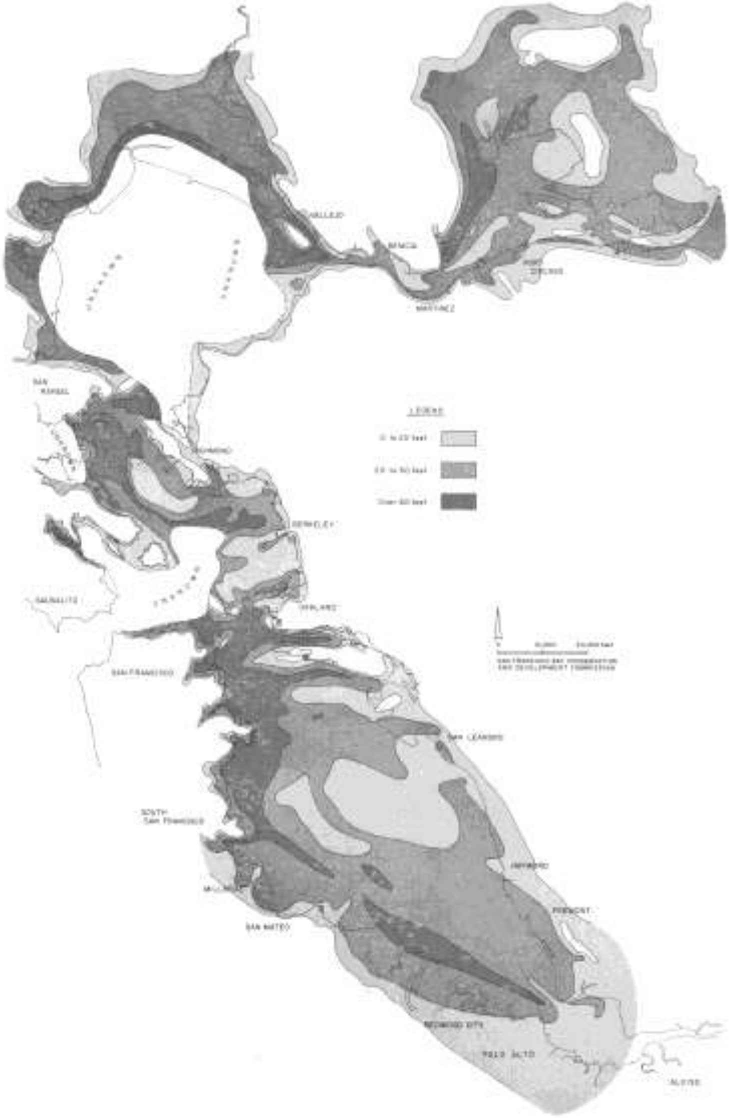
Inverted deltas prograde upstream

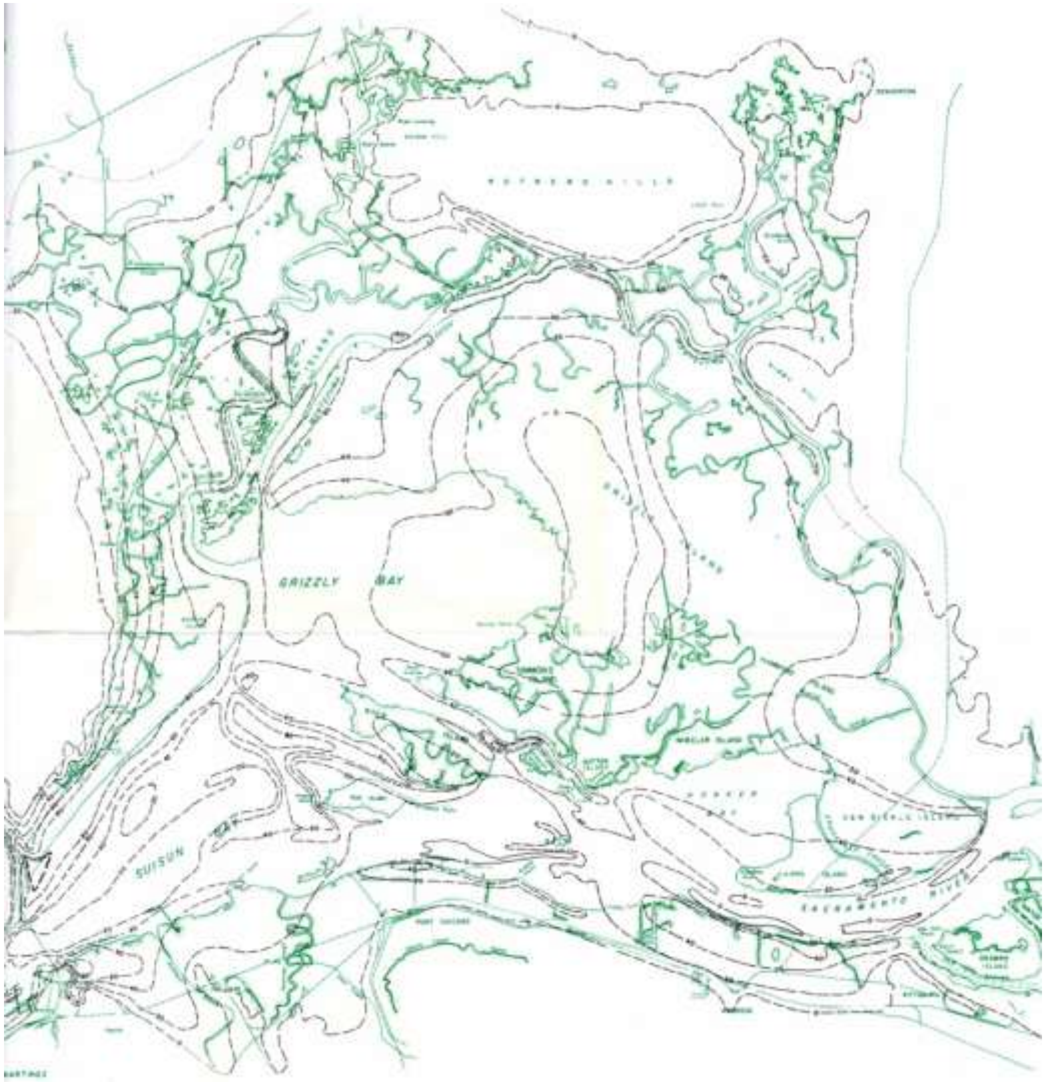
The Sacramento-San Joaquin Delta does not have exhibit a classic deltaic areal geometry nor easily recognized sequences of prodeltaic, distal bar, or similar prograding sequences that fill geology textbooks. It has built itself through upstream migration



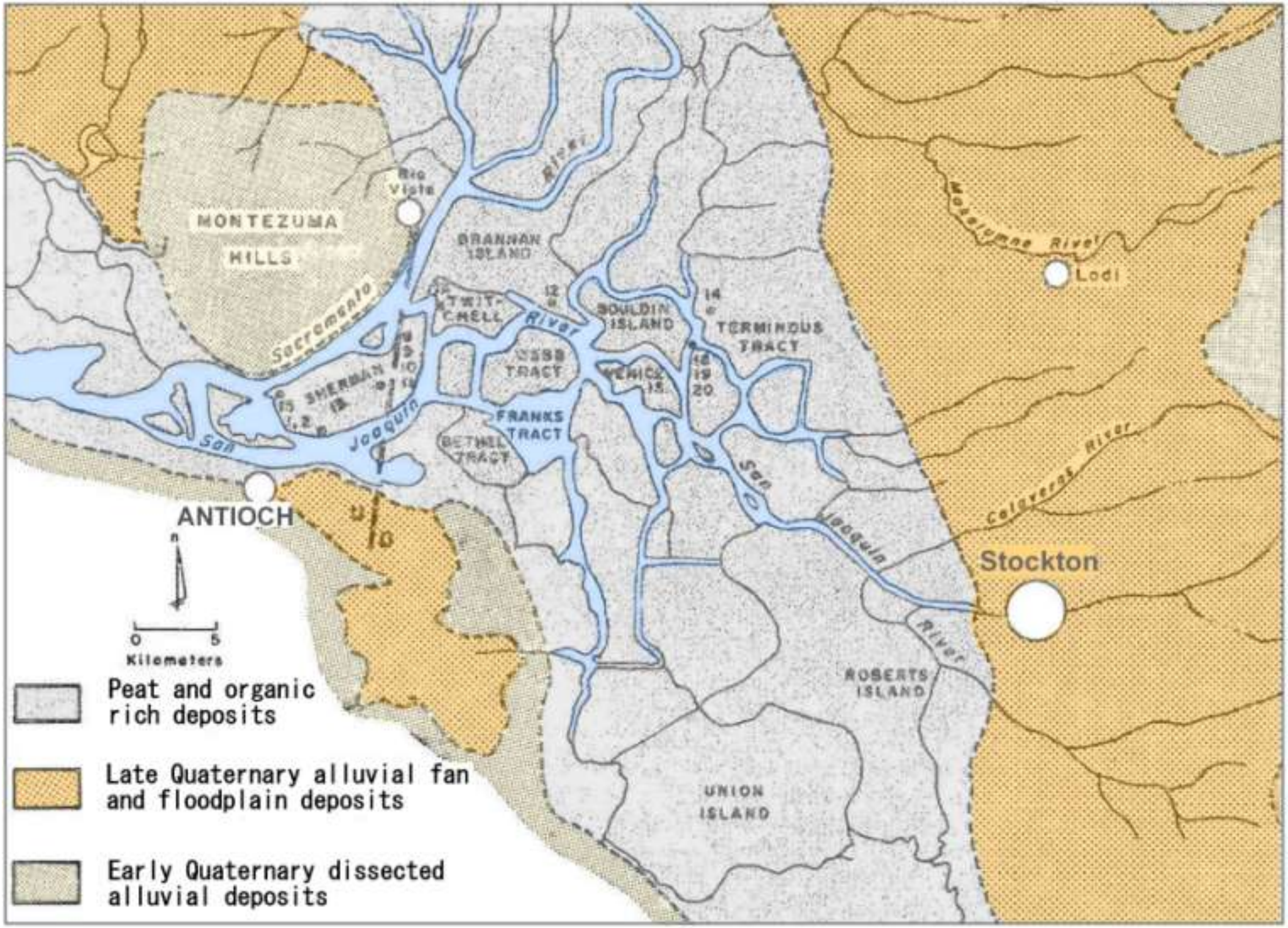
Schematic section through the delta, illustrating the various sediment packages that were deposited during the warm interglacial periods, and eroded during dry spells. The channel sediments coming off the Sierras are considerably lower (95 m) than the bedrock notch in the Carquinez Straits (45 m), suggesting active tectonism

Young Bay Muds deposited west of the delta

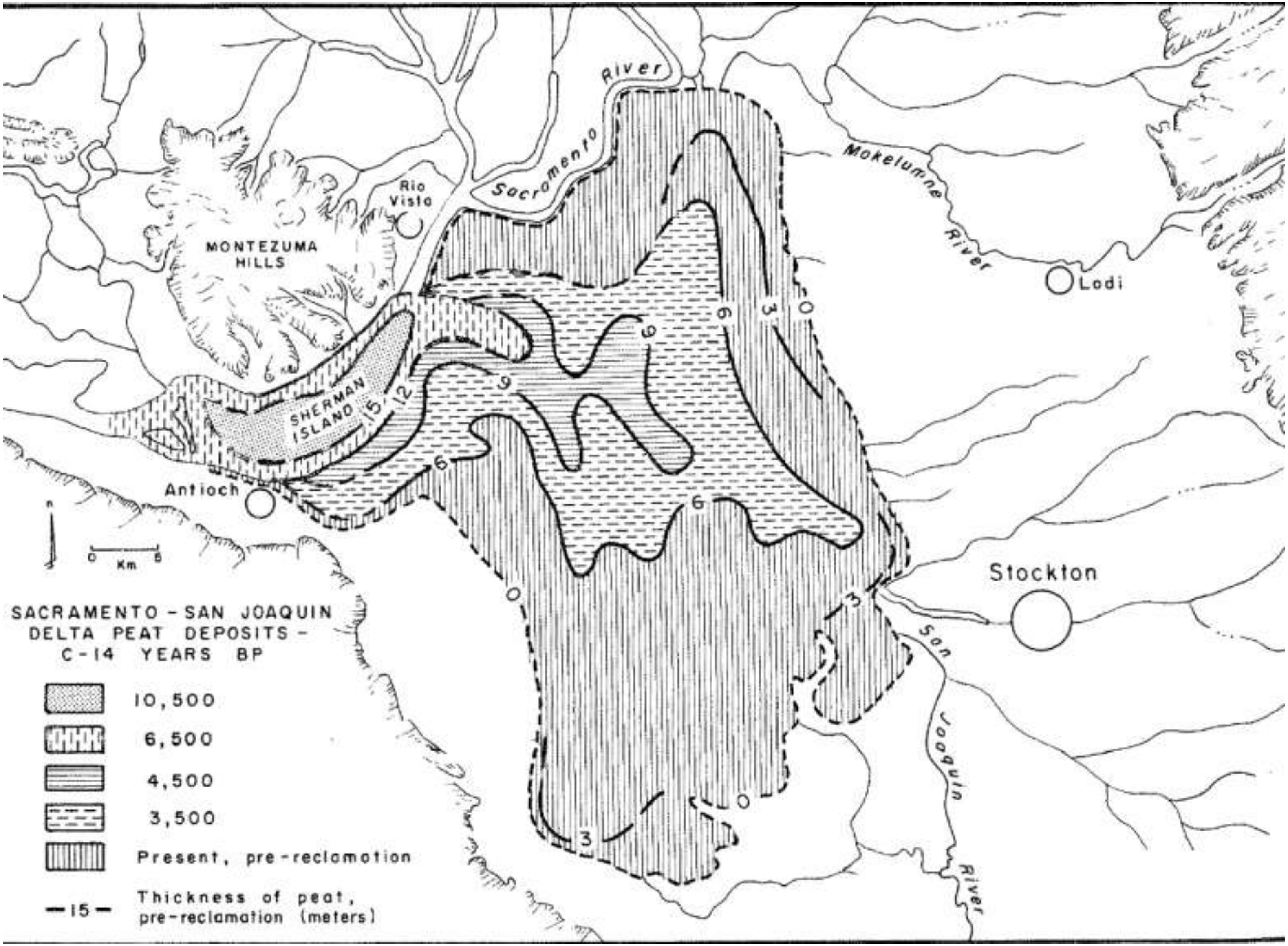




Suisun, Grizzly, and Honker Bays lie within a structurally-controlled basin, lying between the Pittsburg-Collinsville faults and Concord-Green Valley faults.

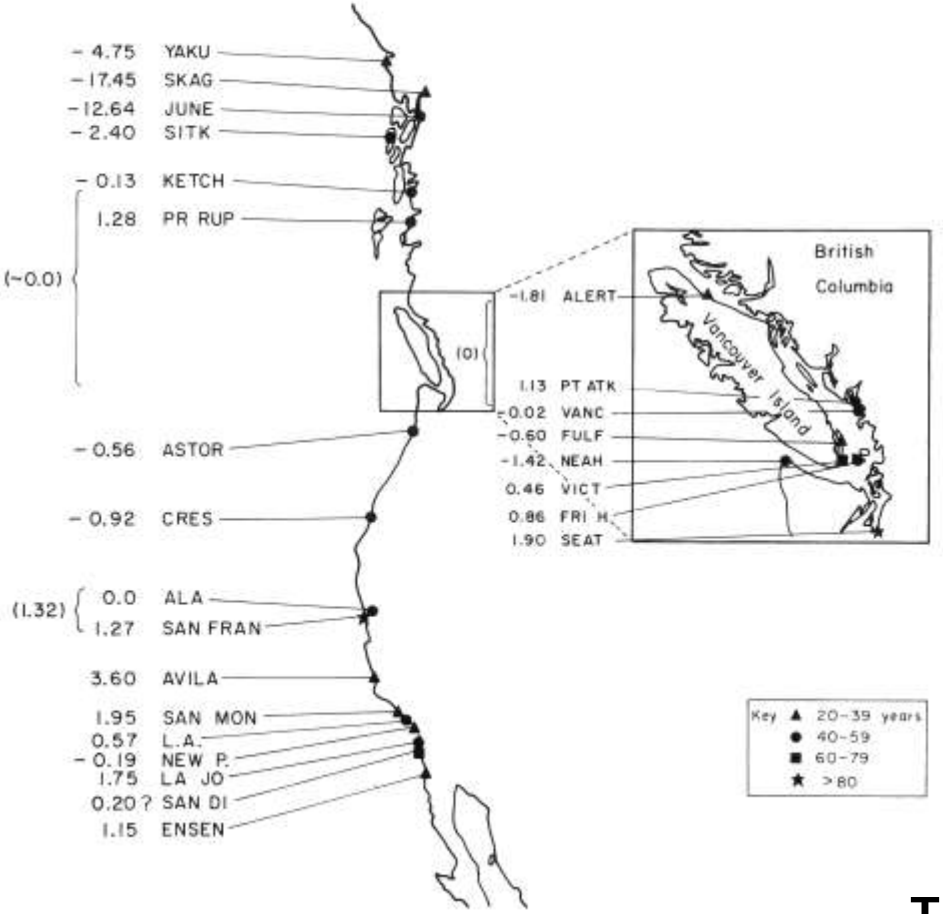


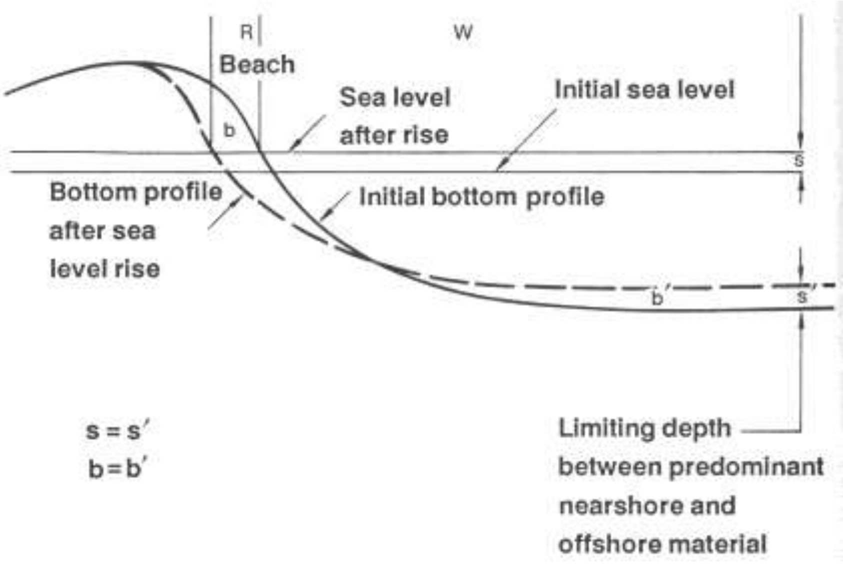
Late Quaternary geology of the Sacramento-San Joaquin, taken from Shlemon and Begg (1975). They were the first workers to suggest the controlling role of active tectonism on the growth and development of the delta, which is now almost universally accepted. The Rio Vista fault was originally identified in 1950, but cannot be traced through the soft, deformable sediments of the modern delta.

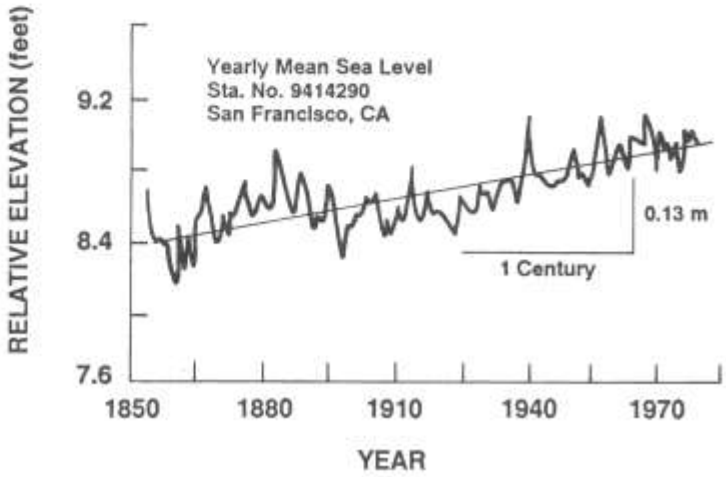


The relative C_{14} ages of peat deposits bear testimony to the rapid enlargement of the delta during the last 10 ka

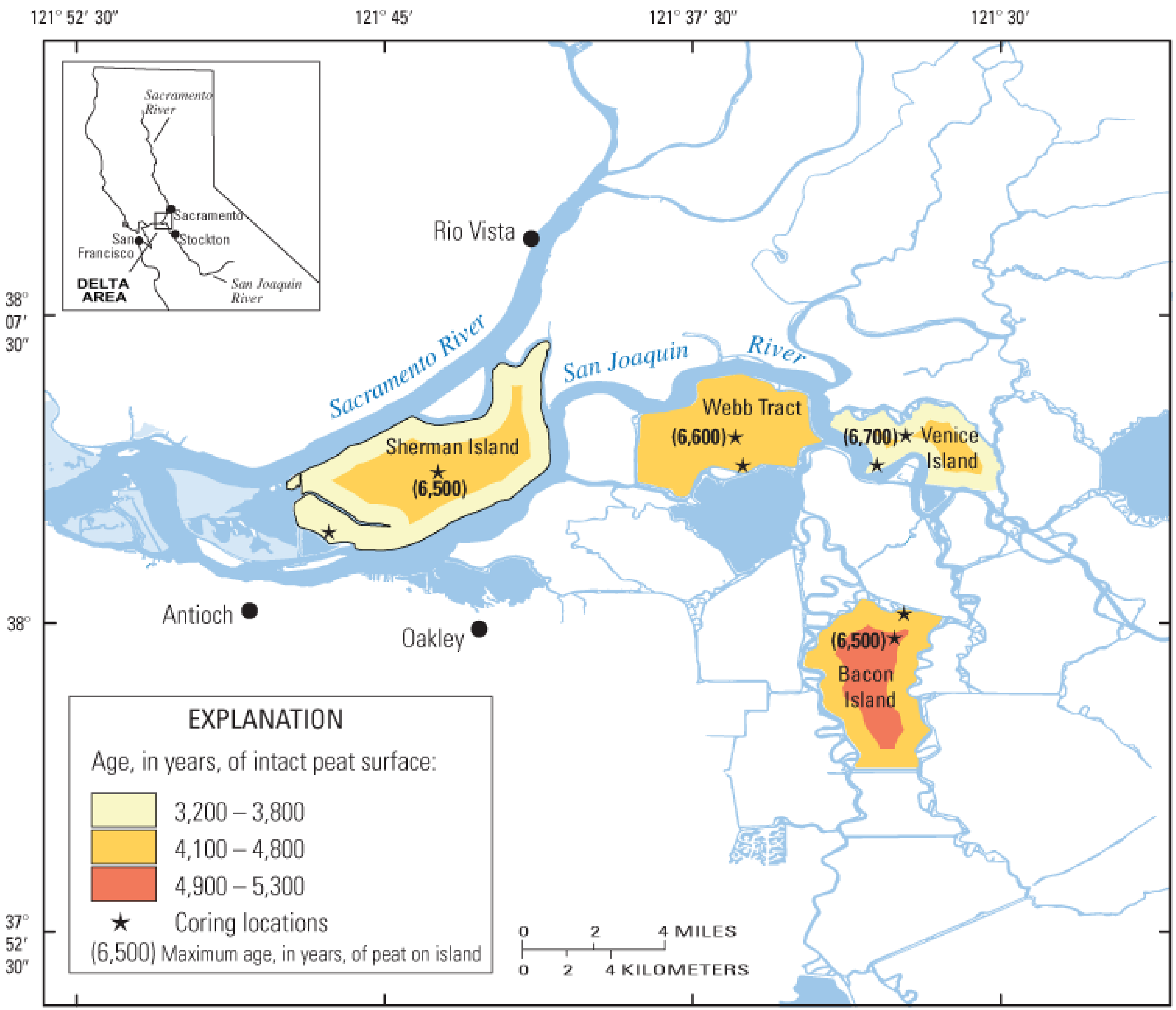
Sea Level Rise enlarges the delta







The delta subsided more or less continuously throughout the Holocene, as sea level rose. During this same interim, faulting continued to elevate the bedrock narrows between the delta and the ocean. As a consequence, the delta continued to enlarge itself over the past 5,000 years, backing further upstream, to the east, north, and south.

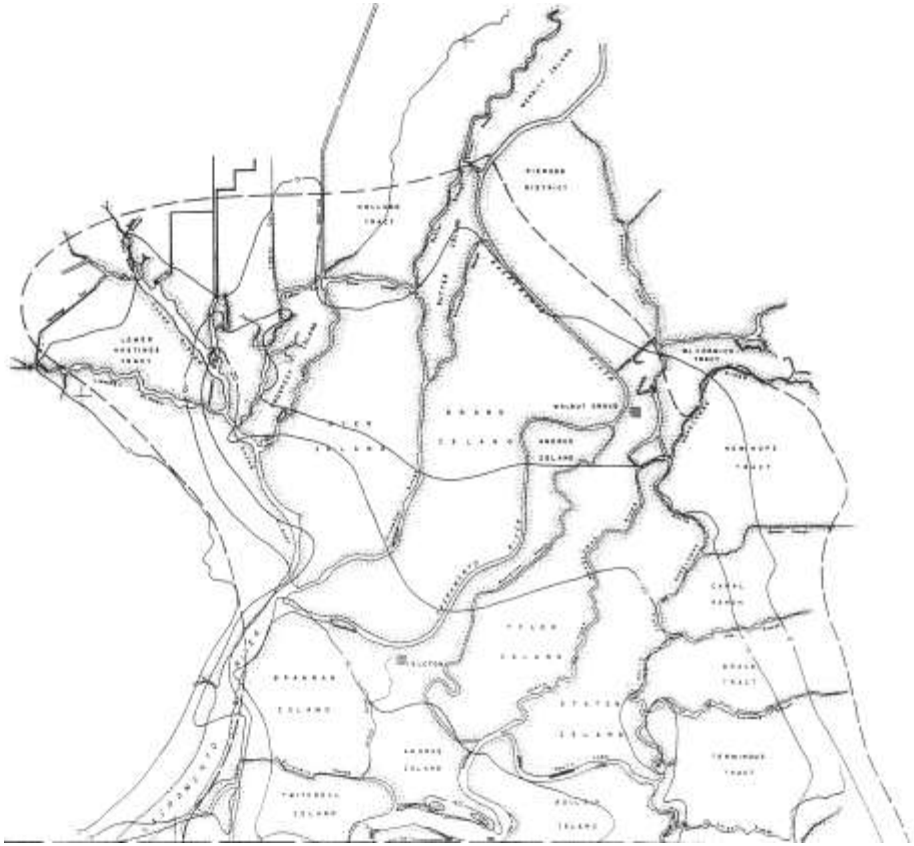


Modified from U.S. Geological Survey National Hydrography Data Set (NHD), 1:100,000 scale, 2001,
Albers Equal-Area Conic Projection

The relative Carbon-14 derived ages of peat soils in the delta testify to relatively stable positions of the Sacramento, San Joaquin, Middle River and Old river channels over the past 7 ka.

Peats derive from tule and bullrush marshes that grow on the seasonally inundated margins of active flood channels. They are not deposited within active channels. Creek willows and other woody species grow along the channel banks.

Isopleths of peat thickness



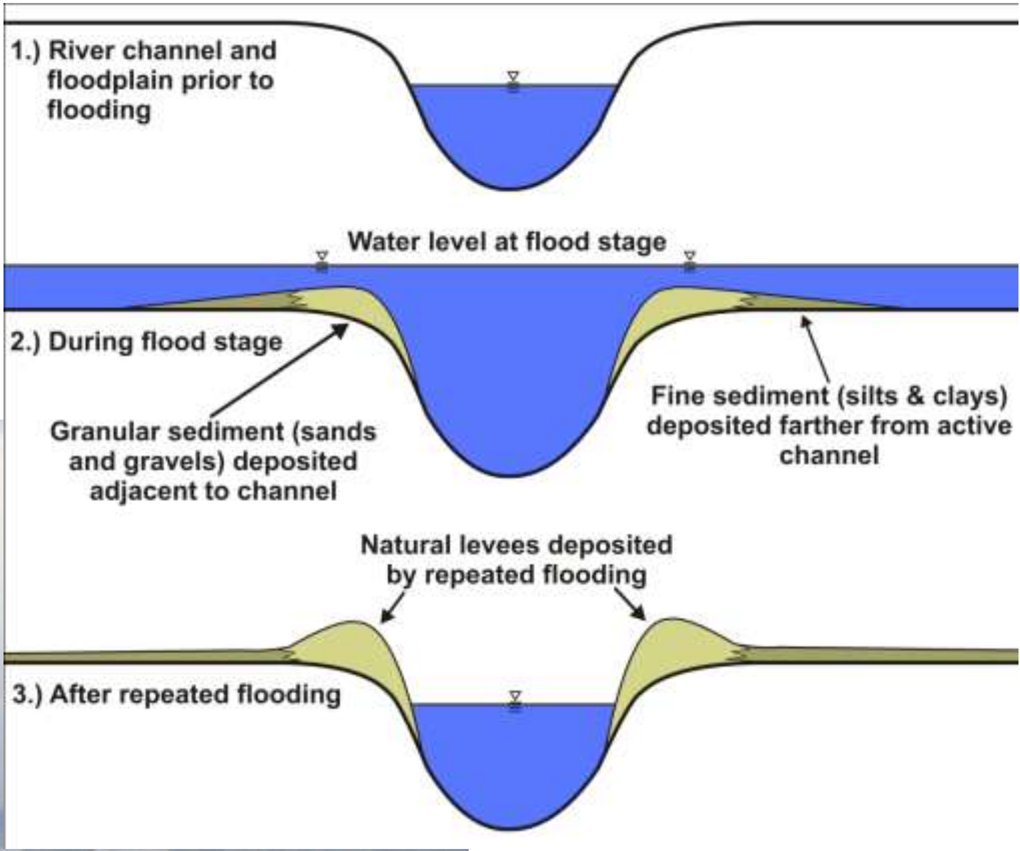
By the early 1960s the Corps of Engineers had begun tabulating data on the peaty soils, noting their variation in thickness and mineral constituency, because they exerted such profound influence on long-term performance

VARIABLE FOUNDATION CONDITIONS

Some materials settle more than others

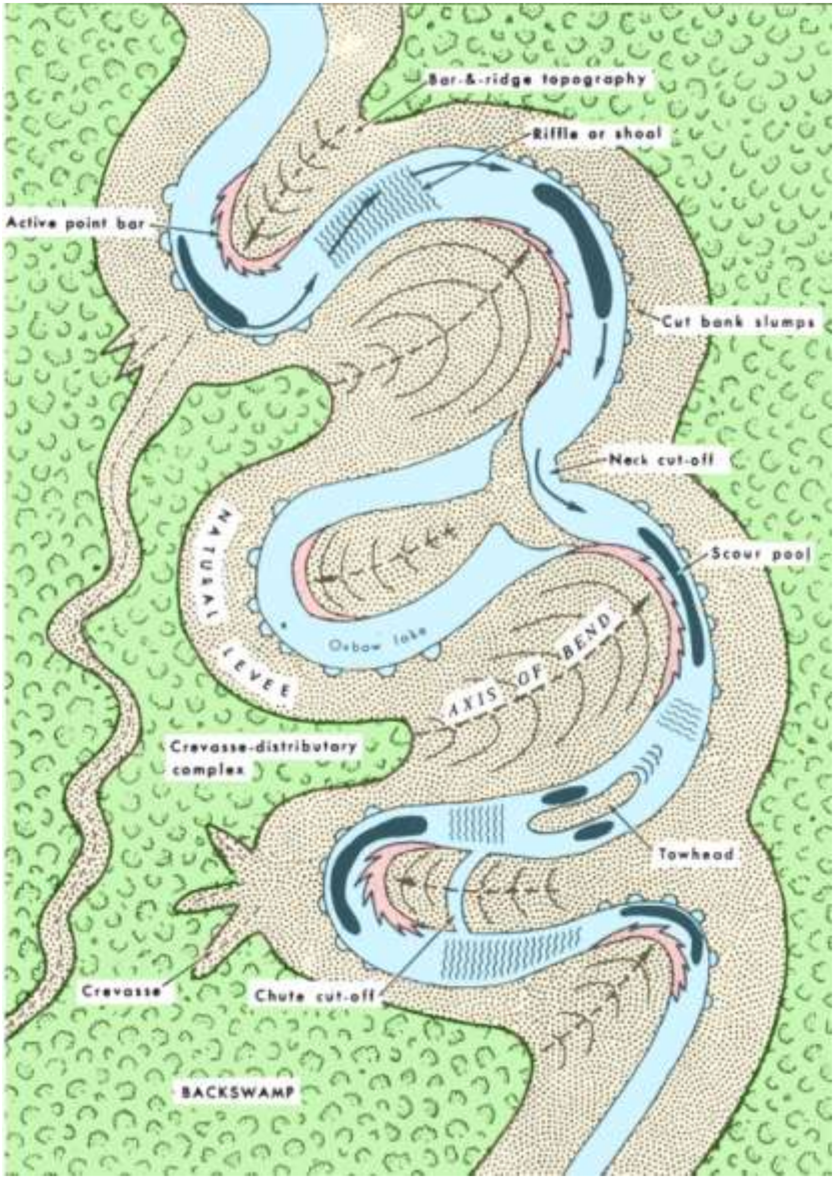
The only constant in the delta is the inconsistency of its foundation conditions – you cannot use rulers anywhere in this environment

