THE PANAMA CANAL

THE WORLDS GREATEST ENGINEERING FEAT.

THE PANAMA CANAL

Geo-risk management at the Panama Canal

Gregory B. Baecher
University of Maryland

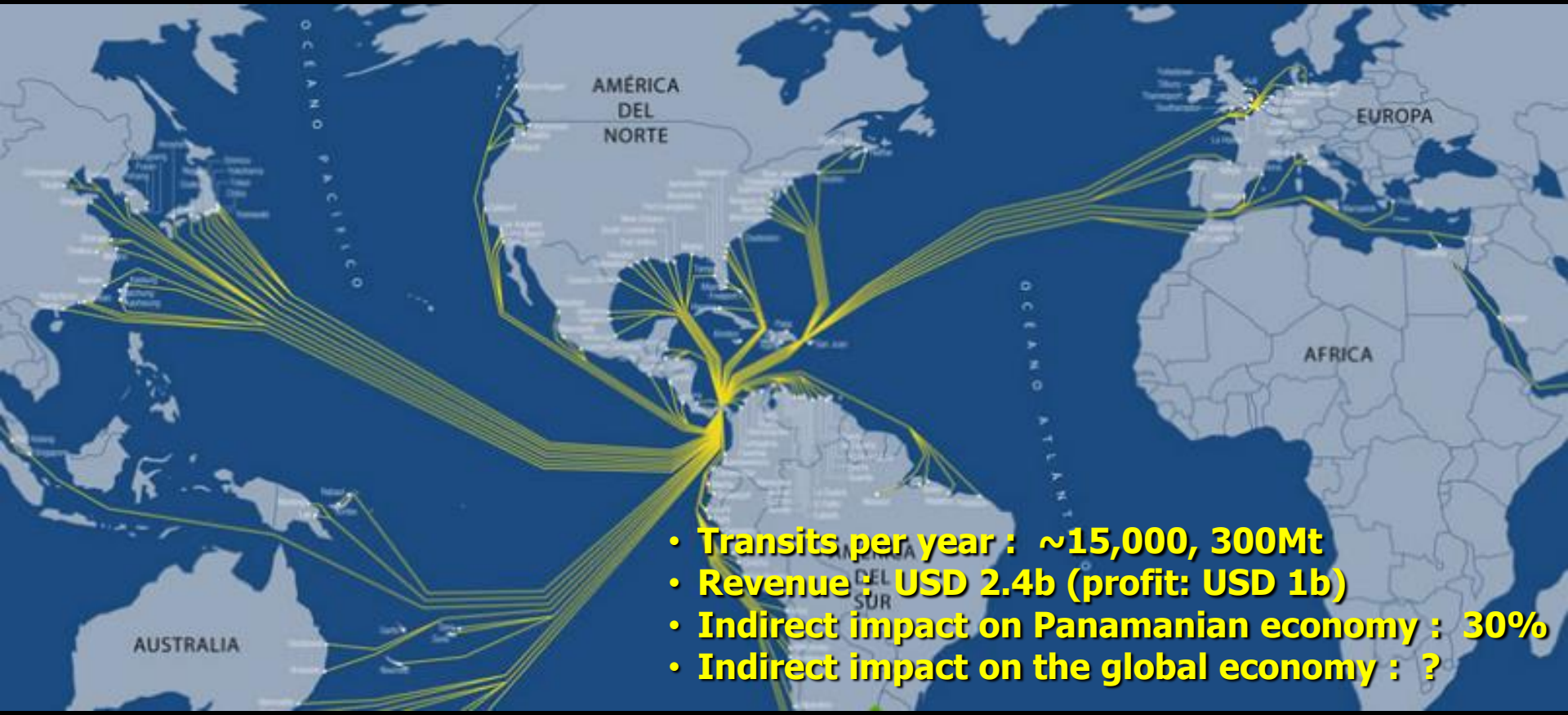
With appreciation to Dr. Luis Alfaro
Vice President, Engineering
Autoridad del Canal de Panamá

Outline

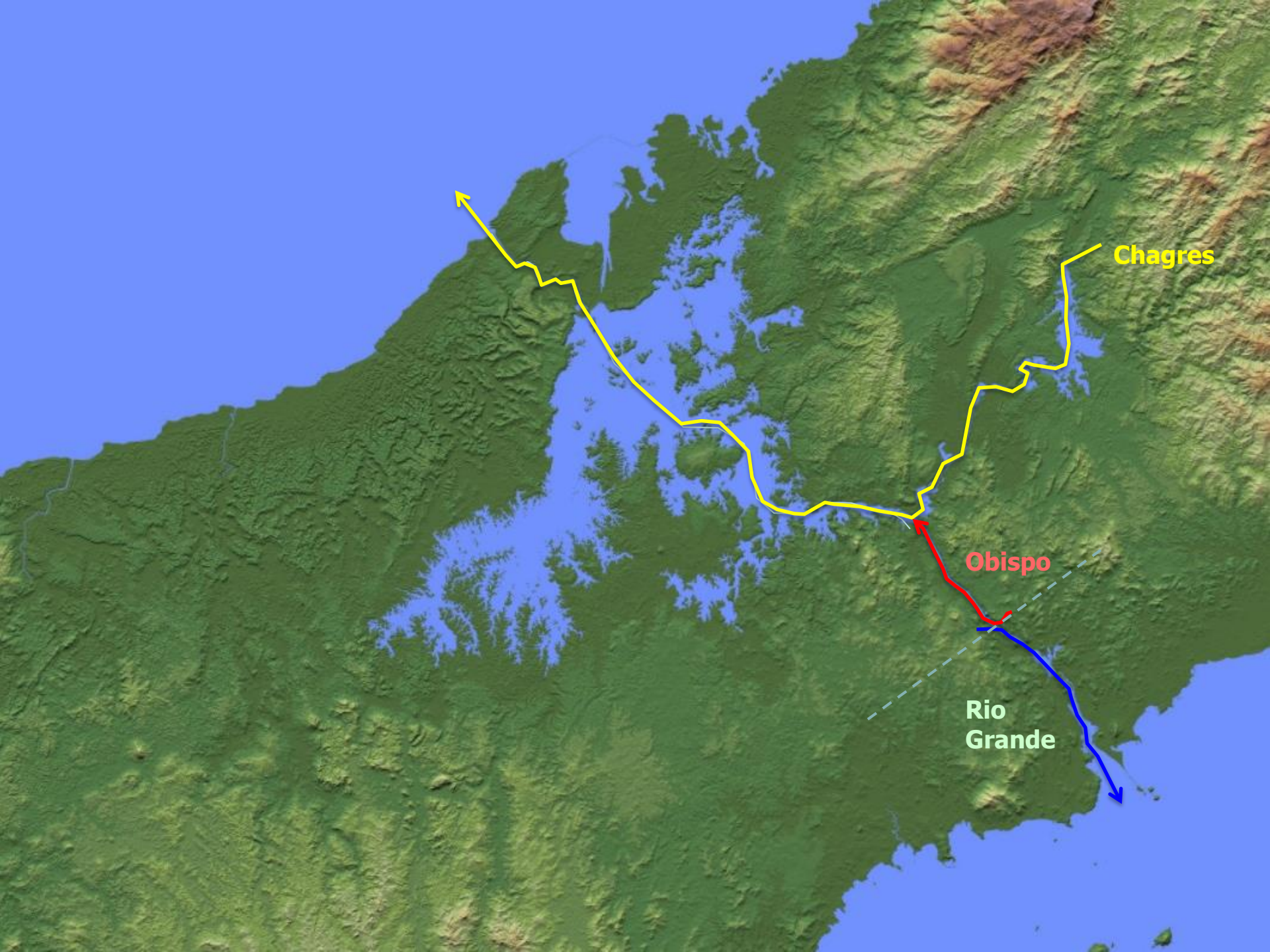
- Why a risk management program
- Recent experiences
- Risk components
- Geotechnical risks
- The new 3d locks

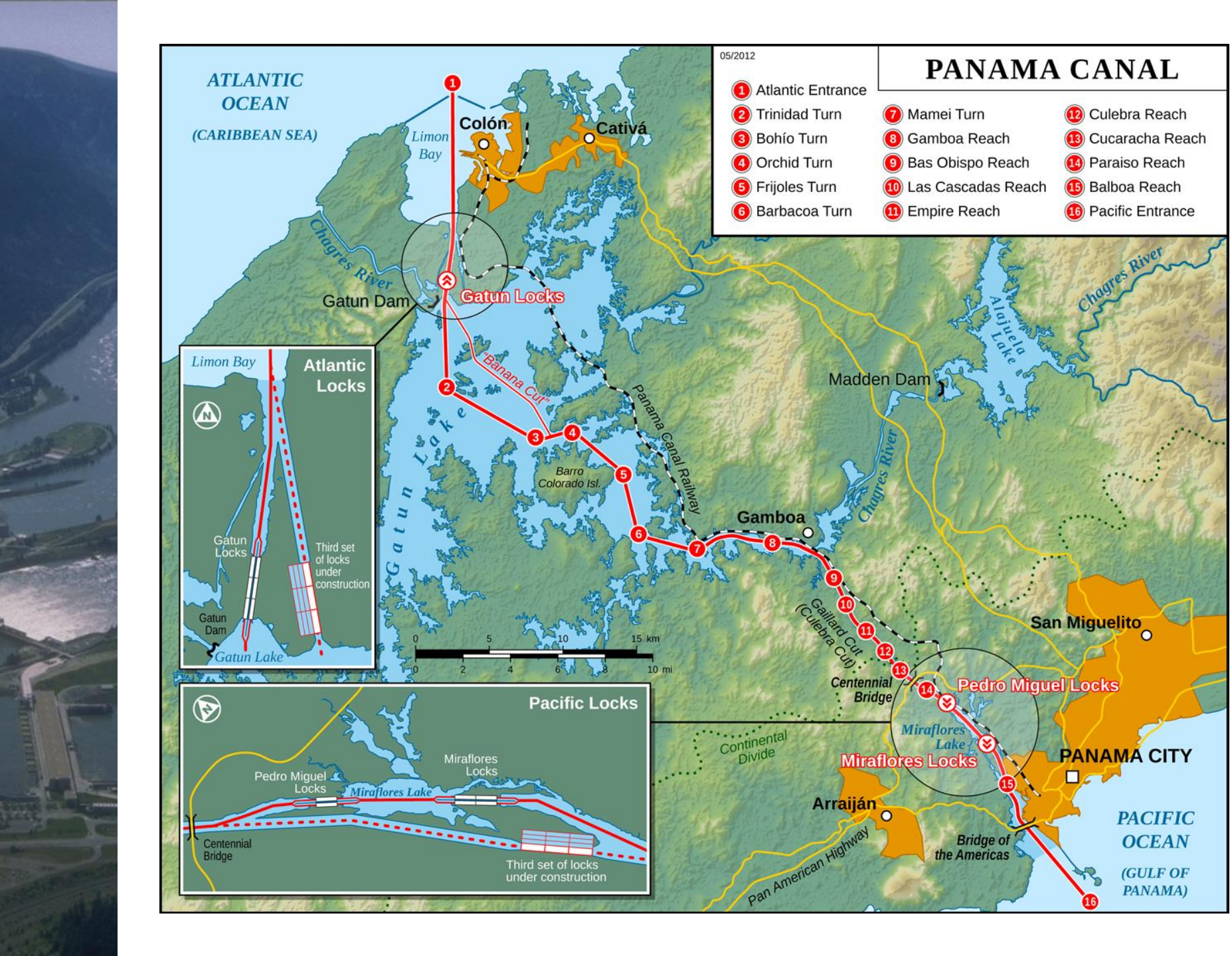
THE WORLDS GREATEST
ENGINEERING FEAT.

Logistical network through Panama

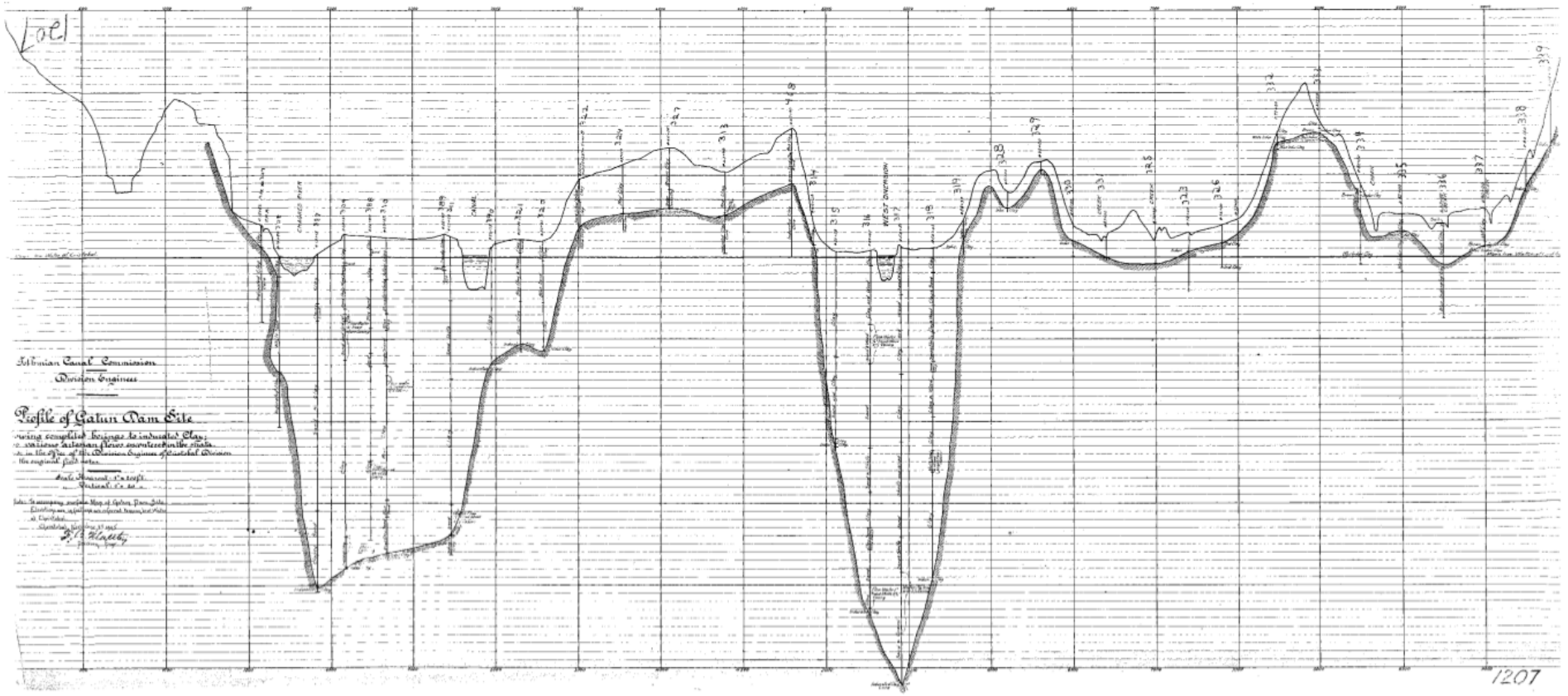


5% of world trade transits the Isthmus

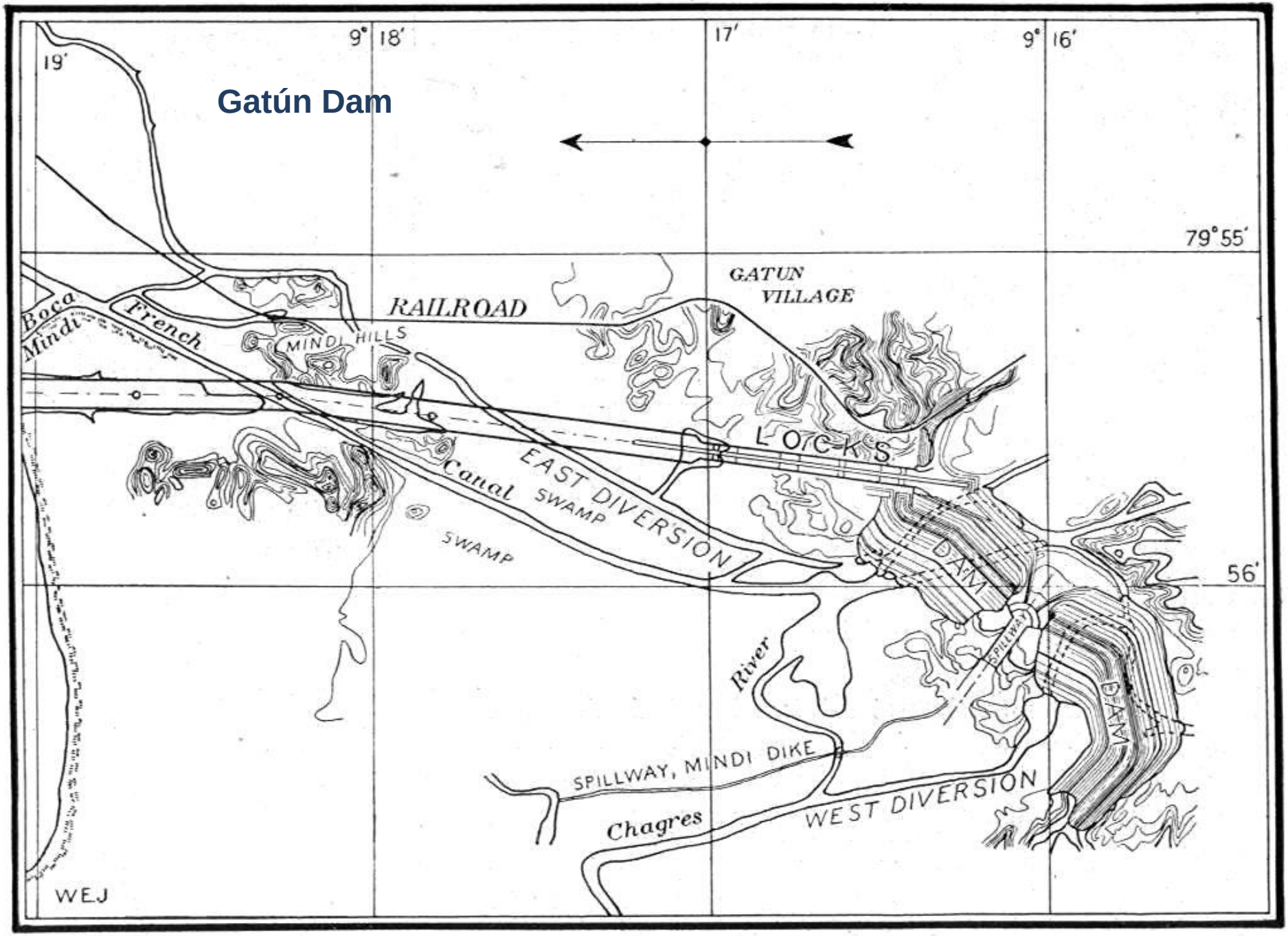

Chagres
Obispo
Rio
Grande

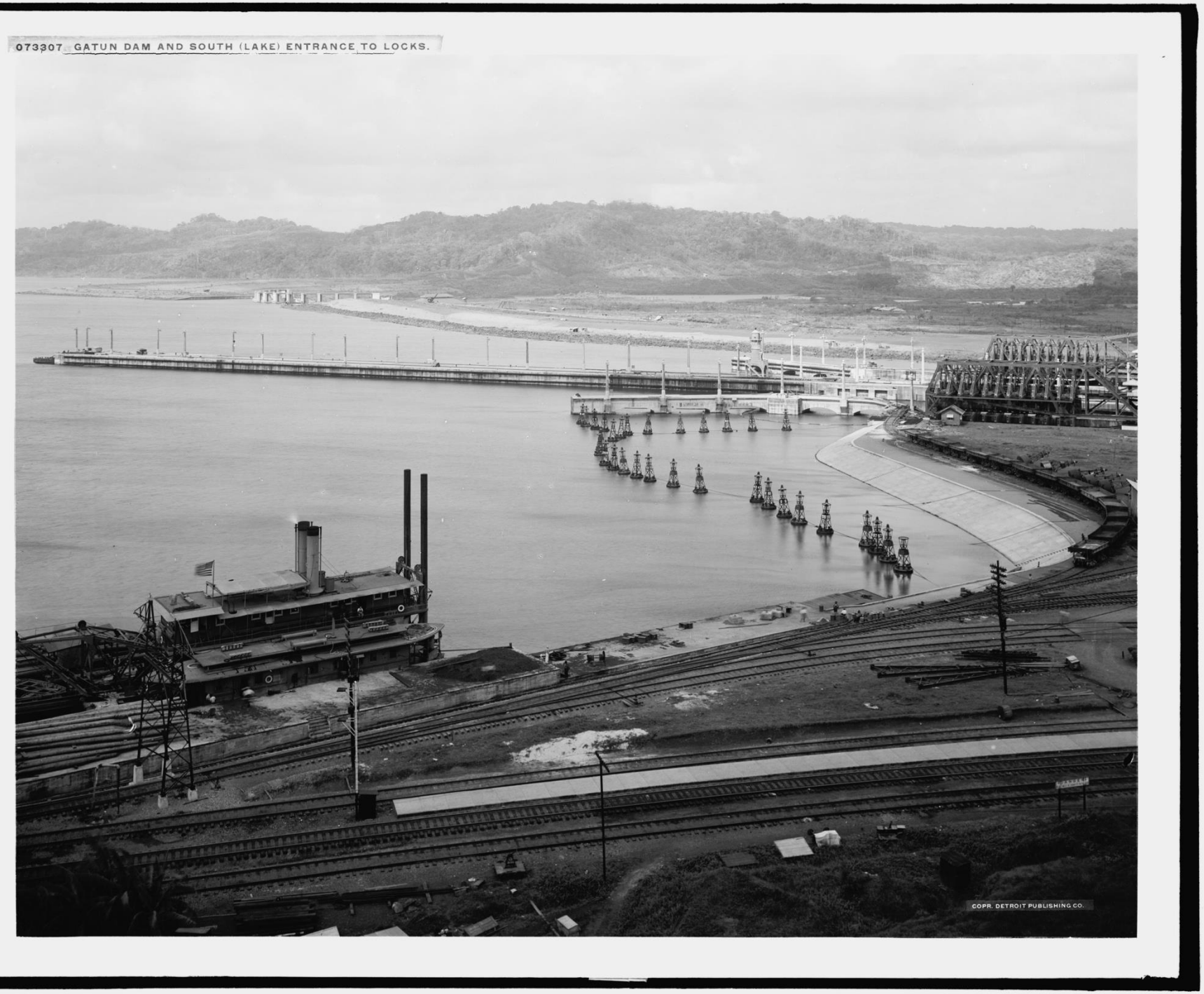

PANAMA CANAL
05/2012
1 Atlantic Entrance
2 Trinidad Turn
3 Bohío Turn
4 Orchid Turn
5 Frijoles Turn
6 Barbacoa Turn
7 Mamei Turn
8 Gamboa Reach
9 Bas Obispo Reach
10 Las Cascadas Reach
11 Empire Reach
12 Culebra Reach
13 Cucaracha Reach
14 Paraiso Reach
15 Balboa Reach
16 Pacific Entrance
ATLANTIC OCEAN
(CARIBBEAN SEA)
Limon Bay
Colón
Cativá
Chagres River
Gatun Dam
Gatun Locks
"Banana Cut"
Gatun Lake
Panama Canal Railway
Barro Colorado Isl.
Madden Dam
Alajuela Lake
Chagres River
Gamboa
Chagres River
Gaillard Cut (Culebra Cut)
Centennial Bridge
San Miguelito
Pedro Miguel Locks
Miraflores Lake
Miraflores Locks
PANAMA CITY
Continental Divide
Arraiján
Bridge of the Americas
Pan American Highway
PACIFIC OCEAN
(GULF OF PANAMA)
Atlantic Locks
Limon Bay
Gatun Locks
Third set of locks under construction
Gatun Dam
Gatun Lake
Pacific Locks
Pedro Miguel Locks
Miraflores Locks
Miraflores Lake
Centennial Bridge
Third set of locks under construction
0 5 10 15 km
0 2 4 6 8 10 mi

