Cascadia subduction earthquakes

Understanding the turbidite record: genesis, transport, and preservation

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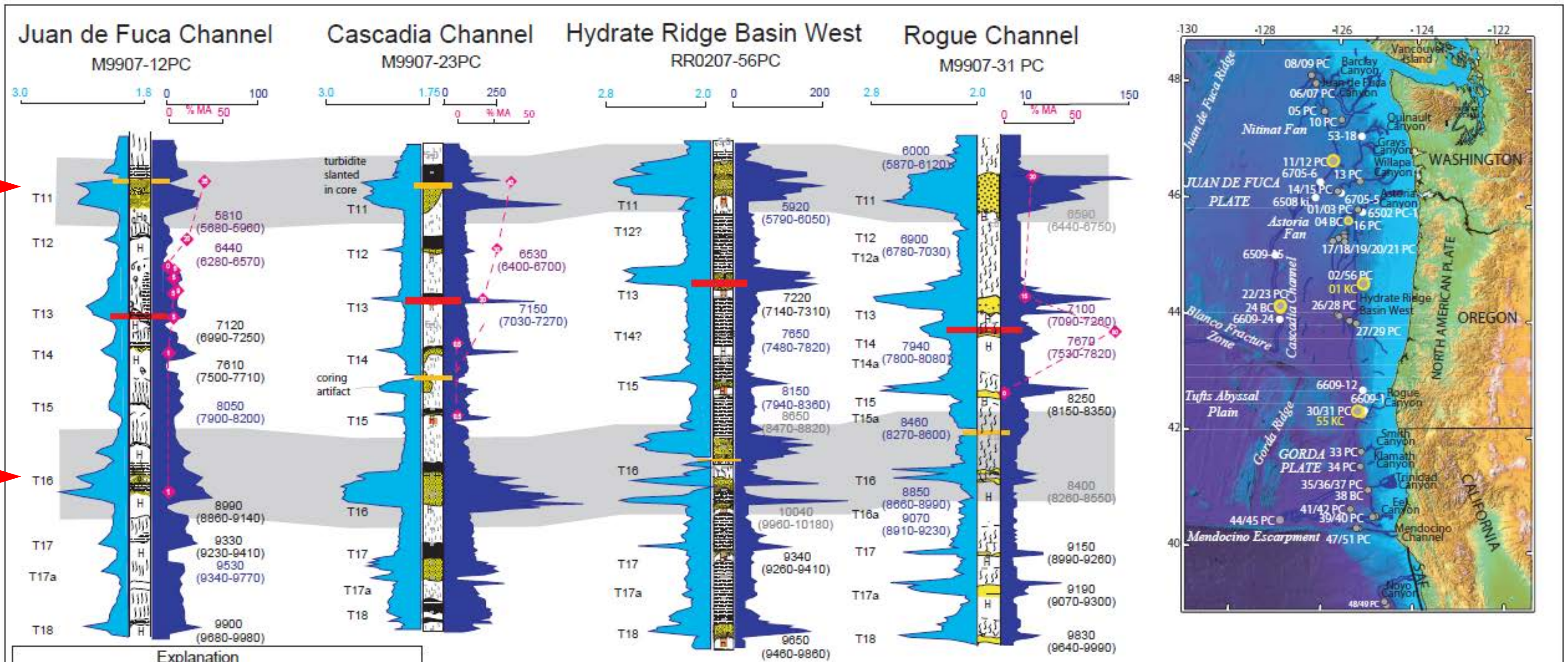
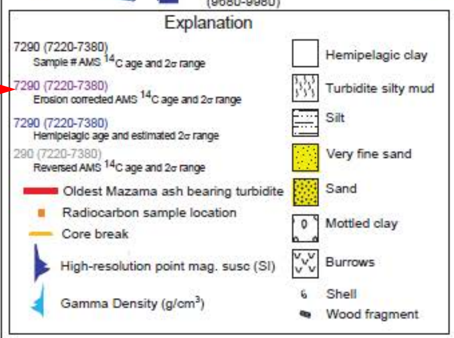
Background

- deep-water turbidite sands and muds seem to preserve a record of major earthquakes on the continental margin
  – Adams, Goldfinger, Nelson, Guttiérez-Pastor and others
- how much can we infer from the turbidite record ?
  – has the utility of turbidites been enthusiastically oversold?