Overbank silts and natural levees

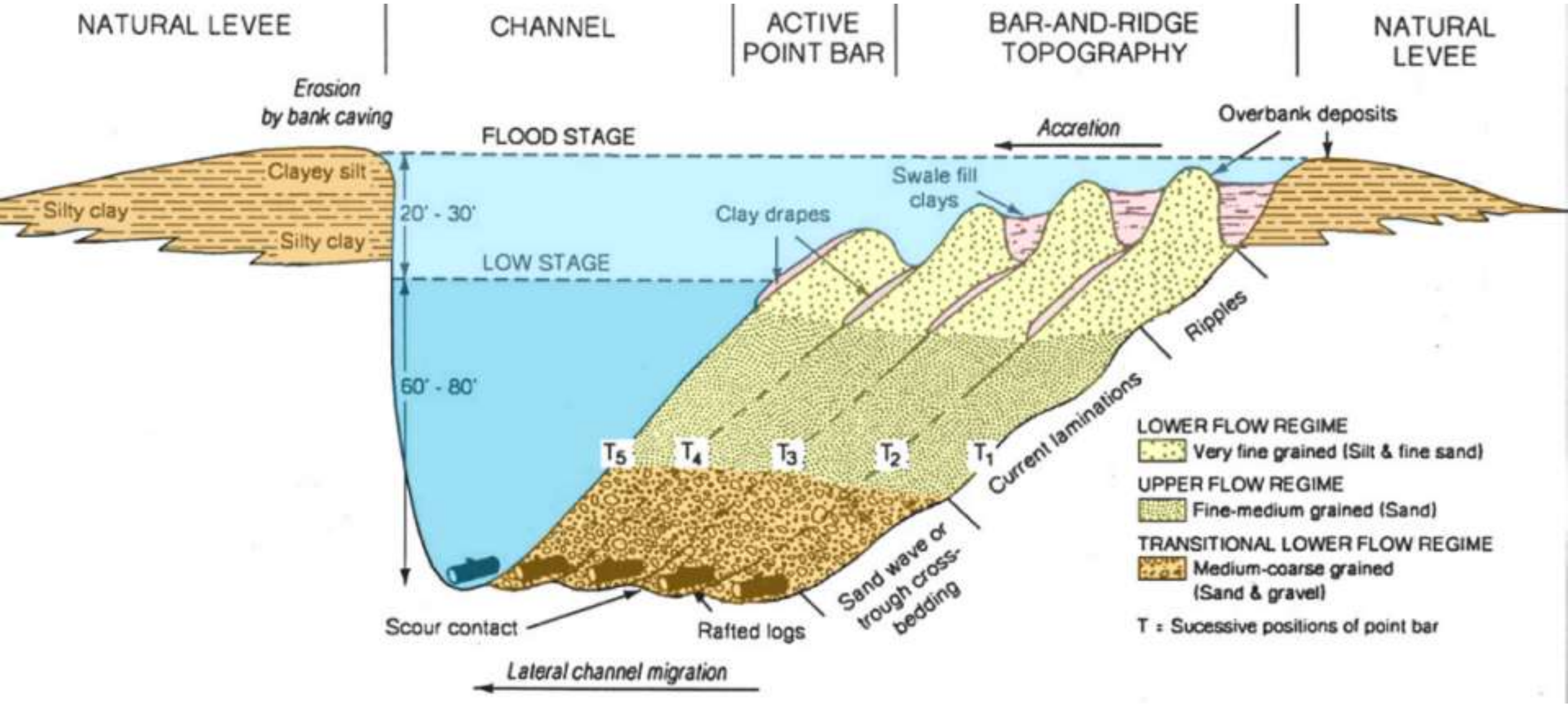


90% of all sediment deposited on the continents is overbank silts

Sediments are orthotropic

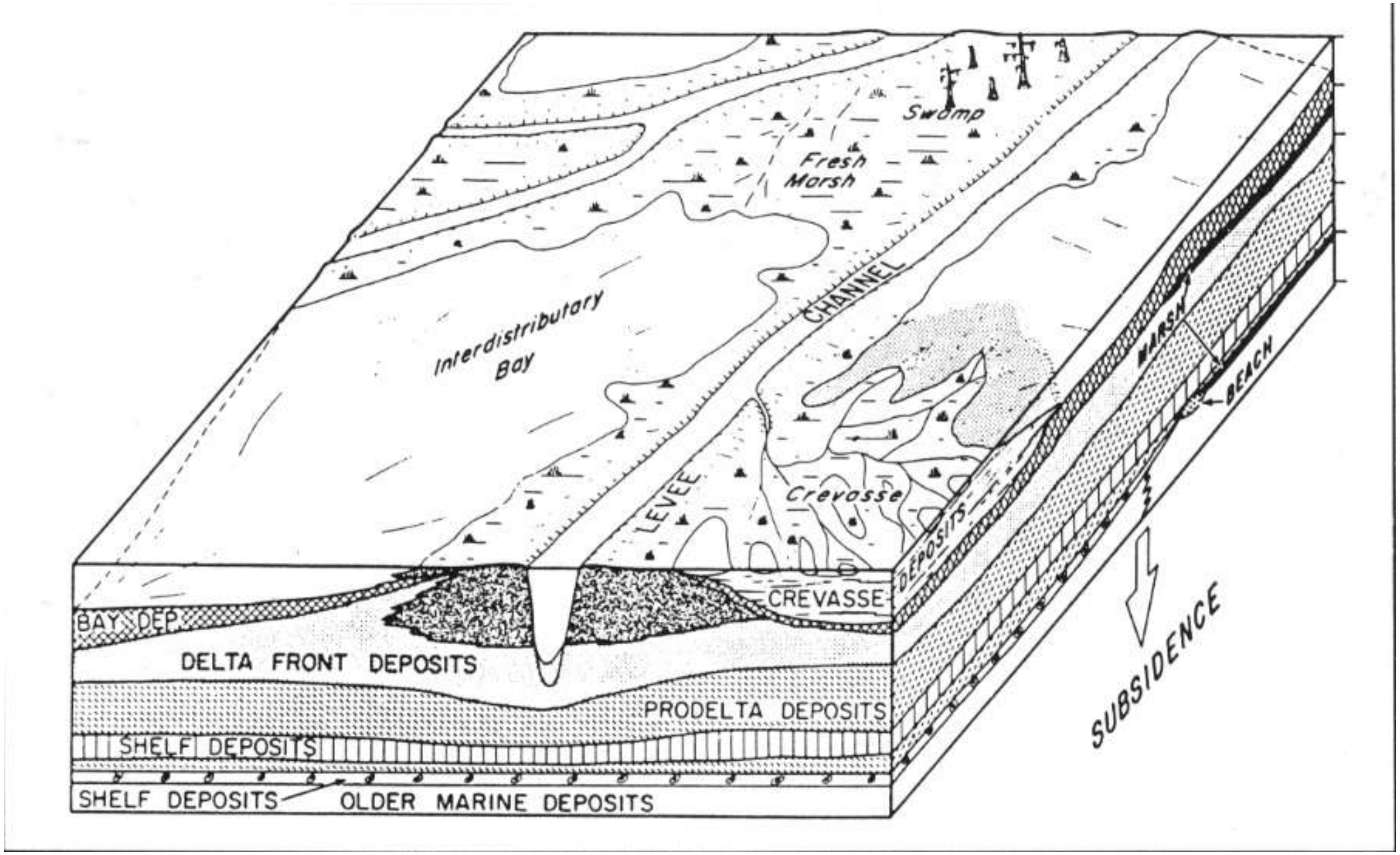


Sediments are lain down with a preferential "depositional grain," which causes them to have differing physical properties in three planes mutually perpendicular to one another



"**Straight-line correlations**" between adjacent geotechnical borings are a very real liability in a low-gradient channel delta with *sinuosity*, because the point bar gravels and sands are deposited on their respective angles-of-repose, as shown here.

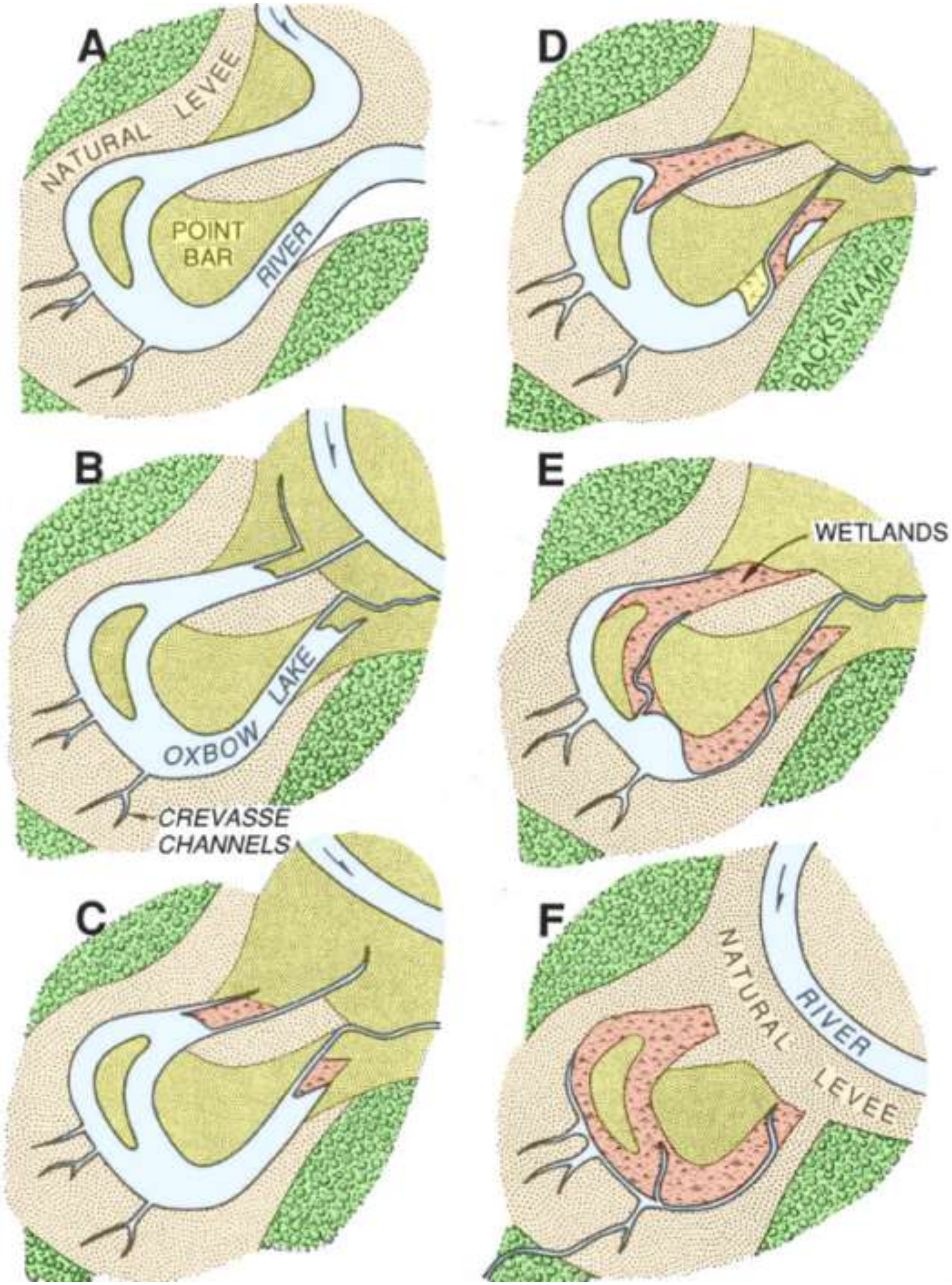
Note the sloping, discontinuous nature of clay drapes and swale fill clay pockets. This kind of depositional environment is anything BUT linear, defying any "one size fits all" sort of design, such as the typical delta levee.



The Sacramento-San Joaquin resembles a marine estuary, where sedimentation has chiefly been influenced by rising sea level, and without any influence of coastal processes such as longshore drift or storm-driven wave-induced erosion and deposition.

Crevasse Splays common

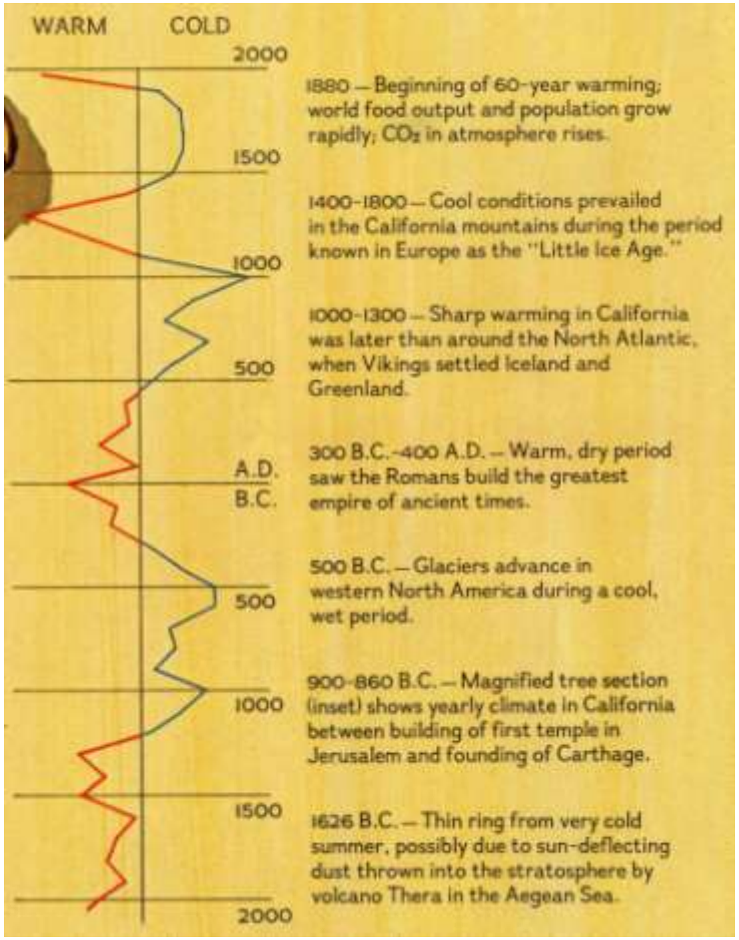
Meandering low-gradient channels tend to breach their own natural bank levees at crevasse splays, often along an outboard turn of the channel. These become prime locations for future seepage problems and repeated bank failures because of the pervious sands that are deposited in the outbreak troughs, as seen above.



The delta's interconnected system of man-made levees are superposed on an intricate network of abandoned channels, filled with a variety of sediments.

Peaty soils, more than any other kind of soil, tend to exhibit a WIDE range of variability in their mineralogical make-up, and hence, their behavior.

Sediments are nature's fingerprint



1880 – Beginning of 60-year warming; world food output and population grow rapidly; CO_2 in atmosphere rises.

1400-1800 – Cool conditions prevailed in the California mountains during the period known in Europe as the "Little Ice Age."

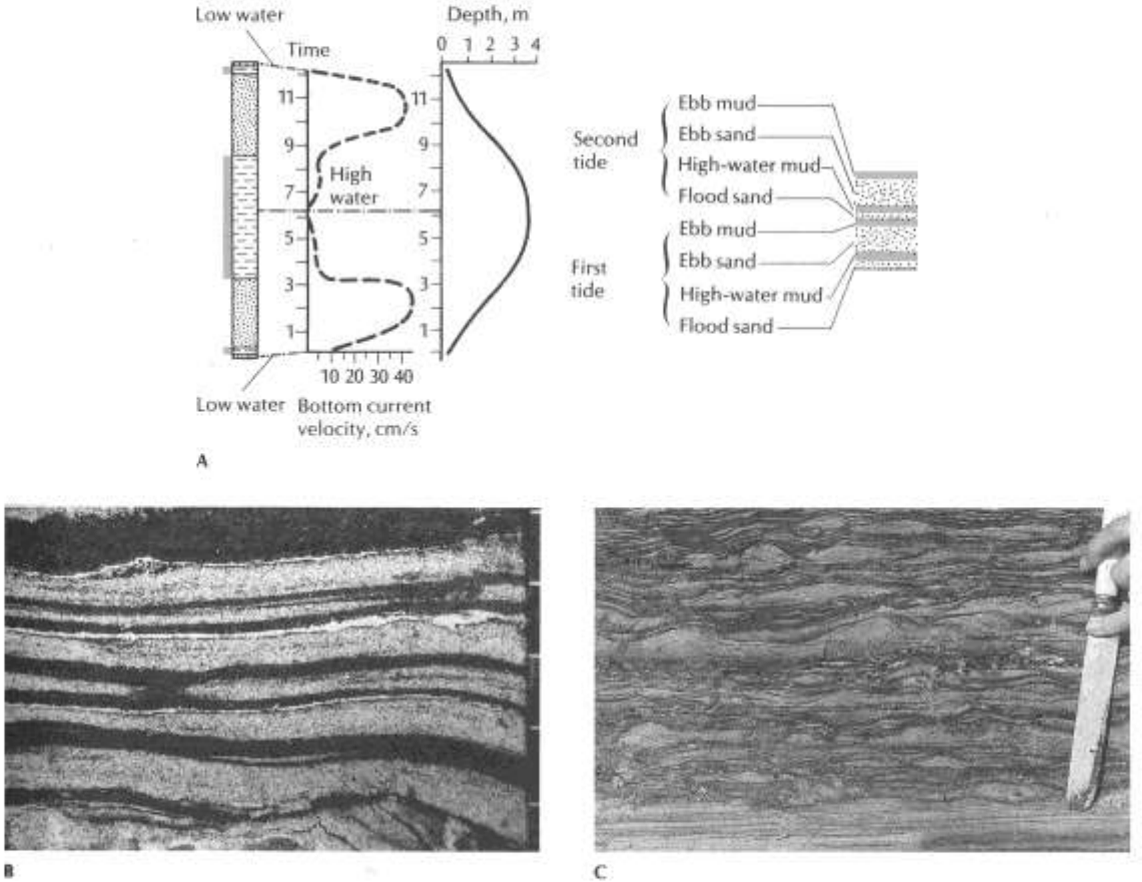
1000-1300 – Sharp warming in California was later than around the North Atlantic, when Vikings settled Iceland and Greenland.

300 B.C.-400 A.D. – Warm, dry period saw the Romans build the greatest empire of ancient times.

500 B.C. – Glaciers advance in western North America during a cool, wet period.

900-860 B.C. – Magnified tree section (inset) shows yearly climate in California between building of first temple in Jerusalem and founding of Carthage.

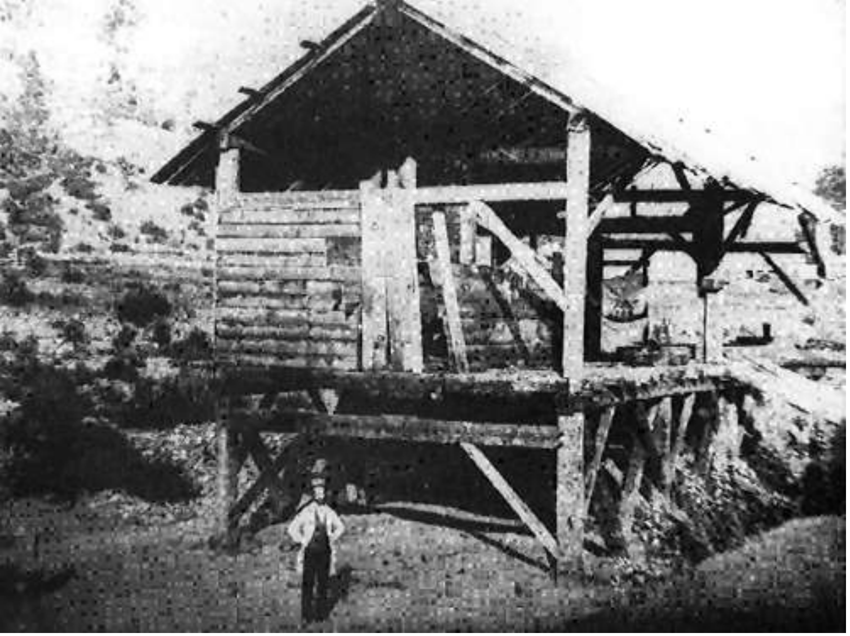
1626 B.C. – Thin ring from very cold summer, possibly due to sun-deflecting dust thrown into the stratosphere by volcano Thera in the Aegean Sea.



Climatic cycles are always recorded in the stratigraphy, whether deposition (datable) or erosion (inferred from missing materials). Chart at left was constructed from tree ring data in California's White Mountains, just east of the Sierras.

ANTHROPOGENIC IMPACTS SINCE 1850

California Gold Rush



- Gold discovered at Sutter's Mill in early 1848.
- 50,000 Americans descended upon California between 1849-52.
- Mining depended solely on riverine navigation. Tidal influence felt as far upstream as Marysville, on the Feather River

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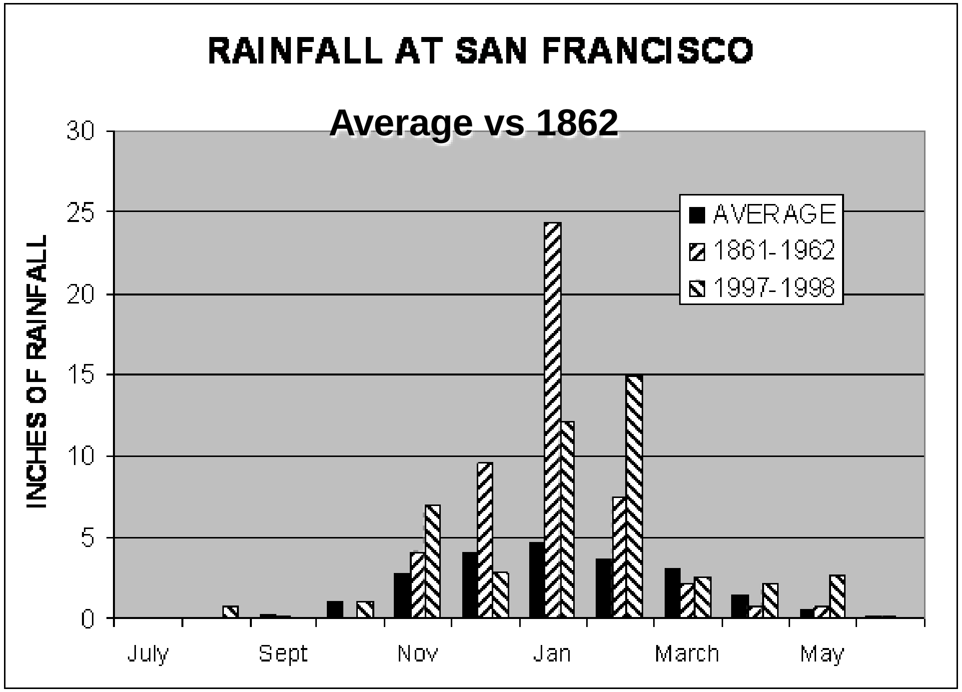
Hydraulic mining

- In 1852-53 a French-Canadian mining engineer named Anthony Chabot and his partner Edward Matteson began using hydraulic monitors to excavate gold-bearing Tertiary age gravels at Buckeye Hill and American Hill, near Nevada City.

Great Flood of 1862

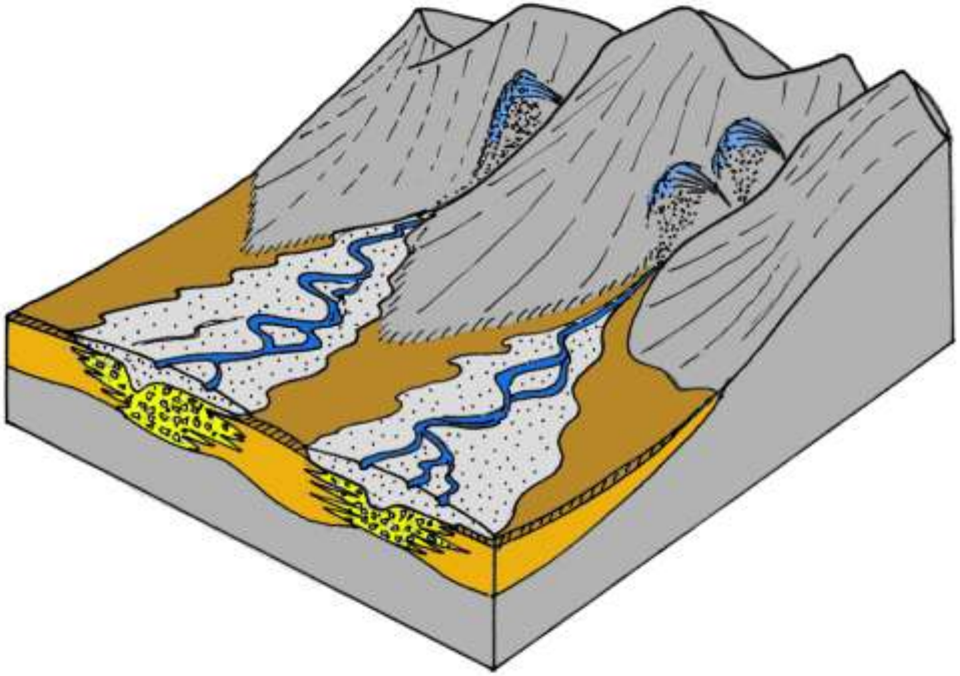


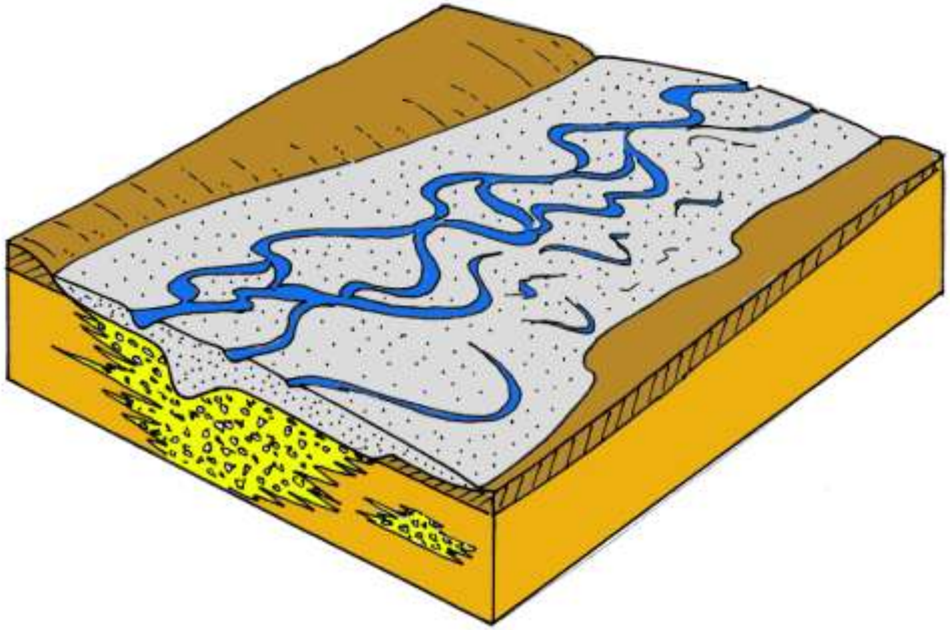
The great flood of 1862 brought record seasonal rainfall, the maximum event since western Europeans descended upon Alta California in the late 18th Century.

It caused massive flooding of Sacramento (K Street, shown at left)

Over the next 40 years, mountain channels disgorged nearly one cubic mile of mine slickens upon the Sacramento Valley and areas downstream.

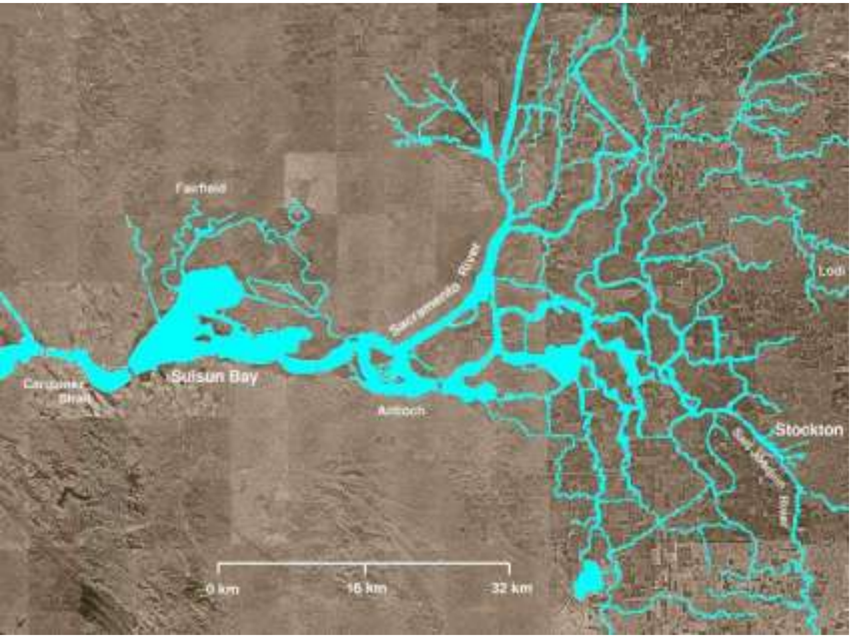
Environmental Catastrophe





- Between 1862-84 the Yuba, Bear, Feather, and American River Basins shed over a cubic mile of silt, termed "*mine slickens*"
- The debris choked the channels, stymied river navigation, and destroyed farmland in the Sacramento Valley.
- In 1884 the Wright Act forbade uncontrolled hydraulic mining
- In 1893 the California Debris Commission was formed

19th Century commerce moved up and down the rivers

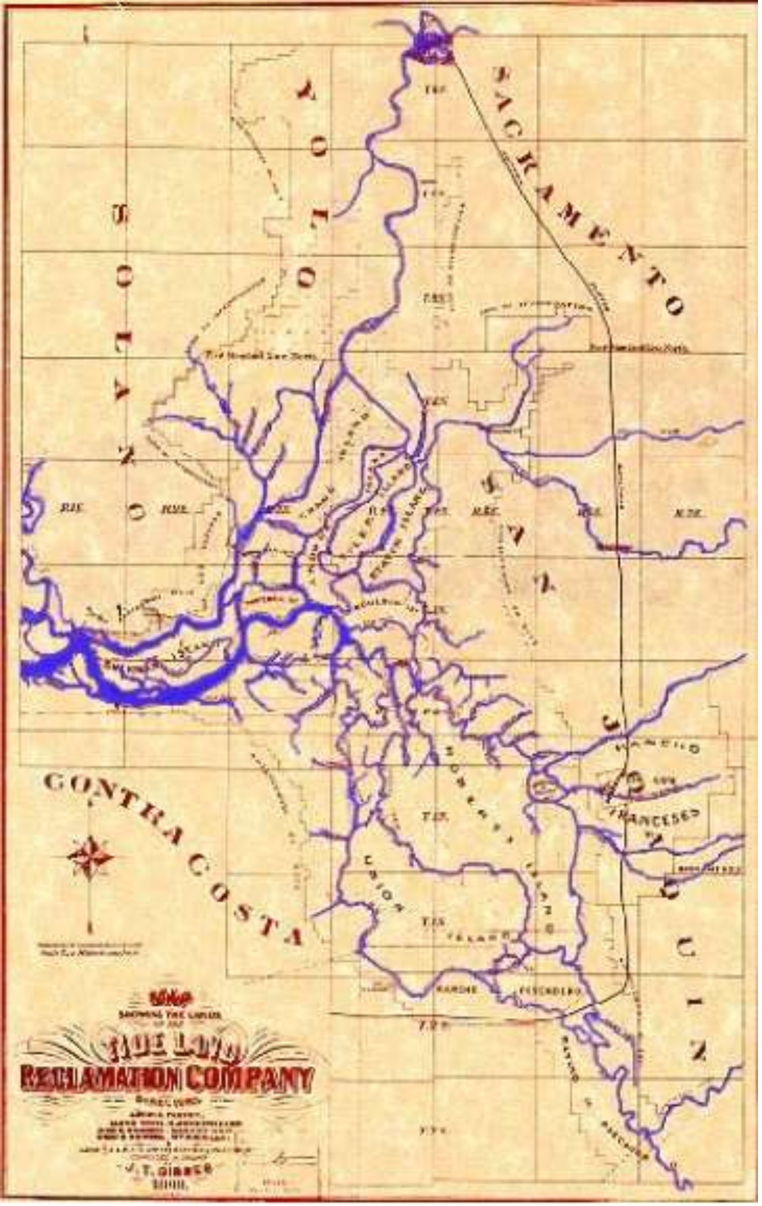


Maintaining riverine navigation was of paramount political import.

The delta was gradually developed by agricultural land speculators, beginning in the late 1860s.

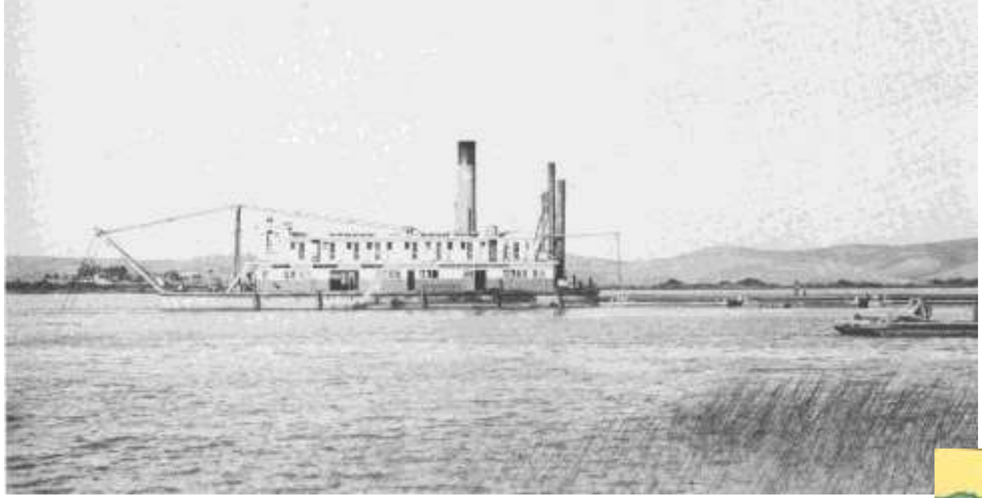
All of the early levees were made by excavating blocks of peat and stacking them atop one another, like bricks

Dredges run amuck 1884-1915

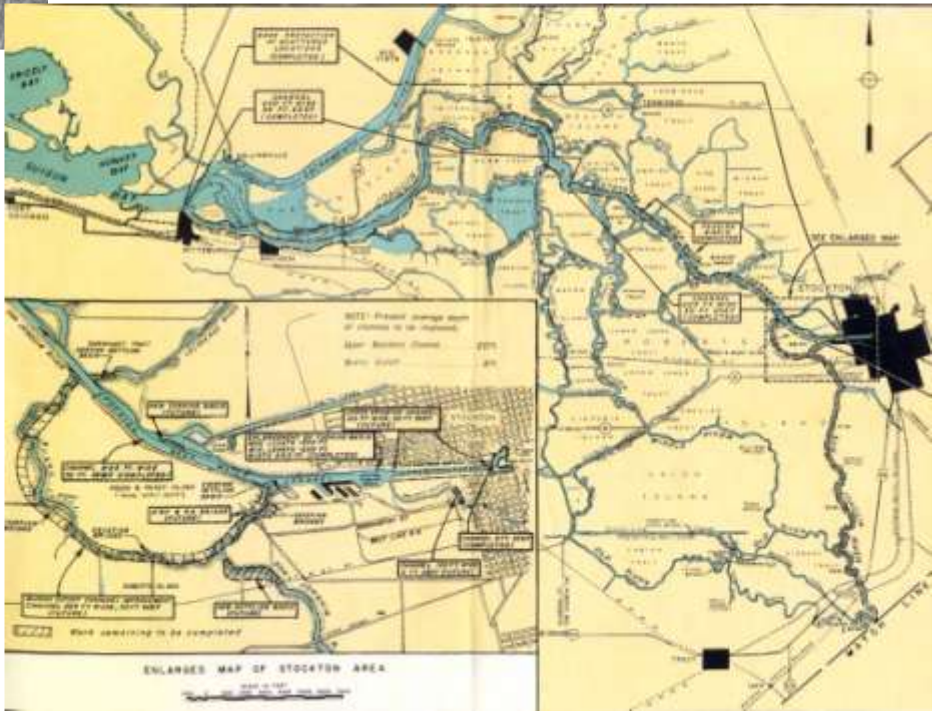


Clamshell dredges completed excavation and diking of almost 60 islands between 1884-1915

Corps' focus on riverine navigation



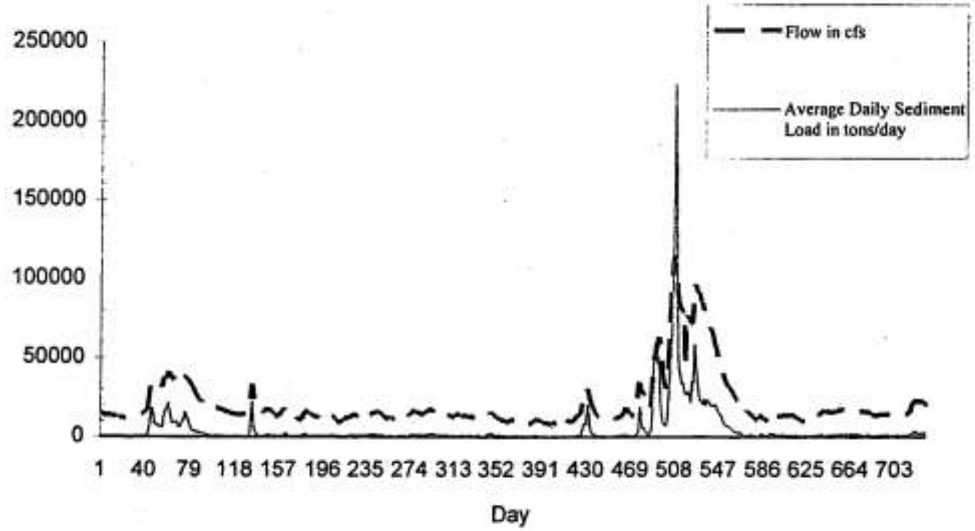
Corps' 20-inch suction dredge Sacramento, as seen in 1913



30-inch suction dredge Papoose, along the Stockton Ship Channel around 1931

River Bypass Flood Control

Carl Grunsky (1855-1934) designed the original system using three bypass weirs for the lower Sacramento River when he was Assistant State Engineer in the late 1890s. It was not adopted till 1913, after a series of destructive floods.