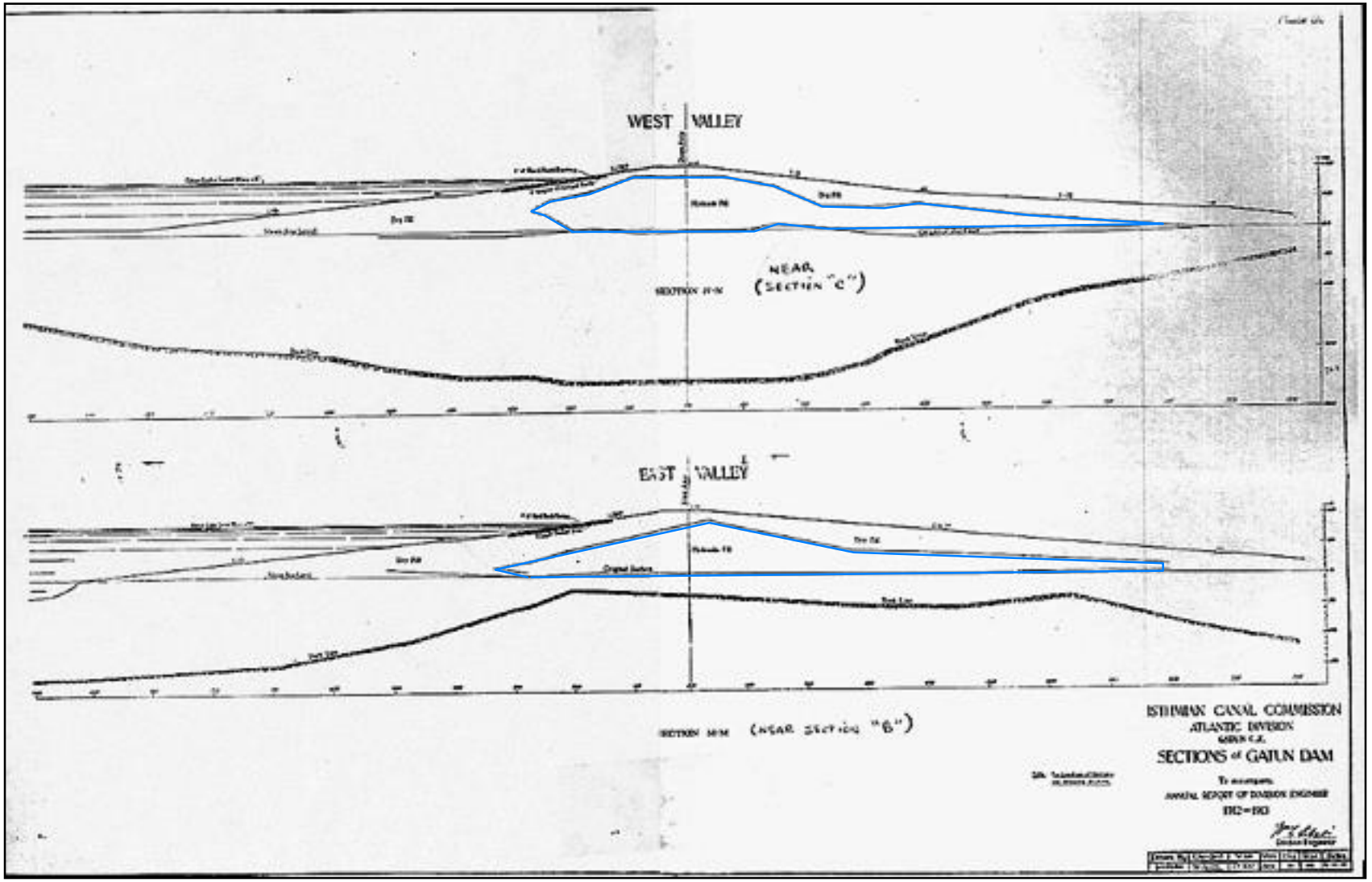

Gatún Dam

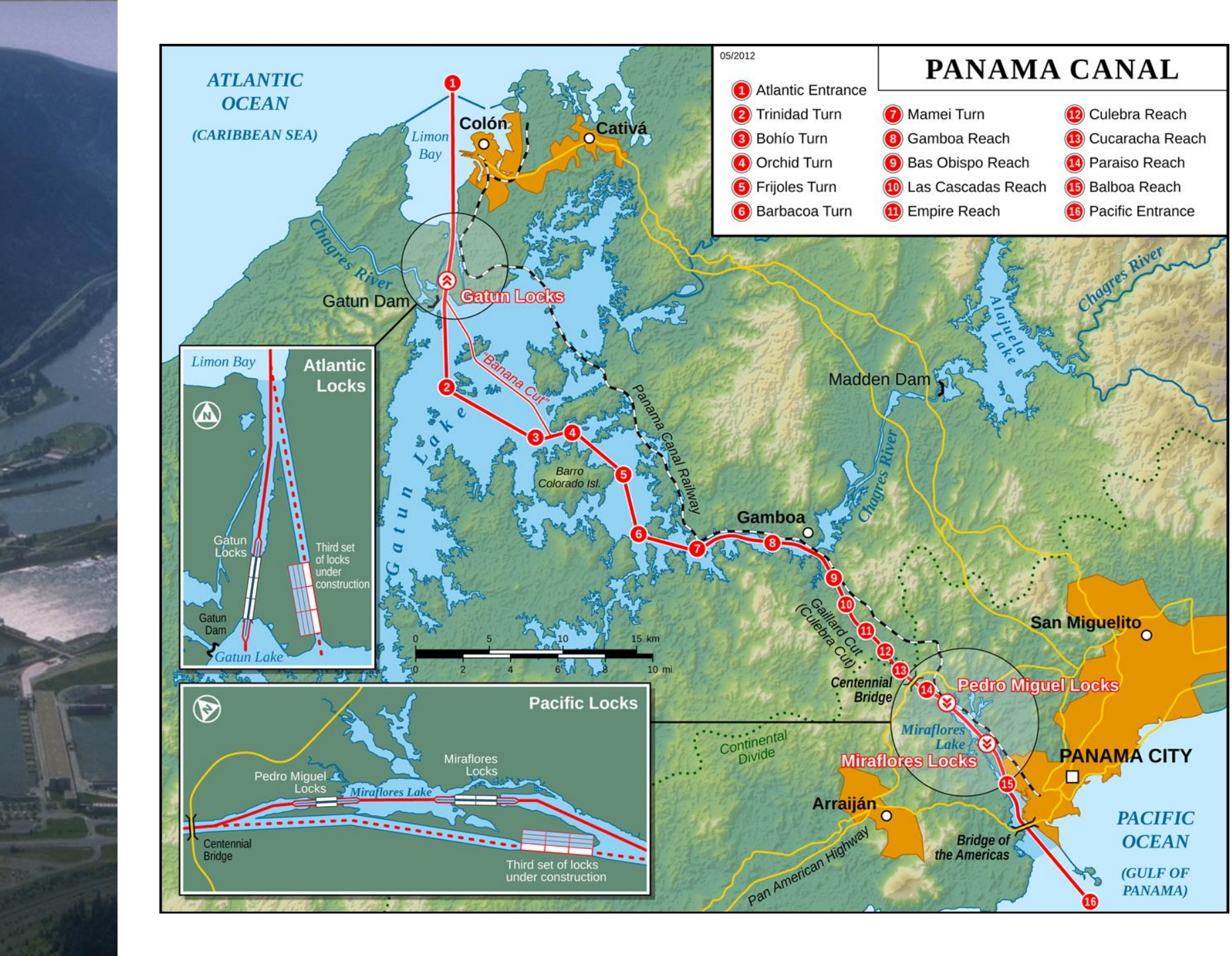

Panama Canal Commission
Division Engineers
Profile of Gatun Dam Site
1207

Gatún Dam


9° 18'
17'
9° 16'
19'
79°55'
56'
GATUN
VILLAGE
RAILROAD
Boca
Mindi
French
MINDI HILLS
LOCKS
EAST DIVERSION
Canal
SWAMP
SWAMP
DAM
River
SPILLWAY
DAM
SPILLWAY, MINDI DIKE
Chagres
WEST DIVERSION
WEJ


073307 GATUN DAM AND SOUTH (LAKE) ENTRANCE TO LOCKS.
COPR. DETROIT PUBLISHING CO.


WEST VALLEY
NEAR (SECTION "C")
EAST VALLEY
(NEAR SECTION "B")
ISTHMIAN CANAL COMMISSION
ATLANTIC DIVISION
SECTIONS of GATUN DAM
ANNUAL REPORT OF DIVISION ENGINEER
1912-1913


PANAMA CANAL
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1 Atlantic Entrance
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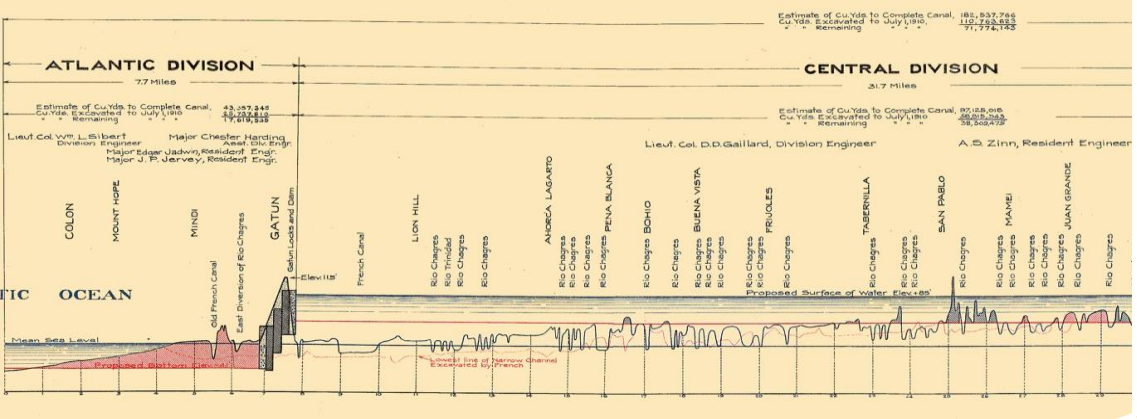
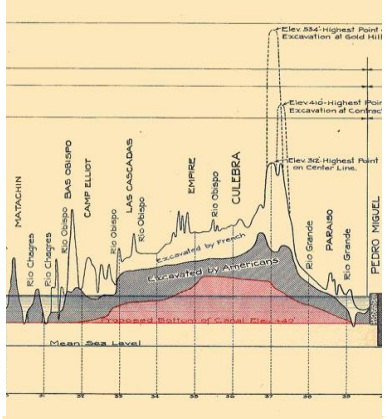
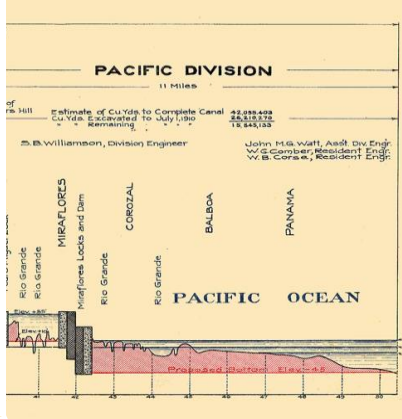
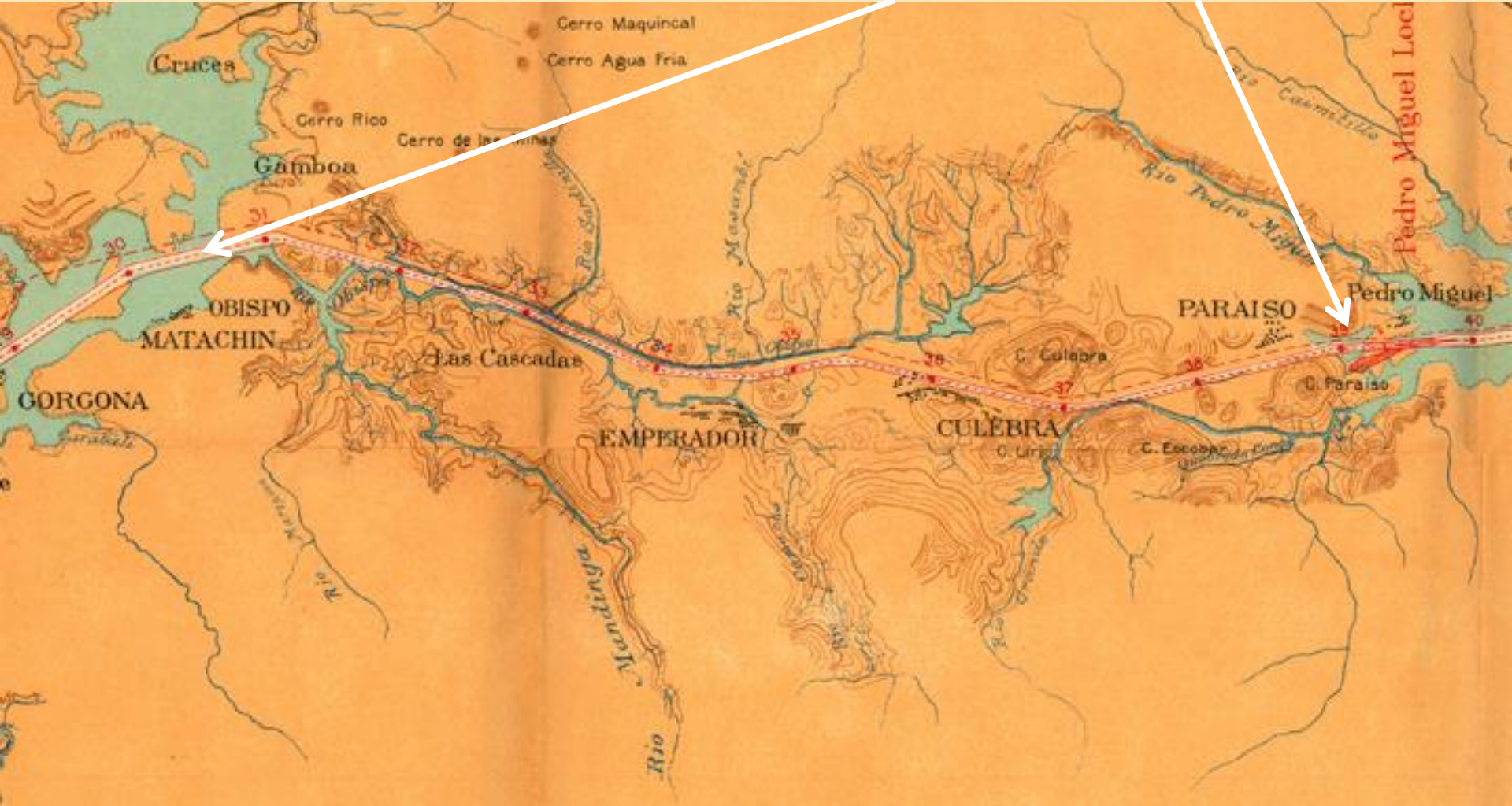
Pedro Miguel Locks
Miraflores Locks
Miraflores Lake
Centennial Bridge
Third set of locks under construction
0 5 10 15 km
0 2 4 6 8 10 mi


ATLANTIC DIVISION
7.7 Miles
CENTRAL DIVISION
31.7 Miles
Lieut. Col. Wm. L. Sibert
Division Engineer
Major Chester Harding
Asst. Div. Engr.
Major Edgar Jadwin, Resident Engr.
Major J. P. Jervey, Resident Engr.
Lieut. Col. D.D. Gaillard, Division Engineer
A.S. Zinn, Resident Engineer
COLON
MOUNT HOPE
MINDI
GATUN
LION HILL
ANDREA LAGARTO
PENA BLANCA
BOHIO
BUENA VISTA
FRIJOLES
TABERNILLA
SAN PABLO
MAMEI
JUAN GRANDE
Old French Canal
East Diversion of Rio Chagres
French Canal
Gatun Locks and Dam
Elev. 115'
Proposed Surface of Water Elev. 85'
Mean Sea Level
Proposed Bottom Elev. 45'
Lowest line of Narrow Channel Excavated by French
Rio Chagres
TIC OCEAN

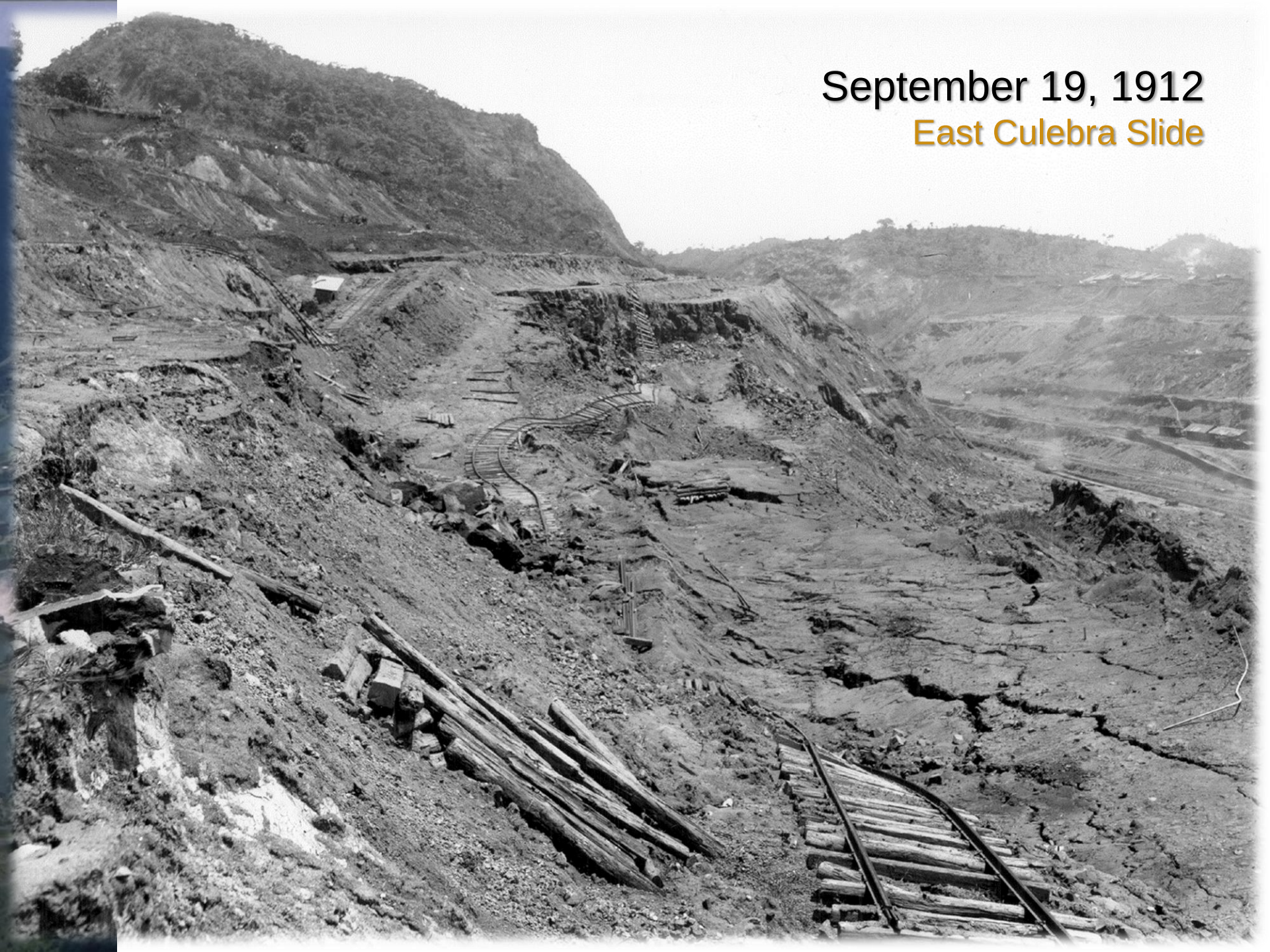

MATACHIN
BAS OBISPO
CAMP ELLIOT
LAS CASCADAS
EMPIRE
CULEBRA
PARAISO
PEDRO MIGUEL
Rio Chagres
Rio Obispo
Rio Grande
Excavated by French
Excavated by Americans
Proposed Bottom of Canal Elev. 42'
Mean Sea Level