FIGURE 2. CORRELATION OF CASCADIA PALEOSEISMIC TURBIDITES





- CORRELATION BY MAZAMA ASH STRATIGRAPHY
- HIGH RESOLUTION RADIOCARBON AGES
- PHYSICAL PROPERTIES OF DENSITY & MAGNETIC SUSCEPTIBILITY

The well known AD 1700 earthquake is thought to be Mw=9.0, yet it is only "average" in the turbidite record, with many like it in the 41 event record over 10,000 years. The largest events are T11 and T16, which we estimate to have been about three times the mass, and possibly ~three times the energy (Mw9.1?) of the 1700 event. SEE FIGURE 12

courtesy Hans Nelson Is the pattern similar to NE Japan? Goldfinger et al., 2011

I know rather little about the Cascadia margin

- DSDP Leg 18 in 1970, follow up work with Bill Normark on Rio Dell Fm. in 1973
- connected John Adams with Gary Griggs in 1983

I do not know most of the protagonists personally

- I was asked to make some general remarks on turbidity currents that might clarify how we interpret the turbidite record
- I have not reviewed in detail the 1000 pages or so of the literature by Goldfinger and colleagues

The promise of the turbidite record

- early work by Adams (1990) proposed that
  - major turbidites had a regional trigger, flowing down multiple canyon systems
  - the recurrence interval of 300-500 years matched ideas about recurrence of great subduction earthquakes

The promise of the turbidite record

- compared with other proxy records, the turbidite record has the potential to
  - provide an accessible record prior to the mid-late Holocene highstand of sea level
  - provide physical evidence of synchroneity of flows from different sources, i.e. to distinguish multiple earthquakes over months or years from single earthquakes, not dependant on precision of geochronology.

Turbidity currents 101

- *Turbidity currents: the most poorly monitored major sediment transport process on Earth* (Pete Talling, ad nauseam)
- Mostly inferred from their deposits (turbidites)
- A few historic events (1929 Grand Banks; 1979 Nice)
- Insights from lakes, tanks and numeric models

The scientific b***s*** threat level

modified from the Dept. of Homeland Security

- SEVERE – my gut feeling, little hard evidence, many might disagree
- HIGH – a possible hypothesis, but others equally improbable given the sparse amount of data
- ELEVATED – probably the best interpretation, but others are possible
- GUARDED – well established geological knowledge that most would not quibble with, although professional gadflies might question
- LOW – boring and uncontroversial

1. What is a turbidity current ?

- density current in which excess density is due to suspended sediment
- turbulent flow (Newtonian fluid)
- may drive a high-density non-Newtonian component near the bed

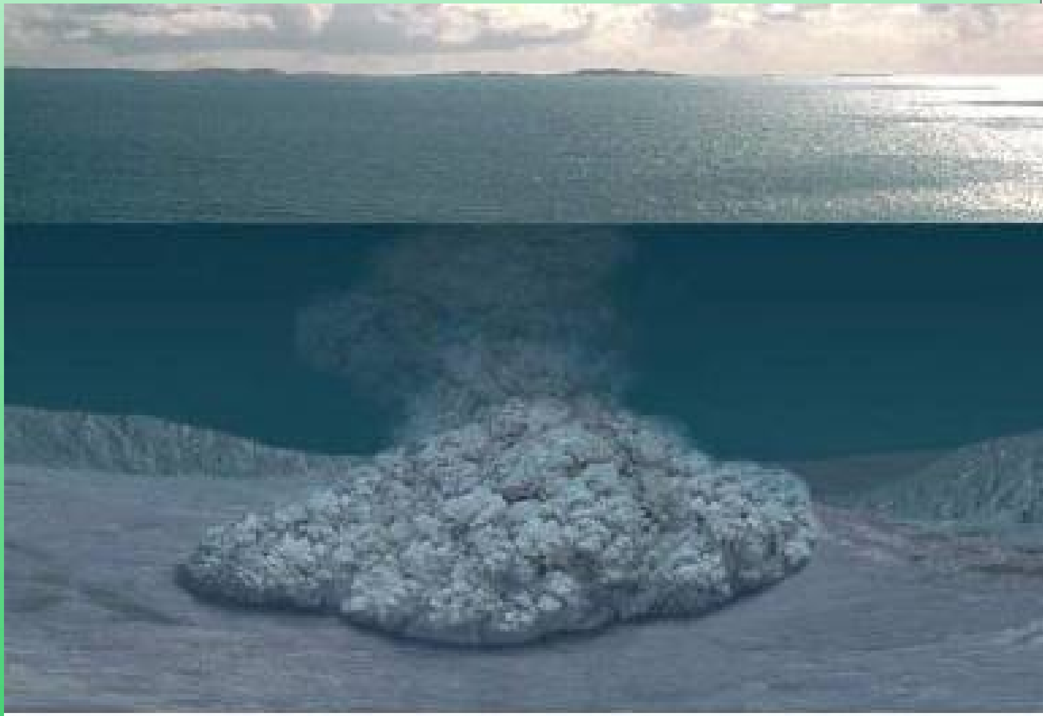
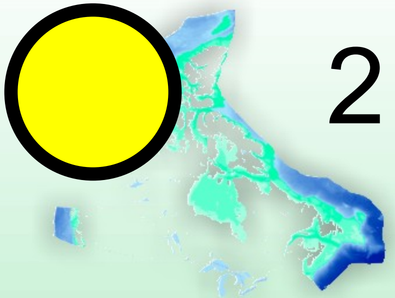