Sediment loads tend to be delivered during seasonal high flow events, generally of limited duration (as compared to the lower Mississippi River system). 1861-62 was the only season that exceeded 60 days of flood level runoff

Sacramento River Bypasses

The Sutter, Yolo, and Tinsdale Flood Bypasses along the lower Sacramento River have spared Sacramento from disastrous flooding, by diverting excess flow into agricultural areas west of the city in 1937, 1940, 1955-56, 1964-65, 1969, 1982, 1986, 1997, etc.

Massive re-engineering of channels

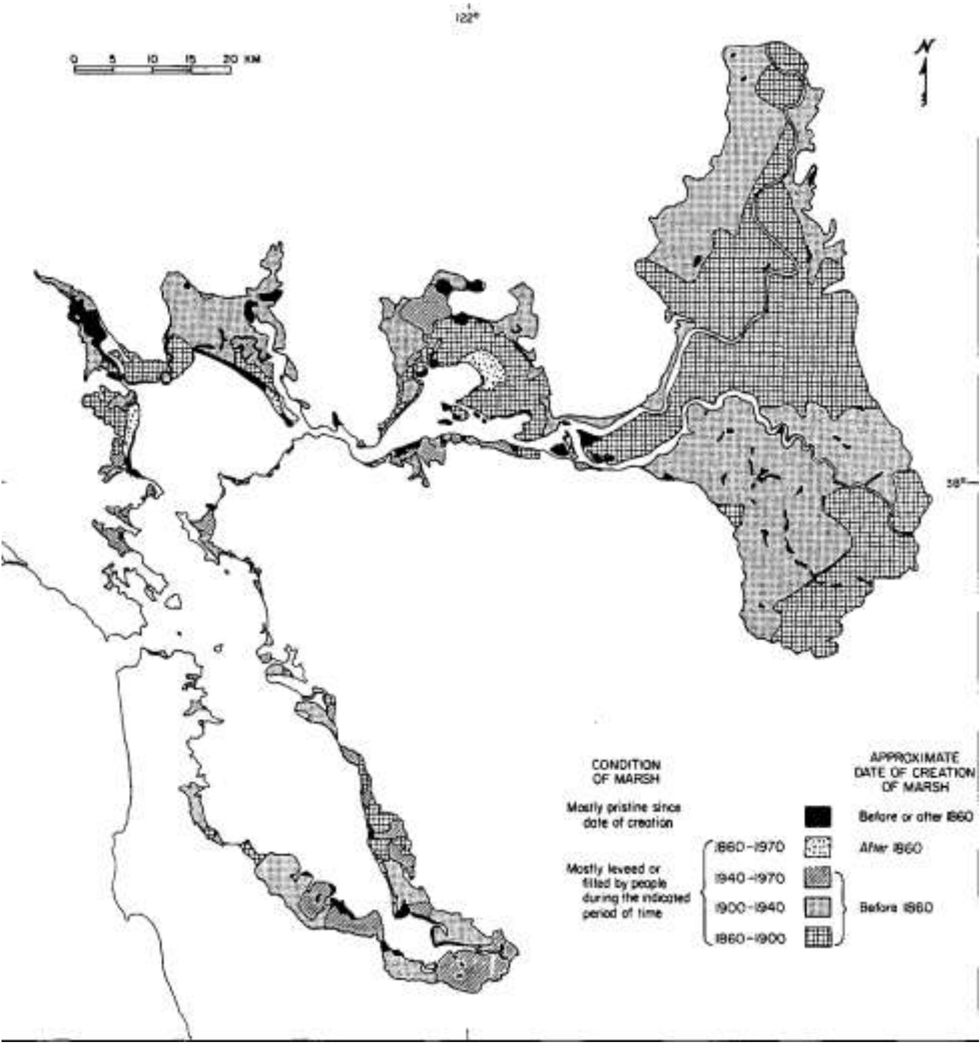
The Stockton Ship Channel was dredged across the heart of the San Joaquin Delta in the 1930s, without any geologic input

The alignment of the Sacramento Ship Channel was chosen because of its favorable geology, west of the delta's soft compressible soils

PEAT CO_2 FLUX AND SUBSIDENCE

Loss of Tidal Marsh

The expansive tidal marsh that existed in 1850 was initially impacted by the flood of 1862, followed quickly by reclamation schemes for agricultural development, beginning in 1866. The tule marshes were gradually reclaimed and were completely diked off by 1912.



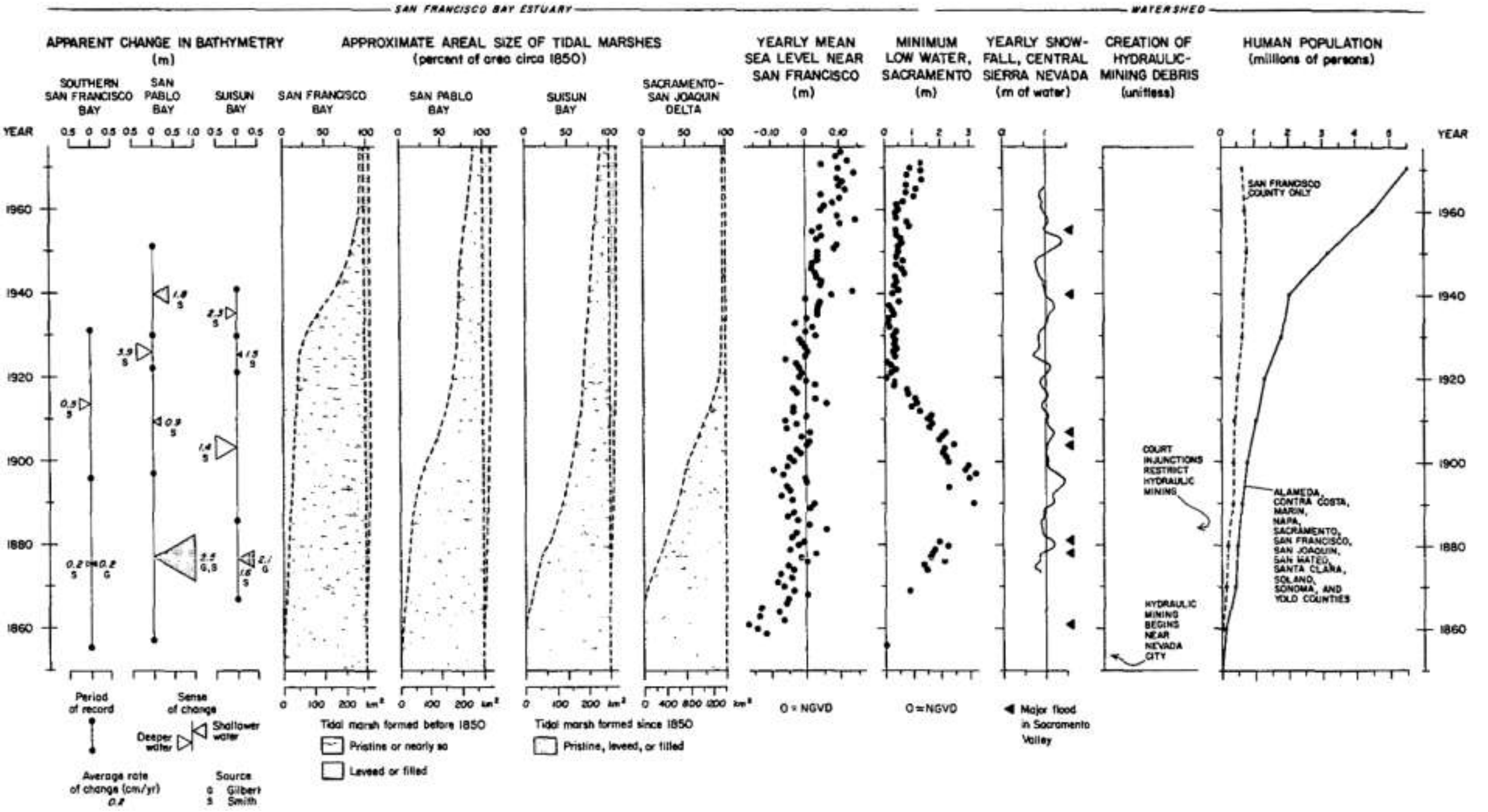
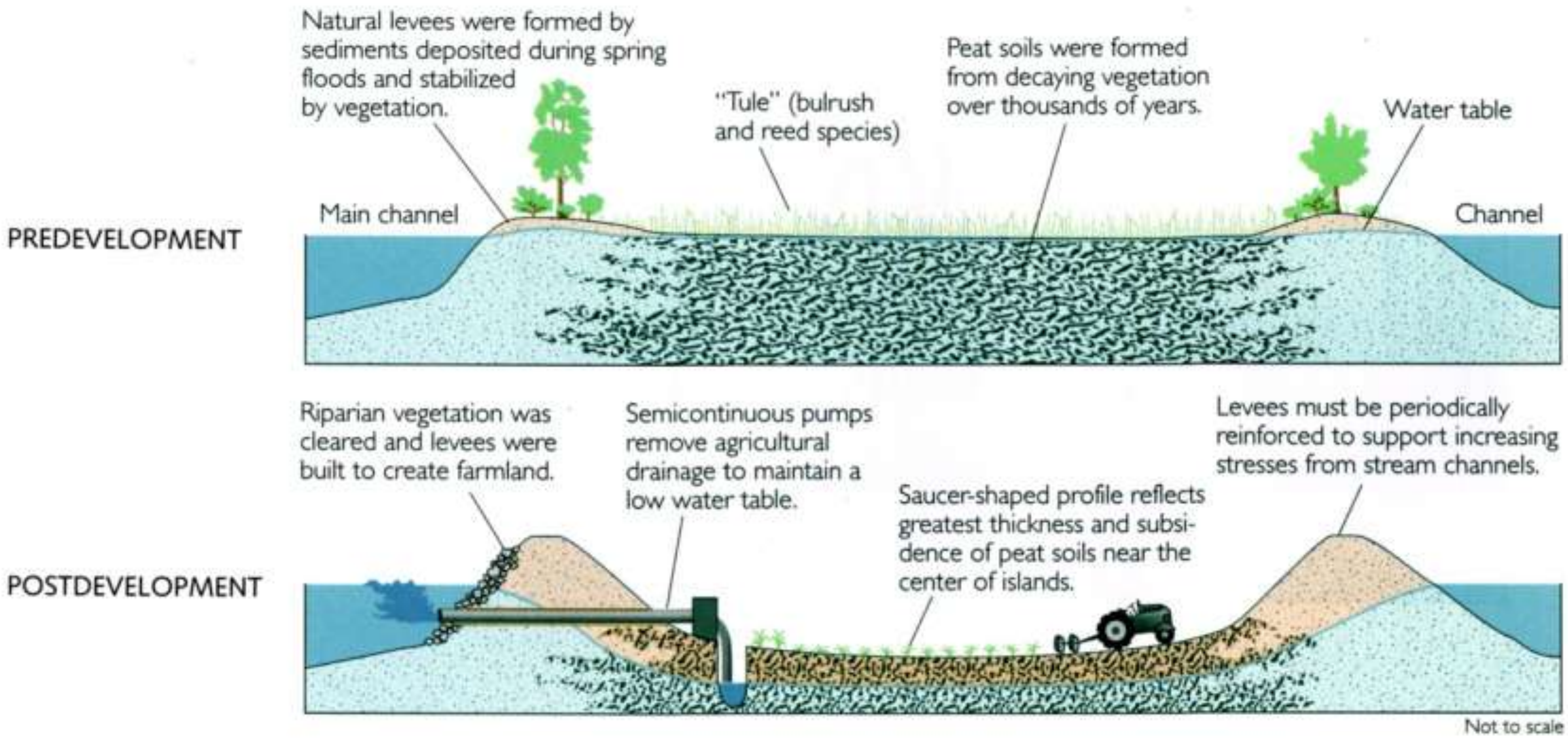
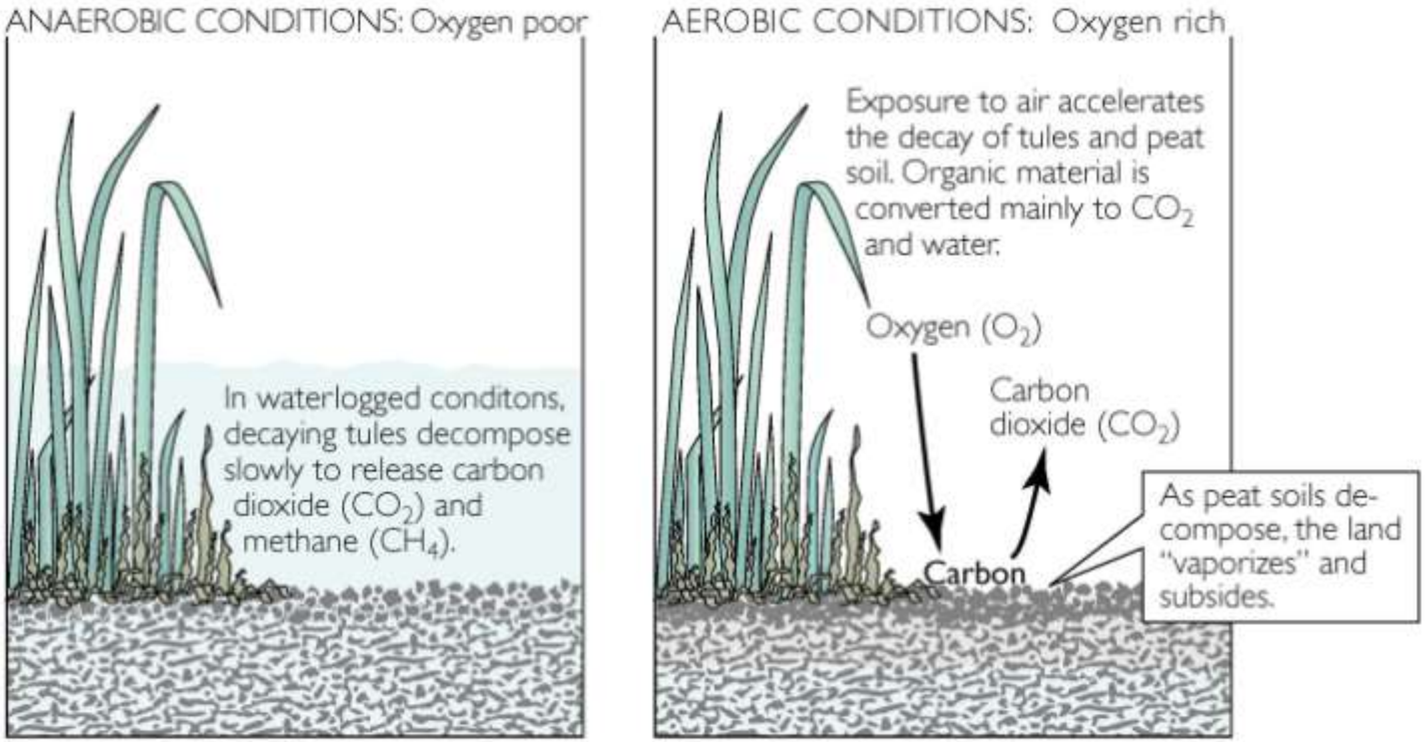


Chart showing correlations between historic events contributing to the loss of the fresh water tidal marshes of the Sacramento-San Joaquin Delta (from Atwater, 1979)

Cultivation promotes decomposition



Peat decomposition is hastened by cultivation of the tule marshes, which accelerates oxidation by drainage, plowing; burning of the old peat soils to reduce weeds and insects and return potash to the soil; wind erosion of loosened peat; and local compaction by farm machinery.



ANAEROBIC CONDITIONS: Oxygen poor

In waterlogged conditons, decaying tules decompose slowly to release carbon dioxide (CO_2) and methane (CH_4).

AEROBIC CONDITIONS: Oxygen rich

Exposure to air accelerates the decay of tules and peat soil. Organic material is converted mainly to CO_2 and water.

Oxygen (O_2)

Carbon dioxide (CO_2)

Carbon

As peat soils decompose, the land "vaporizes" and subsides.

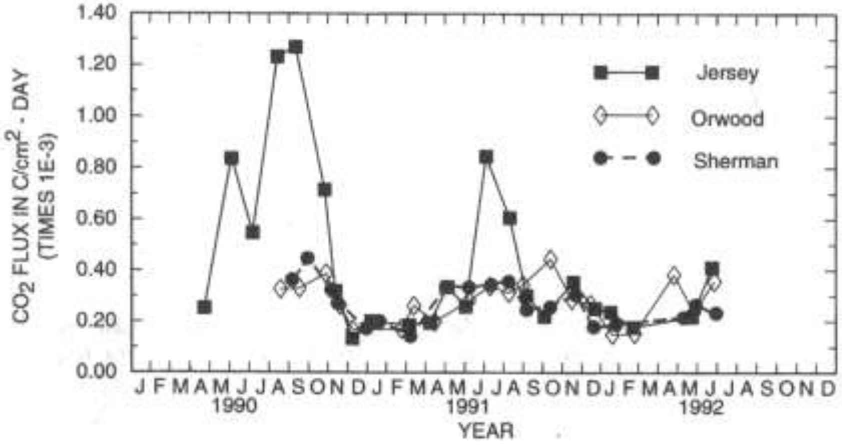


Figure 4. CO_2 flux measured on Jersey Island, Orwood tract, and Sherman Island, March 1990 to May 1992. The points represent the arithmetic average of measurements at five sites on each island or tract.

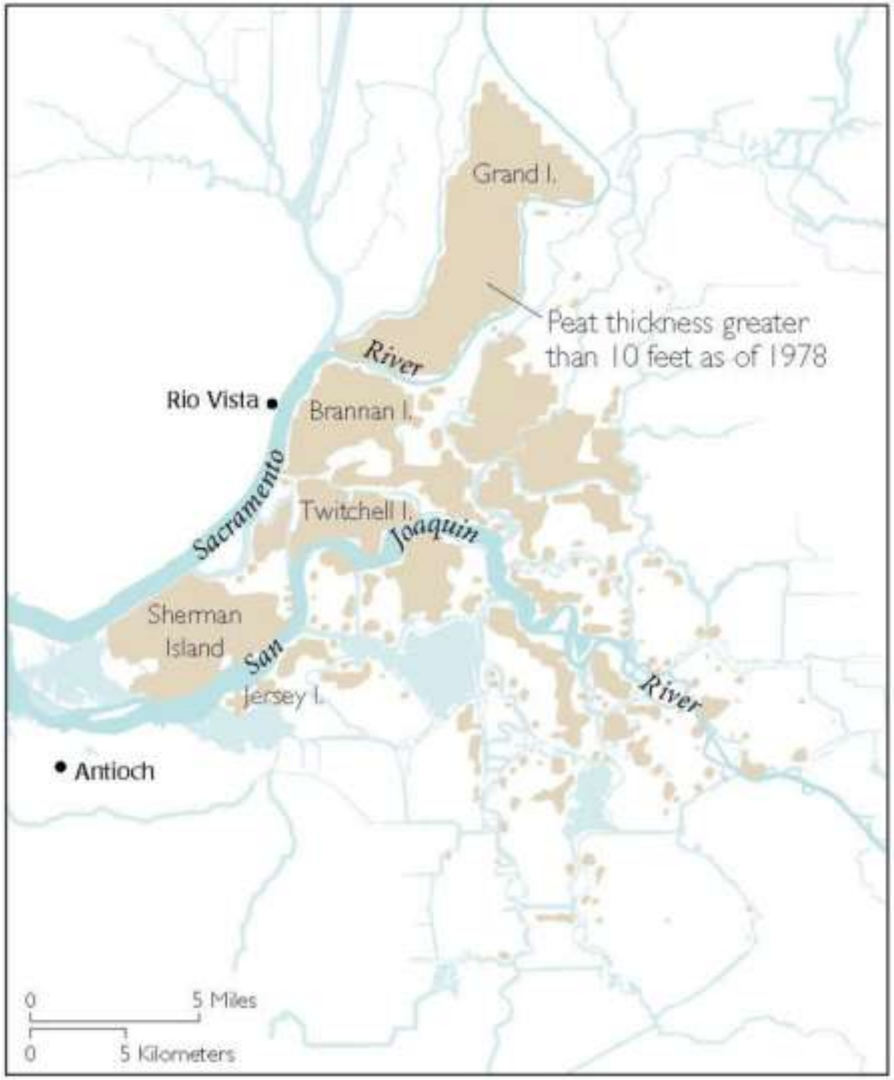
Agricultural cultivation has shifted the tule marshes from anaerobic to aerobic conditions, which diminishes with increasing depth

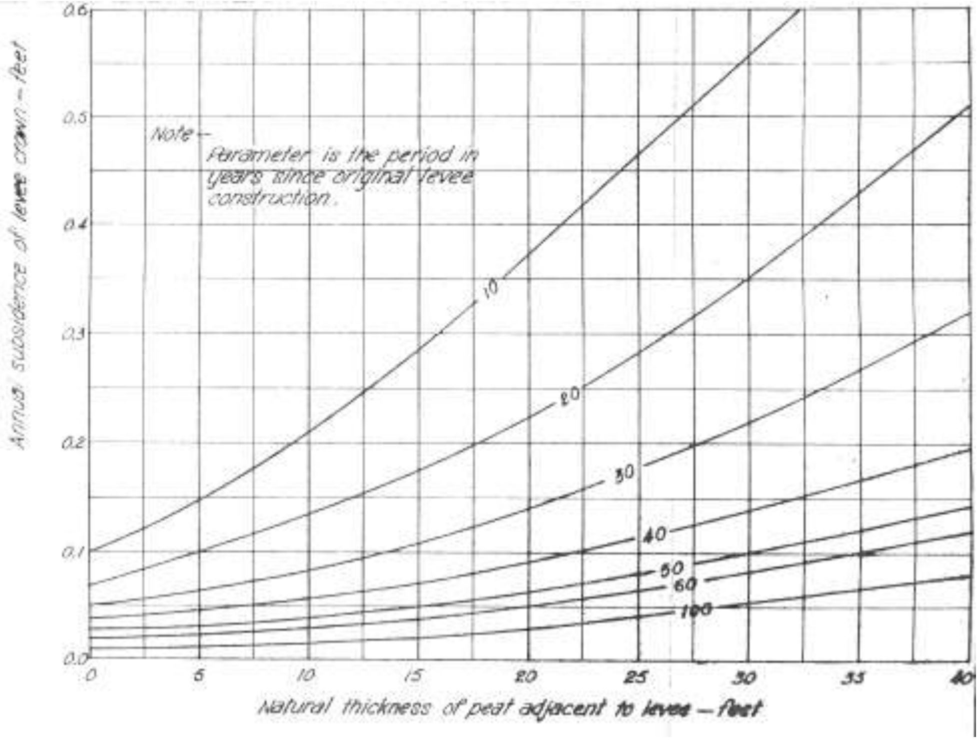
Settlement of peaty soils

Ground settlement in the peaty soils is caused by biochemical oxidation; which is exacerbated by farming, wind erosion , fires, and subsidence due to compaction of underlying units (increased effective stress triggered by groundwater withdrawal)

Deep-measurement compaction recorders are needed to permit differentiation between ground settlement caused by surface oxidation and compaction of the peaty soils from deeper subsidence resulting from groundwater and/or gas withdrawal

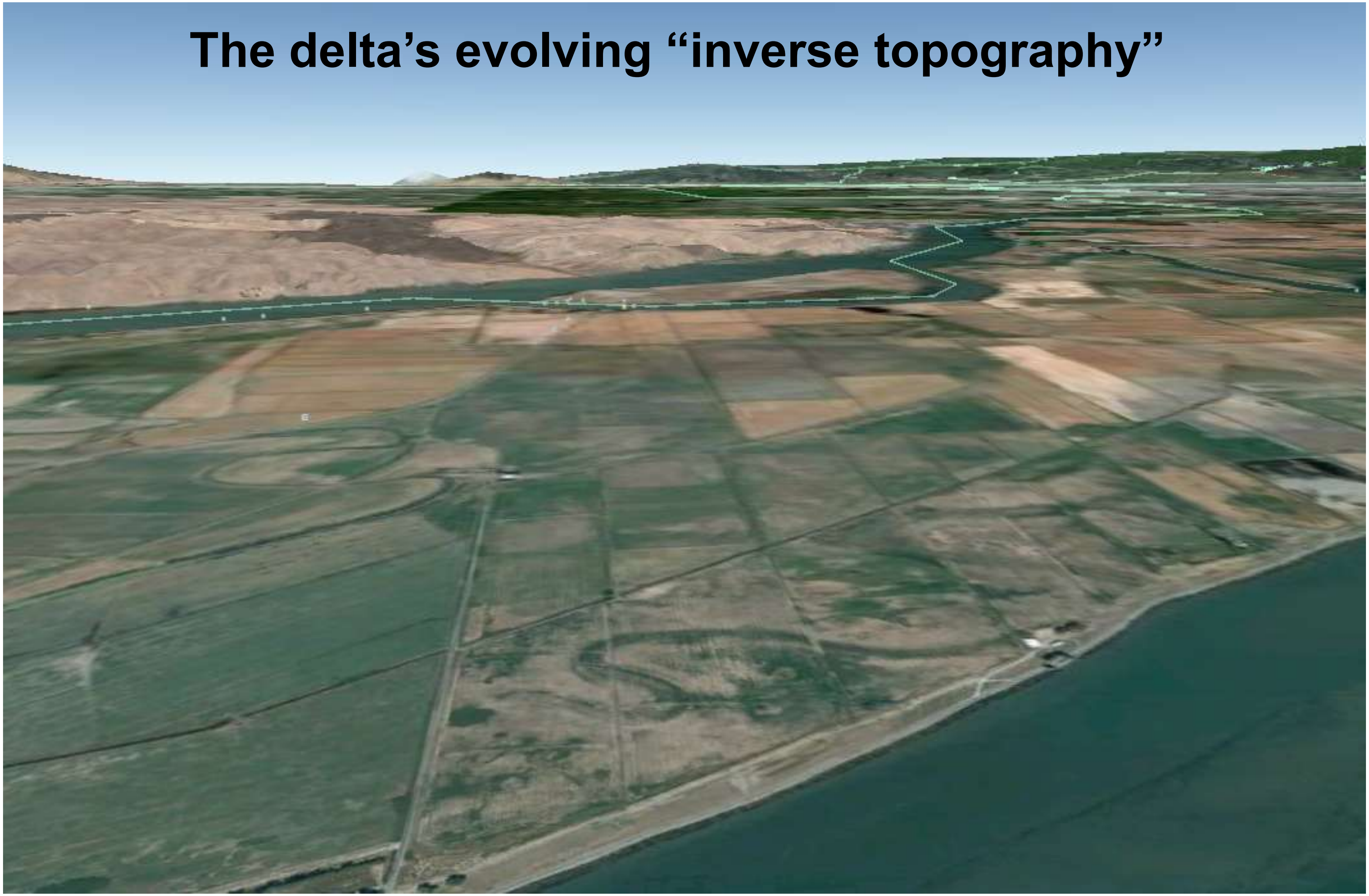
Peat Compaction tied to mineral content, depth of burial, and thickness



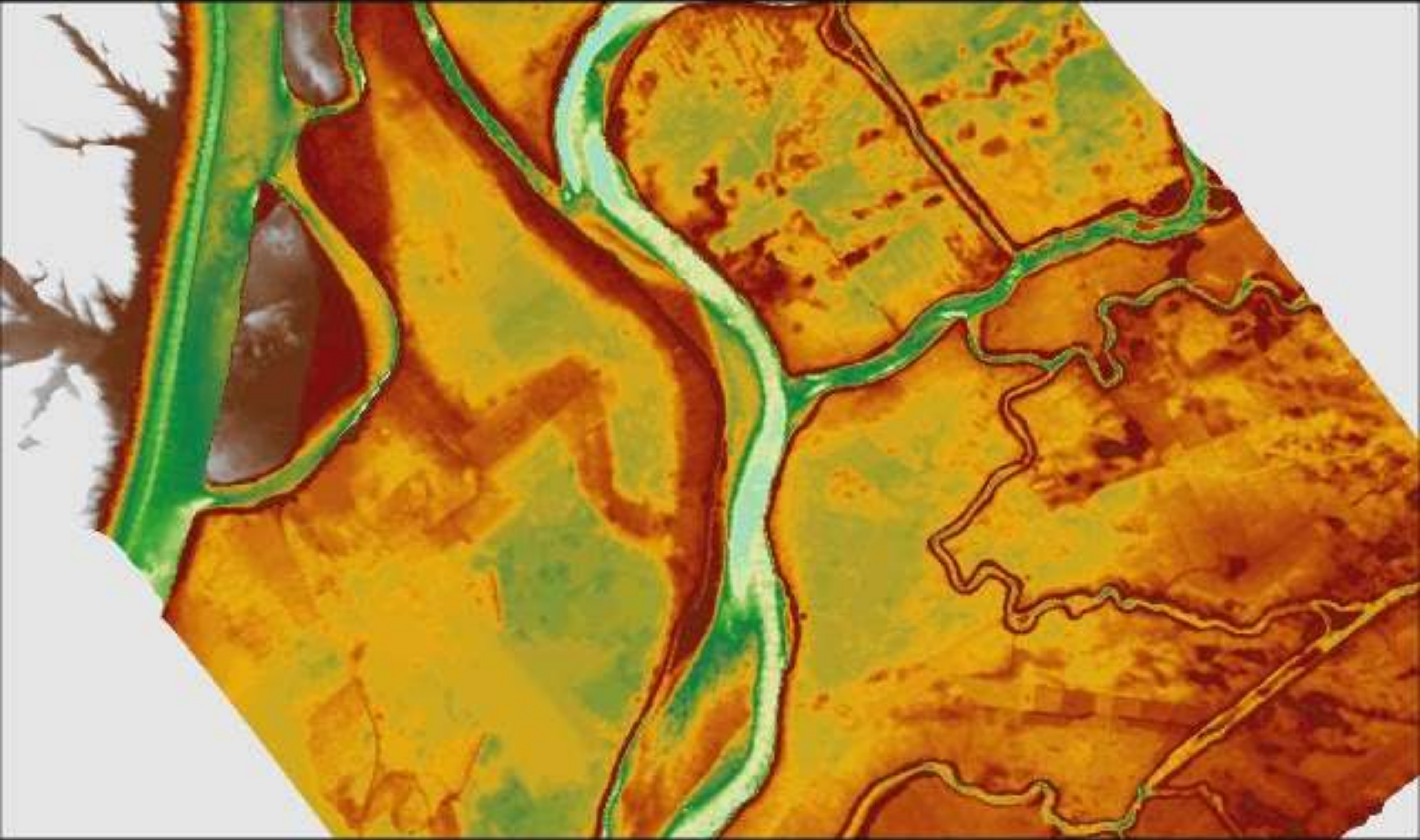


Rough correlations between peat thickness and annual subsidence, drawn between 1910-65

The delta’s evolving “inverse topography”

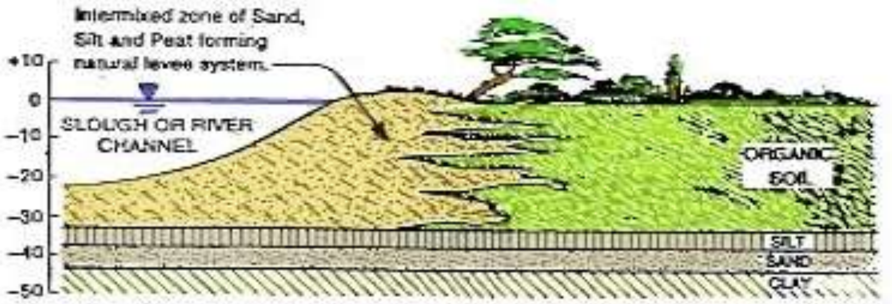


As the organic soils settle across the delta, the relict topography is being increasingly revealed, as the natural levees begin to “push” themselves up, revealing the positions of the most recent distributary channels.