PACIFIC DIVISION
11 Miles
S.B. Williamson, Division Engineer
John M. Wilson, Asst. Div. Engr.
W.G. Comber, Resident Engr.
W.B. Corse, Resident Engr.
MIRAFLORES
COROZAL
BALBOA
PANAMA
Rio Grande
Miraflores Locks and Dam
PACIFIC OCEAN


Cerro Maquincal
Cerro Agua fria
Cruces
Cerro Rico
Gamboa
OBISPO
MATACHIN
Las Cascadas
GORGONA
EMPERADOR
CULEBRA
C. Culebra
C. Paraiso
PARAISO
Pedro Miguel
Rio Pedro Miguel
Pedro Miguel Lock
Rio Chagres
Rio Mandinga

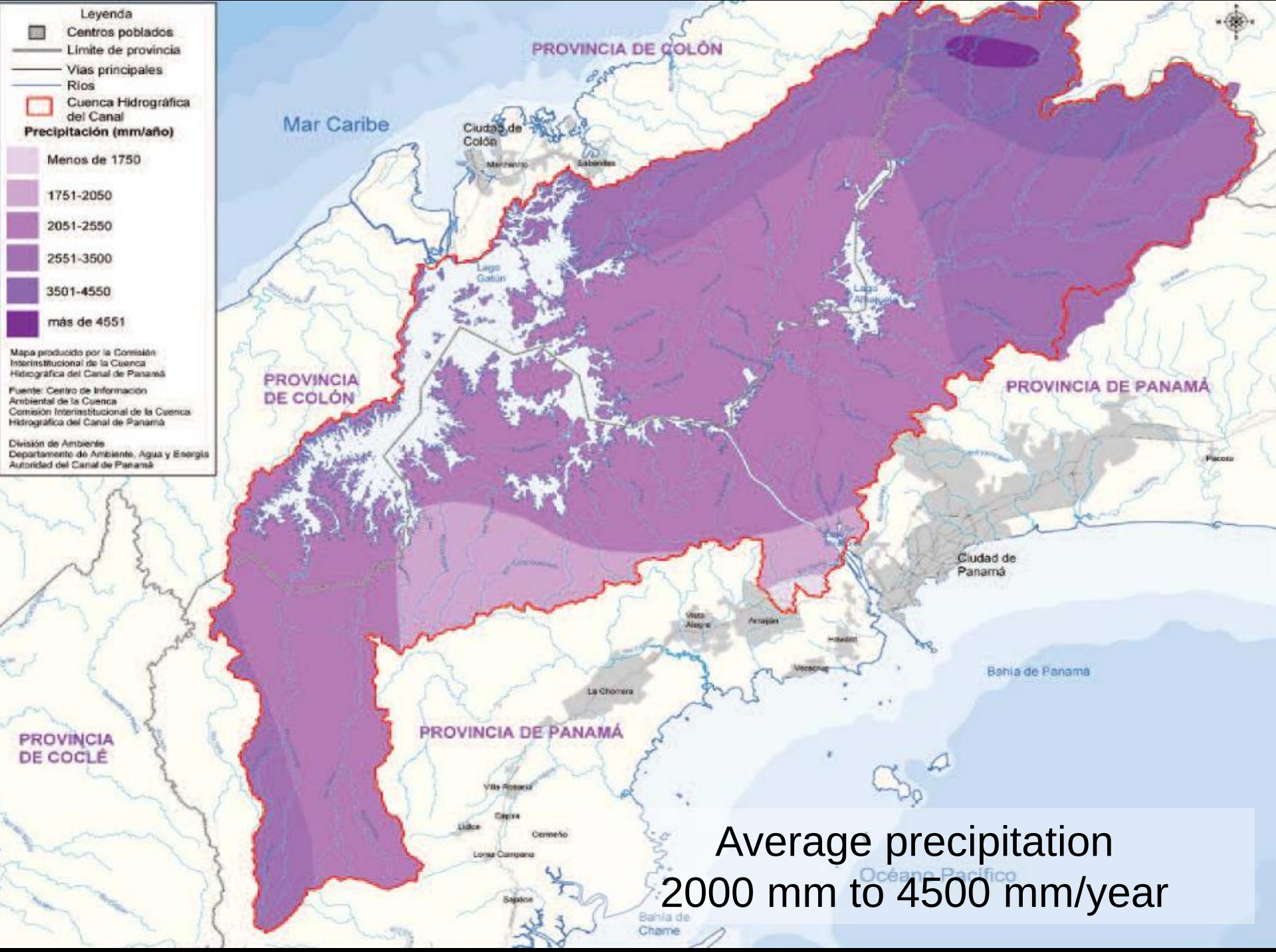
Col. David DuBose Gaillard (1859-1913)

In charge of excavations through the continental divide (Culebra Cut)


September 19, 1912
East Culebra Slide

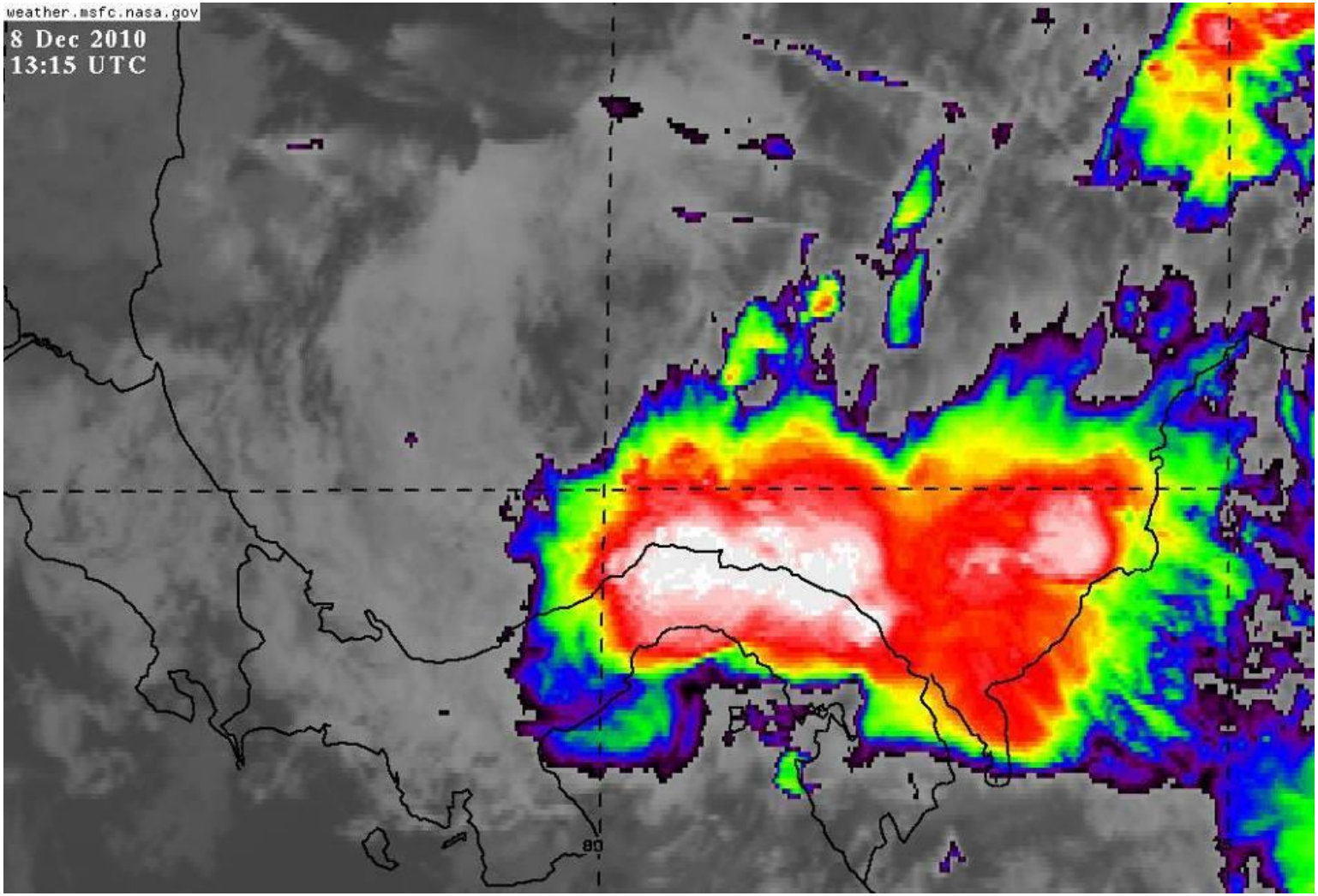
La Purisima 7-9 Dec 2010

Risk

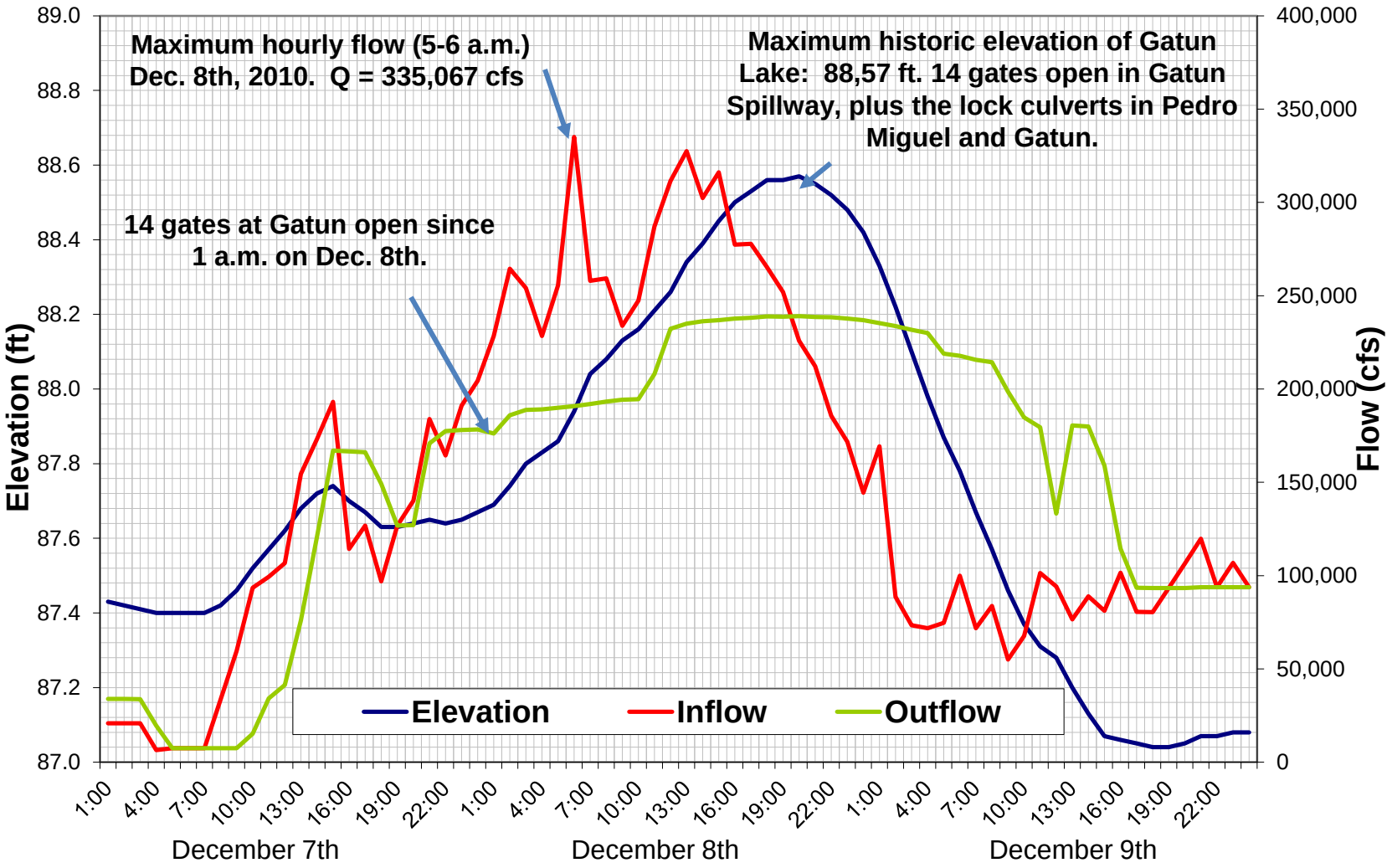


Average precipitation
2000 mm to 4500 mm/year

La Purisima storm 7-9 Dec 2010

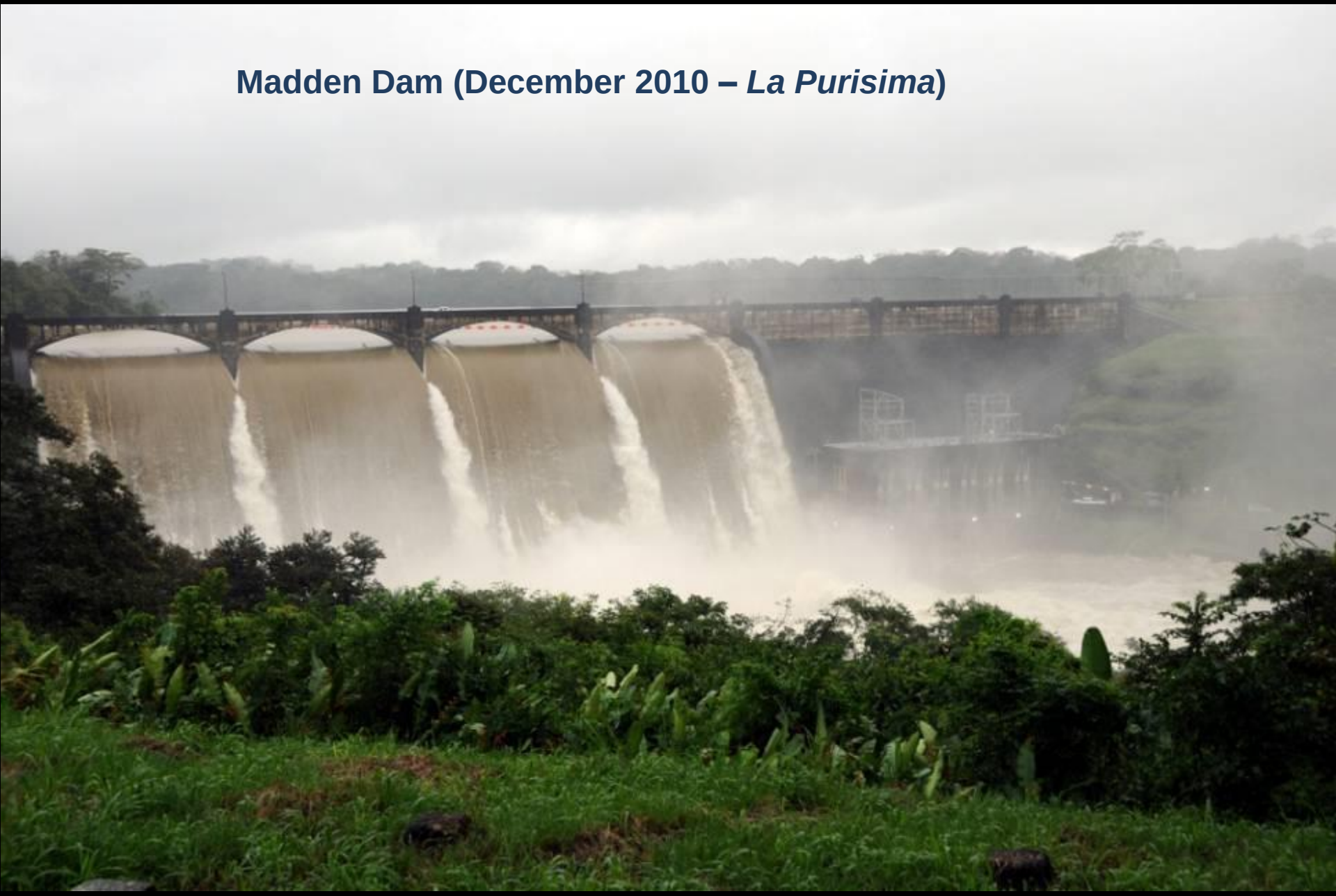


Gatun Lake. Storm of 7-9 December 2010



Gatún Dam (December 2010 – *La Purisima*)

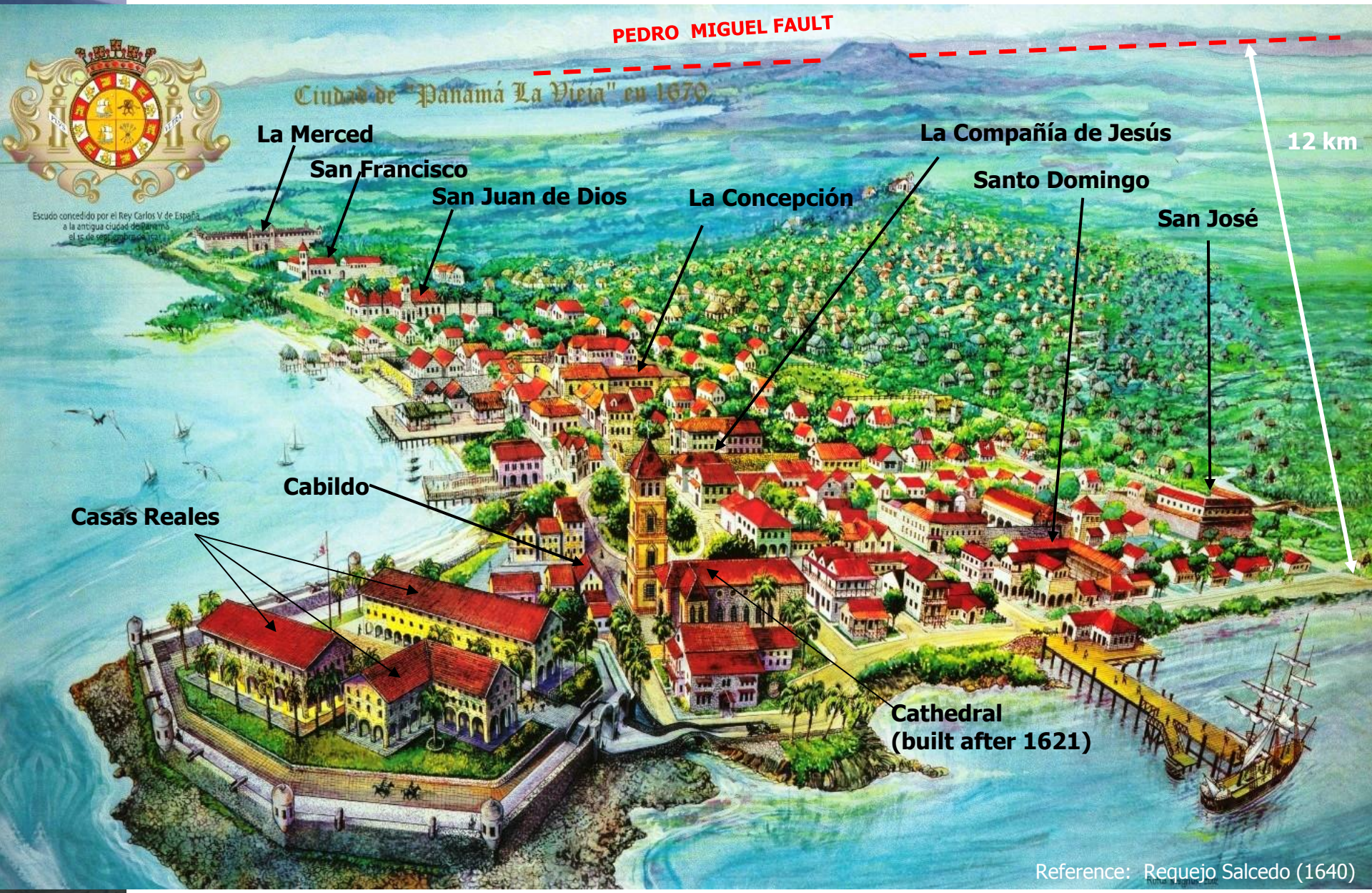
Madden Dam (December 2010 – *La Purisima*)



Alejuela Lake (Madden Dam)

Panama City 1621

More risk


PEDRO MIGUEL FAULT
Ciudad de "Panamá La Vieja" en 1670
La Merced
San Francisco
San Juan de Dios
La Concepción
La Compañía de Jesús
Santo Domingo
San José
12 km
Cabildo
Casas Reales
Cathedral
(built after 1621)
Reference: Requejo Salcedo (1640)