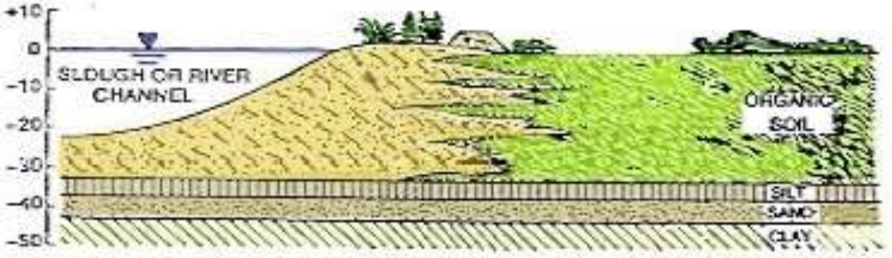


Physical position often dictates levee performance

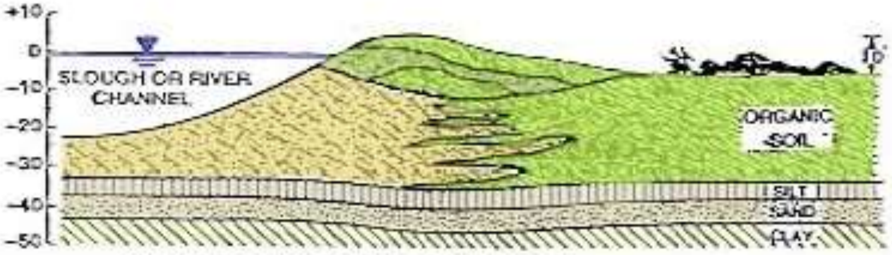
- The delta peats formed along the margins of major distributary channels, under the freshwater tule and bullrush marshes.
- Levees founded on natural channel margins perform better than those adjacent to channels dredged through the tule marshes



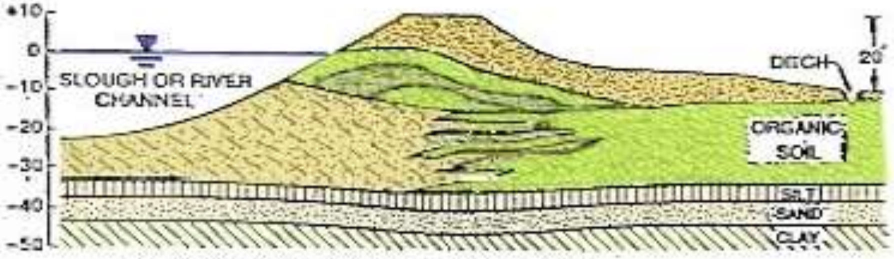
A. NATURAL LEVEE PRIOR TO RECLAMATION



B. INITIAL LEVEE CONSTRUCTION IN EARLY 1870's

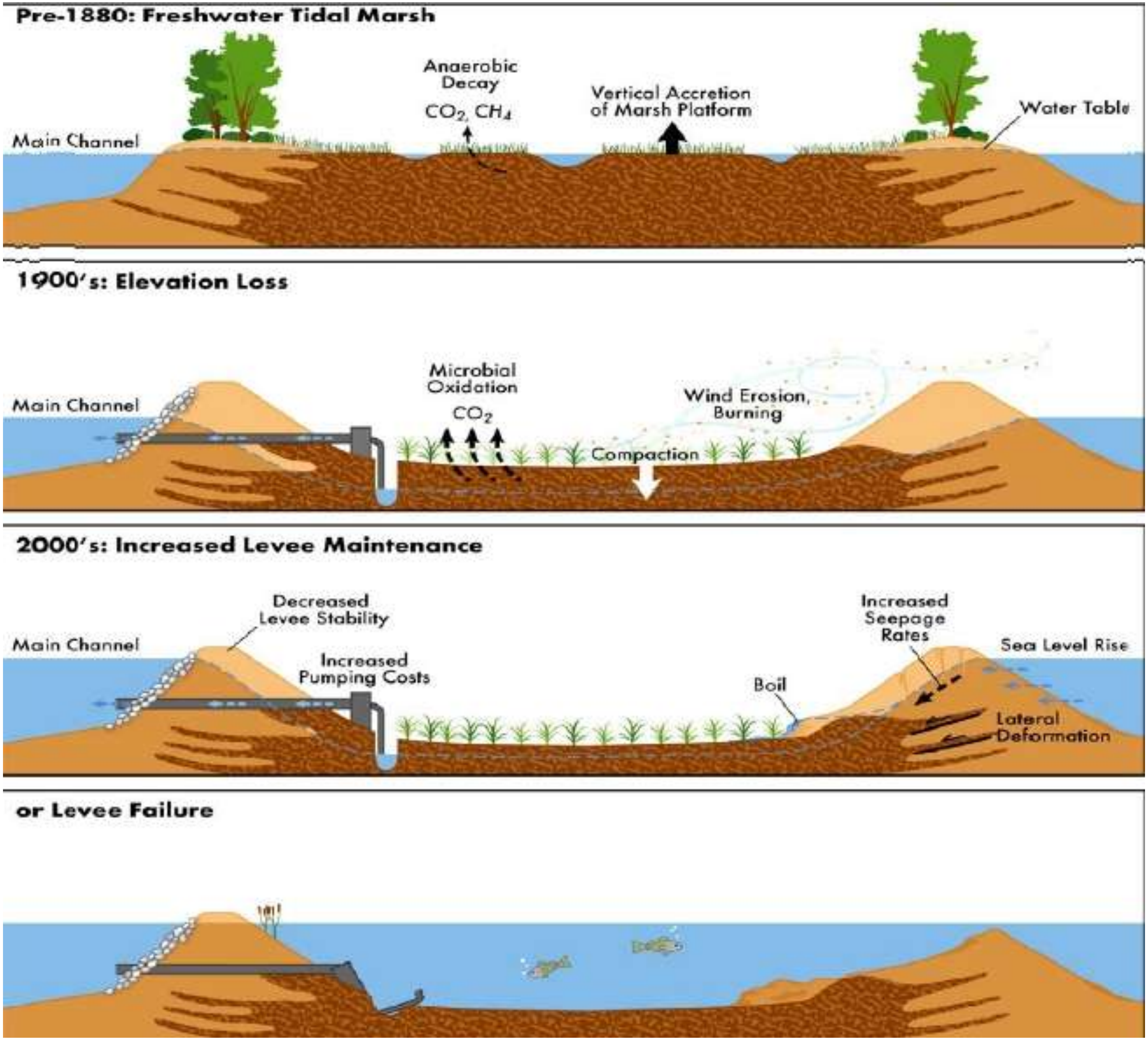


C. LEVEE STAGE IN EARLY 1900's

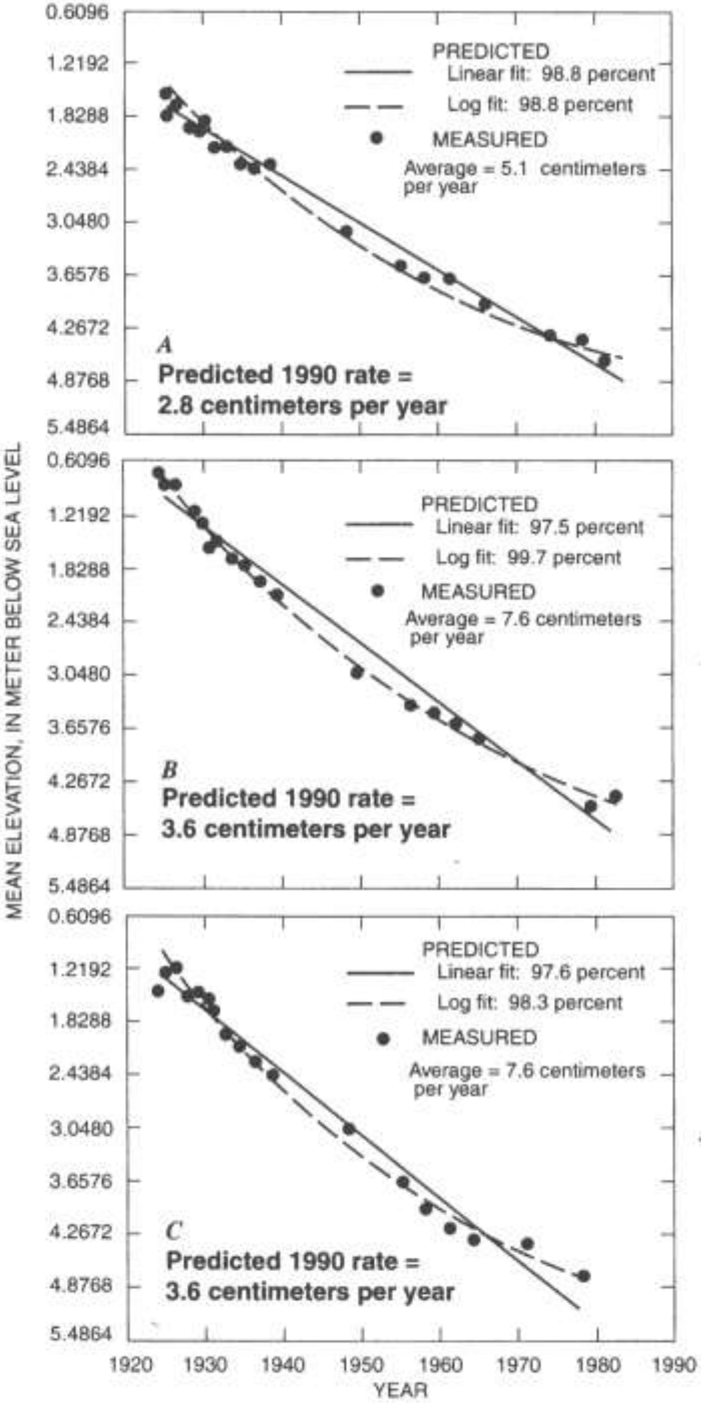


D. CURRENT LEVEE CONDITIONS

The dredged channel at left lies *outboard* of the natural channel, so the levee lies upon compressible peats rather than upon the natural levee bordering the river channel.


Pre-1880: Freshwater Tidal Marsh
Main Channel
Anaerobic Decay
CO2, CH4
Vertical Accretion of Marsh Platform
Water Table
1900's: Elevation Loss
Main Channel
Microbial Oxidation
CO2
Wind Erosion, Burning
Compaction
2000's: Increased Levee Maintenance
Decreased Levee Stability
Main Channel
Increased Pumping Costs
Increased Seepage Rates
Sea Level Rise
Boil
Lateral Deformation
or Levee Failure

Settlement rates depend on organic content



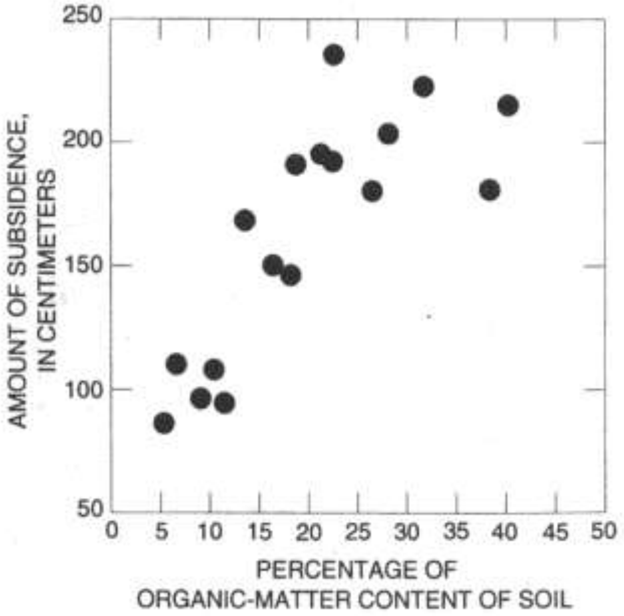
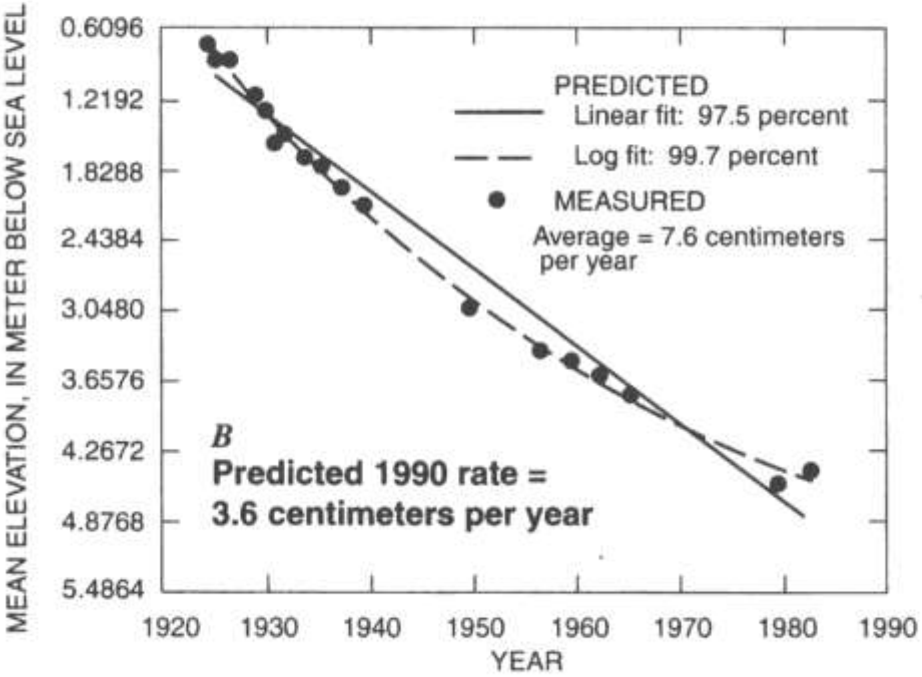


Figure 3. Relation of land-surface elevation and soil organic matter content for Sherman Island.

Peats have the widest range of physical properties of any soil on the Earth! Our delta peats vary between 5% and 40% organics, while those in the Atachafalaya Basin of Louisiana are typically >65% organics. Be careful not to co-mingle Louisiana data with California data

Is the peat oxidation being naturally arrested?



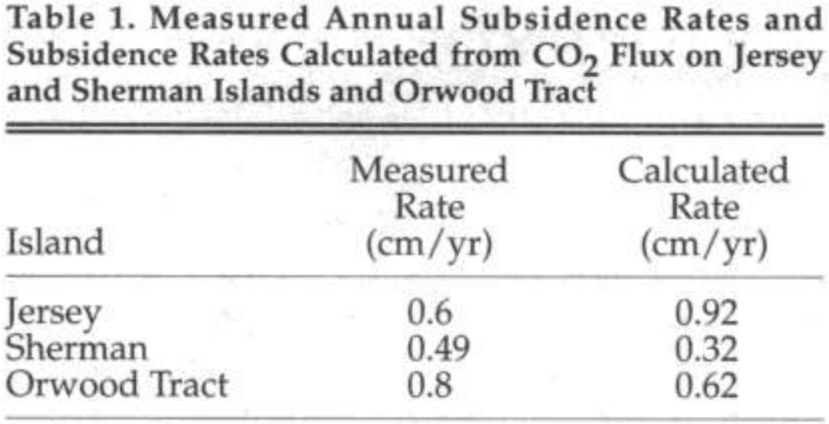
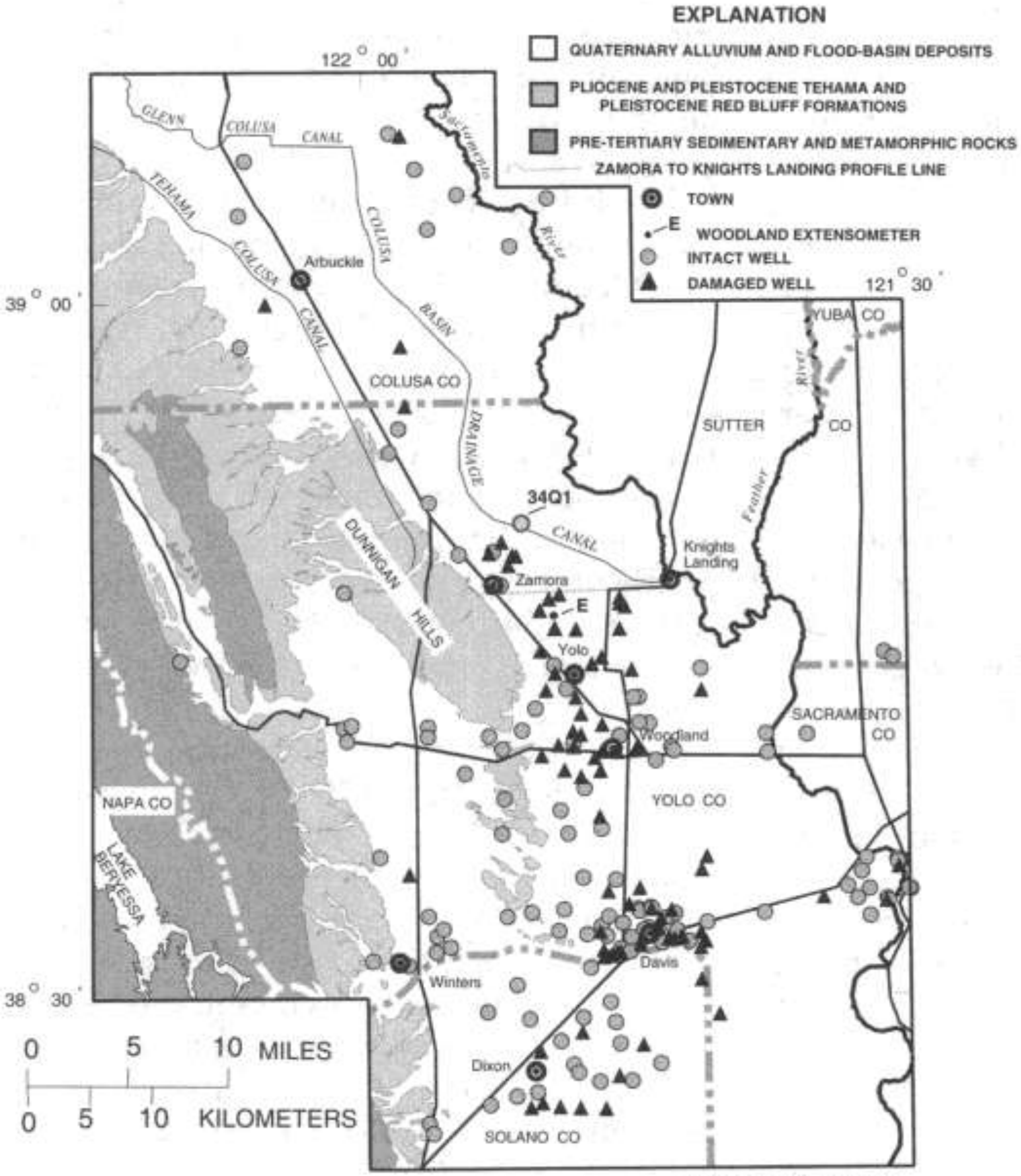


Table 1. Measured Annual Subsidence Rates and Subsidence Rates Calculated from CO_2 Flux on Jersey and Sherman Islands and Orwood Tract

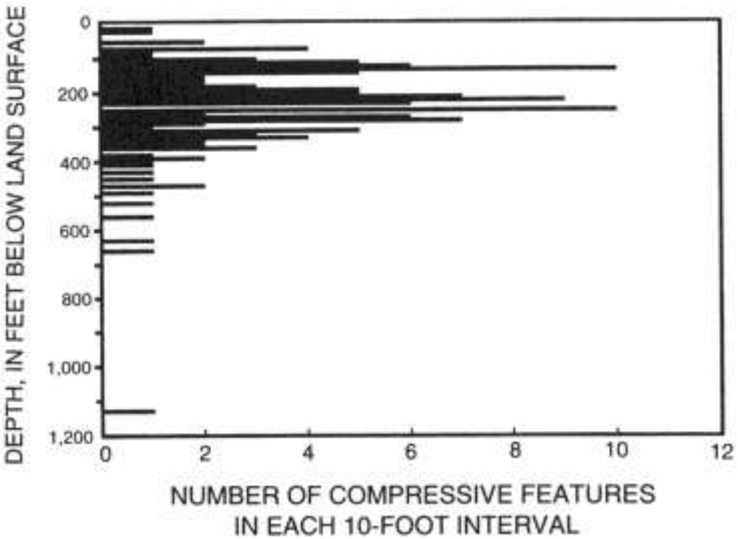
Island	Measured Rate (cm/yr)	Calculated Rate (cm/yr)
Jersey	0.6	0.92
Sherman	0.49	0.32
Orwood Tract	0.8	0.62

Predictions of future peat consolidation and settlement should model the decreasing rates of oxidation, as deeper substrata are exposed to aeration. If agricultural irrigation is suspended , or drought conditions persist, the problem could quickly become non-linear.

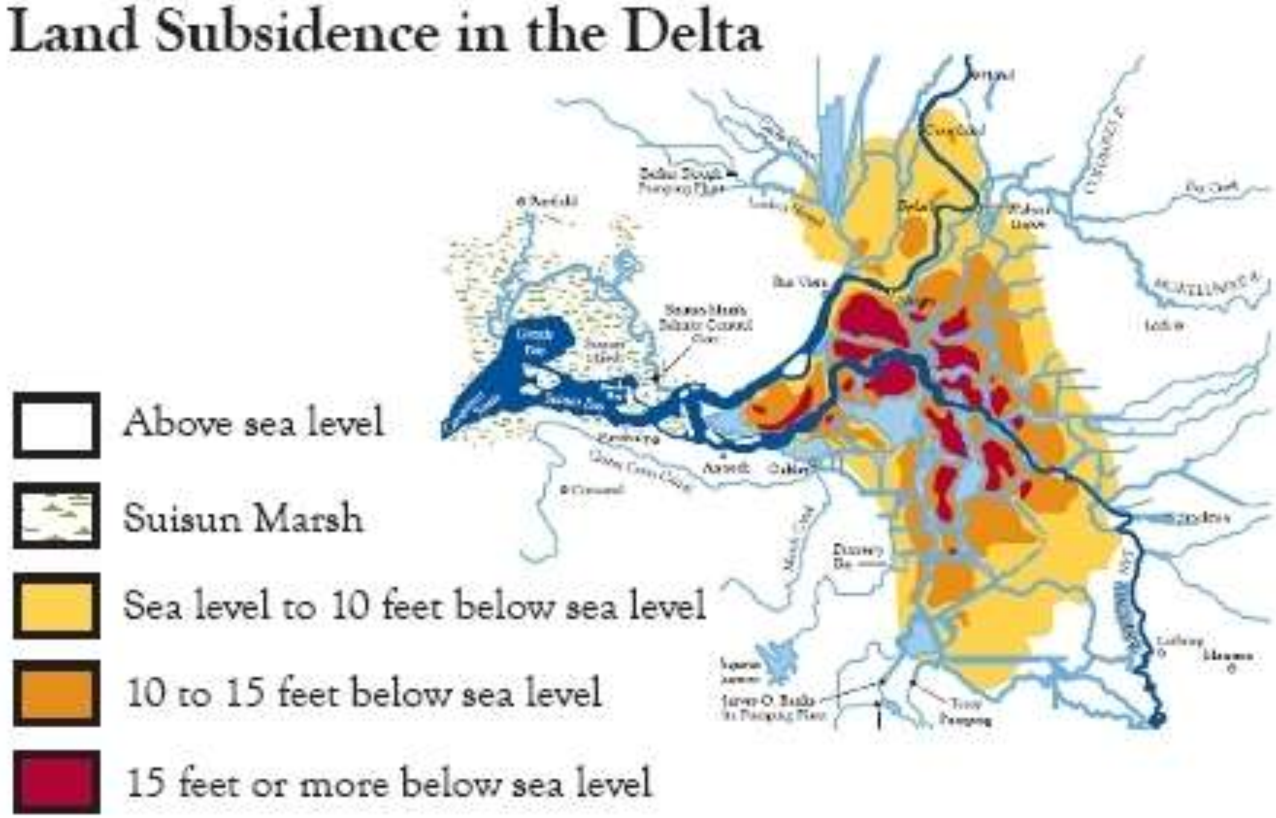
Settlement of older geologic units

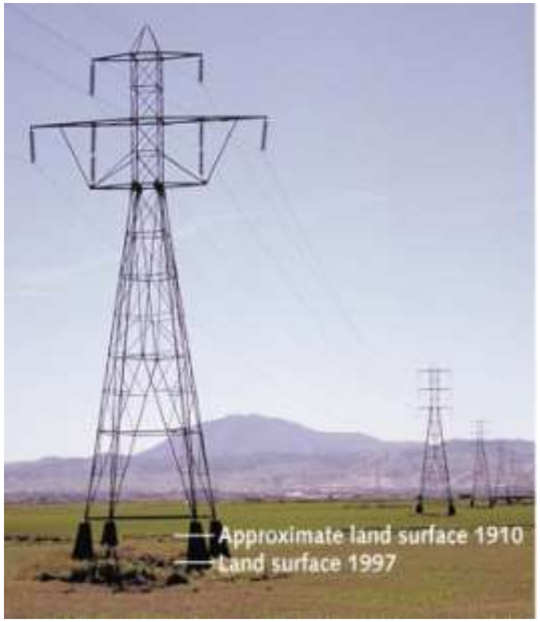


GEOLOGY MODIFIED FROM HELLEY AND HARWOOD, 1985



There is also considerable deep-seated ground settlement in the southwestern Sacramento Valley being triggered by groundwater withdrawal

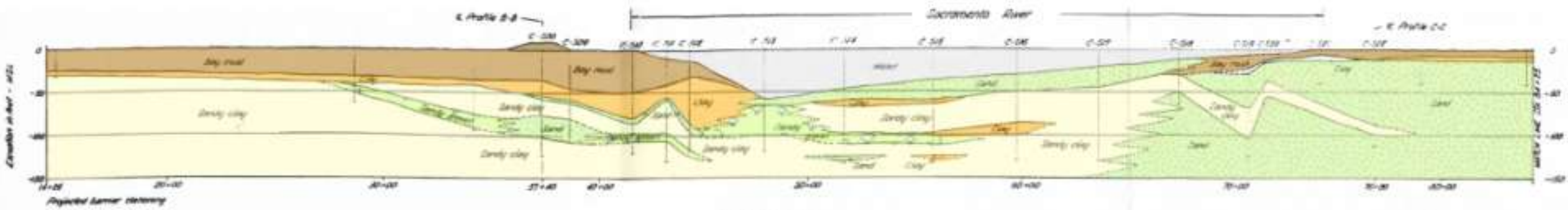




Those islands underlain by the thickest accumulations of peat will be increasingly difficult to maintain, using conventional technologies.

SITE CHARACTERIZATION ISSUES IN THE DELTA

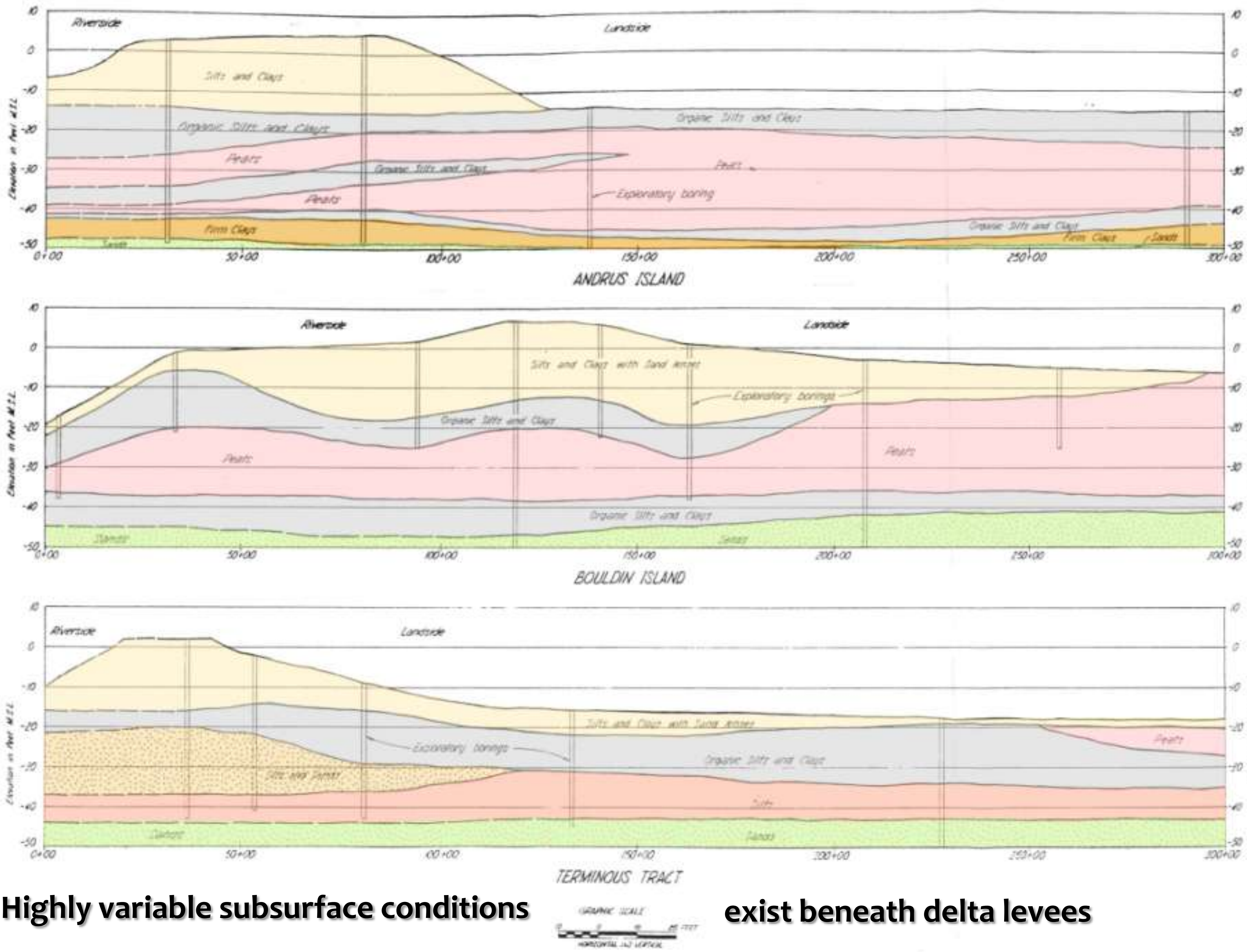
The major historic channels tend to truncate stratigraphic units – you won't find the same materials within, or often, on either side of the channels



PROFILE A-A
ALONG SACRAMENTO NORTHERN RAILWAY

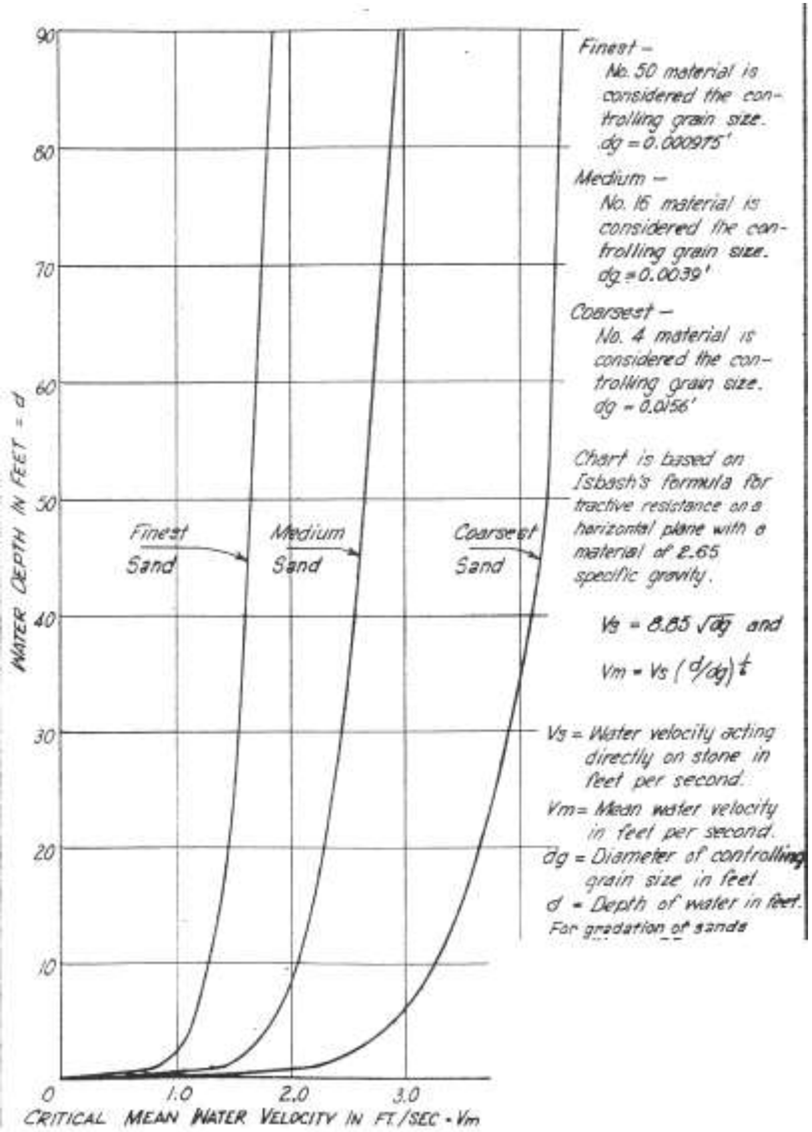
Corps of Engineers geologic cross section through the main Sacramento River channel near Collinsville, circa 1963. Note how the underlying units do not correlate well across such a large channel, which conveys all of the runoff emanating from the Central Valley watershed to the Pacific Ocean.

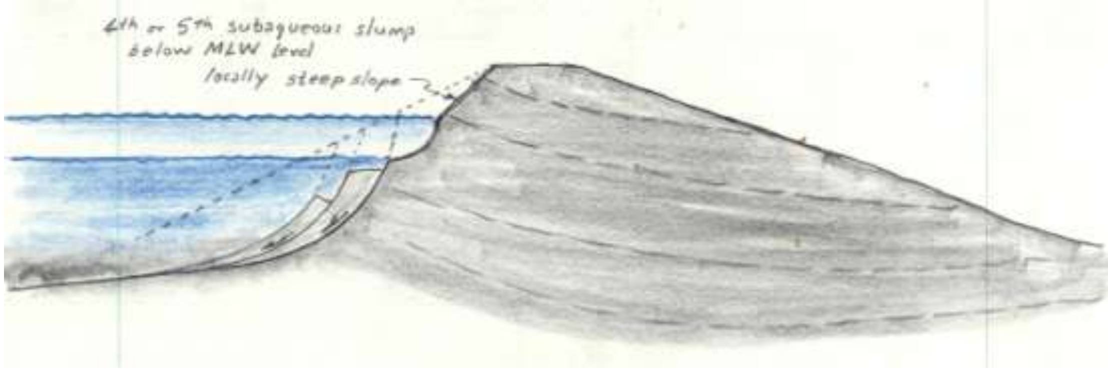
This channel trough has been excavated through a "bedrock notch" in the Montezuma Hills that has controlled the growth of the delta over the past one million years. This structural block lying between the Rio Vista and Pittsburgh faults, has continued to uplift throughout the Holocene.