Father Juan Fonseca 1622

EXCERPTS FROM THE HISTORICAL AND GEOGRAPHICAL REPORT OF THE PROVINCE OF PANAMA ABOUT THE MAY 2, 1621 EARTHQUAKE

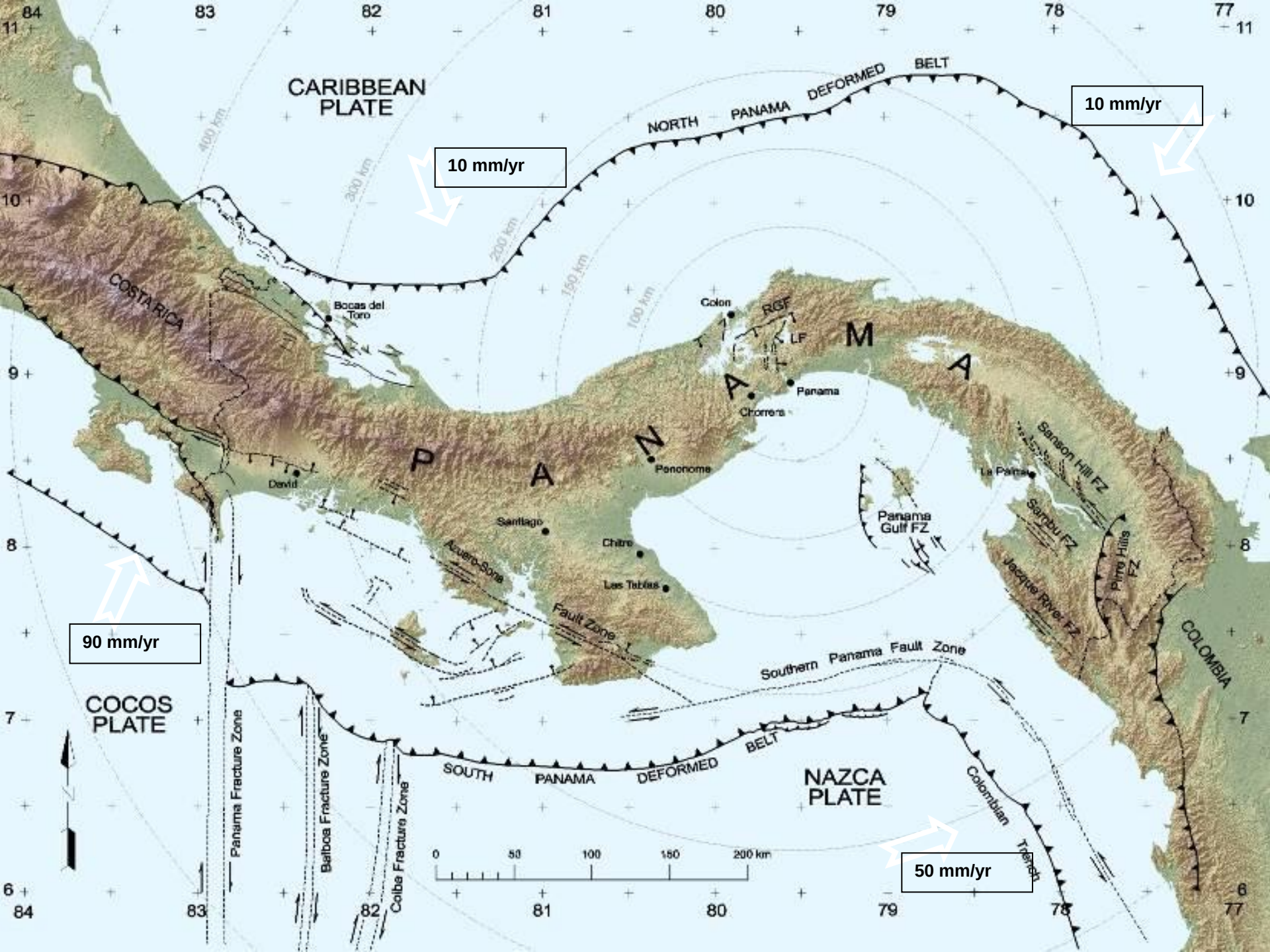
Juan Requejo Salcedo translated by Alice E. Westman

"The majority of the houses are of wood, but there are many of stone and brick including most of the convents. Those of wood are very strong as was clearly shown during an earthquake and its subsequent tremblors which lasted for more than three and a half months from 2 May until 21 August, on the Eve of Saint Bartolomew, in the year 1621, and during which twelve, ten, and six of less quakes were felt daily".

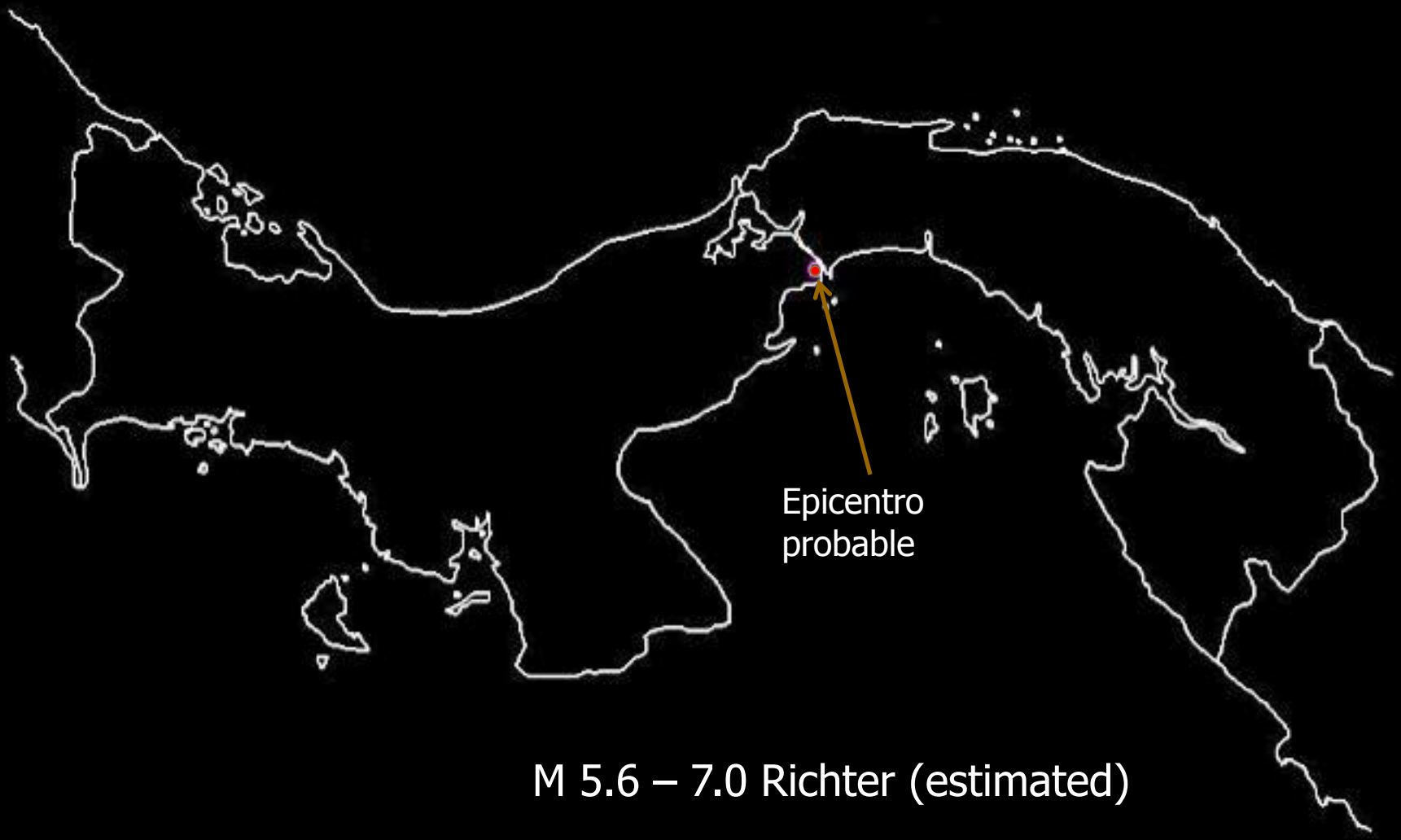
"...if it dealt so severely with this place where the buildings were strongly made of wood and stone, it would leave nothing but rubble from the adobe houses of Lima or Trujillo. It did great damage to the buildings made of stone, mortar and brick, cracking the walls and tearing others, although the oldest houses of wood, termitesaten and supported by props, came through unseathed. It happened as follows:

On Sunday, 2 May, on the feast of Saint Atanasio and Eve of the Invention of the Cross in the year 1621, between nine and ten in the morning the first quake was felt while I was in the sacristy fully vested to go out to say mass. Those of us who were there all felt it kaenly, but it did no damage. However, we did not know what was yet to come, for the first quake was short and passed quickly.

At 4:30 or 4:45 in the afternoon, the


CARIBBEAN PLATE
NORTH PANAMA DEFORMED BELT
10 mm/yr
10 mm/yr
COSTA RICA
Bocas del Toro
Colon
RGF
LF
Panama
Chorrera
PANAMA
Penonome
David
Santiago
Chitre
Las Tablas
Azuero-Sona
Fault Zone
Panama Gulf FZ
La Palma
Sanson Hill FZ
Sambu FZ
Jaqui'e River FZ
Pirre Hills FZ
COLOMBIA
90 mm/yr
COCOS PLATE
Southern Panama Fault Zone
SOUTH PANAMA DEFORMED BELT
NAZCA PLATE
Colombian Trench
50 mm/yr
Panama Fracture Zone
Balboa Fracture Zone
Coiba Fracture Zone
0 50 100 150 200 km
84 83 82 81 80 79 78 77
11 10 9 8 7 6

2 May, 1621 Earthquake



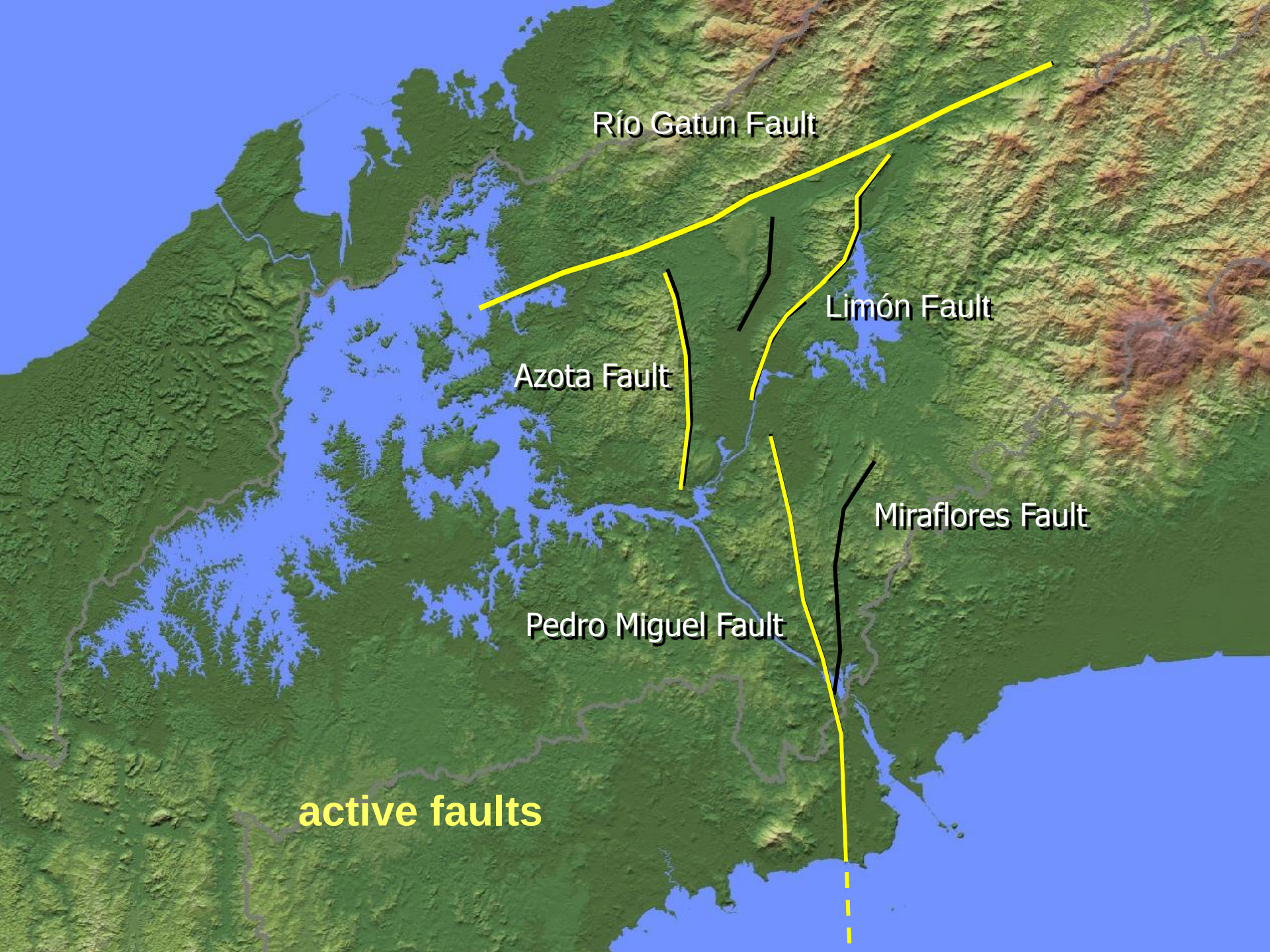
M 5.6 – 7.0 Richter (estimated)

7 September, 1882 Earthquake

M 7.9 Richter (estimated)

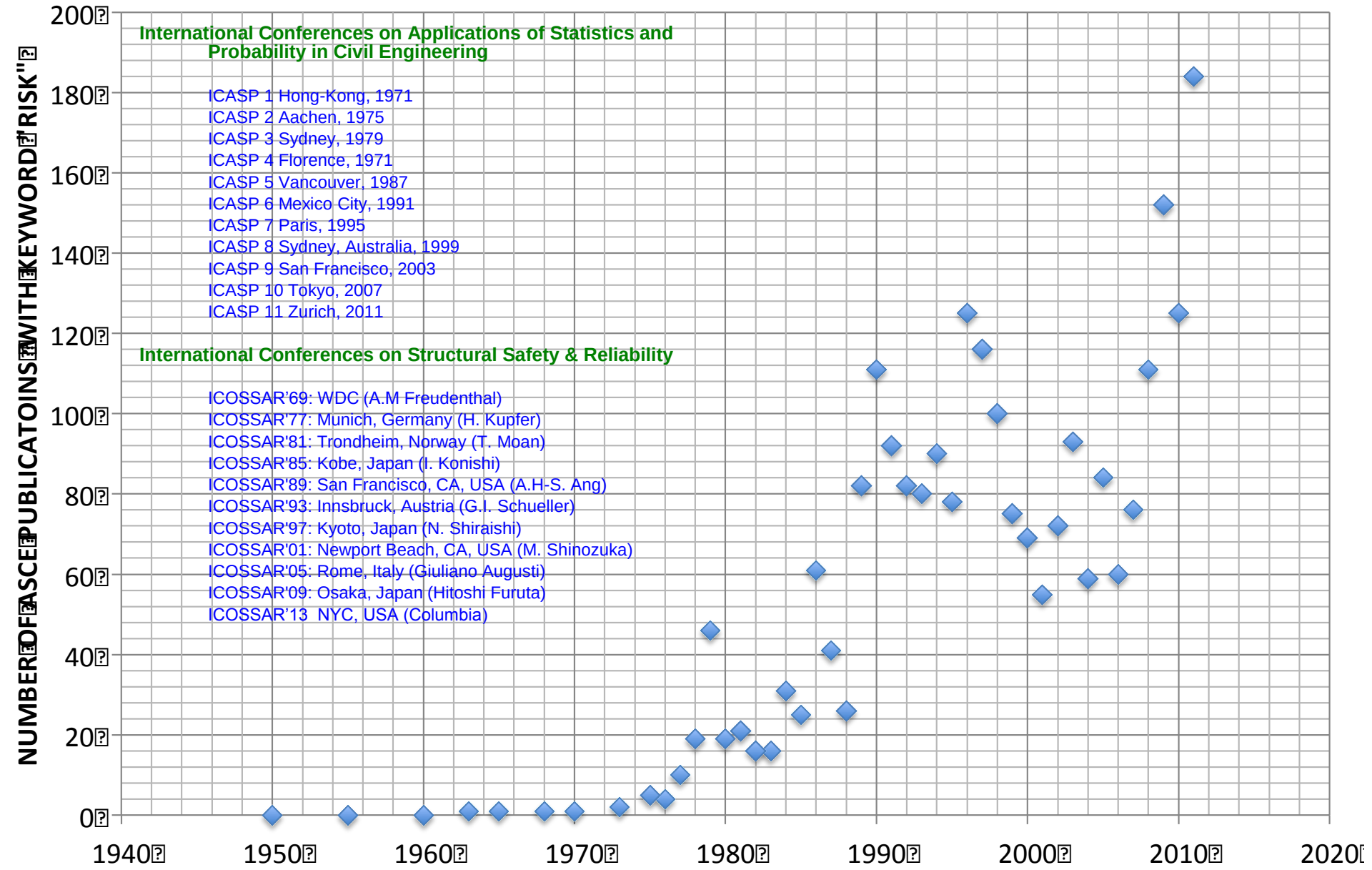
Paleoseismic investigations

Earth Consultants International
William Lettis & Associates


Río Gatun Fault
Limón Fault
Azota Fault
Miraflores Fault
Pedro Miguel Fault
active faults

Paleoseismic investigations

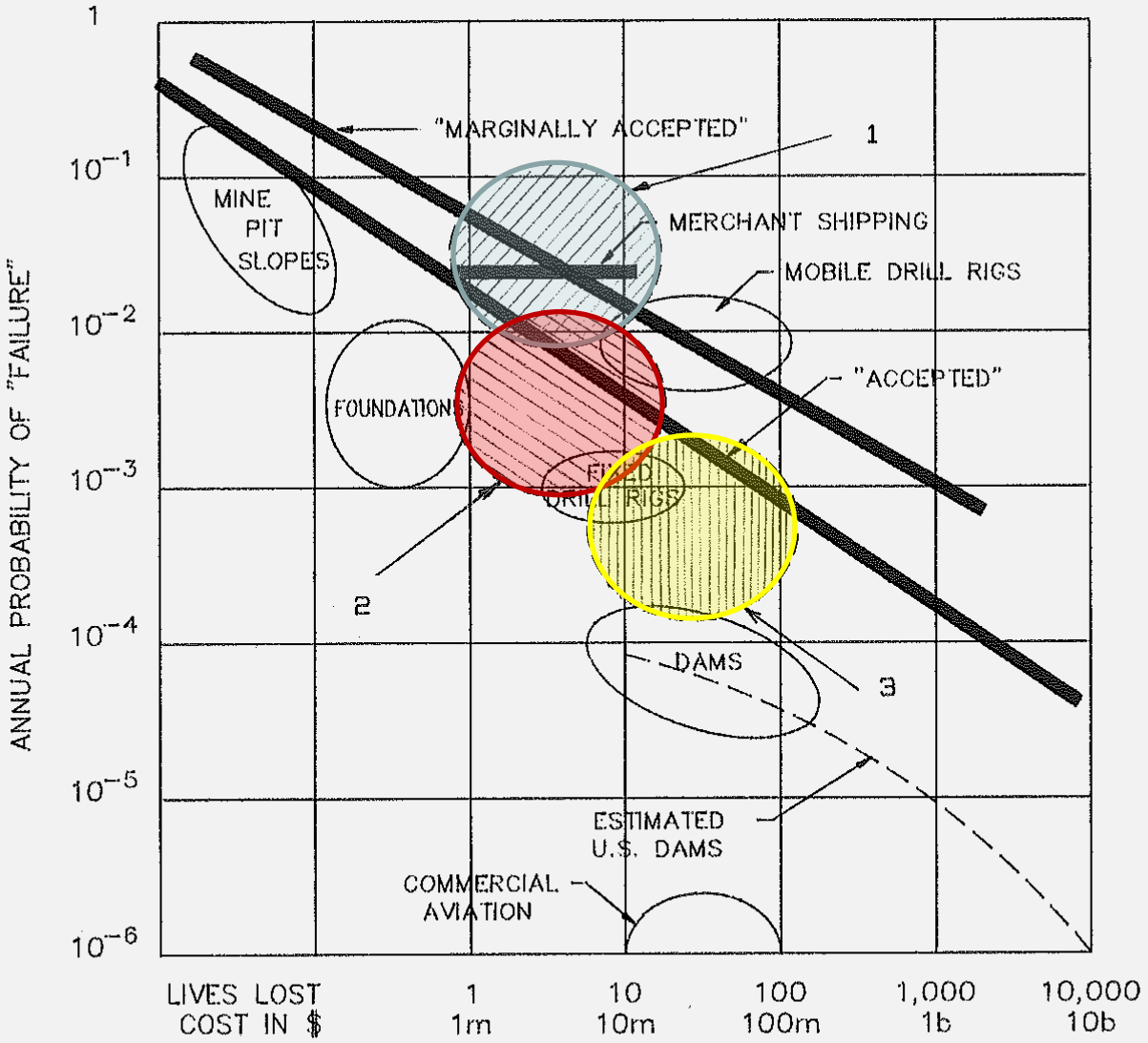

Pedro Miguel Fault


NUMBER OF PUBLICATIONS WITH THE KEYWORD "RISK"
200
180
160
140
120
100
80
60
40
20
0
1940
1950
1960
1970
1980
1990
2000
2010
2020
International Conferences on Applications of Statistics and Probability in Civil Engineering
ICASP 1 Hong-Kong, 1971
ICASP 2 Aachen, 1975
ICASP 3 Sydney, 1979
ICASP 4 Florence, 1971
ICASP 5 Vancouver, 1987
ICASP 6 Mexico City, 1991
ICASP 7 Paris, 1995
ICASP 8 Sydney, Australia, 1999
ICASP 9 San Francisco, 2003
ICASP 10 Tokyo, 2007
ICASP 11 Zurich, 2011
International Conferences on Structural Safety & Reliability
ICOSSAR'69: WDC (A.M Freudenthal)
ICOSSAR'77: Munich, Germany (H. Kupfer)
ICOSSAR'81: Trondheim, Norway (T. Moan)
ICOSSAR'85: Kobe, Japan (I. Konishi)
ICOSSAR'89: San Francisco, CA, USA (A.H-S. Ang)
ICOSSAR'93: Innsbruck, Austria (G.I. Schueller)
ICOSSAR'97: Kyoto, Japan (N. Shiraishi)
ICOSSAR'01: Newport Beach, CA, USA (M. Shinozuka)
ICOSSAR'05: Rome, Italy (Giuliano Augusti)
ICOSSAR'09: Osaka, Japan (Hitoshi Furuta)
ICOSSAR'13 NYC, USA (Columbia)

History of the Management of Physical Risks in the Canal

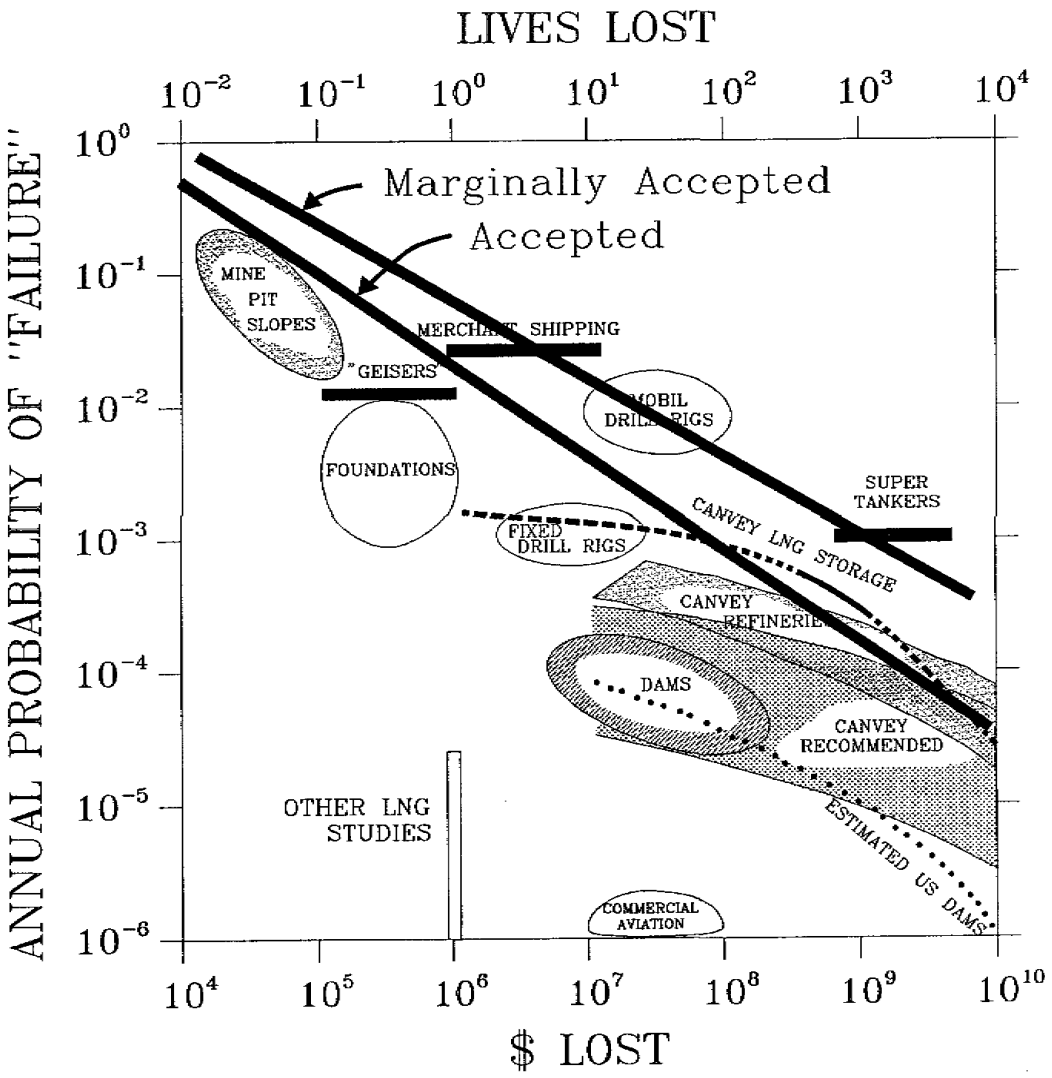
- **USACE design criteria (1904-1914)**
- **Flood Control Program (since construction)**
- **Protection of the Canal (since 1909)**
- **Landslide Control Program (modern program since 1968)**
- **Erosion Control Program (aggravated by larger ships and tugs)**
- **Dam Safety Program (since 1979)**
- **Corrosion Control (since construction)**
- **Structural codes for buildings (CZ Code was implemented 1907)**
- **Seismic Risk criteria (since 1991)**

Alfaro, L. (1988). "The risk of landslides in Galliard Cut," Panama Canal Commission.



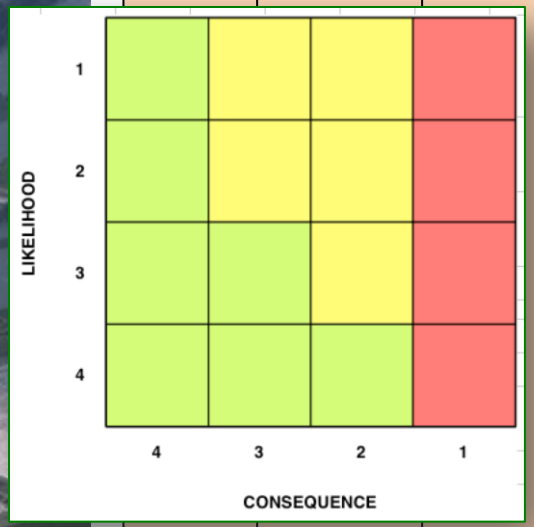
1 - Slopes in Gaillard Cut (no LCP)
2 - Slopes in Gaillard Cut (with LCP)
3 - Large Igneous Hills in Gaillard Cut

TONEN Tank Farm (1978)



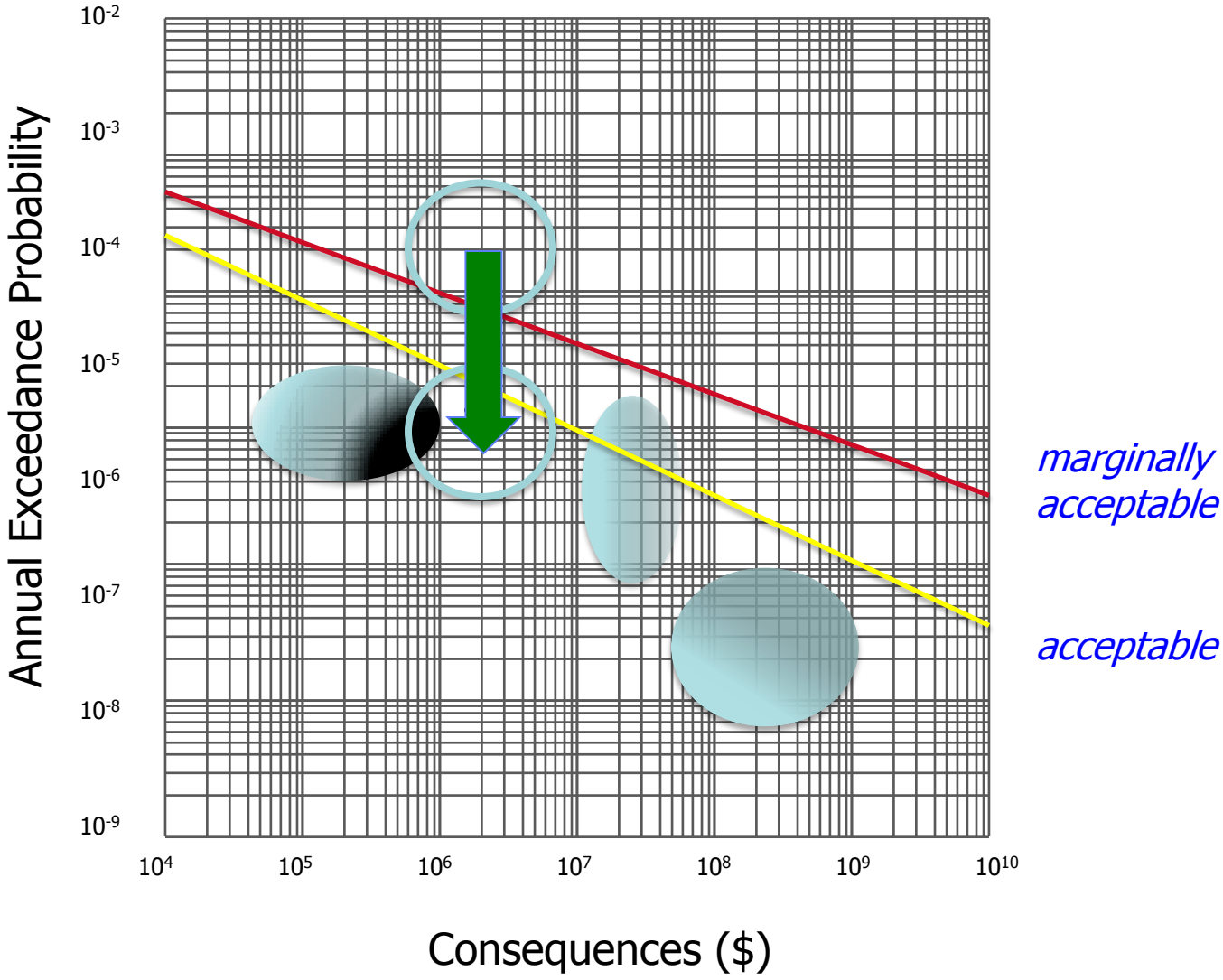
Panama Canal Infrastructure Risk Administration

Risk Register



#	Category	Structure	Event	Description	Component	Description	Failure Mode	Failure Cause	Likelihood of occurrence	Severity of consequences	Remark	Risk Index
1	Spillways	Gatun spil	Floods	PMF	Gates	Steel structure, and all castings in concrete	Gate out of commission	Overload, mechanical, under maintenance or repair, impact by barge or large object	2	4	Se asumio la falla en una sola compuerta y la misma esta cerrada	0
							Gate loss	Loose lateral support, under maintenance or repair, impact by barge or large object	3	3	Considering that one gate is lost and the flow is unrestricted. In this case nothing can be placed in the slot and the level reaches 69 feet in one week. **	0
							Open gate can't be closed due to blockage	Debris blockage	1	3		0
					Concrete piers		Concrete damage	Previous damage from EQ	4	4		0
					Concrete main section		Cavitation	High water velocity	2	4		0
							Stability issues	Uplift forces, overload, cavitation	4	1		1
							Over stress in concrete	Overload	4	4		0
					Discharge channel	Including baffle blocks, retaining walls, and spillway bridge piers	Cavitation	High water velocity and low water pressure	2	4		0
							Loss of baffle blocks	Overload	3	4		0
							Overtopping	Lack of discharge capacity and bank erosion behind walls	1	4	Criticality- Los contrafuertes evitarian la propagacion de la erosion aguas arriba y la perdida de la represa	0
					Gate machinery	Mechanical, electrical, and control systems (control house and gallery)	Gate out of commission	Gate motor's circuit breaker tripped and/or motor failure	3	4		0
								Motor damage	3	4		0
			Earthquakes	MCE (Maximum Credible Earthquake)	Gates	Steel structure, and all castings in concrete	Gate out of commission	Welding failures, bending	3	3	C	0
							Gate jamming	Foot bridge colapse on top of gate	2	3	C queda abierta	2
					Concrete piers		Structural failure	Concrete overstressed	2	3	C	2

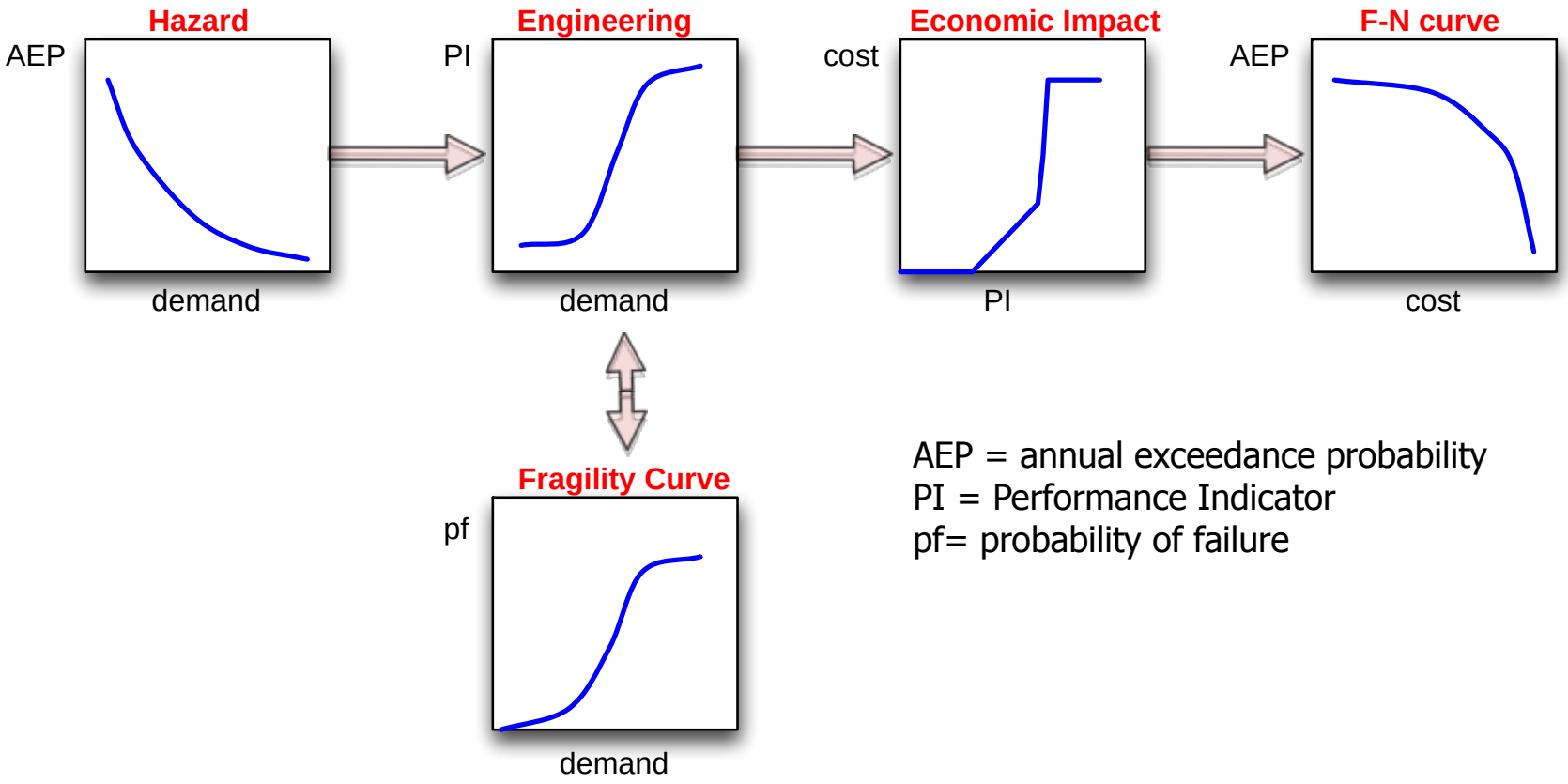
Rational Investment Decisions (using F-N charts)



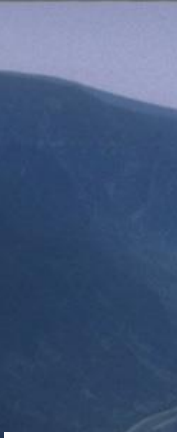
Risk mitigation

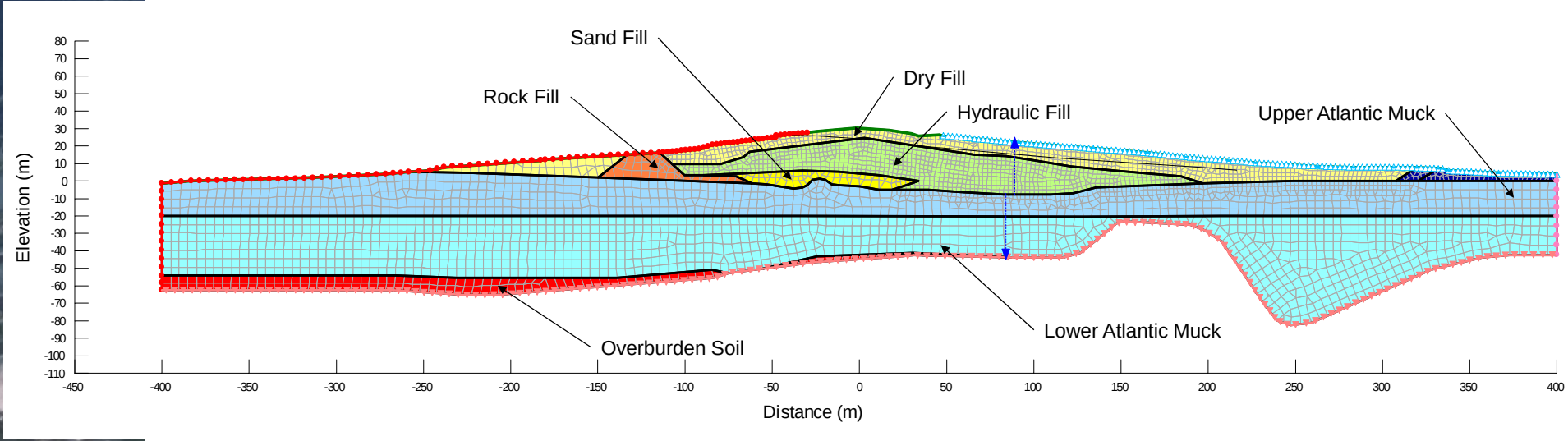
Type	Catastrophic Natural Risks	Chronic Natural Risks	Anthropogenic Risks
Drivers	• Meteorological • Seismic	• Time • Degradation use	• Human activities
Events	• Floods • Earthquakes • Landslides • Droughts	•Erosion •Sedimentation •Corrosion •Aging	• Terrorism • Sabotage • Accidents
Mitigation Strategy	*Improve Capacity of Structures through Engineering Analysis*	*Implement Maintenance Programs through systematic inspections*	*Implement appropriate operations and protection policies*