Highly variable subsurface conditions exist beneath delta levees

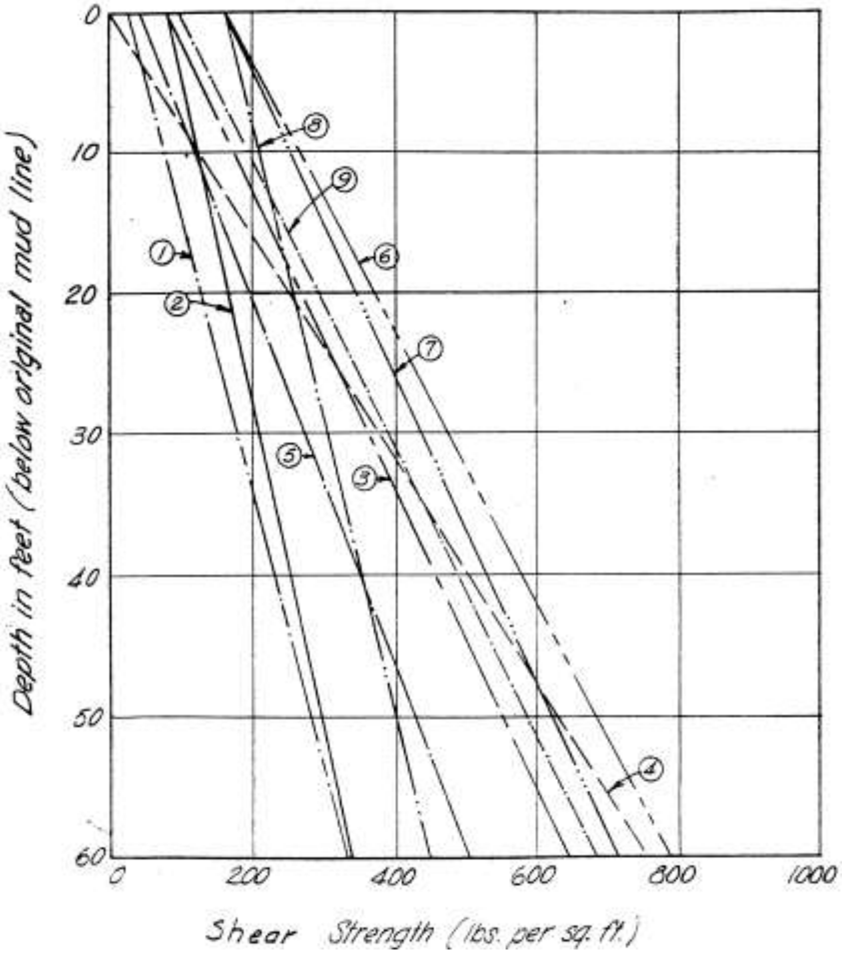
Erosion we all too often don’t see or appreciate



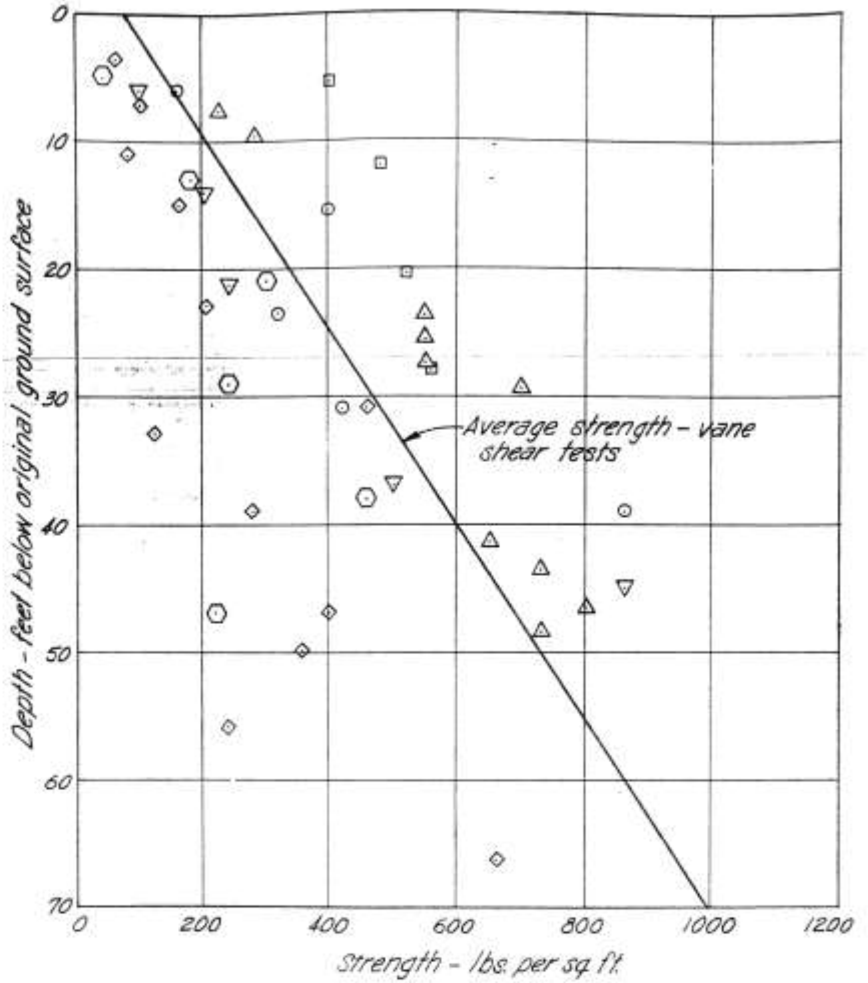


Detailed bathymetry surveys during the past ~15 years have revealed extensive erosion of levees along many of the trunk channels, below the mean low water surface, where it can’t be seen by inspectors

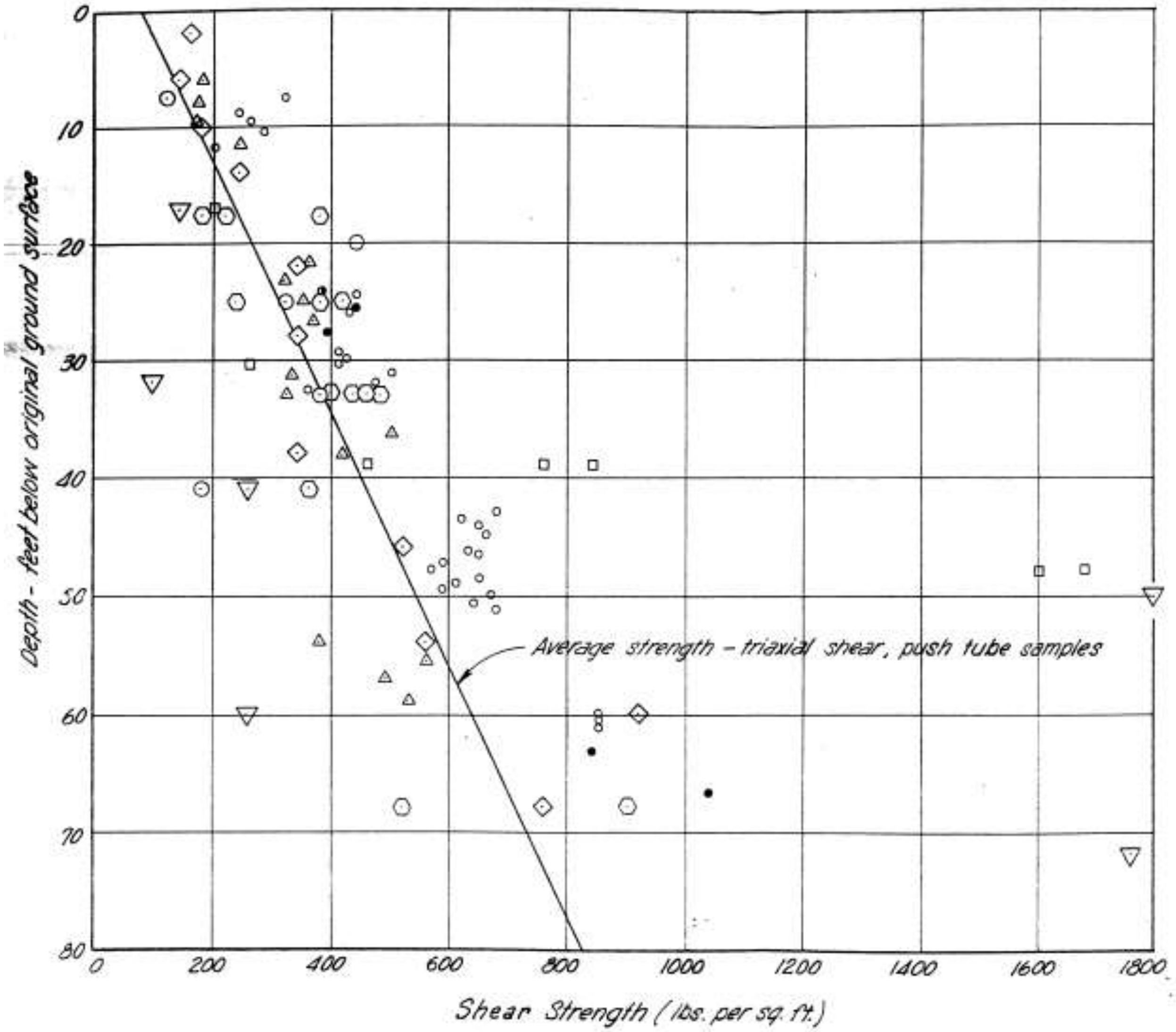
Variability in soil properties ascribable to depositional origin, depth of burial, and load history



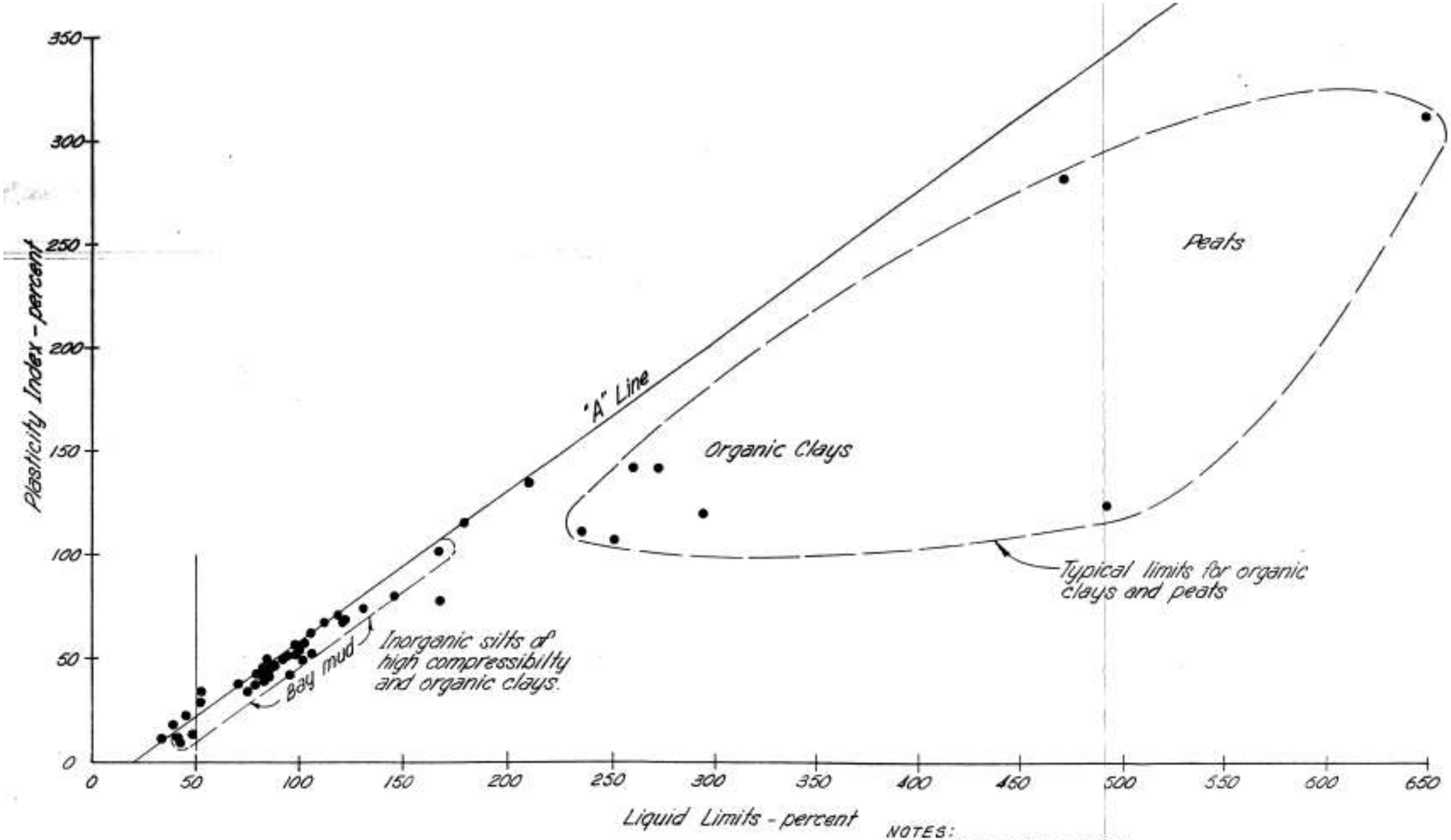
Design shear strengths used for Young Bay Mud at various sites in SF Bay



Vane shear strengths of delta clays. Which value do we use?



Triaxial shear strength test of delta soils; note average strength. If an "average levee" sits on an old soft channel fill, with less than the average strength, then it can experience stability problems

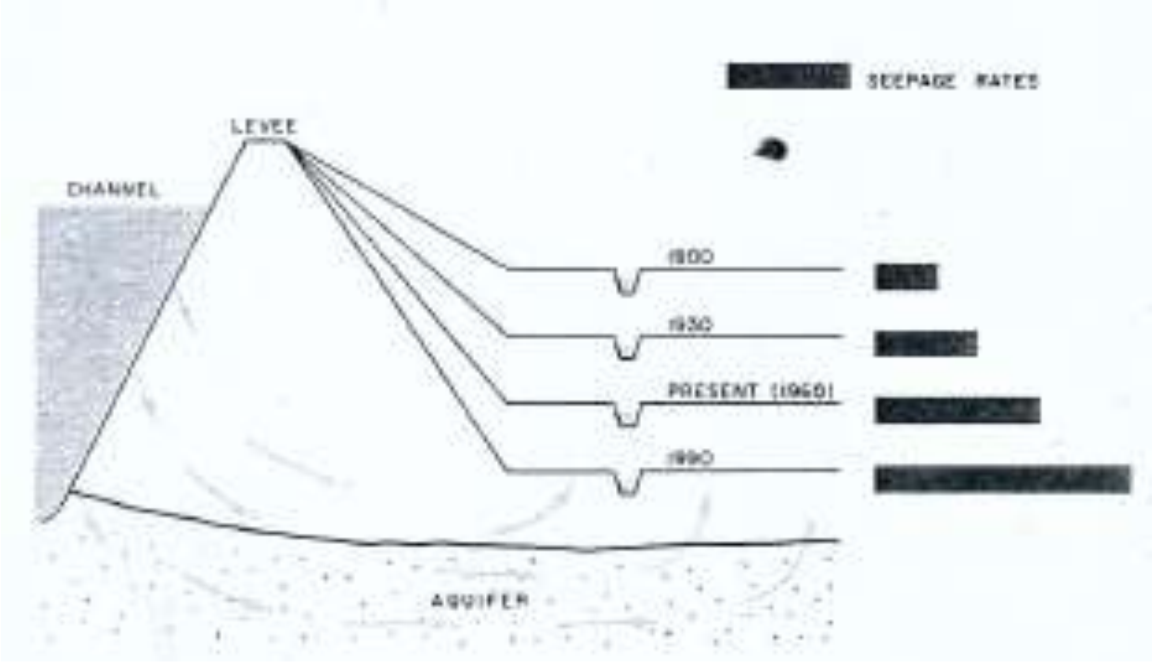


NOTES:
1. Data from borings B-506 thru B-527 and B-228.
2. For location of borings see Plates 8 and 11.
3. For logs of borings see Plates 41 and 42.

Soil plasticity exhibited by delta peats and Young Bay Mud. Note the high degree of spatial variability exhibited by the peats. The use of "average strength parameters" will inevitably lead to over estimates of levee performance and stability

WE CAN EXPECT PREFERENTIAL SEEPAGE PROBLEMS

Degrading Factor of Safety

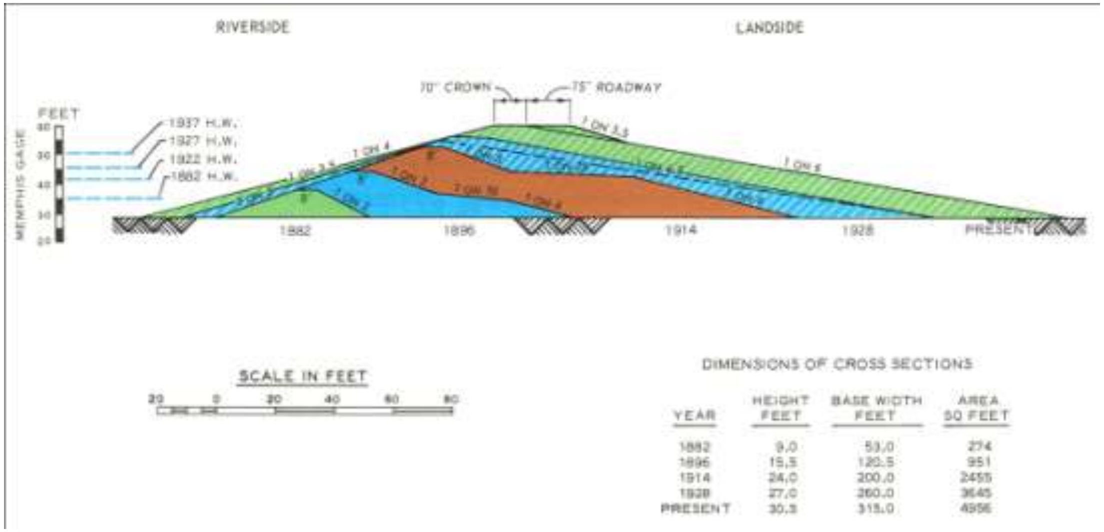


- As the delta continues to subside, the levees become higher, with increased seepage gradients, lowering their relative factor of safety, absent other aging effects.


Levee failures can be triggered by any number, or combination of factors. The most common is overtopping, followed by underseepage and piping. Aging effects and the variability of channel geometry, foundation materials, and penetrations through embankment materials combine to make reliable stability analyses difficult.

Preferentially directed seepage

Photo: MBK Engineers



DIMENSIONS OF CROSS SECTIONS

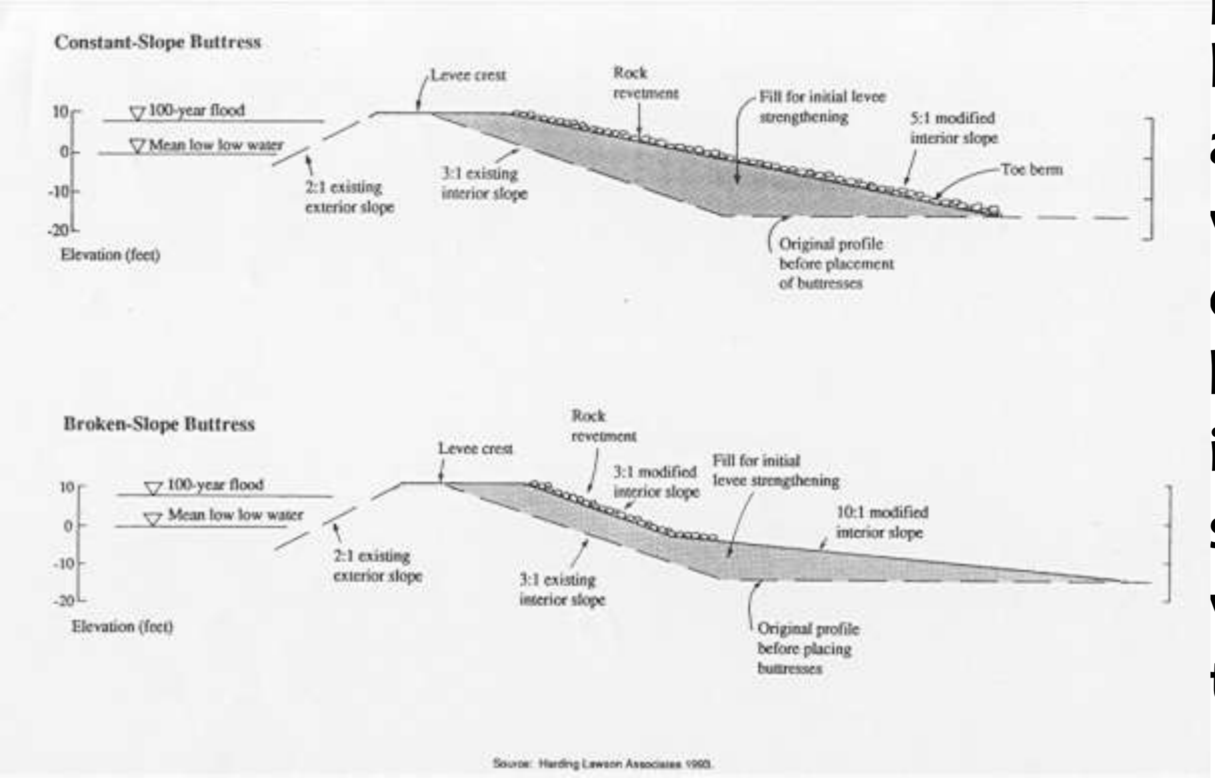
YEAR	HEIGHT FEET	BASE WIDTH FEET	AREA SQ FEET
1882	9.0	53.0	274
1896	15.5	120.5	951
1914	24.0	200.0	2455
1928	27.0	260.0	3645
PRESENT	30.3	315.0	4956

Preferential seepage paths **are a given in a sinuous, low- gradient tidal marsh environment, but can also be induced by the *multiple generations* of fill placement (lower left); and *structural "penetrations,"* such as pipes, trenches, pole holes, roads, and animal burrows.**

Inundation of adjacent flooded tracts serve to increase the pore water pressure acting on shallow and deeper-seated aquifers underlying the delta. In some instances this seepage emanates from the late Pleistocene channel sands blanketing the delta beneath the Holocene peats.

Toe and Stability Berms

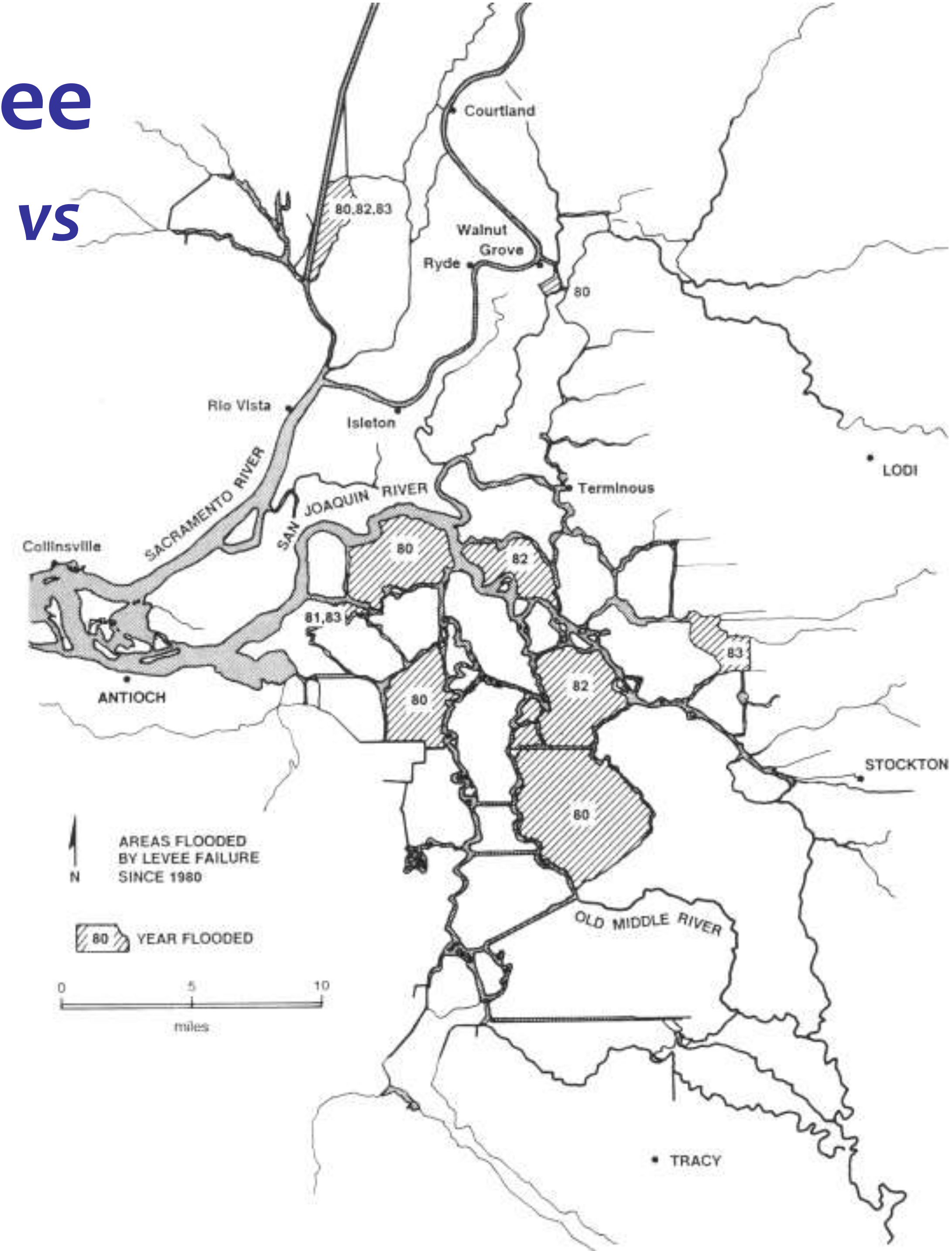
Levee stability degrades with increasing settlement of the protected islands, as levees become higher and erosion scours the water side of the embankment. Stability berms can be added to increase the levee cross section; and uplift relief wells can be installed on the land side.



Source: Harding Lawson Associates 1993

Frequency of levee failures: *peak flow vs streampower*

Between 1980-87, 12 of the delta's 60 diked islands experienced levee failures. None of these were triggered by extreme flood events (> 50 yr recurrence frequency) or seismic activity. In fact the flood water heights on a number of the breaches were considerably lower than the peak levels recorded in 1955 or 1964, but a greater volume of water (Q) passed through the delta in the early 1980s.



What if we experienced a repeat of the 1861-62 flood season?

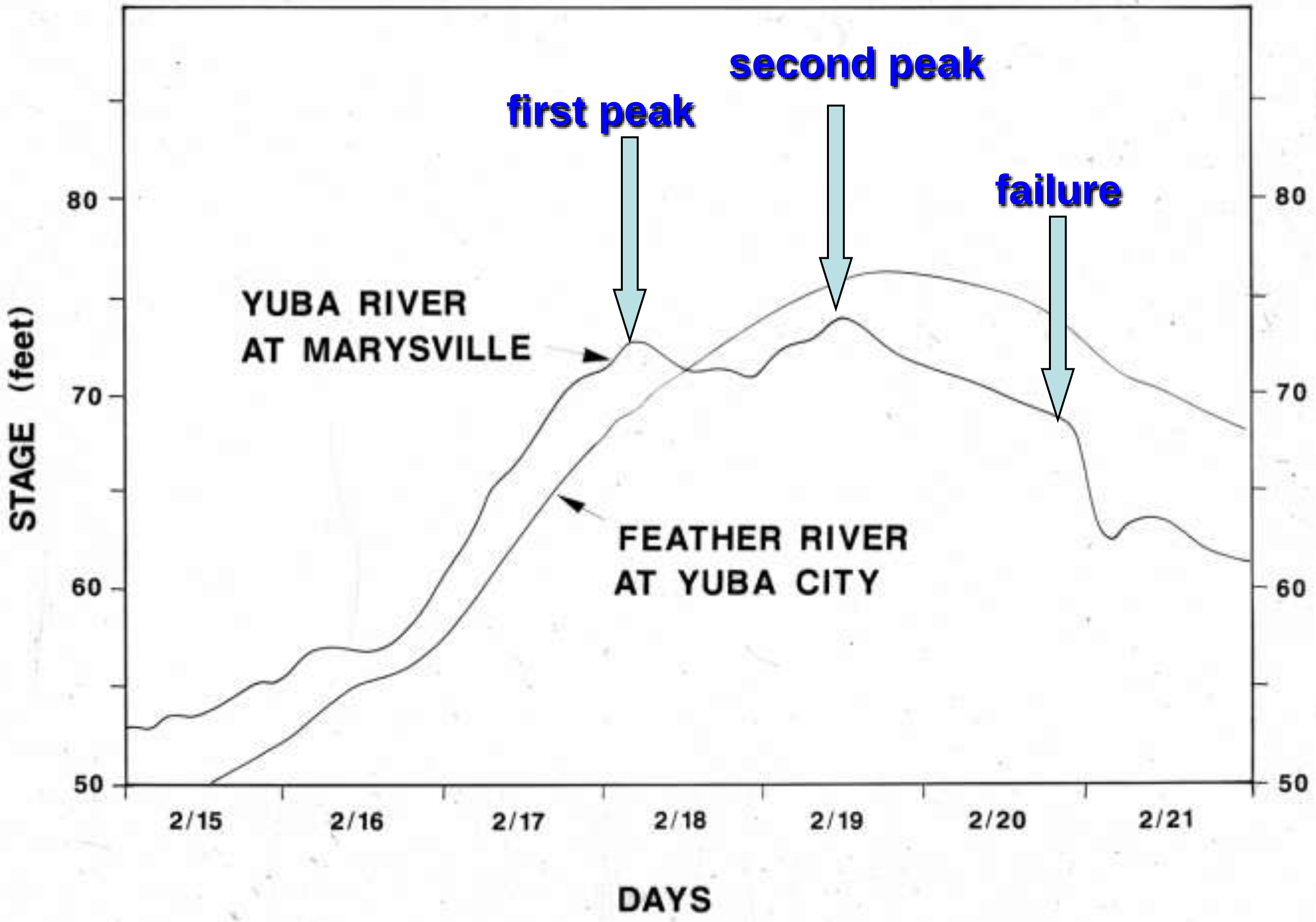
The modern engineered system of flood control constructed after 1913 has never been tested to design capacity, except at a few locations, such as Yuba City in December 1955, before the construction of Oroville Dam. The 1862 flood was notable for its duration, and the entire Sacramento Valley was flooded to the extent that one could row a boat around the Marysville Buttes. A recurrence of this magnitude event could spell all sorts of unforeseen problems for the delta, because seepage problems tend to correlate well with duration of high flows.

A FEW CASE STUDIES

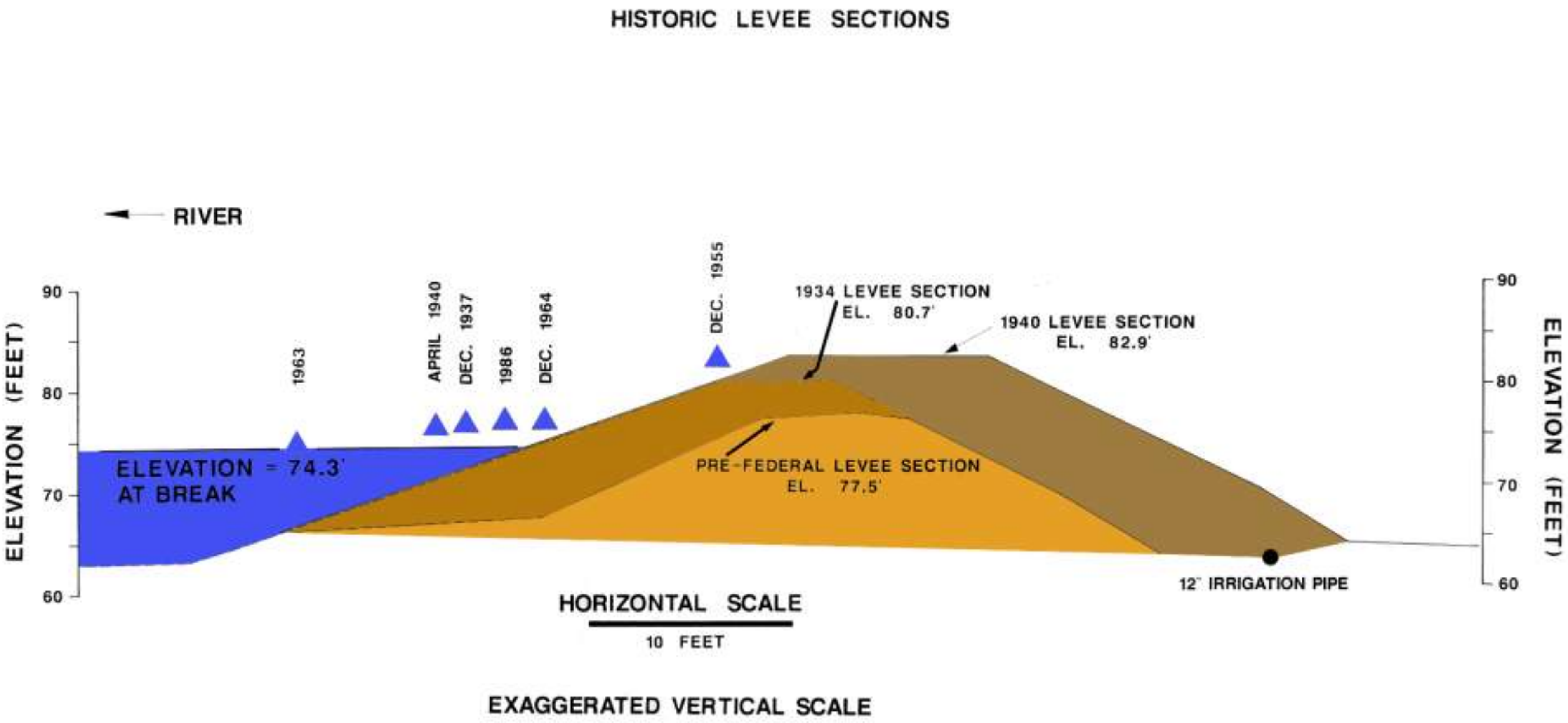
The 1986 breach at Linda

- The breach of the Linda Levee along the south side of the Yuba River near its mouth on the evening of February 20, 1986. The break was *only 170 feet wide*, even after flood waters had poured through the opening for five days.

- **The Linda Levee suddenly broke around 6 PM on February 20, 1986, on the south side of the Yuba River about half a mile above its junction with the Feather River.**

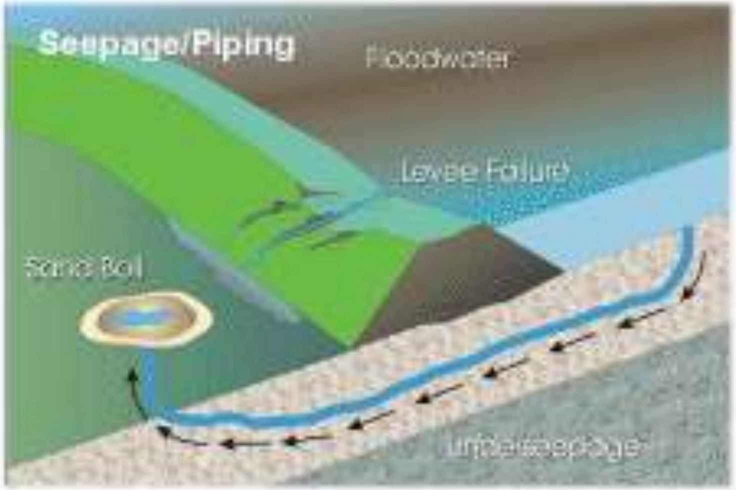


- In the February 1986 storm event the peak flows of the Yuba and Feather Rivers nearly coincided with one another at Marysville. Flood duration appeared to be a significant factor from the outset.

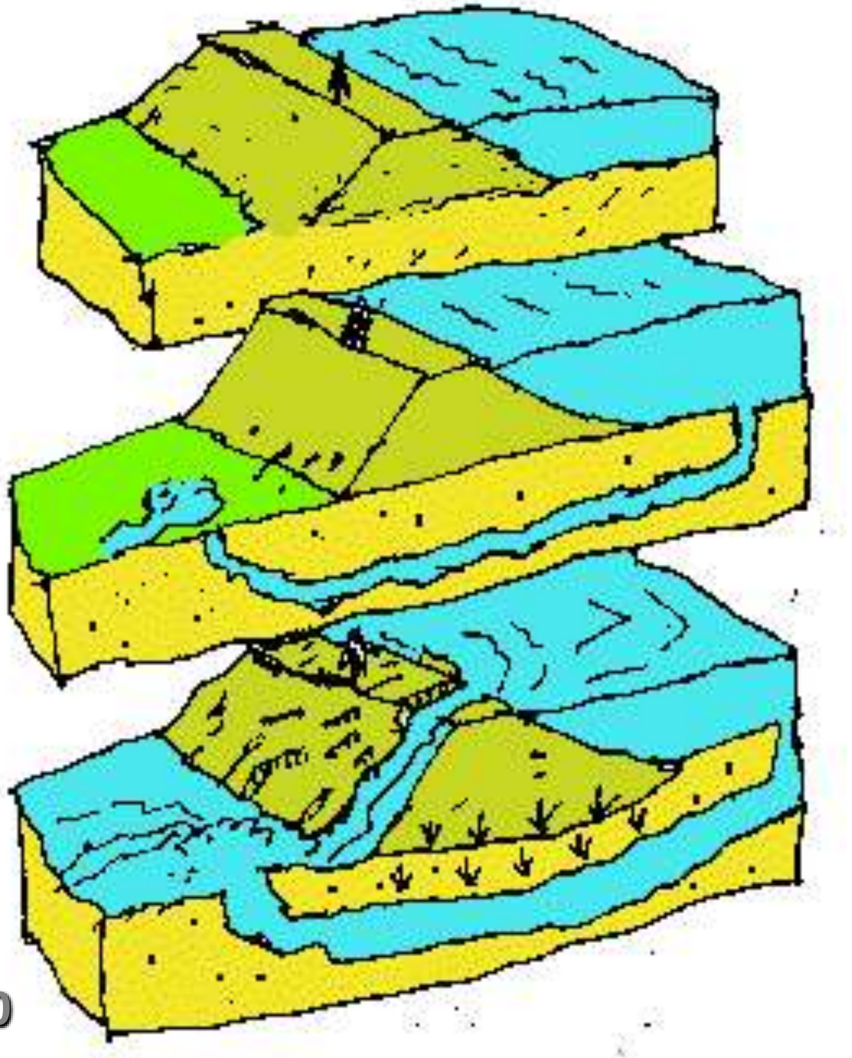


- The February 20th failure occurred *after* the flood had crested, 8.6 feet *below* the levee crest. *This is what fascinated us.*

The traditional model for piping-induced failure



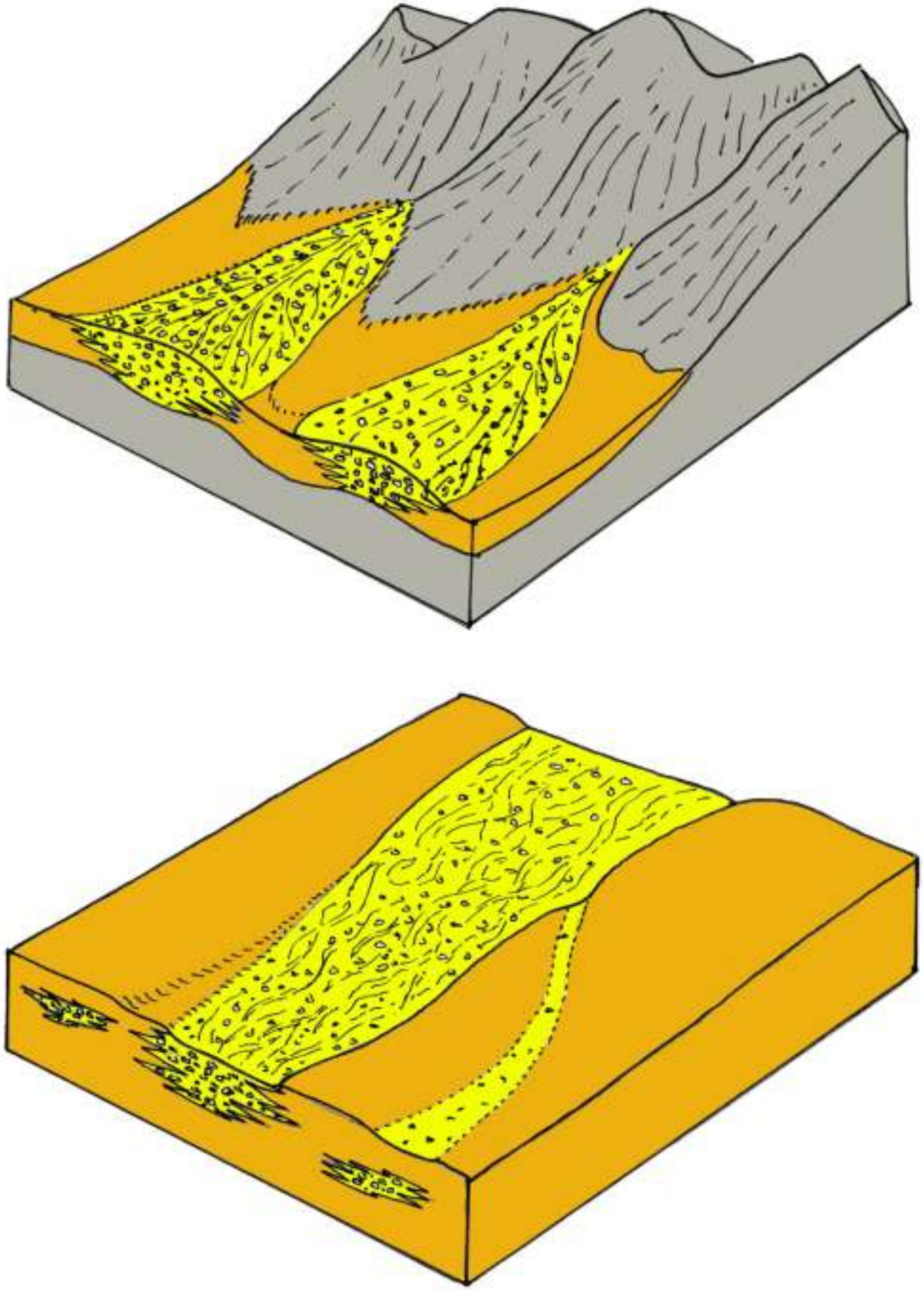
from State of California website in 1997



From Meehan deposition in 1990

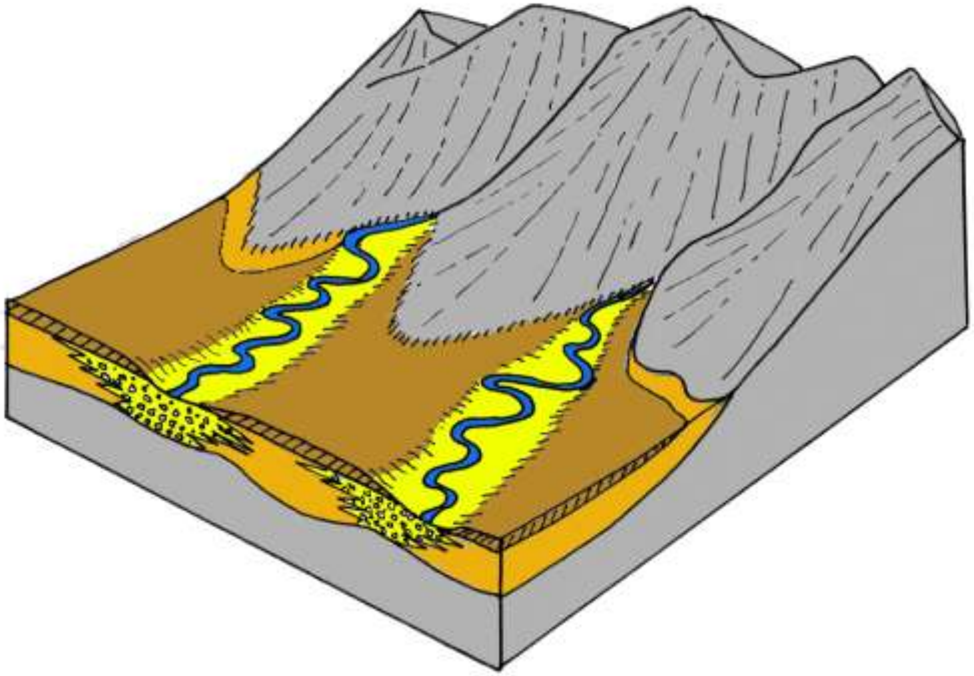
- The precise mode of failure remained a major mystery. Eyewitness accounts described a catastrophic landslide-style failure, not the conventional piping style failure we all assume when analyzing earthen levees, as shown here.

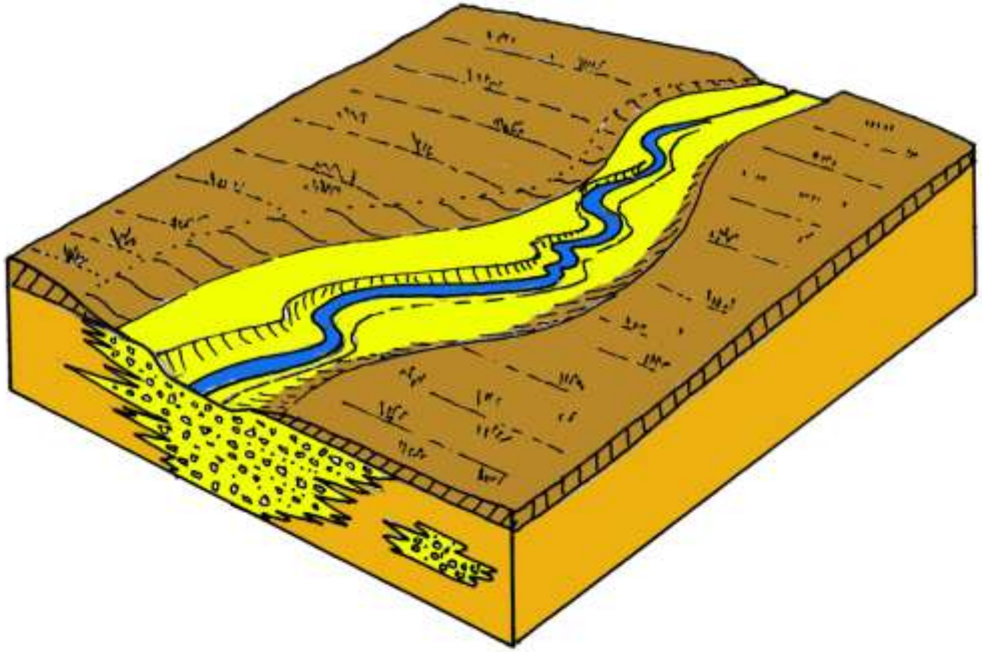
What defines the geomorphic setting?



- During the Pleistocene epoch the Sierras were shedding *coarse debris* from confined bedrock canyons.
- These gravels were deposited in *braid bar channels* along fairly narrow corridors, often *with outliers*

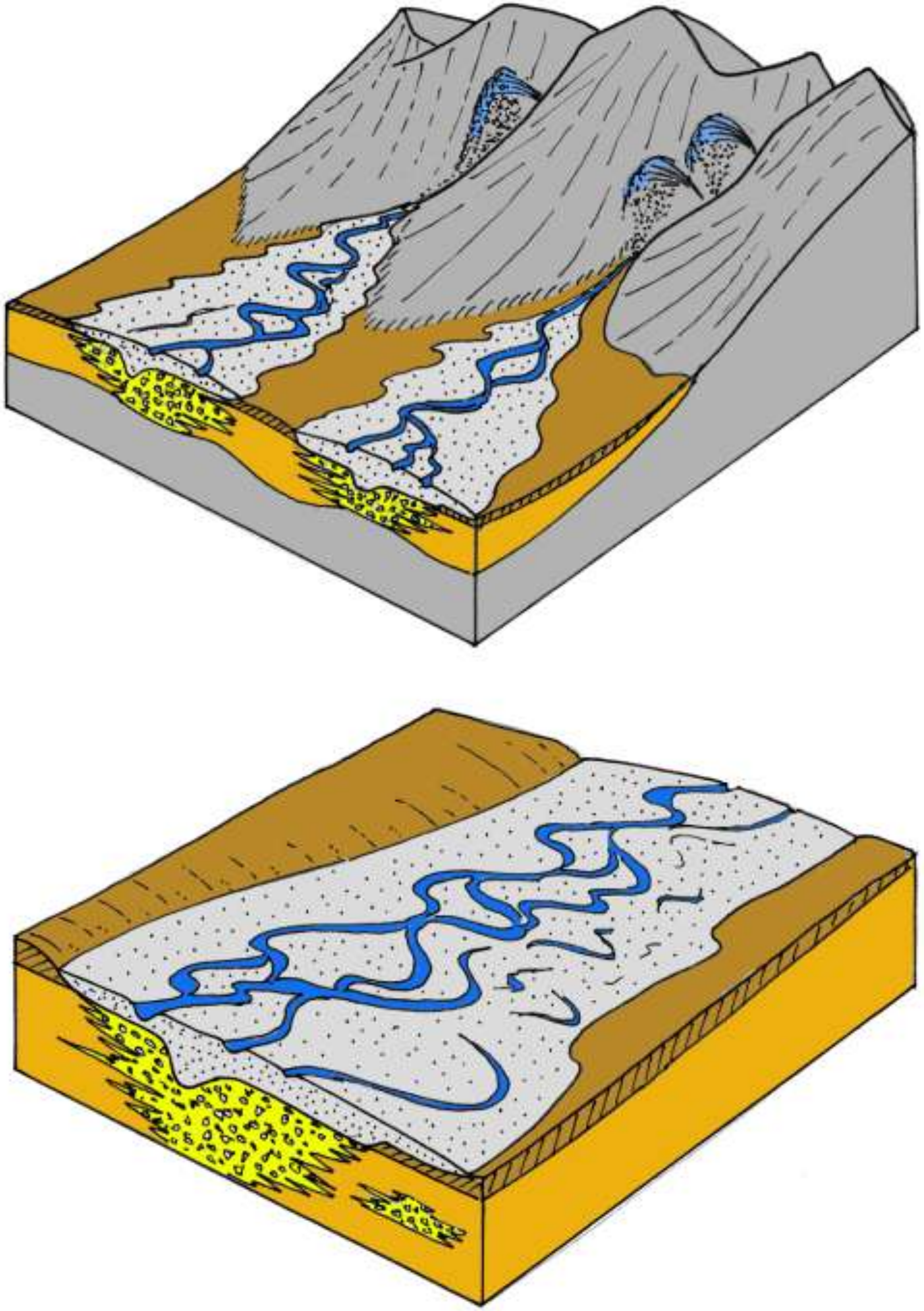
Late Pleistocene weathering



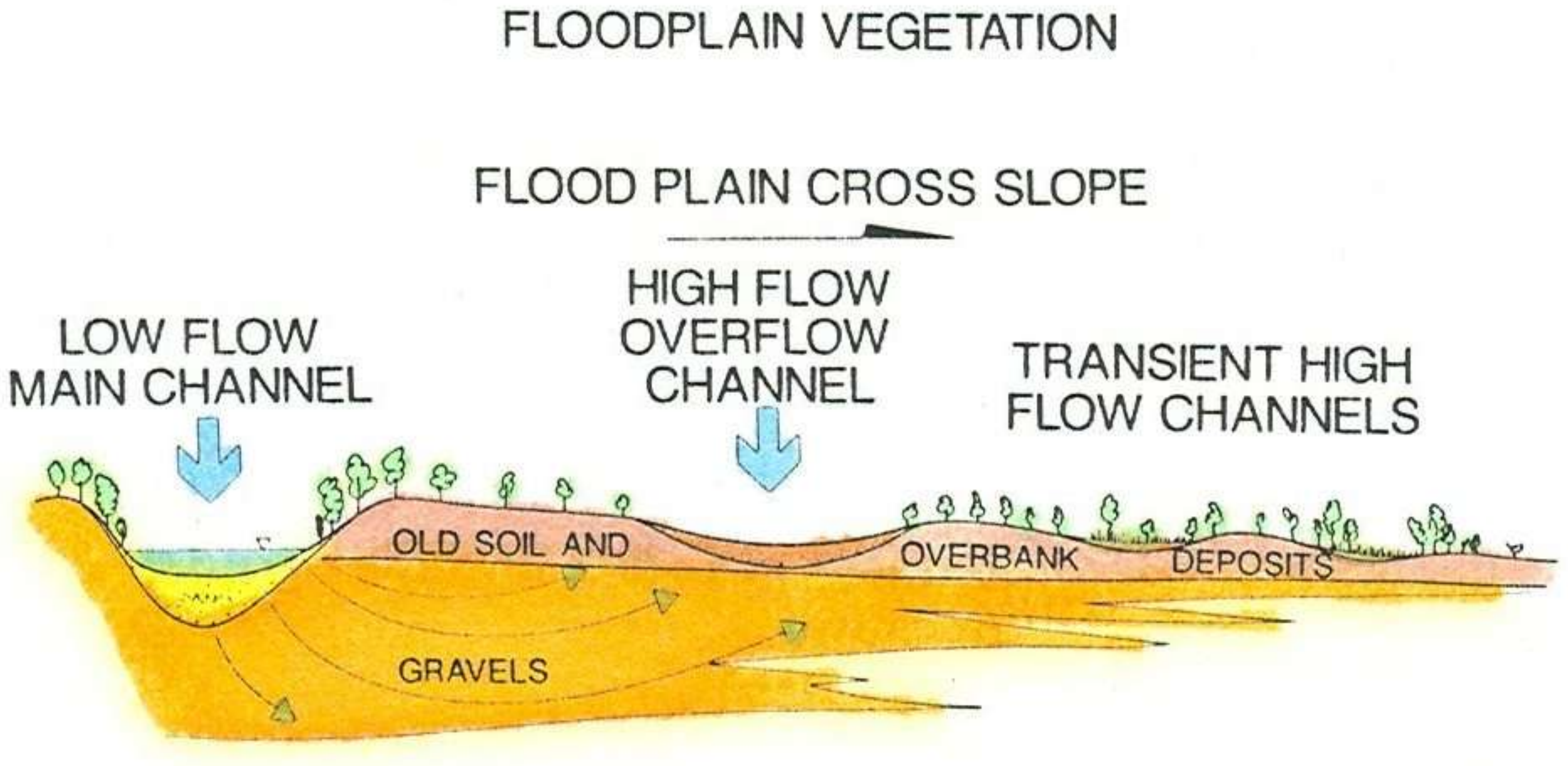


- Sea level rise *lowers channel gradients*
- Shift to drier summers enhances *channel entrenchment* and development of distinctive weathered horizon
- These *Riverbank Terraces* are a compact dark brown to red alluvium, composed of gravel, sand and silt, with minor clay

Environmental Catastrophe

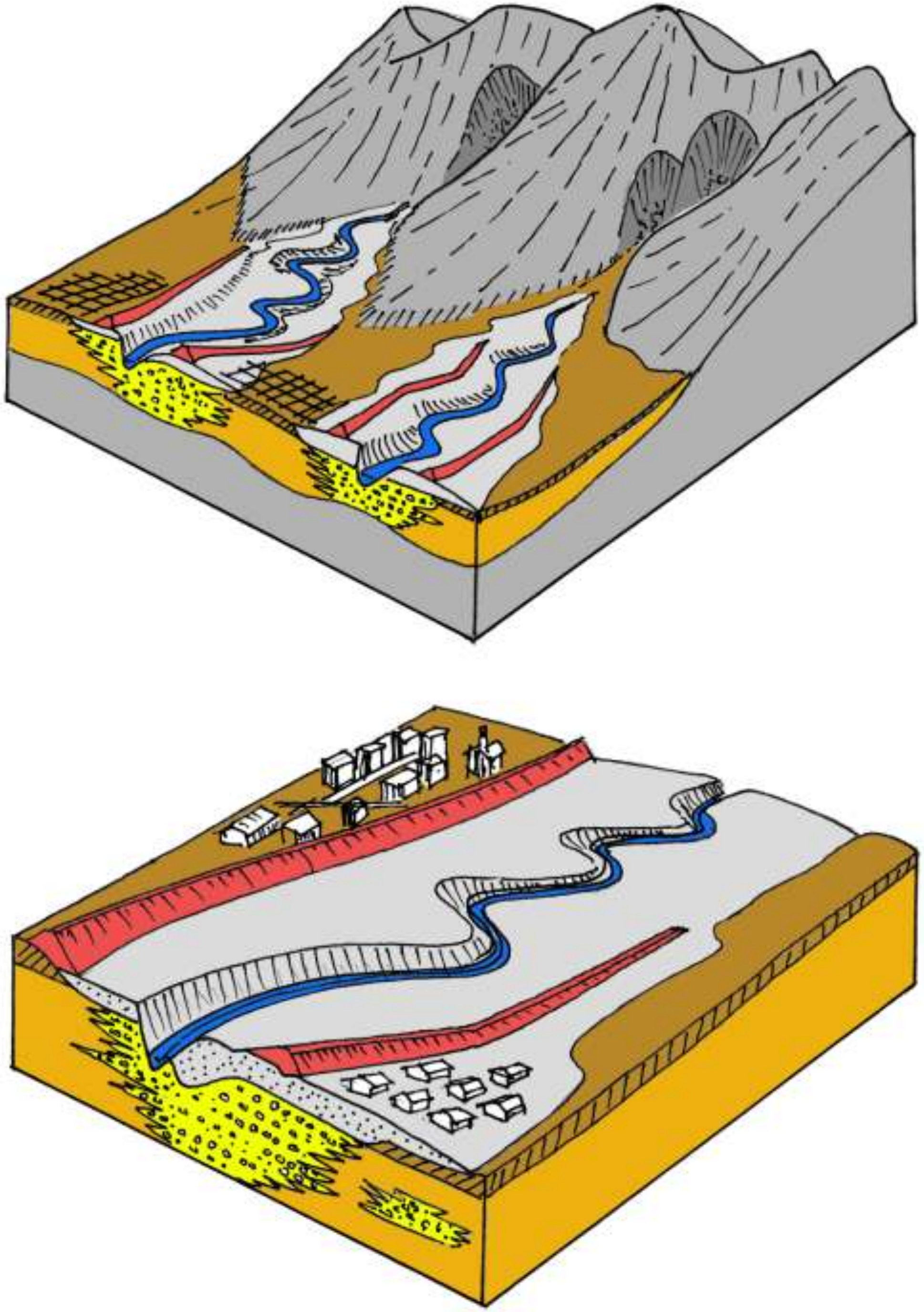


- The Yuba, Bear, Feather, and American River Basins produced the greatest quantities of silt, termed "*mine slickens*"
- The debris choked the channels, stymied river navigation, and destroyed farmland in the Sacramento Valley.
- After 20 years of lawsuits, the Wright Act of 1884 forbade uncontrolled hydraulic mining



- Like any overbank silt, the hydraulic mine slickens deposited after 1862 tended to be thickest near the main stem channels, diminishing outward. Overflow channels would periodically carve material off, reducing thickness of the slickens and overbank silts along those ephemeral channels.

Levees Required

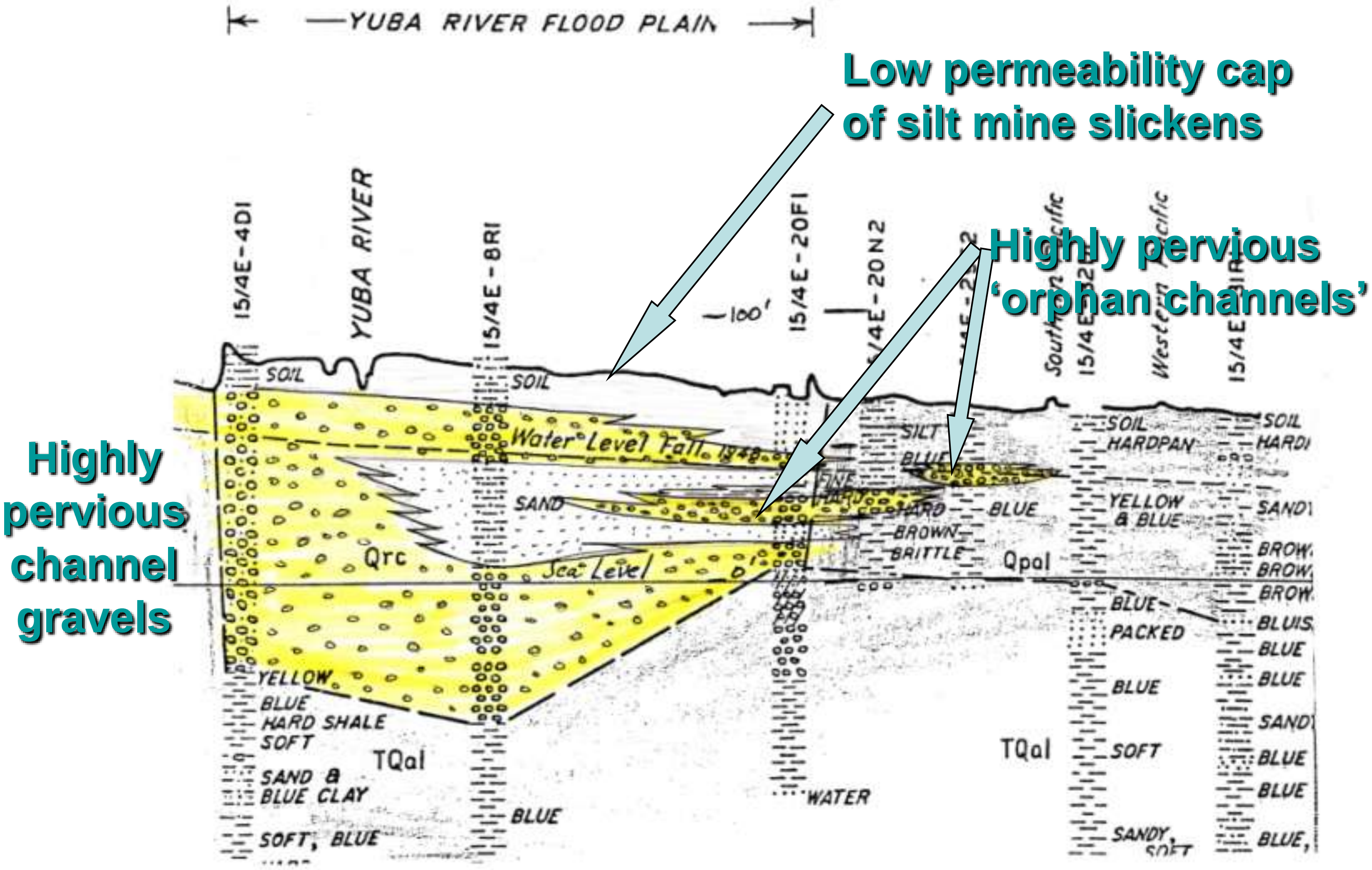


- Marysville began building a protective ring levee after the 1862 floods
- The city was obliged to continue raising the levees incrementally, until 1960, as the flood levels continued rising.

Dredge Mining until 1970

- The Wright Act allowed hydraulic mining and dredging, if the permitee could guarantee that

no debris would be carried downstream. The Yuba Gold Field near Hammonton was the last active gold dredging activity in California.

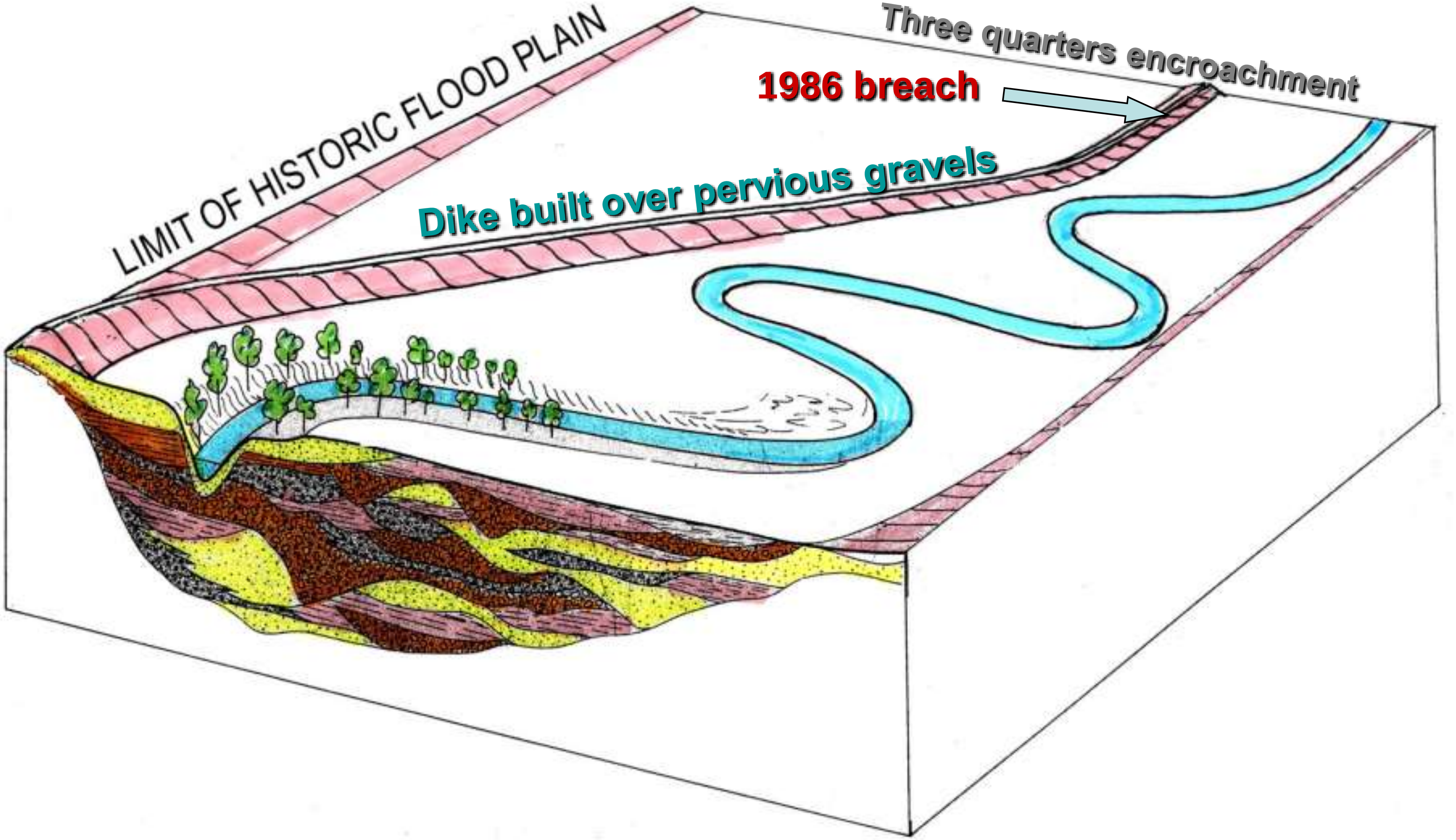


Low permeability cap of silt mine slickens

Highly pervious 'orphan channels'

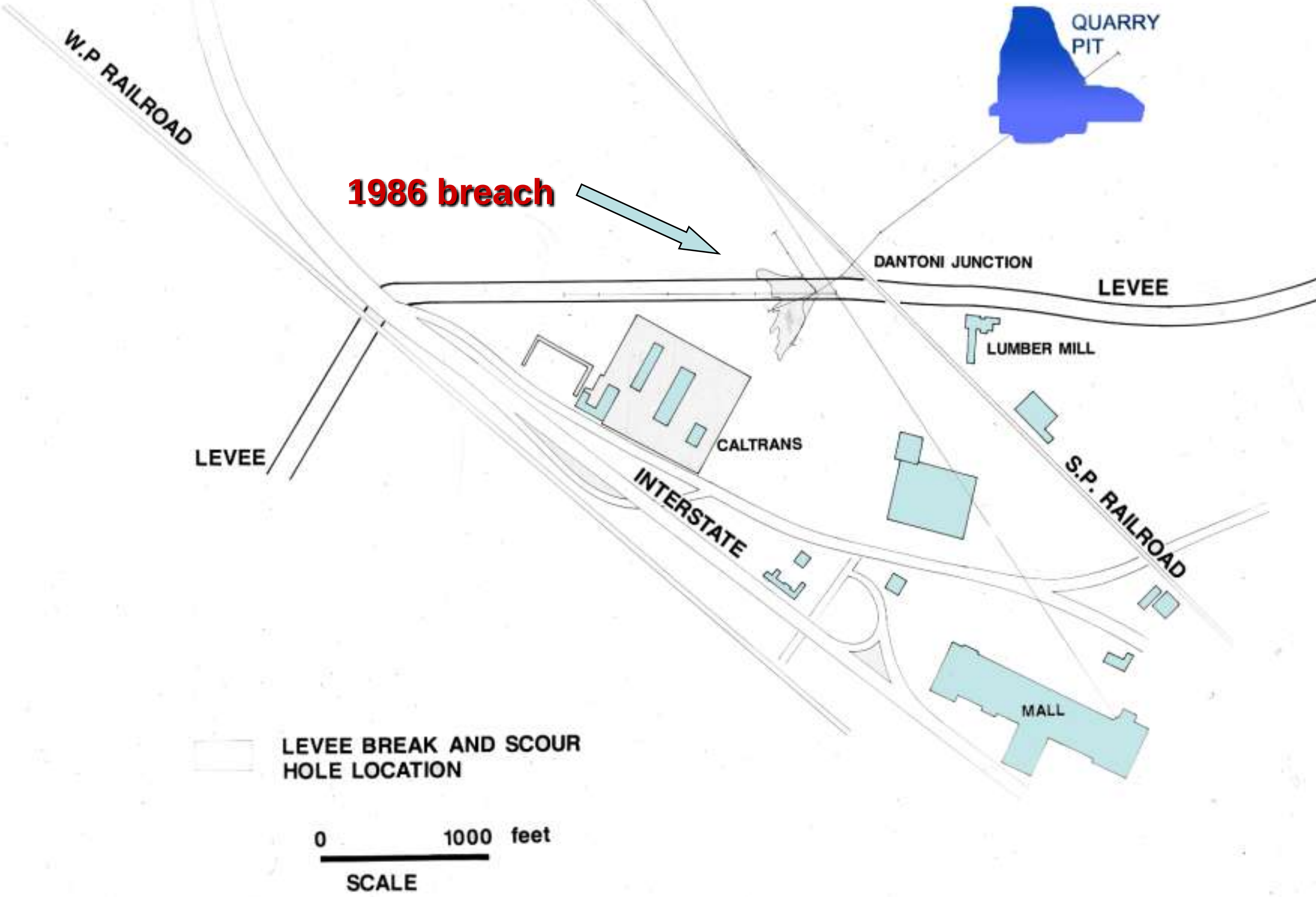
Highly pervious channel gravels

- Our interpretation of the well logs along a section through the lower Yuba River, about three miles upstream of its mouth (from Bulletin 6). Water levels were rapidly declining along the south (right) side of the flood plain in the late 1940s. The farmers were drafting water from the channel gravels.