Risk Analysis Procedure

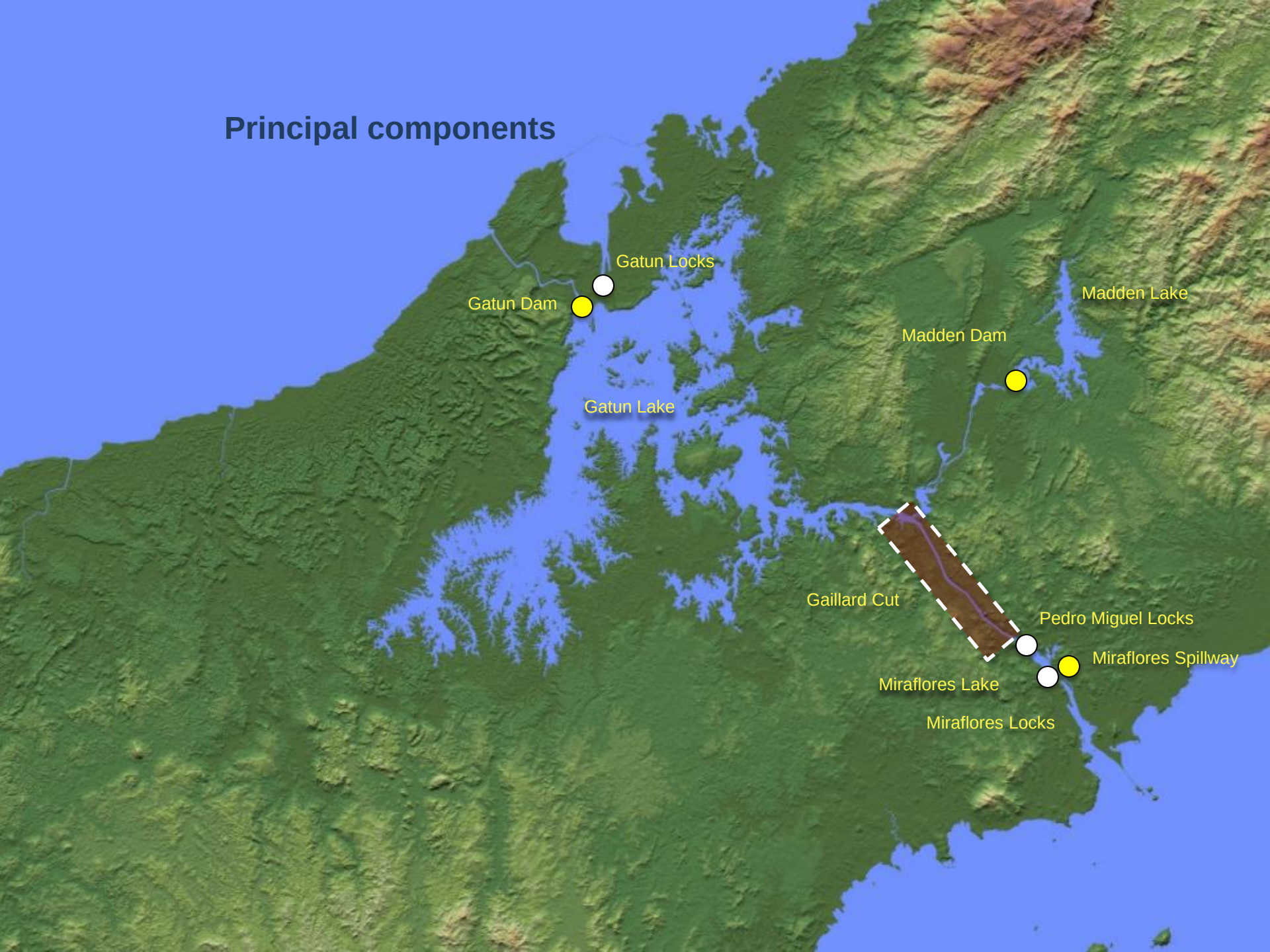


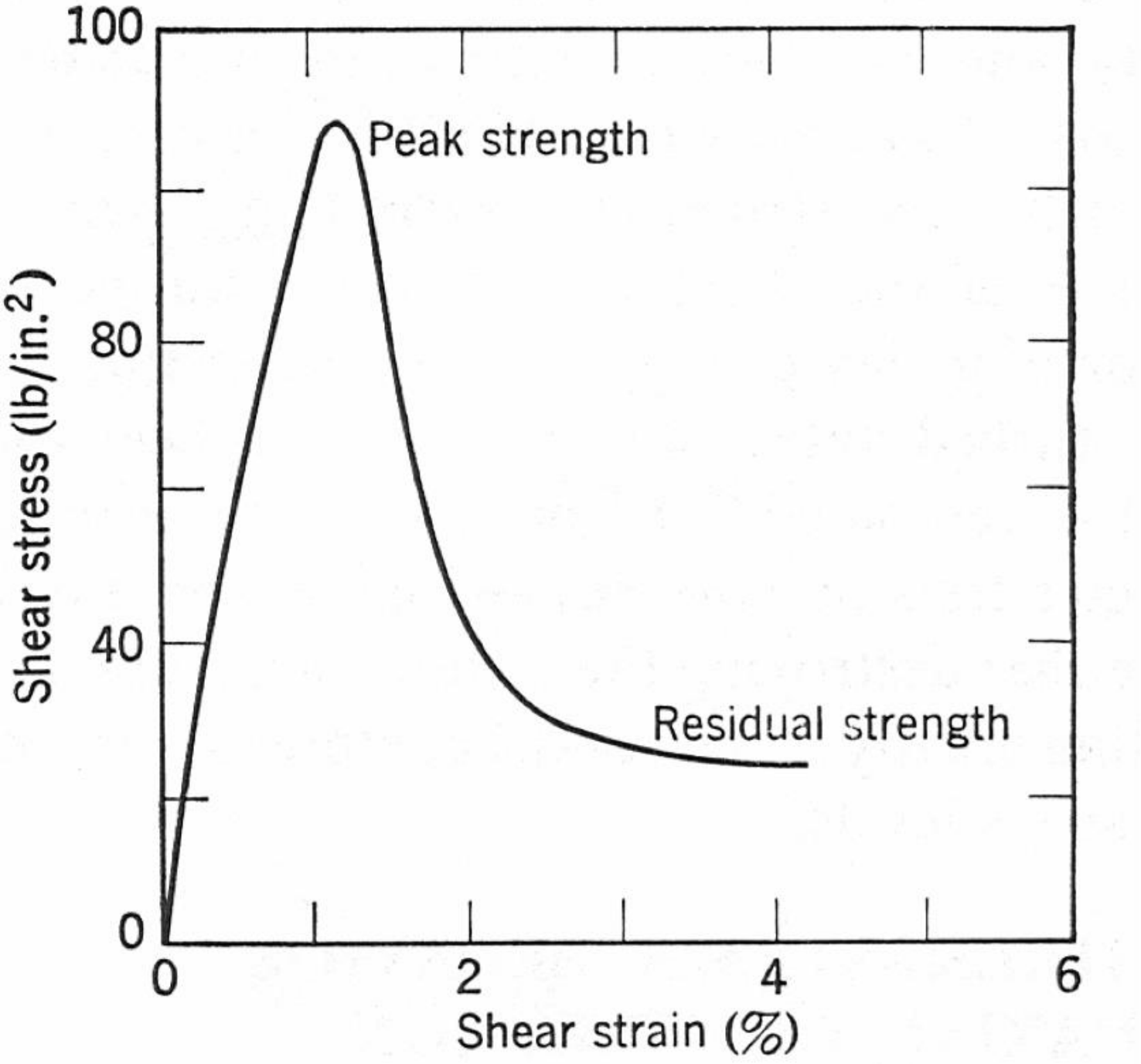
AEP = annual exceedance probability
PI = Performance Indicator
pf= probability of failure

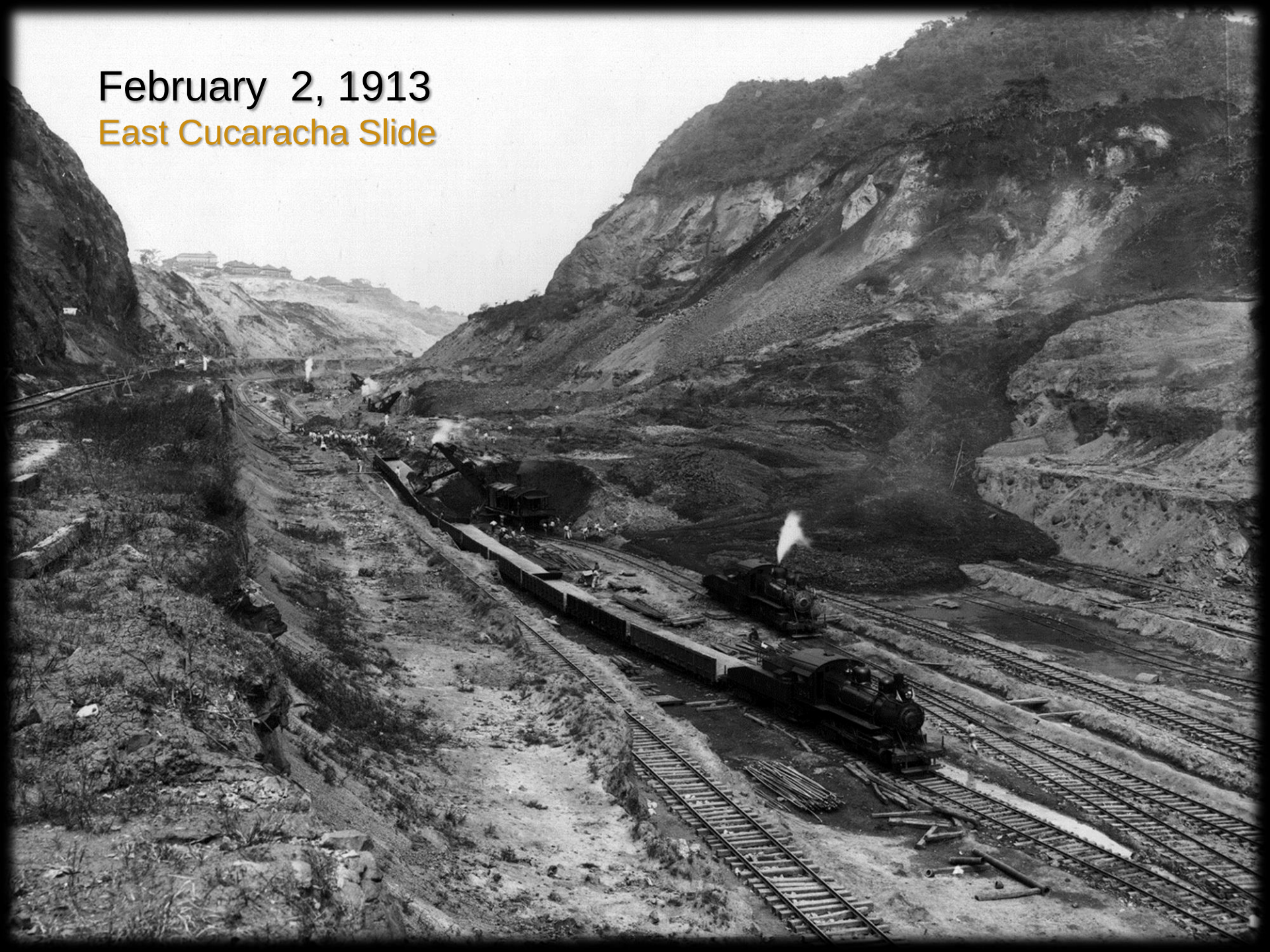




Project No. 26818045	GATUN DAM & GATUN LAKE SADDLE DAMS EVALUATION	Analysis Section for Seepage Gatun Dam, East Embankment Section B	Figure 10-1
URS			


Principal components
Gatun Locks
Gatun Dam
Madden Lake
Madden Dam
Gatun Lake
Gaillard Cut
Pedro Miguel Locks
Miraflores Spillway
Miraflores Lake
Miraflores Locks

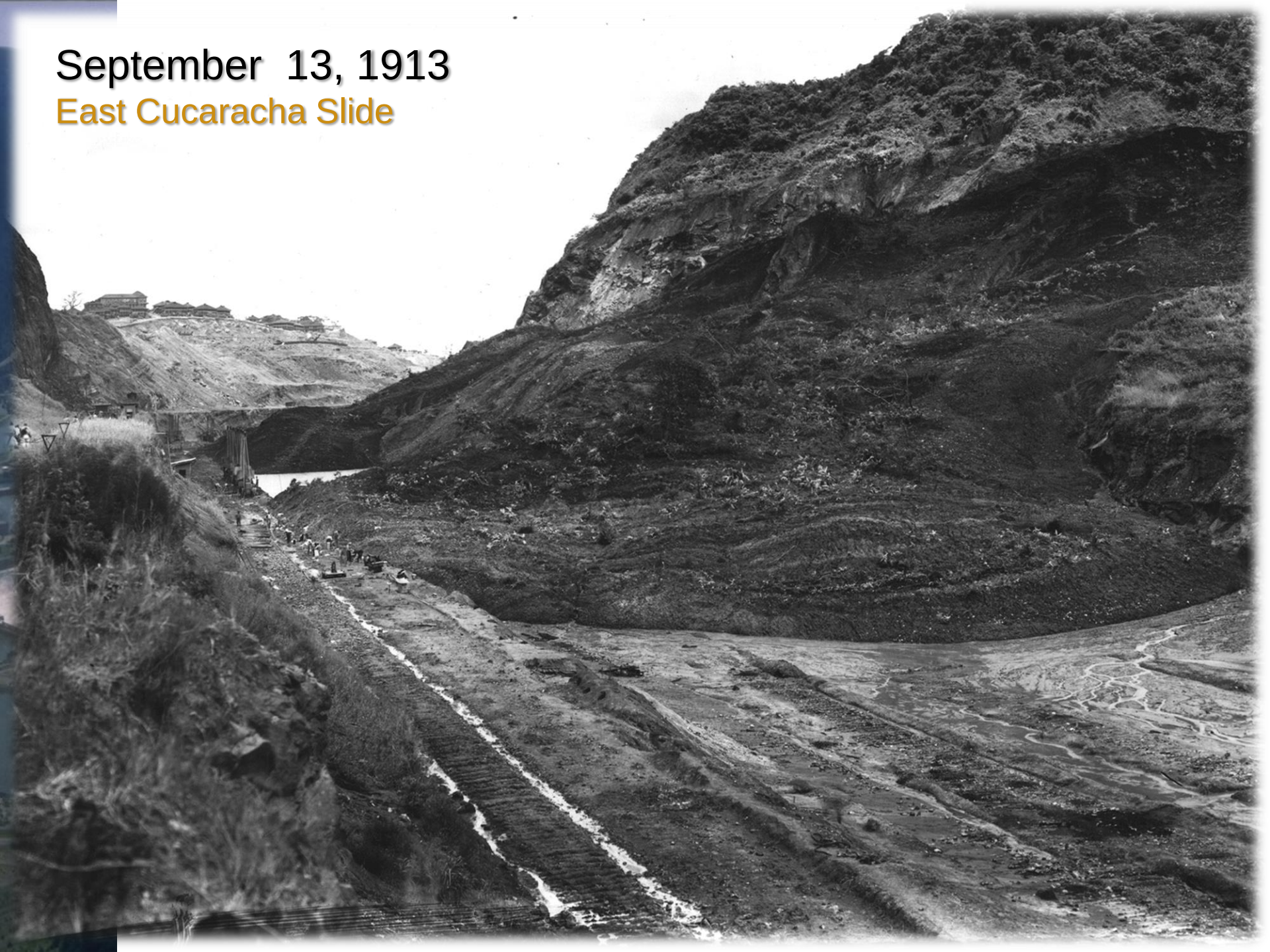

100
80
40
0
Shear stress (lb/in.^{2})
Peak strength
Residual strength
0
2
4
6
Shear strain (%)