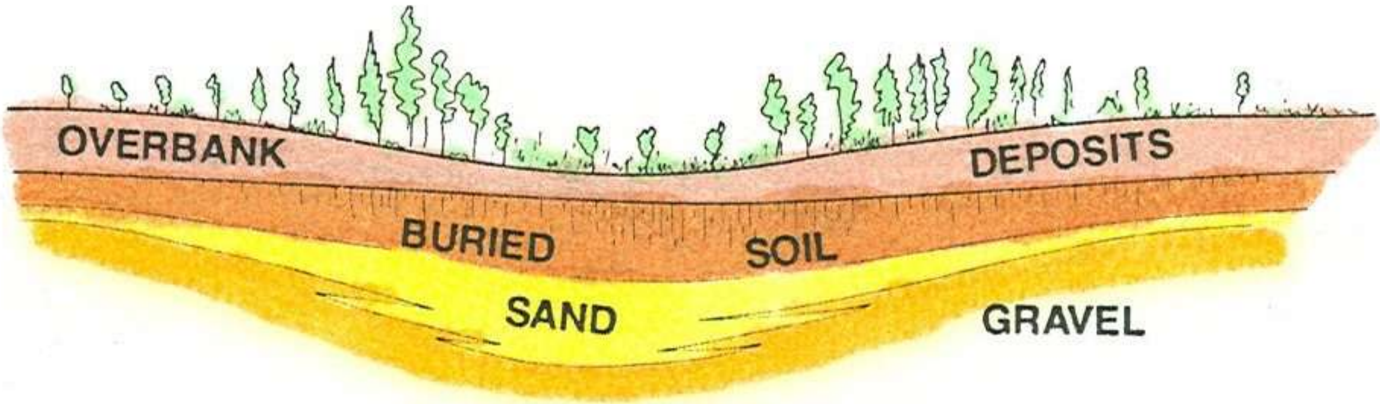
- The original protective dike graded in 1873 was along the southern margins of the Yuba River's *modern flood plain*. The Morrison Grade completed in 1904, and heightened in 1936 and 1940, encroached *three quarters of the river's flood plain, as depicted here.*

Proximity of the Speckert Gravel Pit begun in 1973 to the Linda Levee Failure in 1986

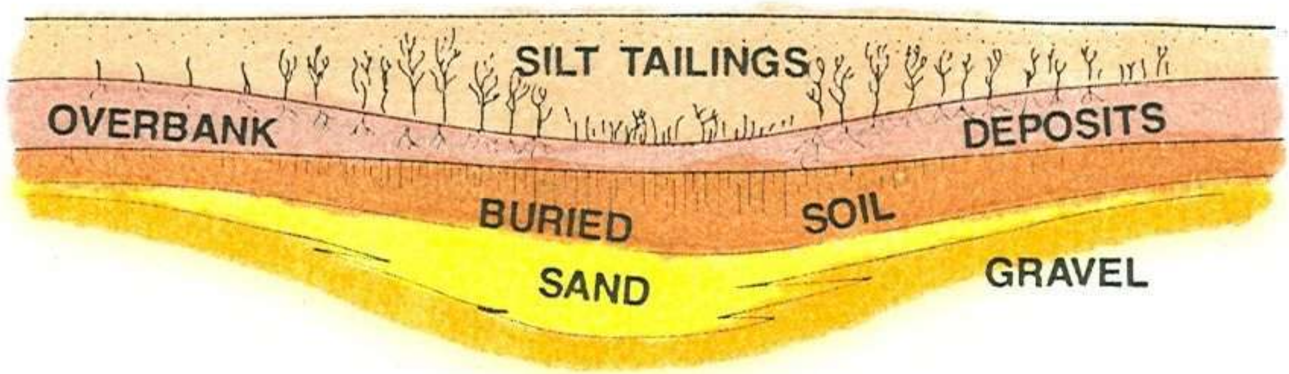


1849 to 1884

LIKELY FLOODPLAIN CONFIGURATION AROUND 1849

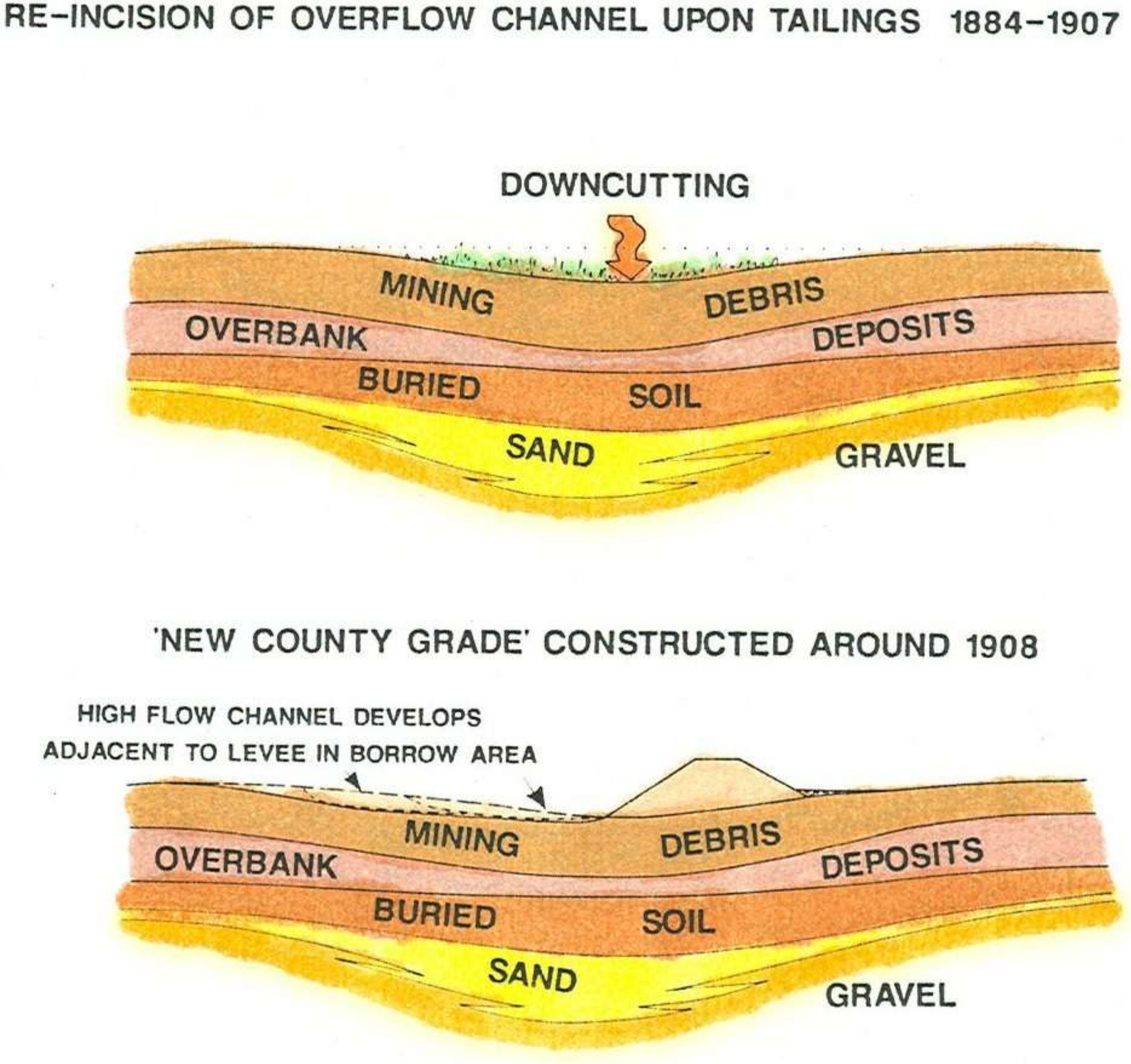


DEPOSITION OF MINE TAILINGS 1860 TO 1884



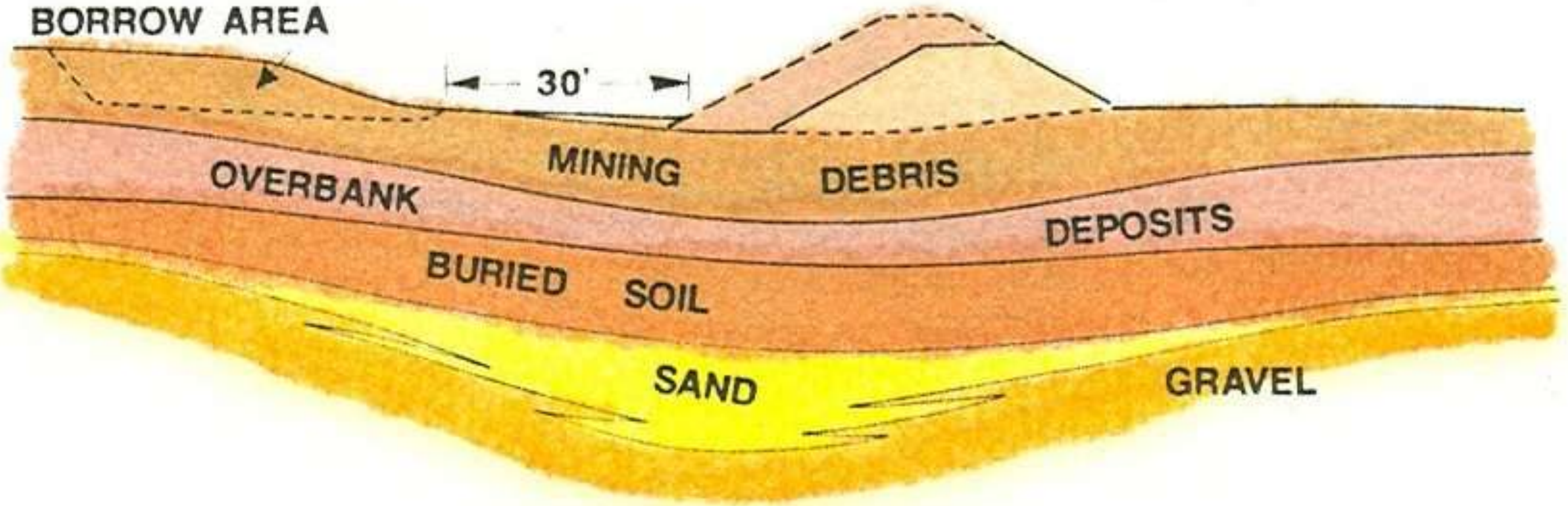
- The pre-1849 flood plain was inundated by silt tailings from 1862 till at least 1884
- Note axis of swale, beneath breach area

1884 to 1908



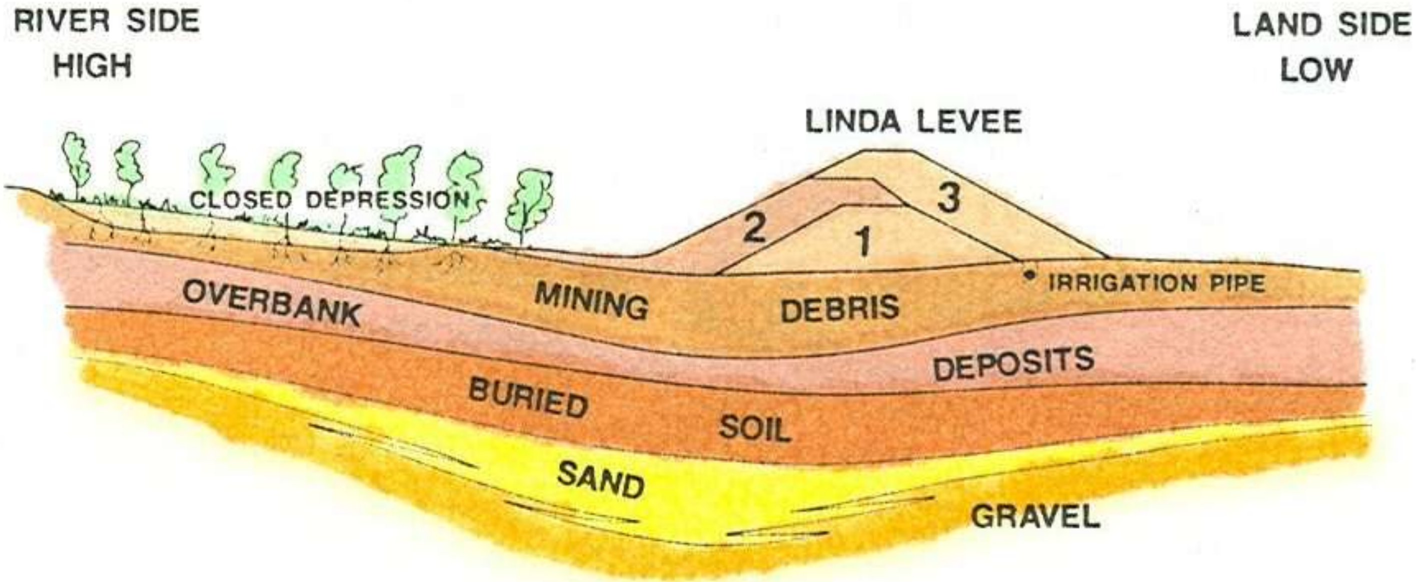
- The mine slickens were reworked several times by major floods, then used as fill for the original levee in 1904

CONSTRUCTION OF THE MORRISON GRADE IN 1936



- The **Morrison Grade** was heightened in 1936, using borrow material from the river side of the embankment.

CORPS OF ENGINEERS LEVEE HEIGHTENING IN 1940



OTHER MAN ACTICITIES

- IRRIGATION PIPELINE CONNECTED TO WELL BURIED BENEATH EMBANKMENT
- S.P.RR BRIDGE PARTIALLY INFILLED ACROSS FLOODPLAIN
- CLOSED DEPRESSION AREA LEFT FALLOW

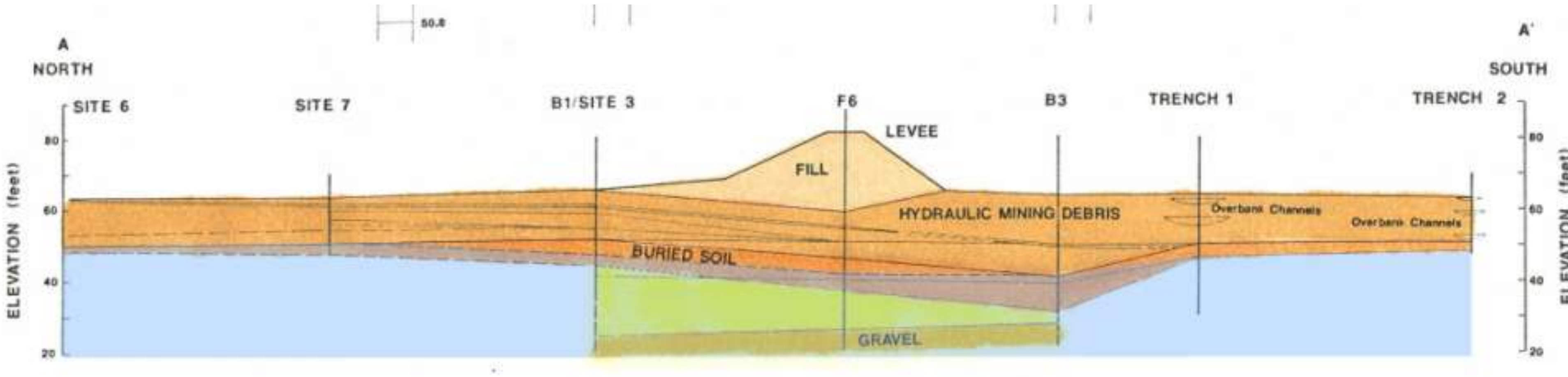
LATER

- SPECKERT PIT OPENED
- ORCHARD WITH WELL PLACED IN CLOSED DEPRESSION

1940

- **The Corps of Engineers raised the Morrison Grade a third and final time in 1940**

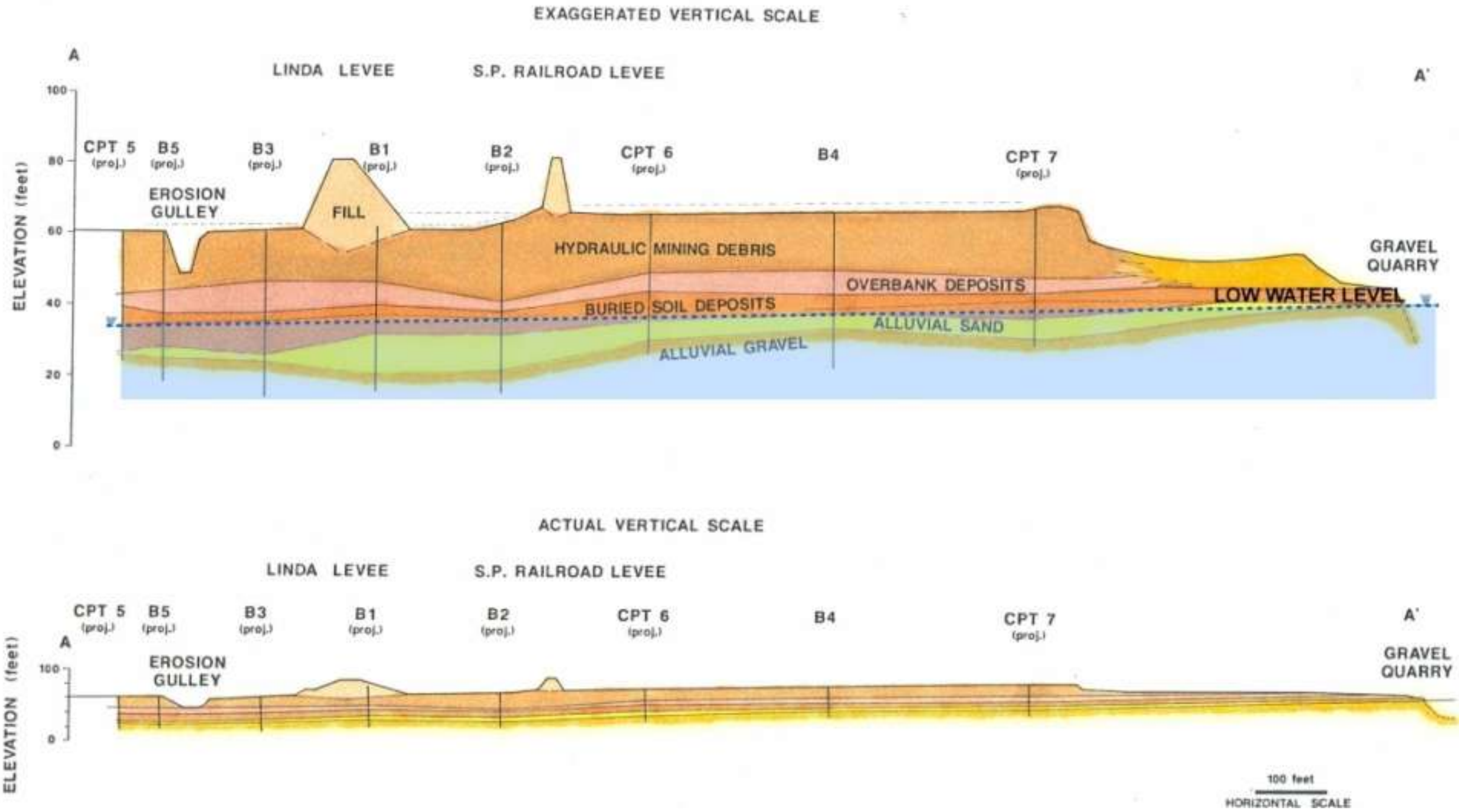
The critical seepage analysis should be performed along actual preferential seepage path (like that shown here), not simply 90 degrees to axis of the levee



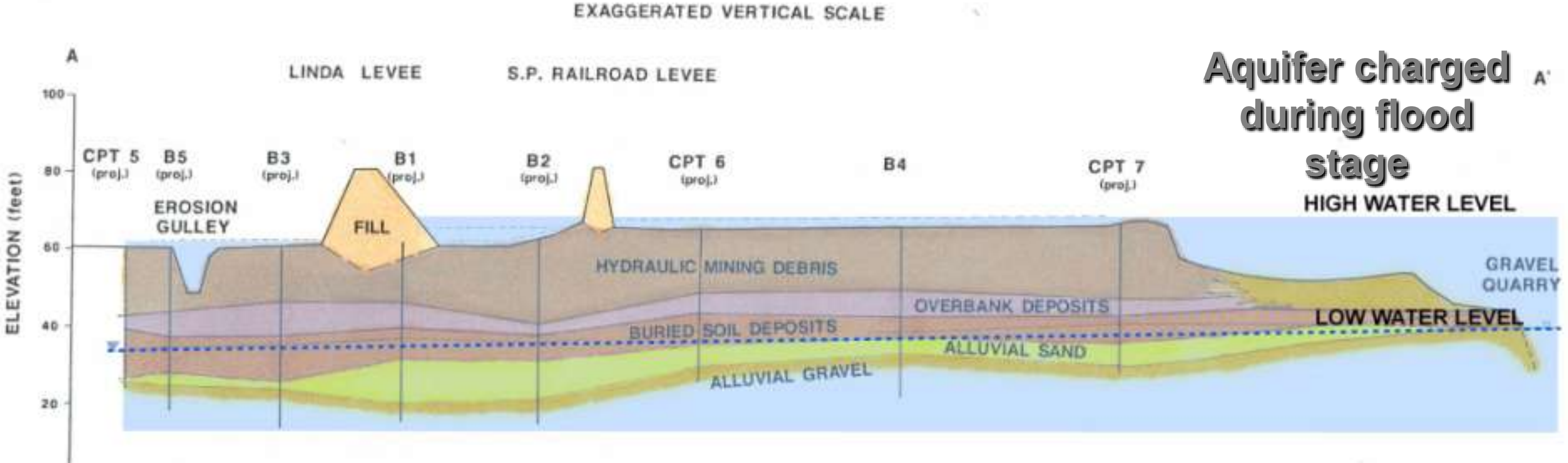
Preliminary Section A-A' cut the levee at 50 degrees to its alignment, along the 'flow path' of the river channel.

It highlighted what might be a serious problem: highly conductive channels feeding *upward*, into a lower permeability paleosol cap, deposited in previous overflow channels.

This is a classic "leaky aquifer" condition.

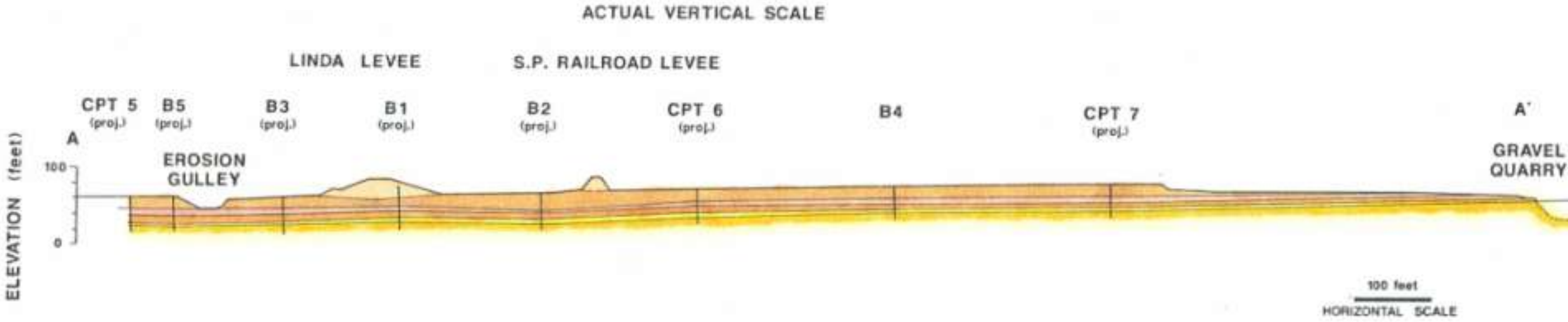


- **Prior to the river transition to flood stage, this is how the leaky aquifer appeared along the 1800 feet lying between the Speckert Gravel Pit and that portion of the Linda Levee that failed in Feb 1986.**



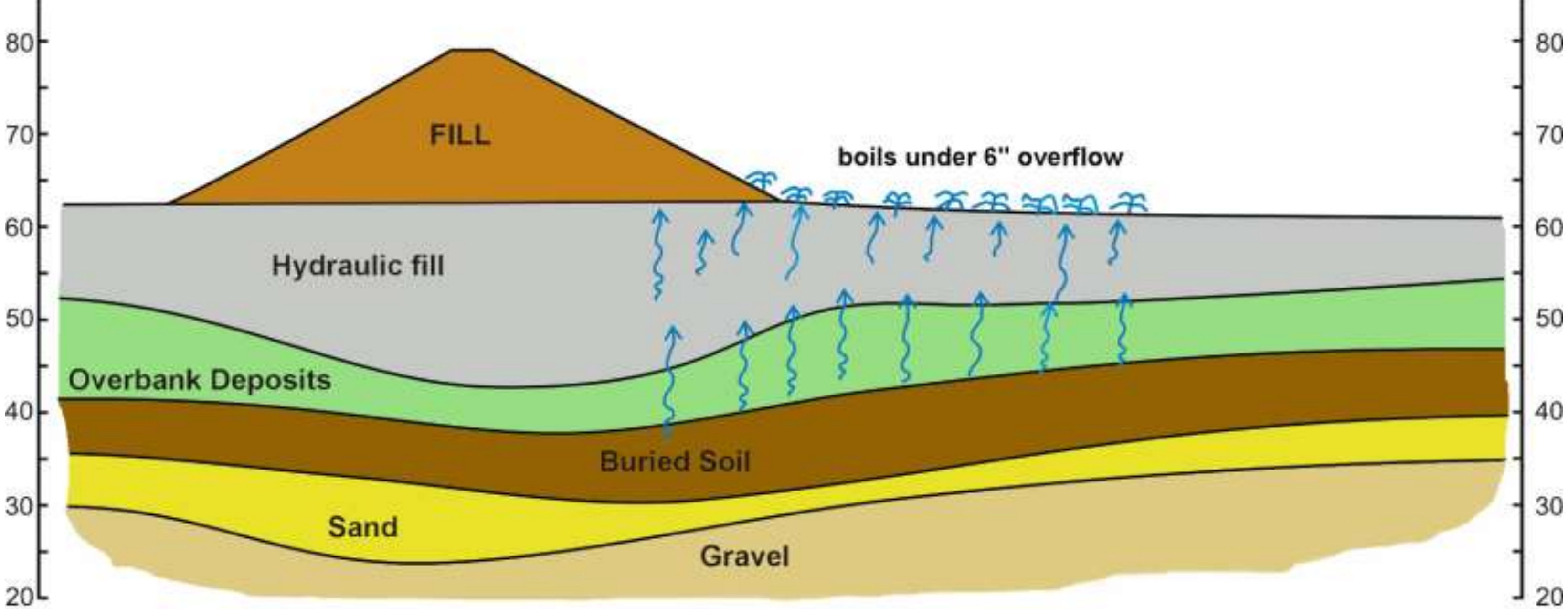
Aquifer charged during flood stage

Note upward dip of the alluvial gravels, into the gravel quarry

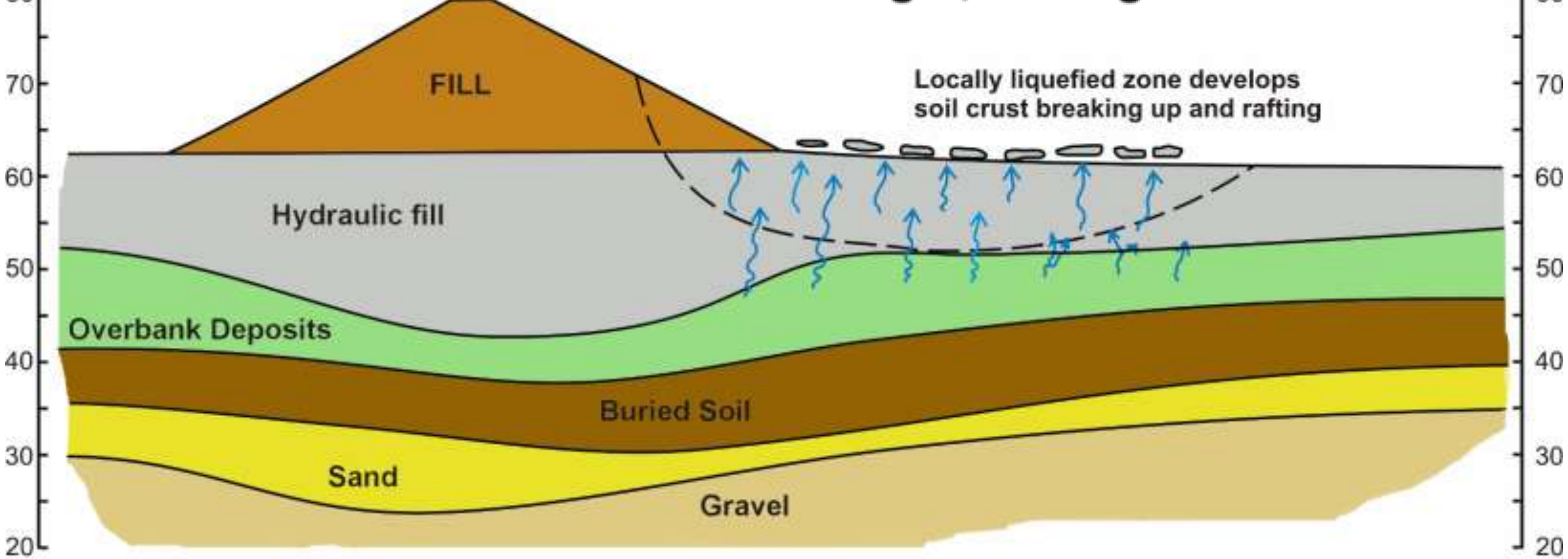


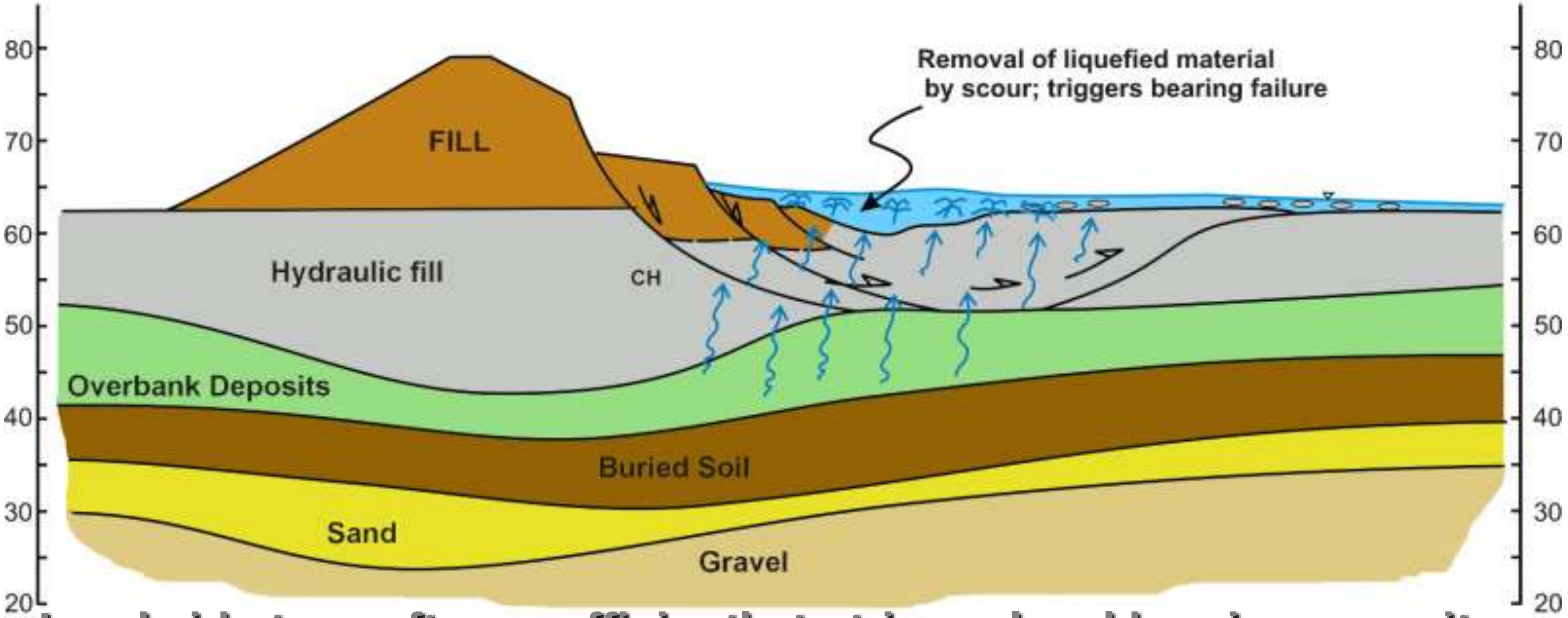
- **Section A parallels the line of expected seepage and surface flow, from NE to SW. This was extended 1800 ft, to the Speckert Gravel Pit. *Note slope of the alluvial materials between the pit and the levee.***

- The coarse channel gravels had not been detected in any of the previous geotechnical investigations, <u>not even those FOLLOWING the 1986 levee failure</u>! Ouch!!