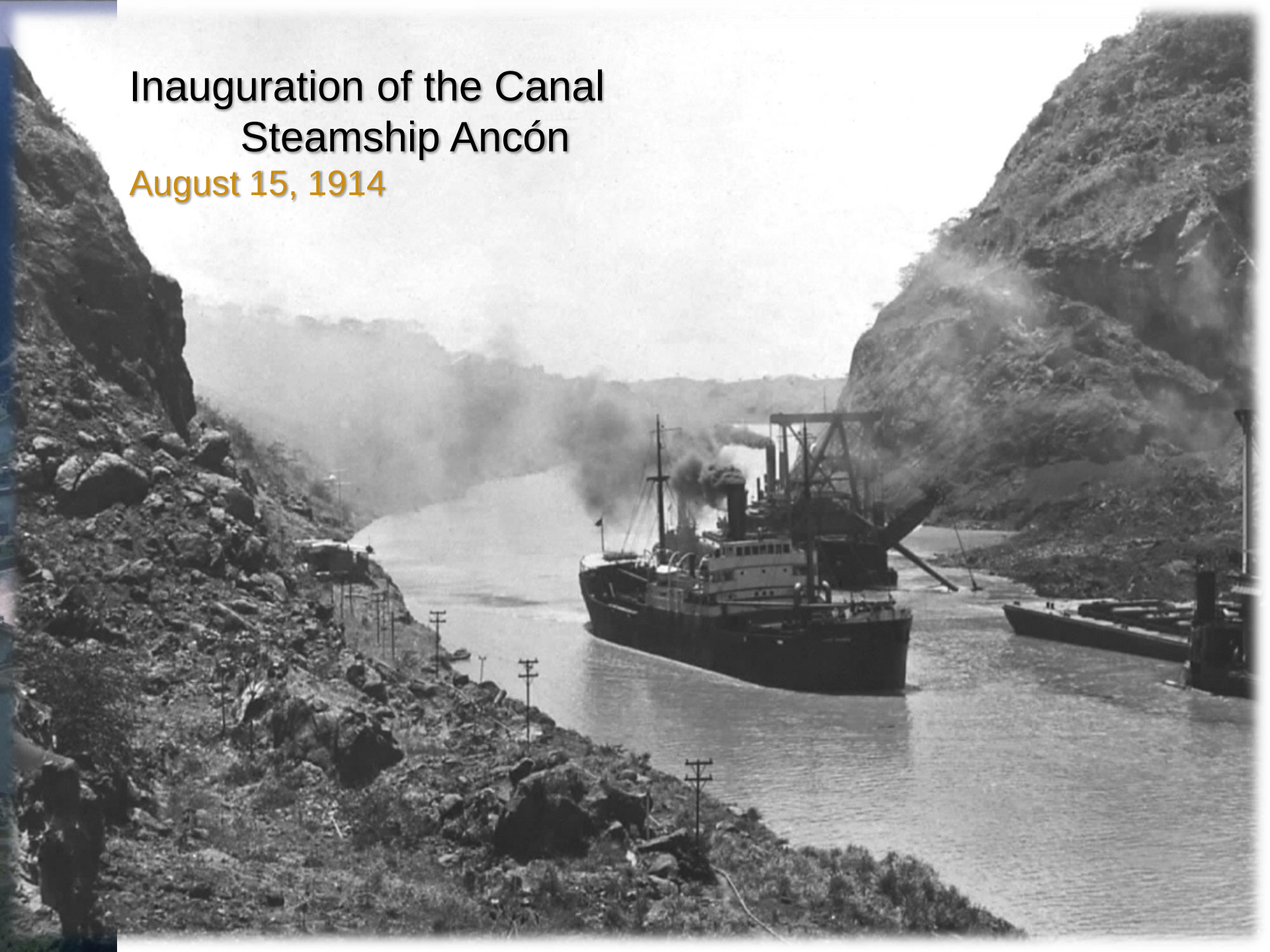

February 2, 1913
East Cucaracha Slide

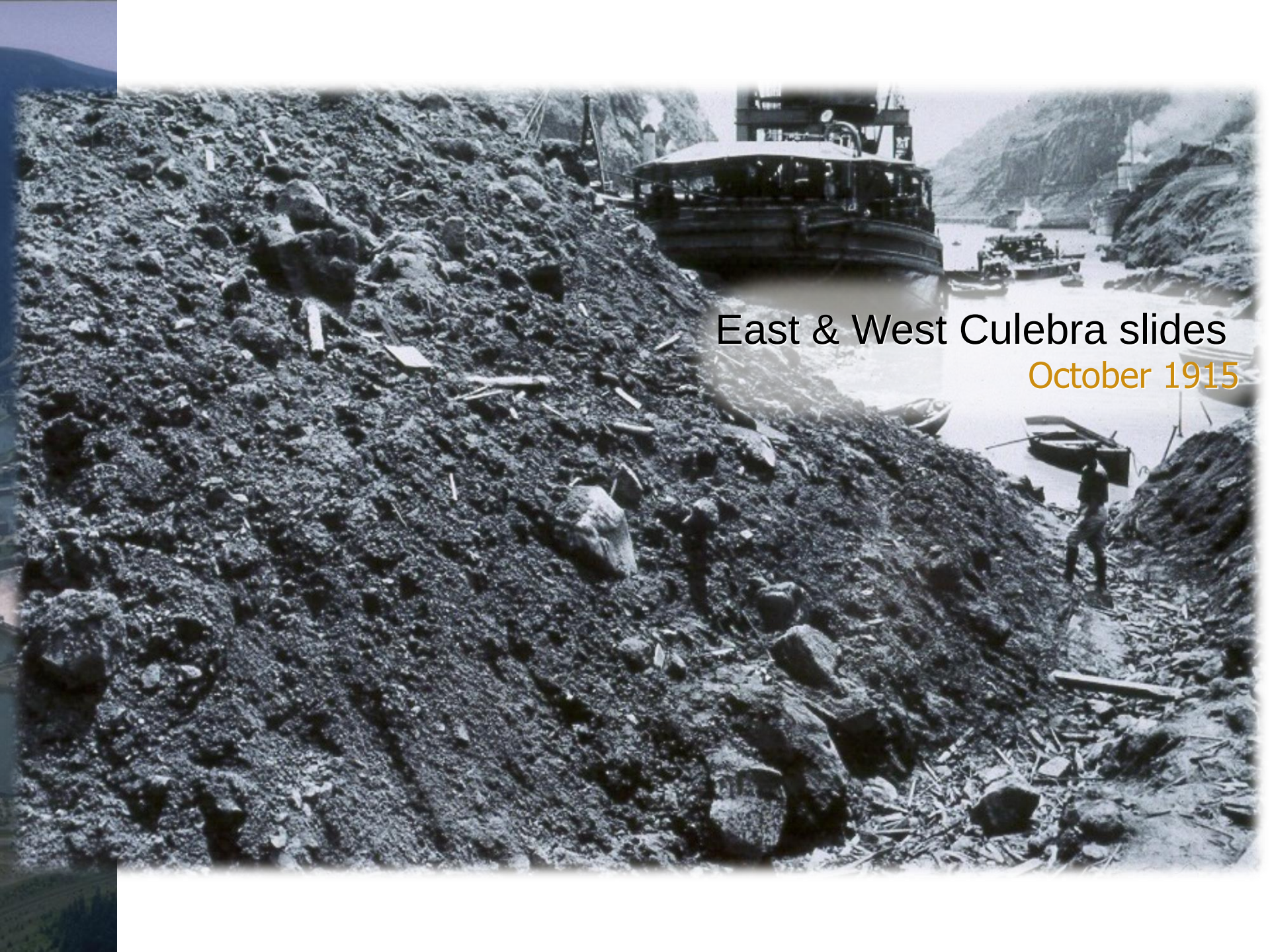

May 29, 1913
East Cucaracha Slide

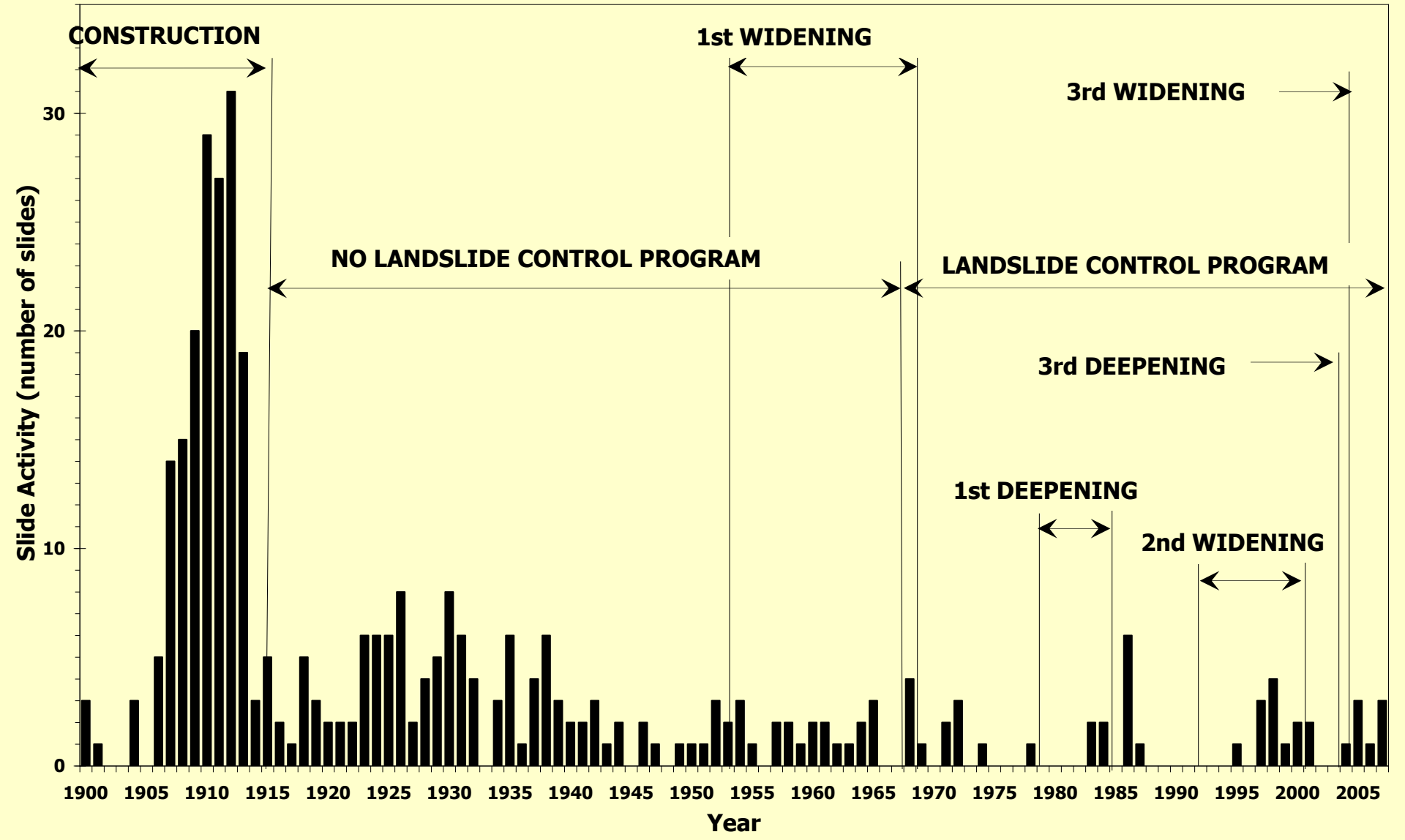
September 13, 1913

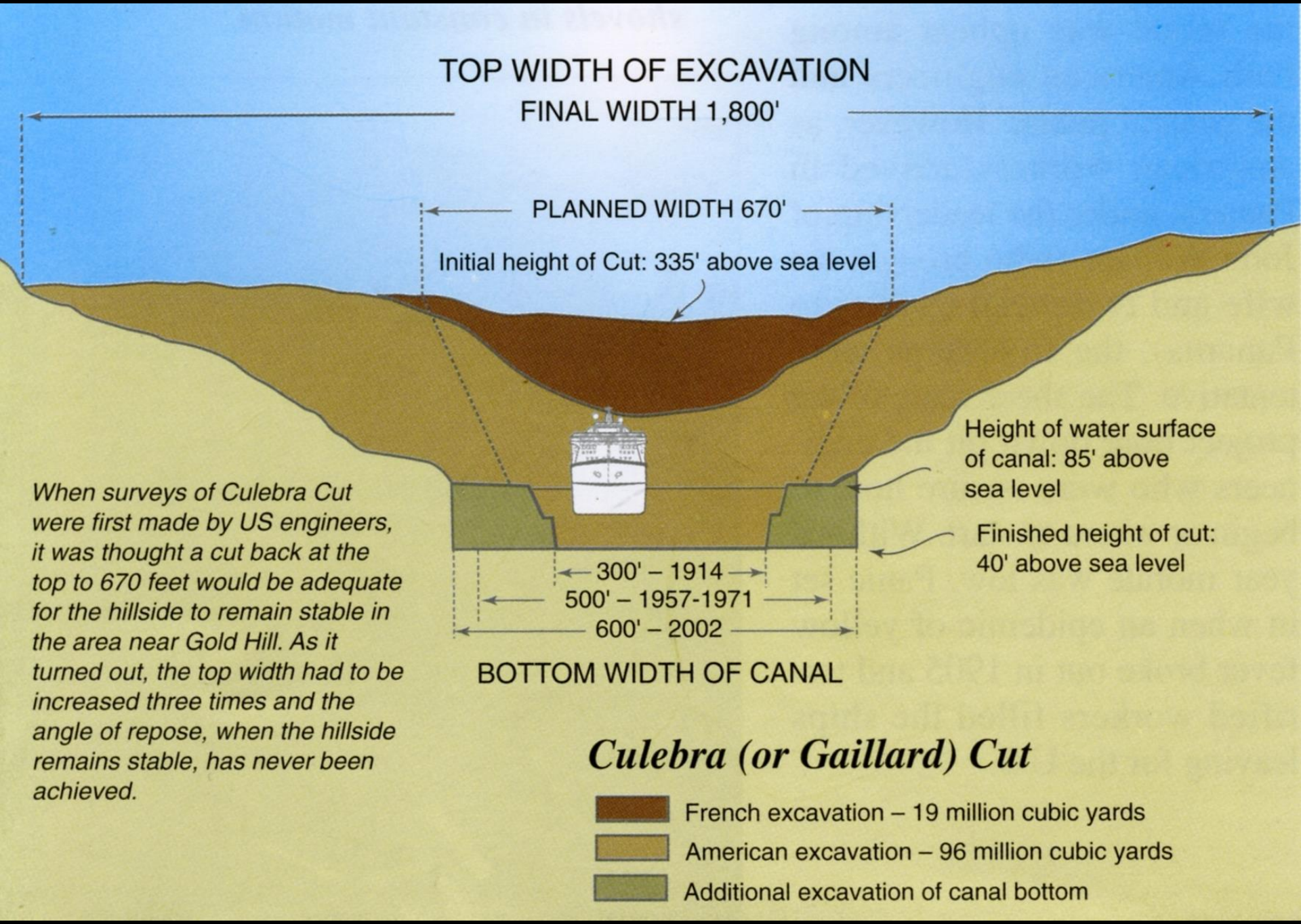
East Cucaracha Slide



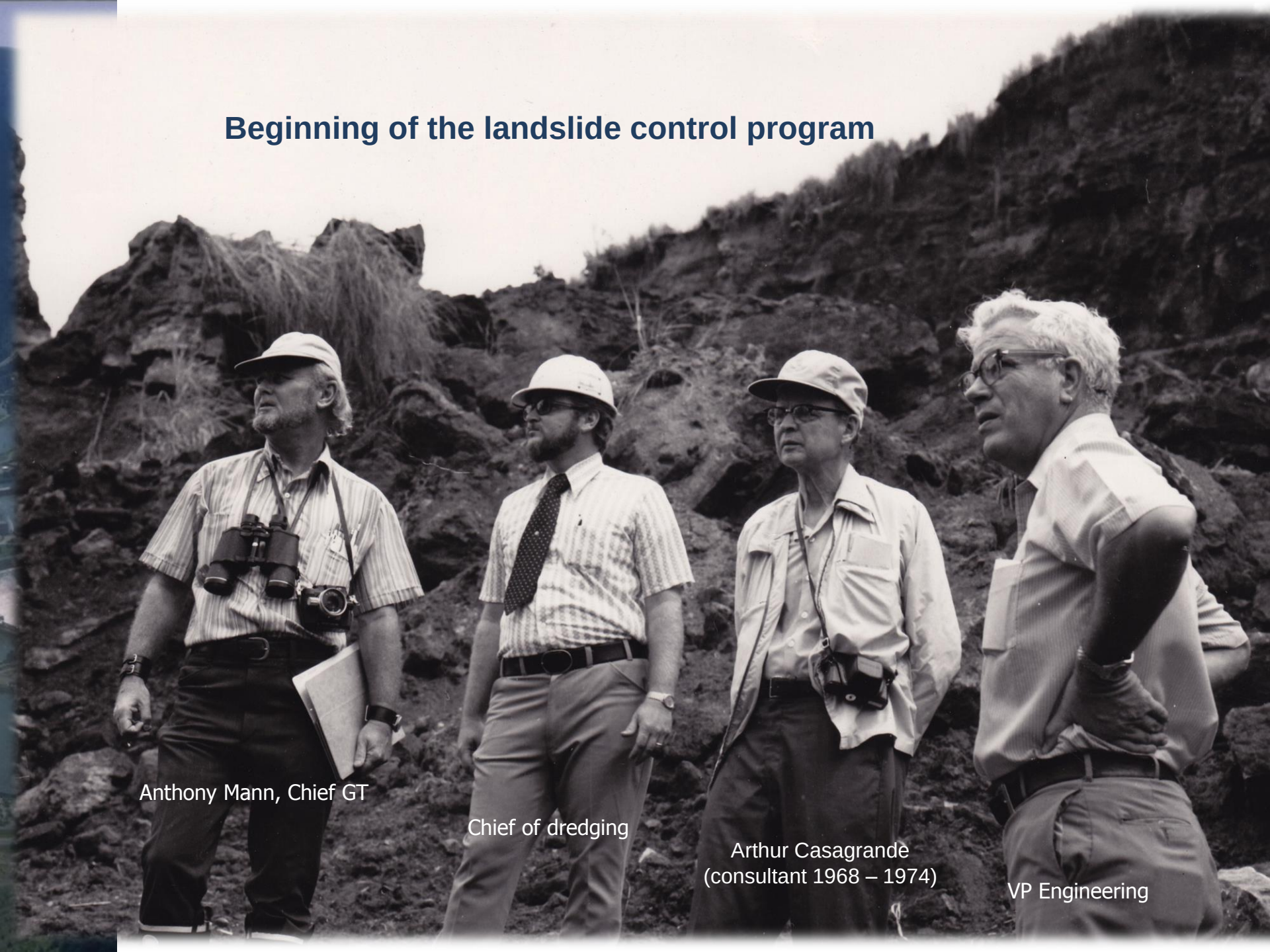

Inauguration of the Canal
Steamship Ancón
August 15, 1914

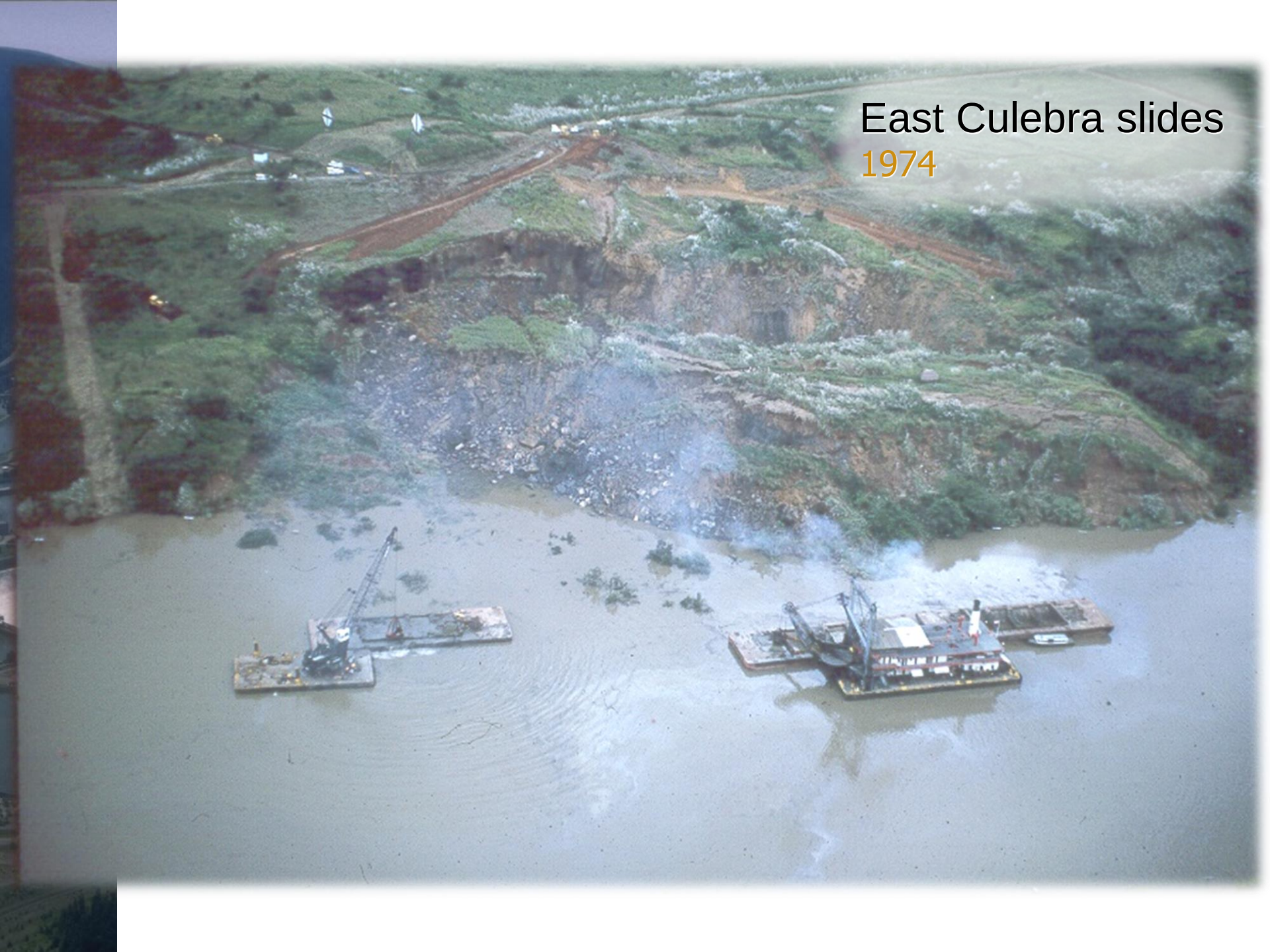

East & West Culebra slides
October 1915


CONSTRUCTION
1st WIDENING
3rd WIDENING
NO LANDSLIDE CONTROL PROGRAM
LANDSLIDE CONTROL PROGRAM
3rd DEEPENING
1st DEEPENING
2nd WIDENING
Slide Activity (number of slides)
0
10
20
30
1900
1905
1910
1915
1920
1925
1930
1935
1940
1945
1950
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
Year


TOP WIDTH OF EXCAVATION
FINAL WIDTH 1,800'
PLANNED WIDTH 670'
Initial height of Cut: 335' above sea level
Height of water surface of canal: 85' above sea level
Finished height of cut: 40' above sea level
300' – 1914
500' – 1957-1971
600' – 2002
BOTTOM WIDTH OF CANAL
When surveys of Culebra Cut were first made by US engineers, it was thought a cut back at the top to 670 feet would be adequate for the hillside to remain stable in the area near Gold Hill. As it turned out, the top width had to be increased three times and the angle of repose, when the hillside remains stable, has never been achieved.
Culebra (or Gaillard) Cut
French excavation – 19 million cubic yards
American excavation – 96 million cubic yards
Additional excavation of canal bottom

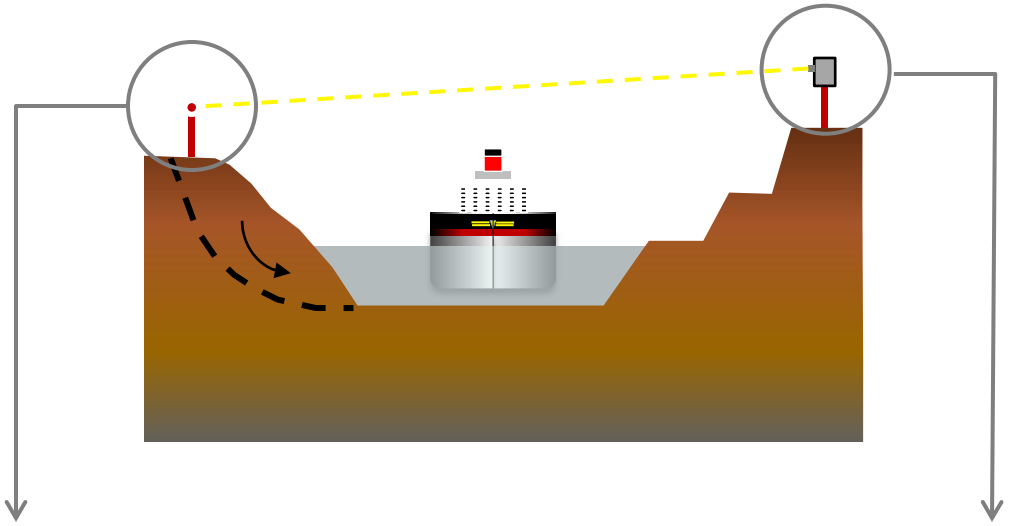
Beginning of the landslide control program




East Culebra slides
1974


East Cucaracha Slide
October 13, 1986

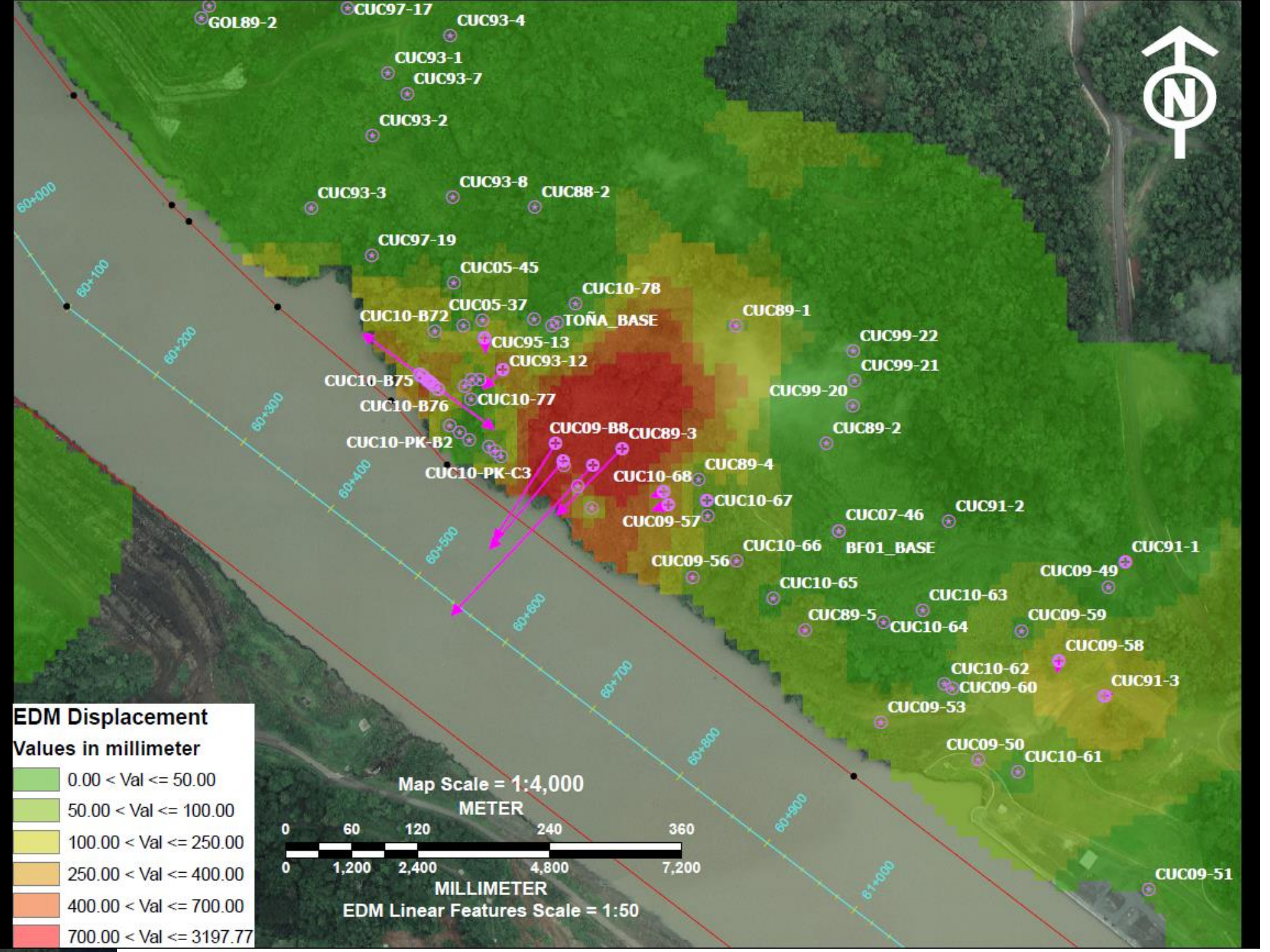
Modern Landslide Control Program



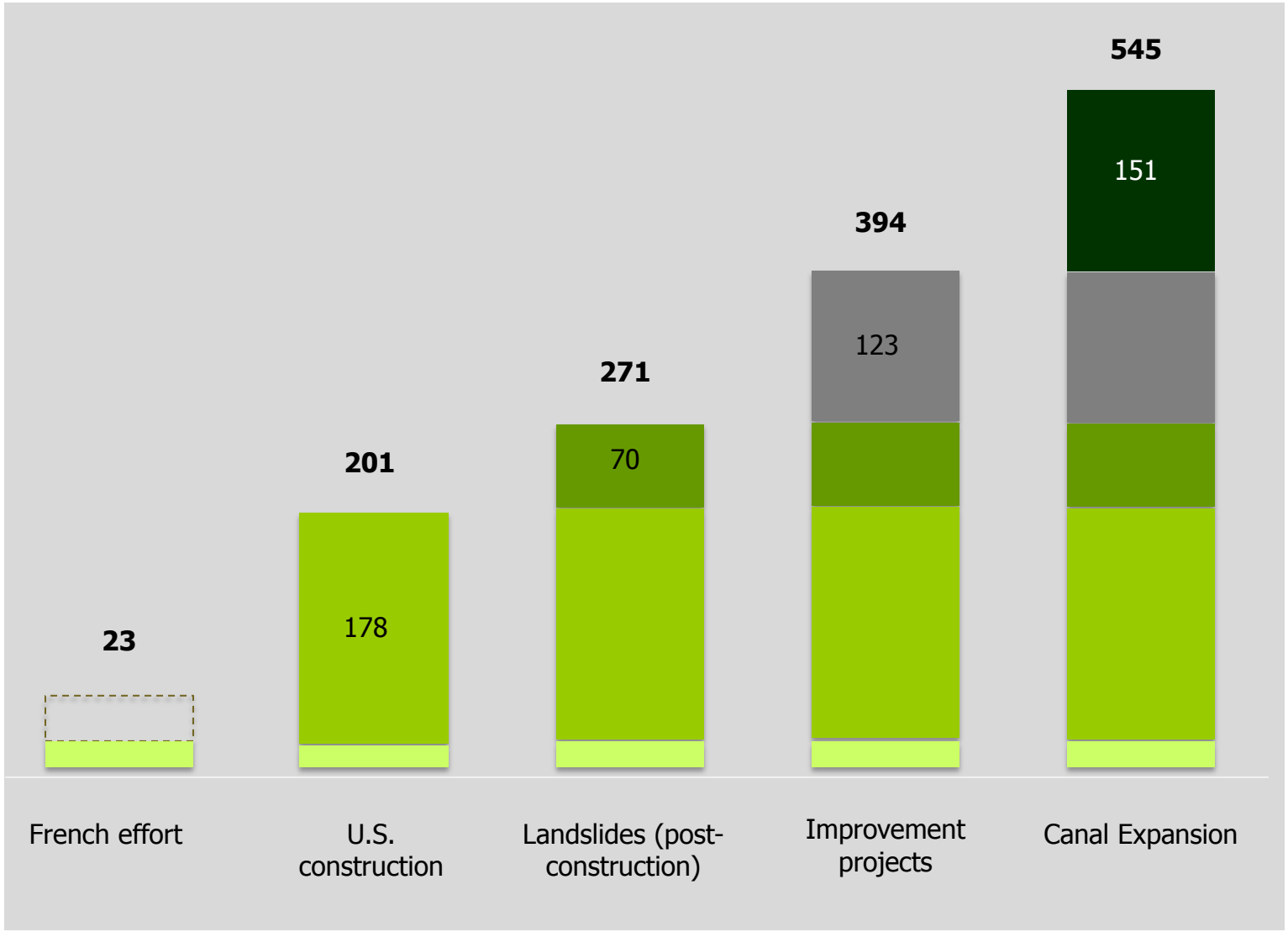
Threshold Values

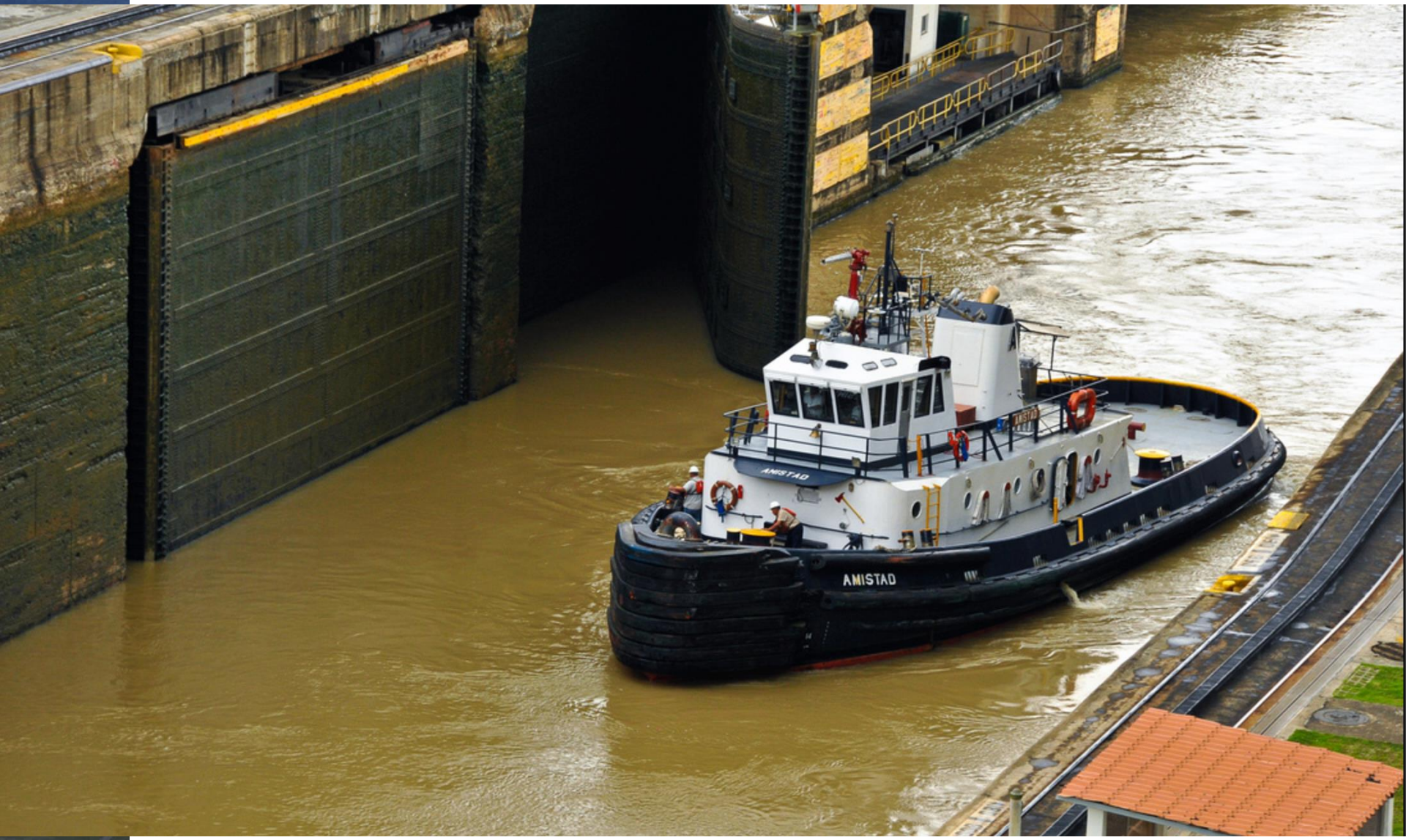
> 30mm / month

> 100mm / year

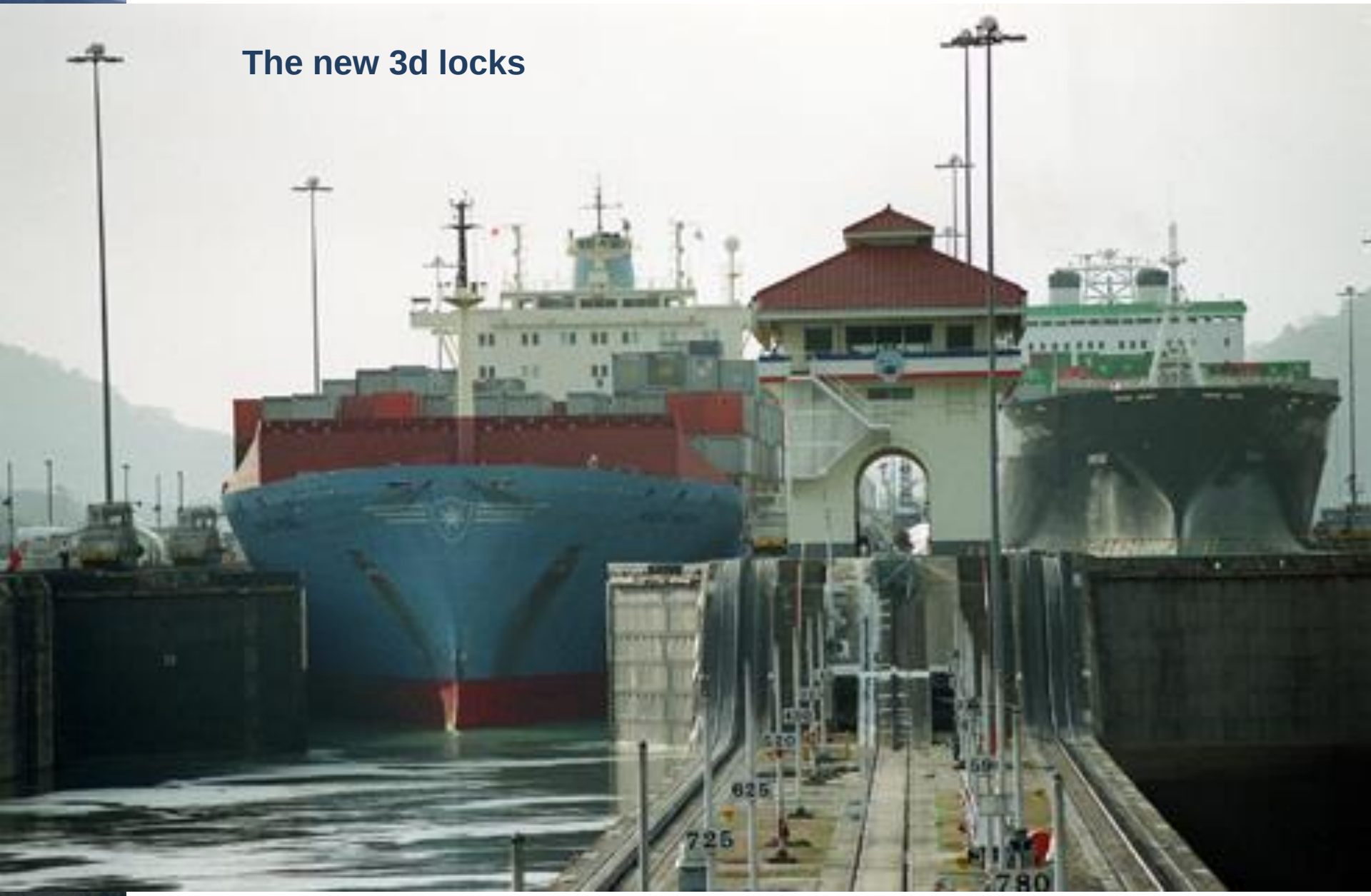

GOL89-2
CUC97-17
CUC93-4
CUC93-1
CUC93-7
CUC93-2
CUC93-3
CUC93-8
CUC88-2
CUC97-19
CUC05-45
CUC10-78
CUC05-37
CUC10-B72
TOÑA_BASE
CUC89-1
CUC95-13
CUC93-12
CUC99-22
CUC99-21
CUC10-B75
CUC99-20
CUC10-77
CUC10-B76
CUC09-B8
CUC89-3
CUC89-2
CUC10-PK-B2
CUC10-PK-C3
CUC89-4
CUC10-68
CUC10-67
CUC09-57
CUC07-46
CUC91-2
CUC10-66
BF01_BASE
CUC91-1
CUC09-56
CUC09-49
CUC10-65
CUC10-63
CUC89-5
CUC10-64
CUC09-59
CUC09-58
CUC10-62
CUC09-60
CUC91-3
CUC09-53
CUC09-50
CUC10-61
CUC09-51
60+000
60+100
60+200
60+300
60+400
60+500
60+600
60+700
60+800
60+900
61+000
N
EDM Displacement
Values in millimeter
0.00 < Val <= 50.00
50.00 < Val <= 100.00
100.00 < Val <= 250.00
250.00 < Val <= 400.00
400.00 < Val <= 700.00
700.00 < Val <= 3197.77
Map Scale = 1:4,000
METER
0 60 120 240 360
0 1,200 2,400 4,800 7,200
MILLIMETER
EDM Linear Features Scale = 1:50

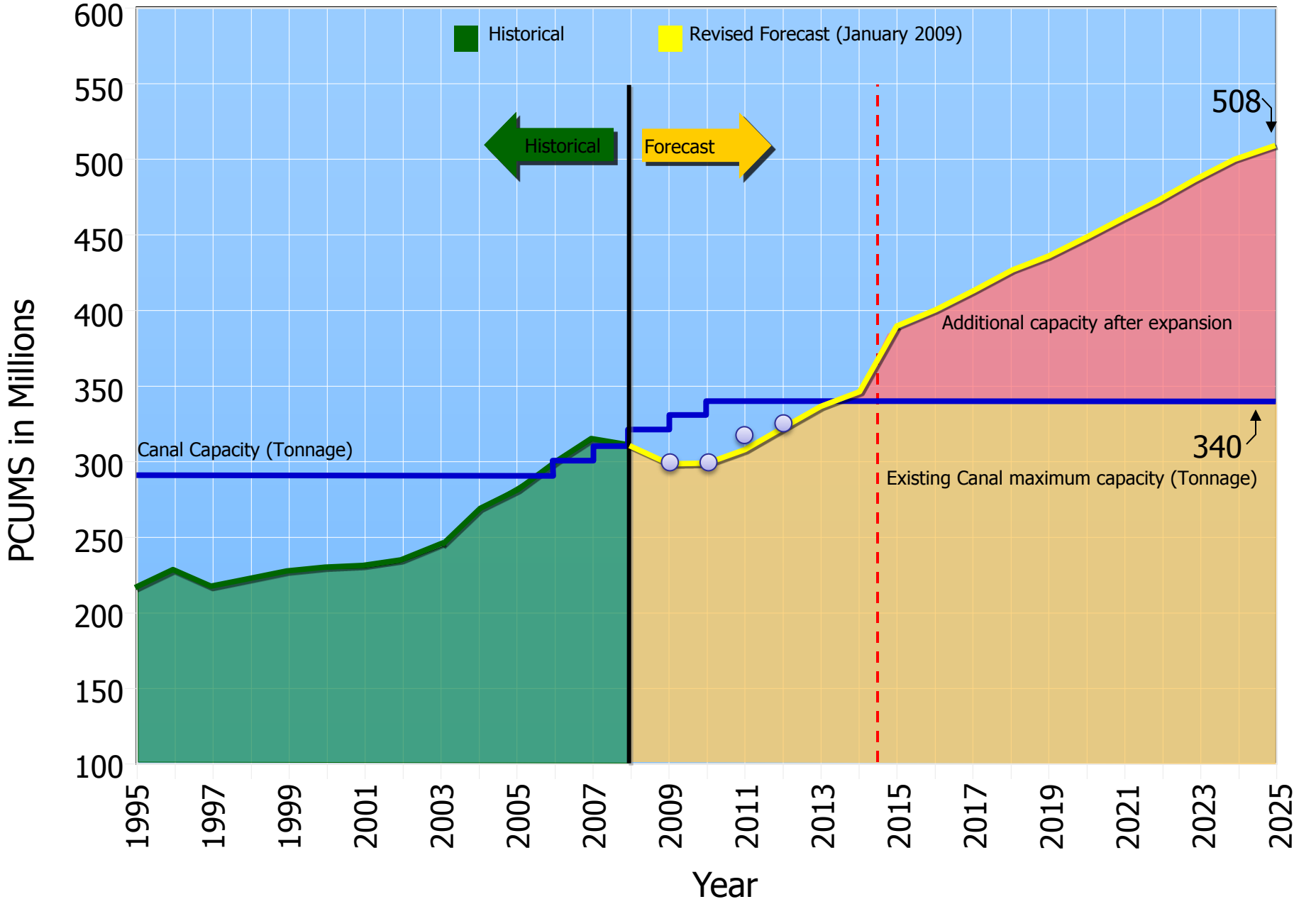
Historical Excavation Volumes (Mm^3)




AMISTAD
AMISTAD

The new 3d locks




Historical
Revised Forecast (January 2009)
Historical
Forecast
508
Additional capacity after expansion
Canal Capacity (Tonnage)
340
Existing Canal maximum capacity (Tonnage)
PCUMS in Millions
Year
600
550
500
450
400
350
300
250
200
150
100
1995
1997
1999
2001
2003
2005
2007
2009
2011
2013
2015
2017
2019
2021
2023
2025

New Atlantic Locks

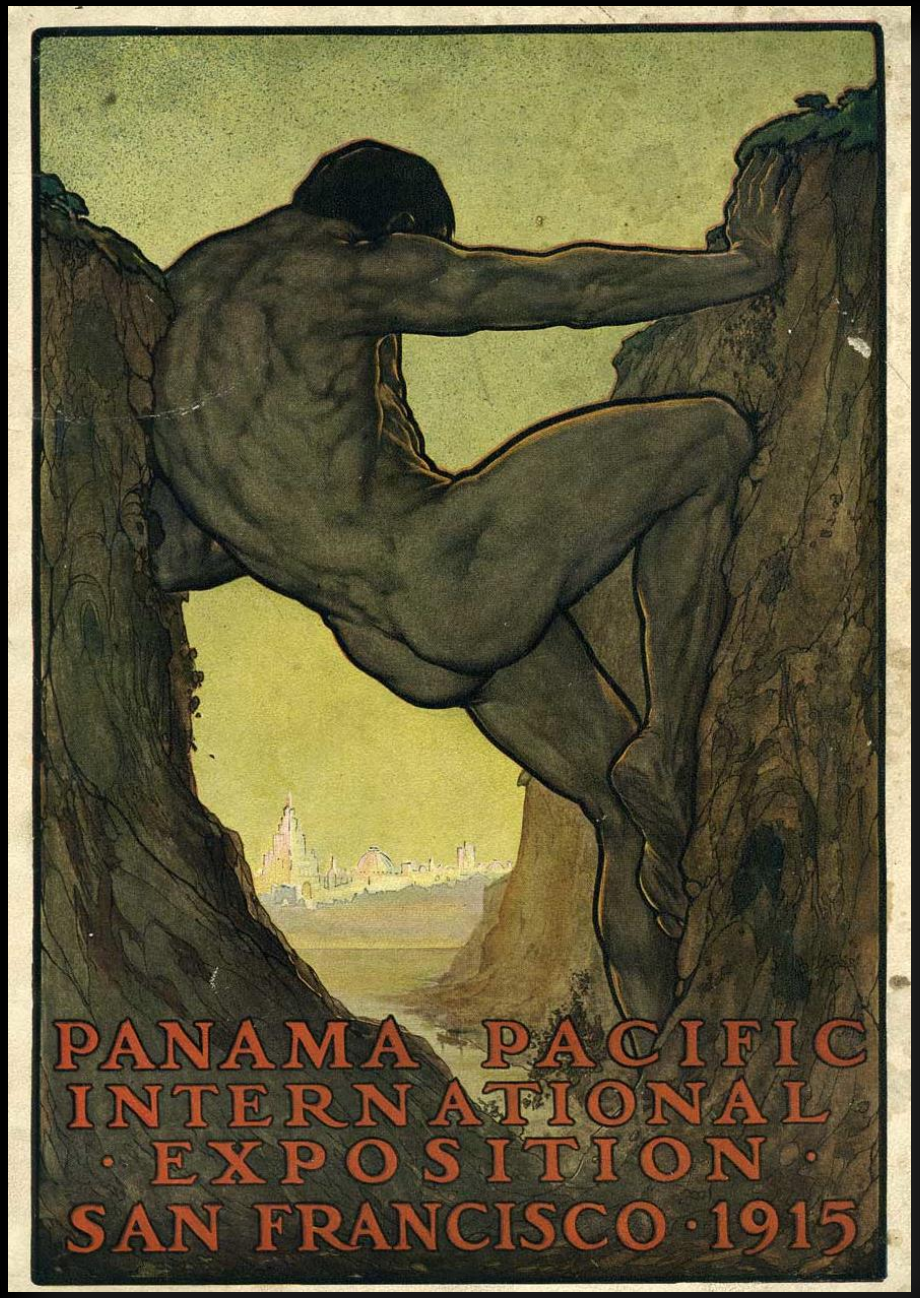
2.10M m3 of structural concrete

New Pacific Locks

2.34M m^3 of structural concrete

Thank you.

Thank you.


PANAMA PACIFIC
INTERNATIONAL
· EXPOSITION ·
SAN FRANCISCO · 1915