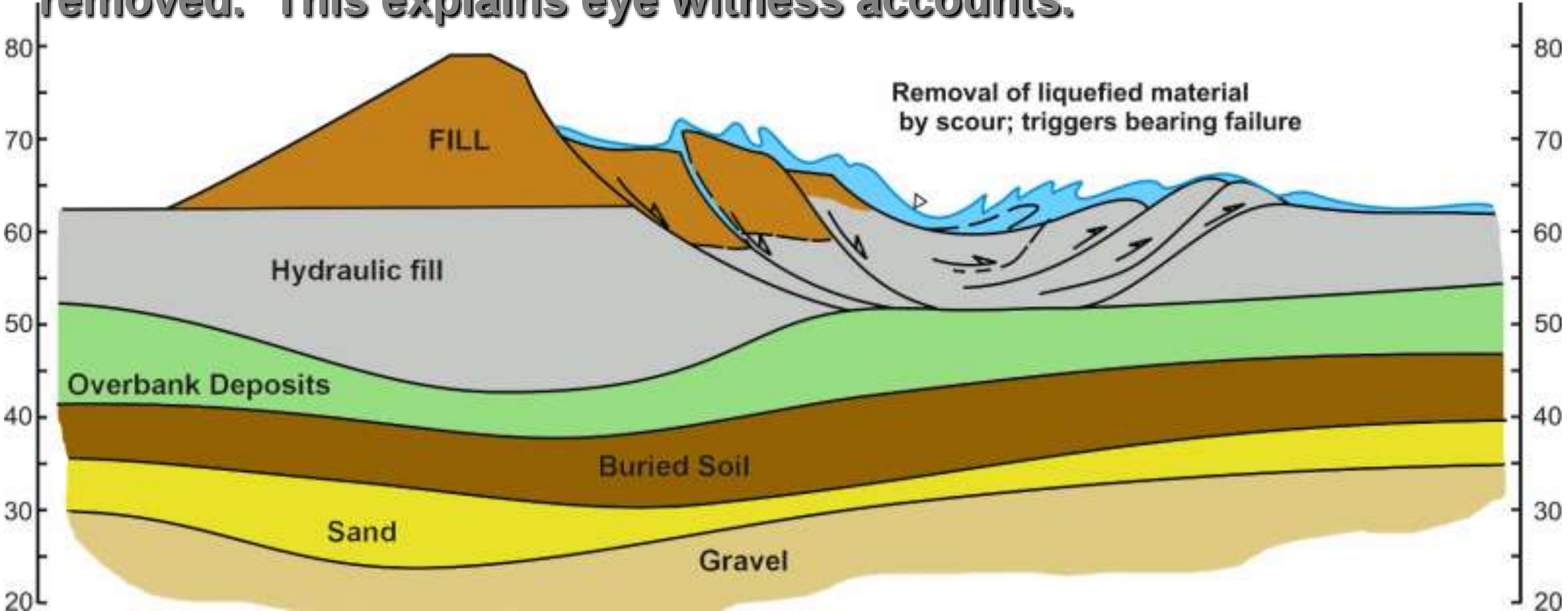


Hydraulic uplift from confined gravel aquifer under considerable pressure head. As head increases, unconsolidated low density materials turn to soften and lose strength, turning to ‘mush’



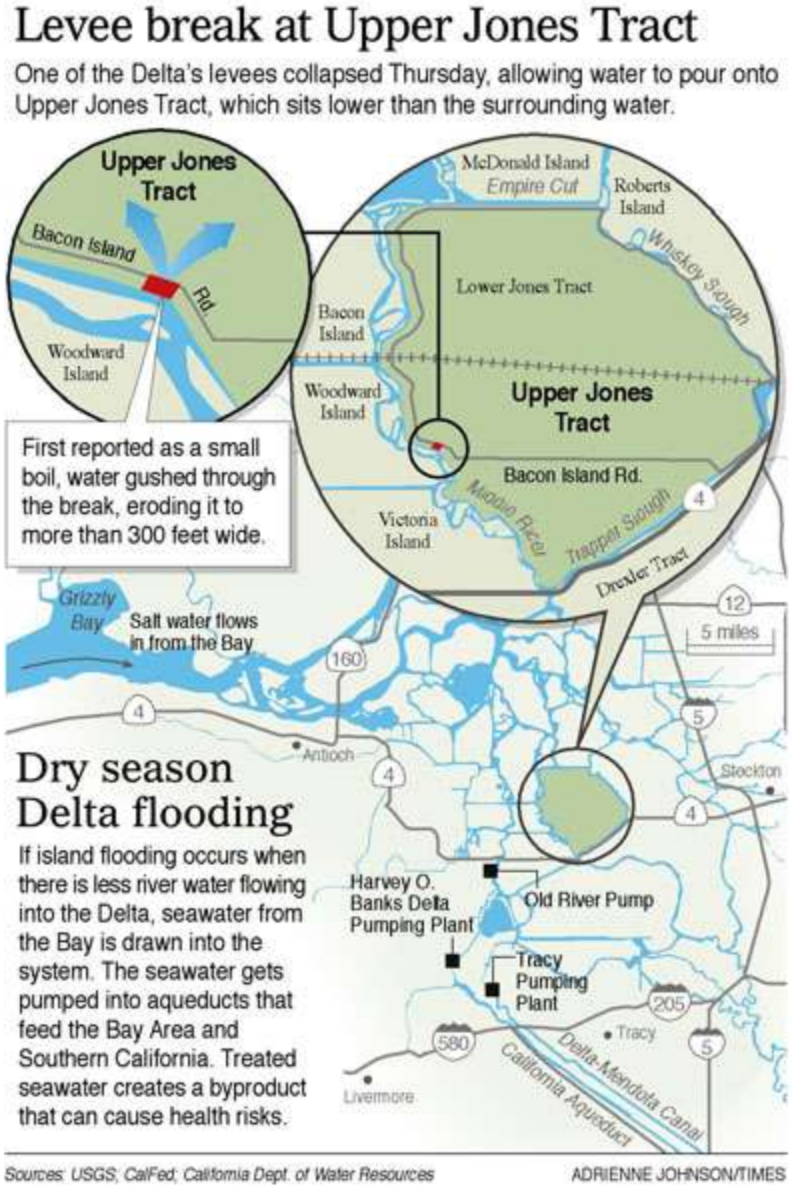


Land side toe softens sufficiently to trigger local bearing capacity failure; which triggers retrogressive slumping, as lateral restraint is removed. This explains eye witness accounts.



2004 Jones Tract Breach

- 08:15 Fishermen See Boil
  - Falling (ebb) Tide
- 08:55 DWR Notified
- 10:00 Pumping Reduced*
  - SWP: 0 cfs
  - CVP: 800 cfs
  - Delta Cross Gates Opened
- 15:00 Dutra Hired by RD
  - First barges arrive ~22:00



Levee break at Upper Jones Tract

One of the Delta's levees collapsed Thursday, allowing water to pour onto Upper Jones Tract, which sits lower than the surrounding water.

First reported as a small boil, water gushed through the break, eroding it to more than 300 feet wide.

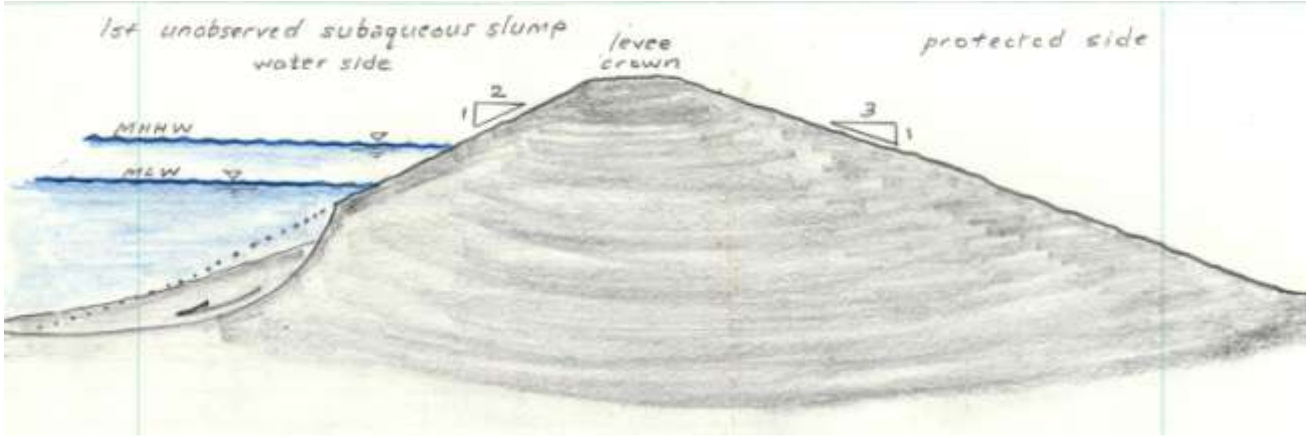
Dry season Delta flooding

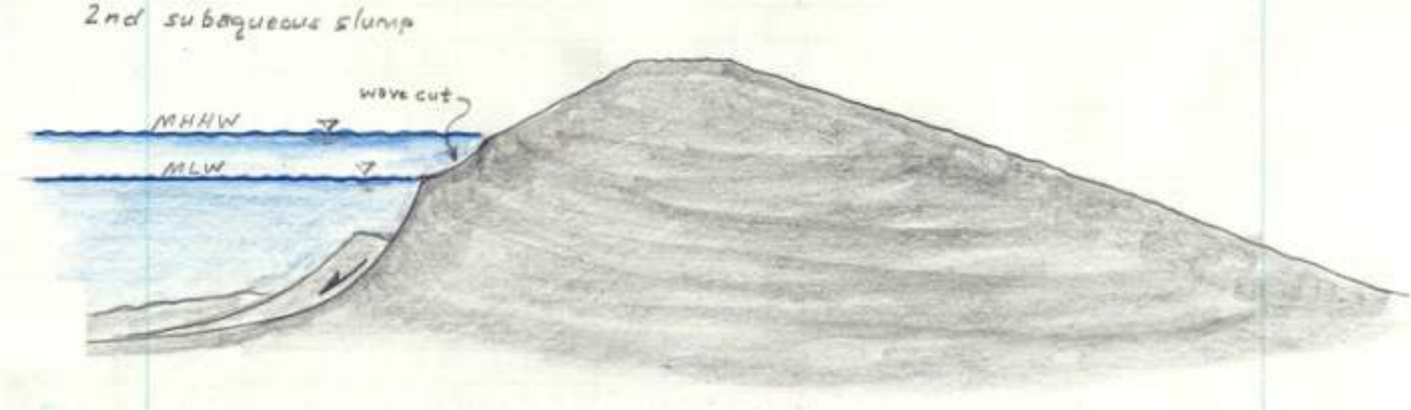
If island flooding occurs when there is less river water flowing into the Delta, seawater from the Bay is drawn into the system. The seawater gets pumped into aqueducts that feed the Bay Area and Southern California. Treated seawater creates a byproduct that can cause health risks.

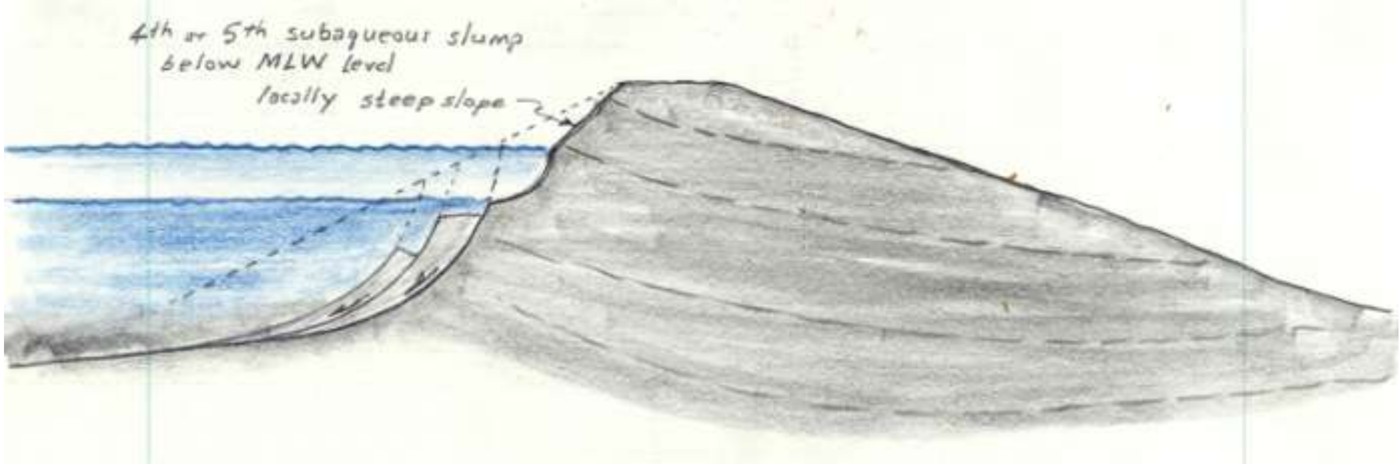
Sources: USGS; CalFed; California Dept. of Water Resources

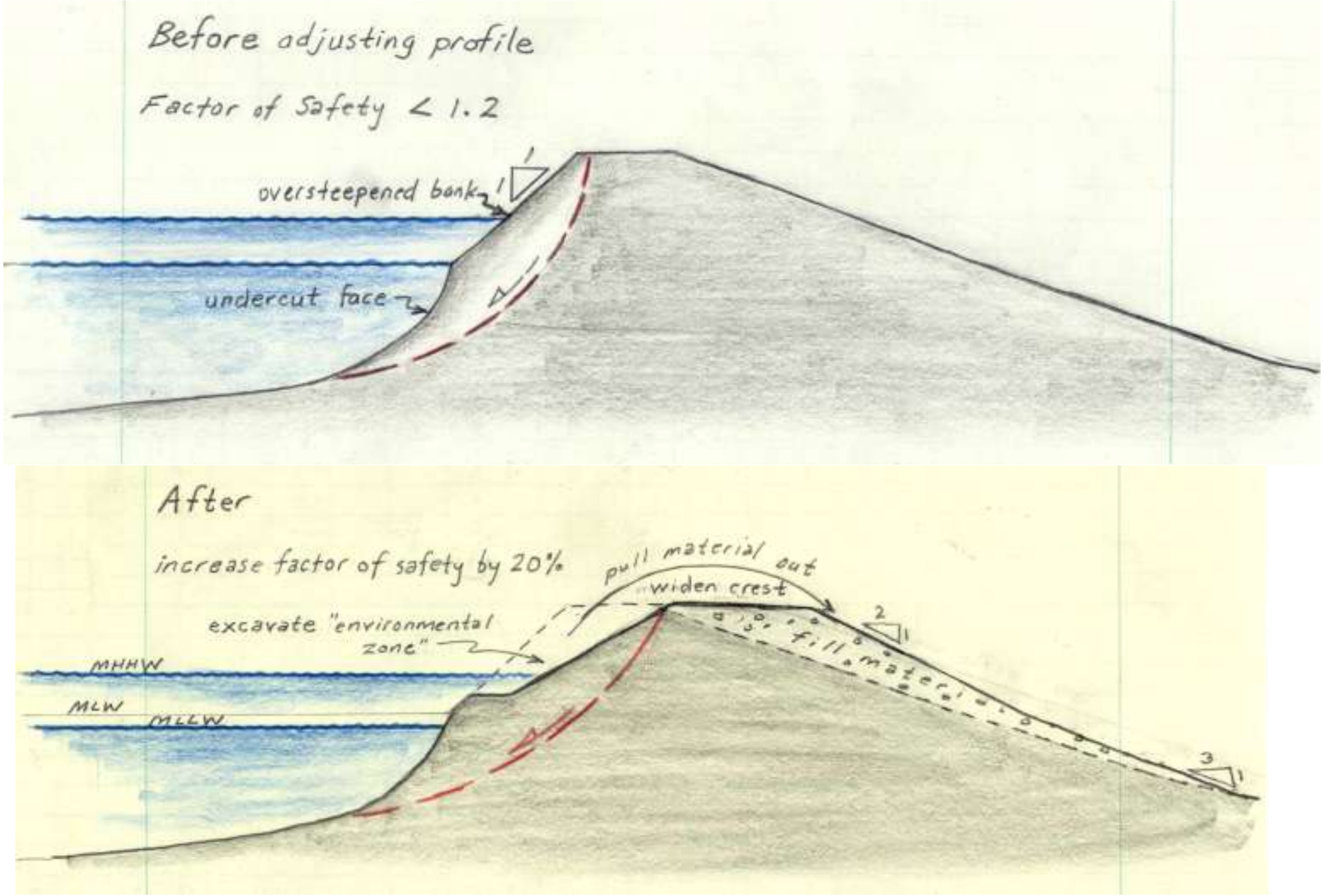
ADRIENNE JOHNSON/TIMES

*Doesn't match pumping records


1st unobserved subaqueous slump
water side
levee crown
protected side
2
1
3
1
MHHW
MLW

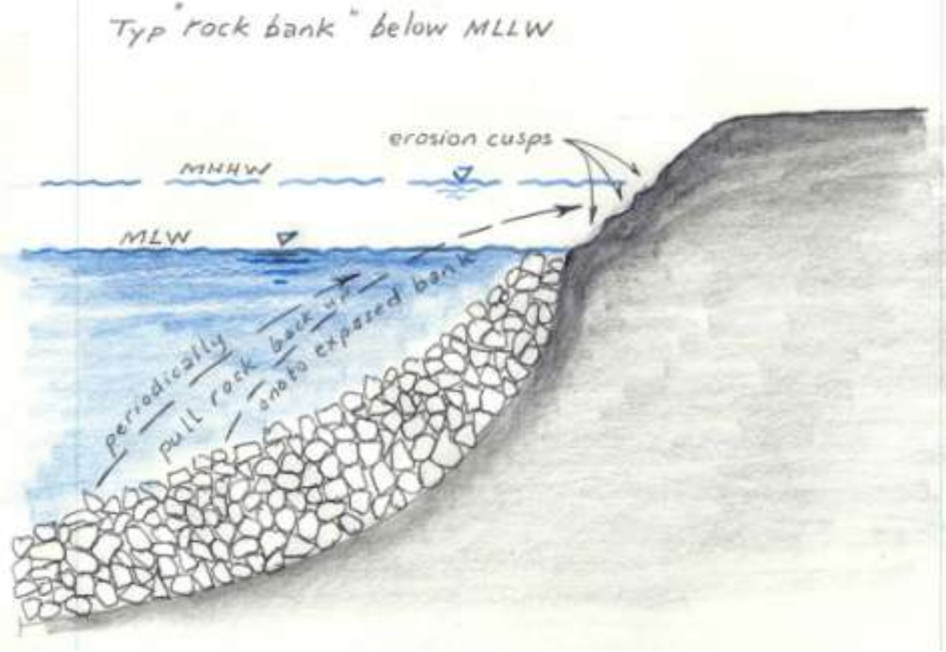

2nd subaqueous slump
wave cut
MHHW
MLW


4th or 5th subaqueous slump
below MLW level
locally steep slope

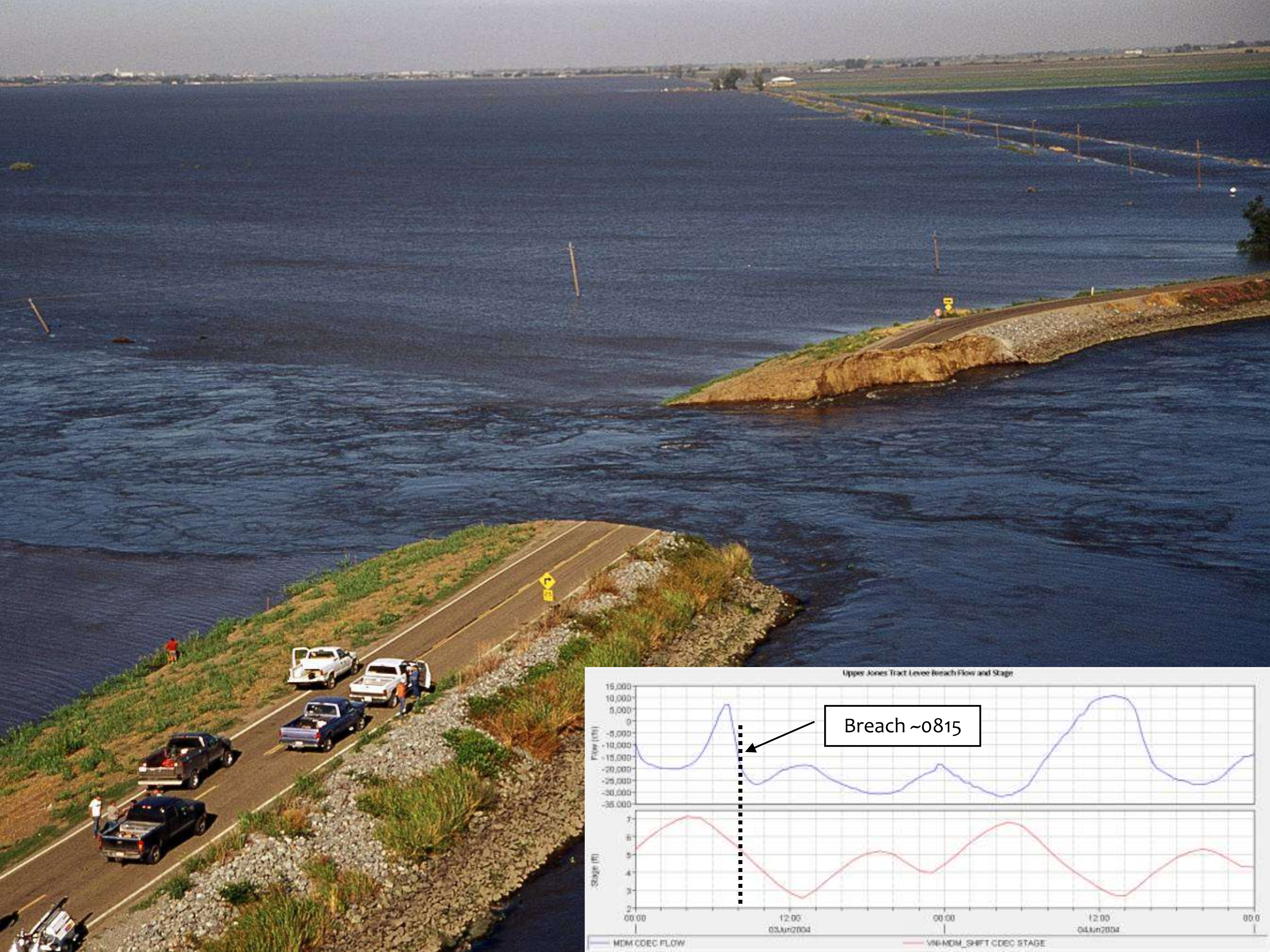


Most of the reclamation districts mitigate oversteepened slopes by trimming the levee crest and infilling the land side of the levee crown, as sketched here

Rip-rap face protection can be dumped on the submerged undercut face of a levee, but this usually requires Depot of Fish & Game approval, a process that takes time and cost money.



Many RD's simply "bank" additional rip-rap beneath the Mean Low Water surface, where it can't be seen by state inspectors , as sketched here

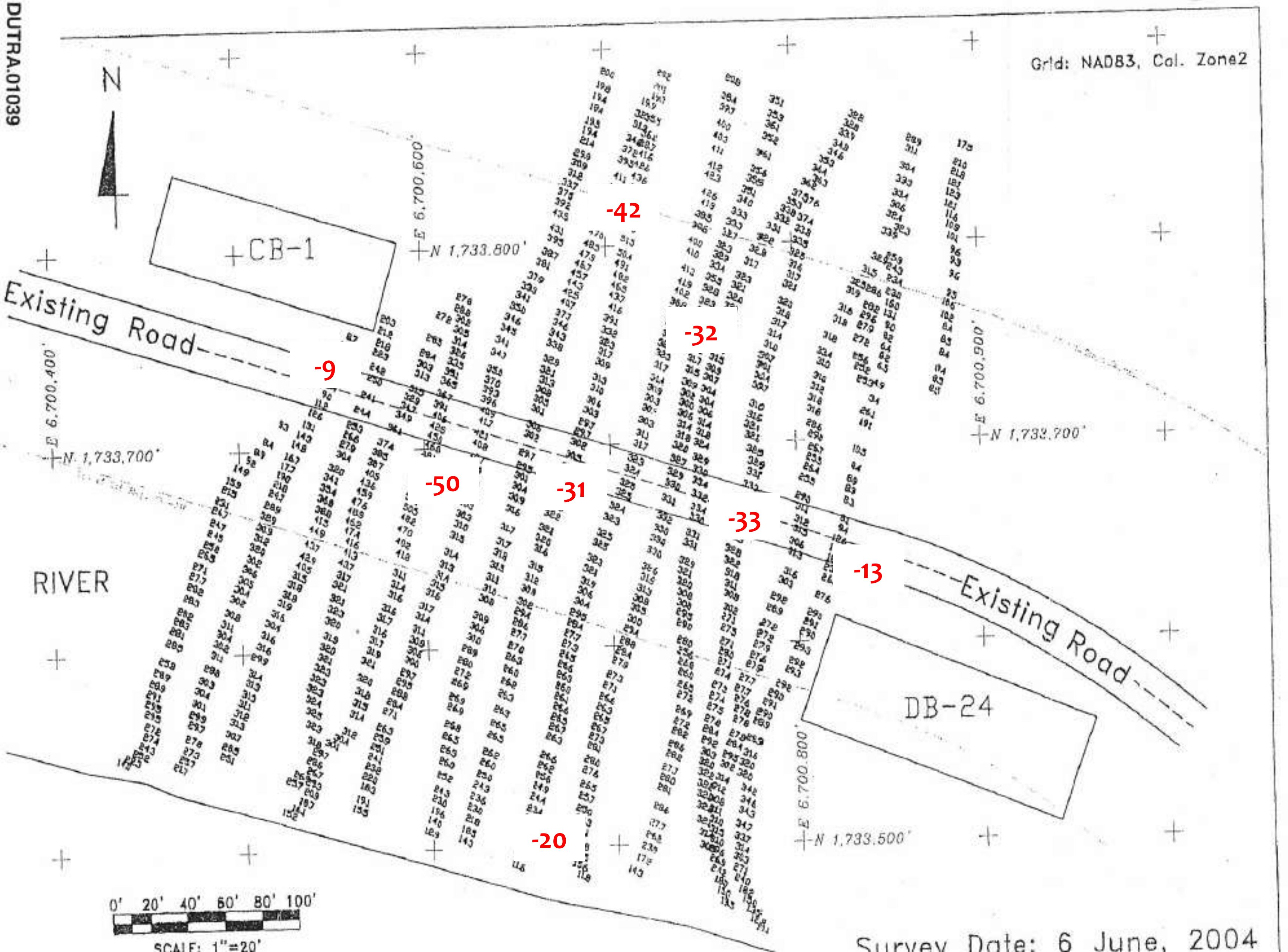

Upper Jones Tract Levee Breach Flow and Stage
15,000
10,000
5,000
0
-5,000
-10,000
-15,000
-20,000
-25,000
-30,000
-35,000
Flow (cfs)
7
6
5
4
3
2
Stage (ft)
00:00
12:00
03Jun2004
00:00
12:00
04Jun2004
00:0
MDM CDEC FLOW
VNI-MDM_SHIFT CDEC STAGE

Breach ~0815

To: Harry ASAP

NGVD29?

NGVD 29

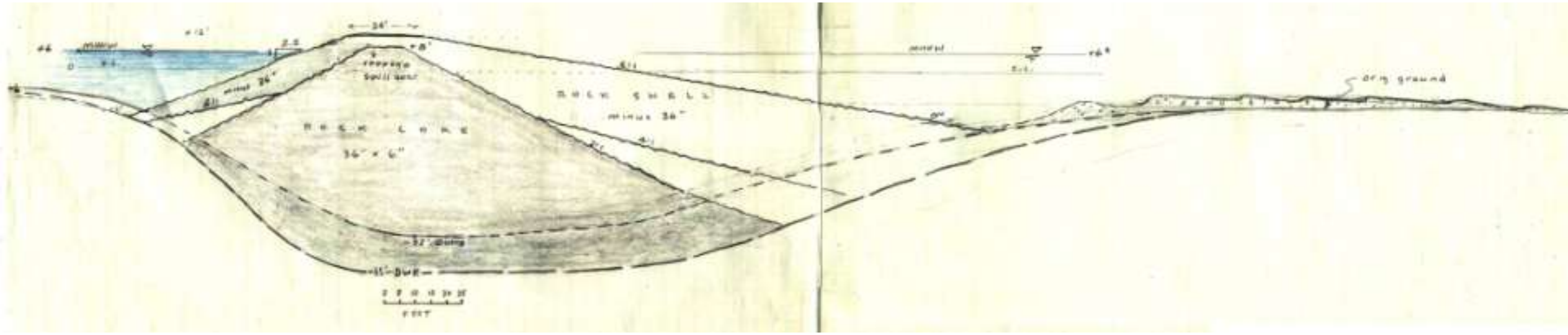


Survey Date: 6 June, 2004

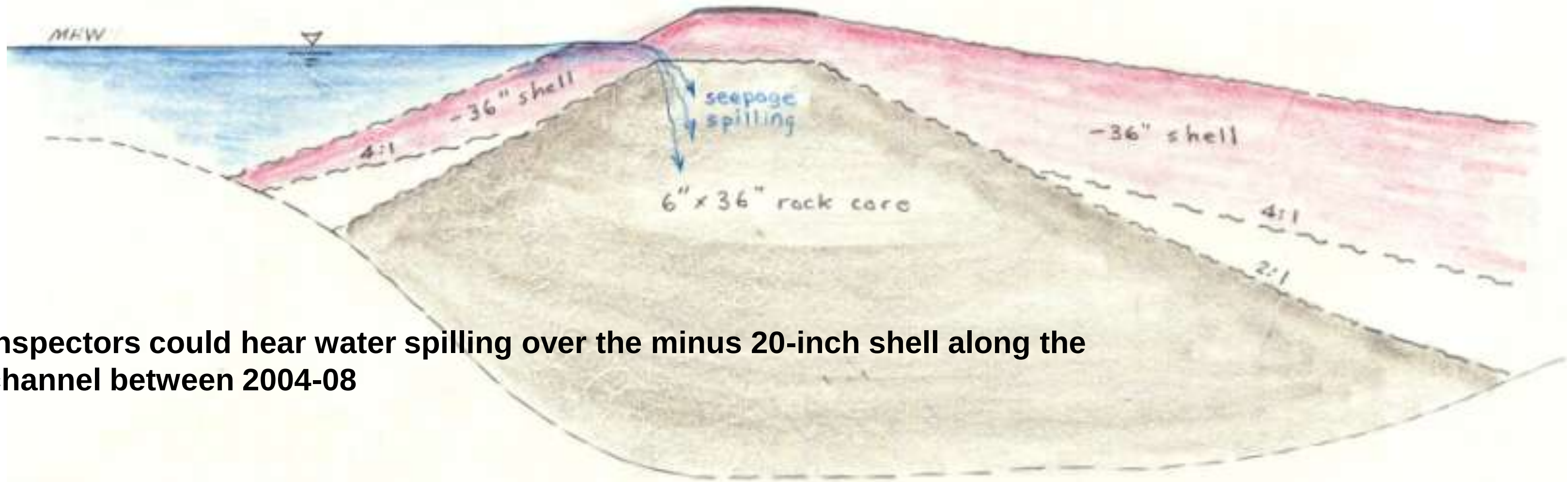
Air Mailing fill at the breach

Delivering the minus 36-inch rock mixture via "air-mailing" (shown at right) allows the fines to be swept away by the inrushing current (shown at left). This can result in an overly very pervious dike closure. This is what appears to have occurred at the north end of the 2004 closure, which leaked.

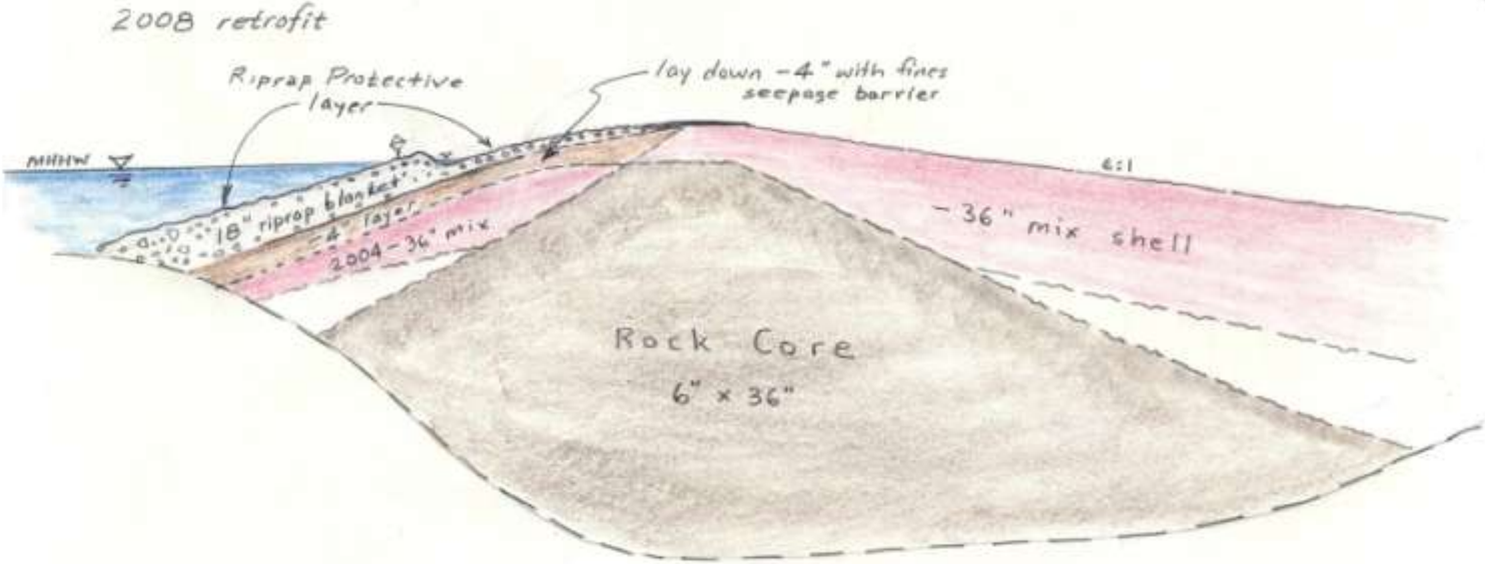
Jones Tract was one of the deepest breaches in delta history



By beginning the filling several days before the inflow equilibrated, a scour hole more than 55 ft deep was excavated between the two end caps, shown at left



Inspectors could hear water spilling over the minus 20-inch shell along the channel between 2004-08



The breached section was retrofitted twice to reduce excess seepage through the north abutment, which exceeded 50 cfs. These measures were implemented in the fall of 2004, and an extensive retrofit was implemented in the spring of 2008