Image courtesy of the Open University

Flow in turbidity currents

Sequeiros/Hybrid saline/**turbidity current** over mobile bed
vtchl.illinois.edu

- head motion due to pressure effect of a column of dense fluid
- motion of body essentially a balance of gravity force (depends on slope) against the frictional retarding force

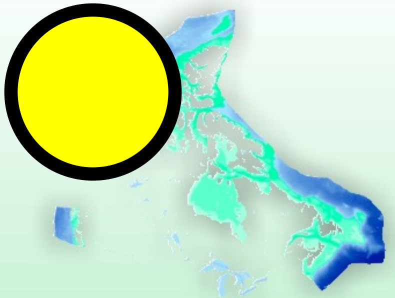


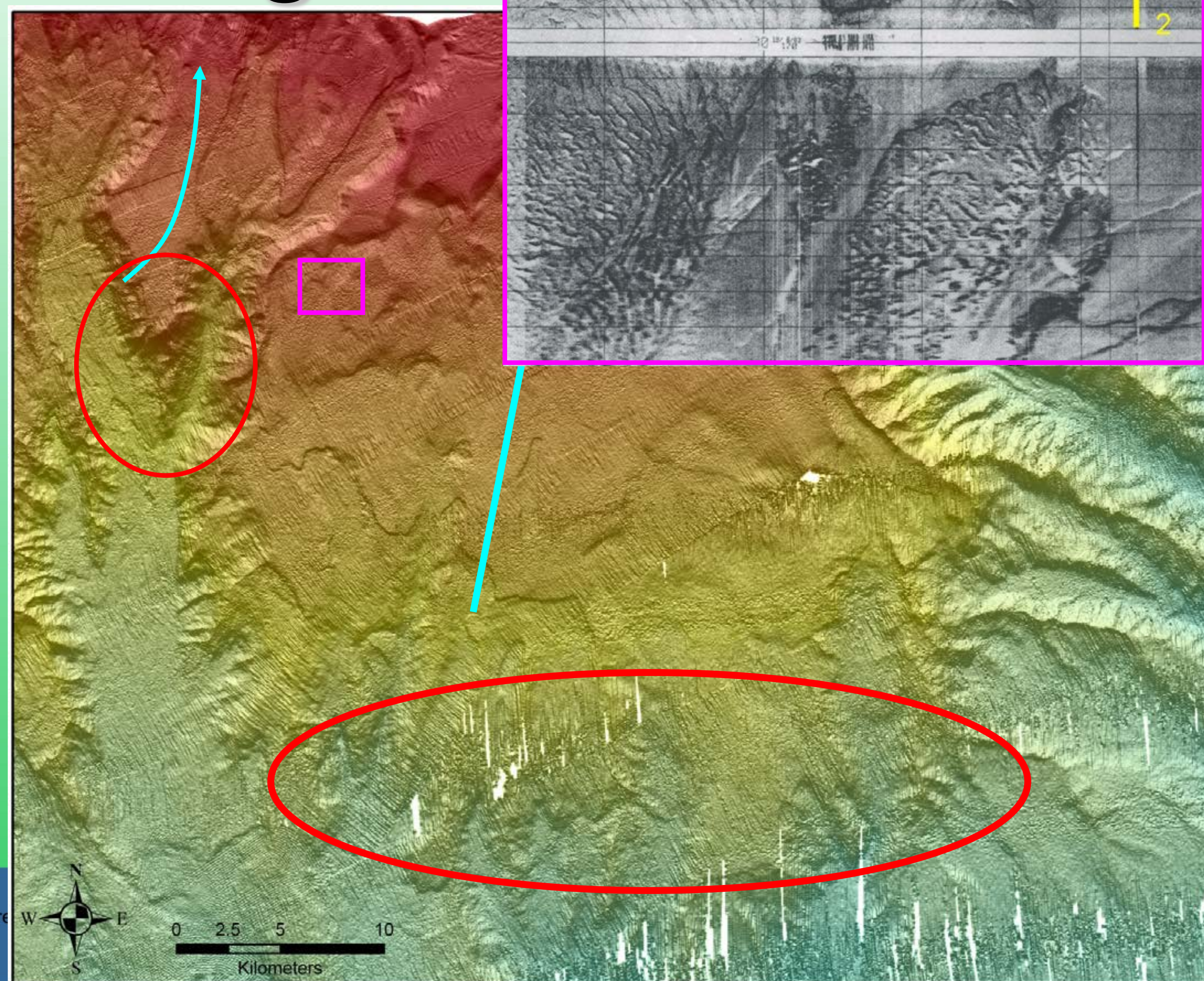
2. Examples of hist
turbidity curre
from sediment failu

BANKS FAILED IN 1929

- very limited information
  - may create a small, short-lived surge: sandy delta-front failures – fjords, e.g. Squamish, Iterbilung, Norway AND sidewall failures, e.g. Saguenay, Chile
  - may erode seafloor sediment and become a self-sustaining turbidity current (Nice airport 1979)
  - retrogressive failure may also prolong the flow process (Grand Banks 1929)

Style of fa
retrogress

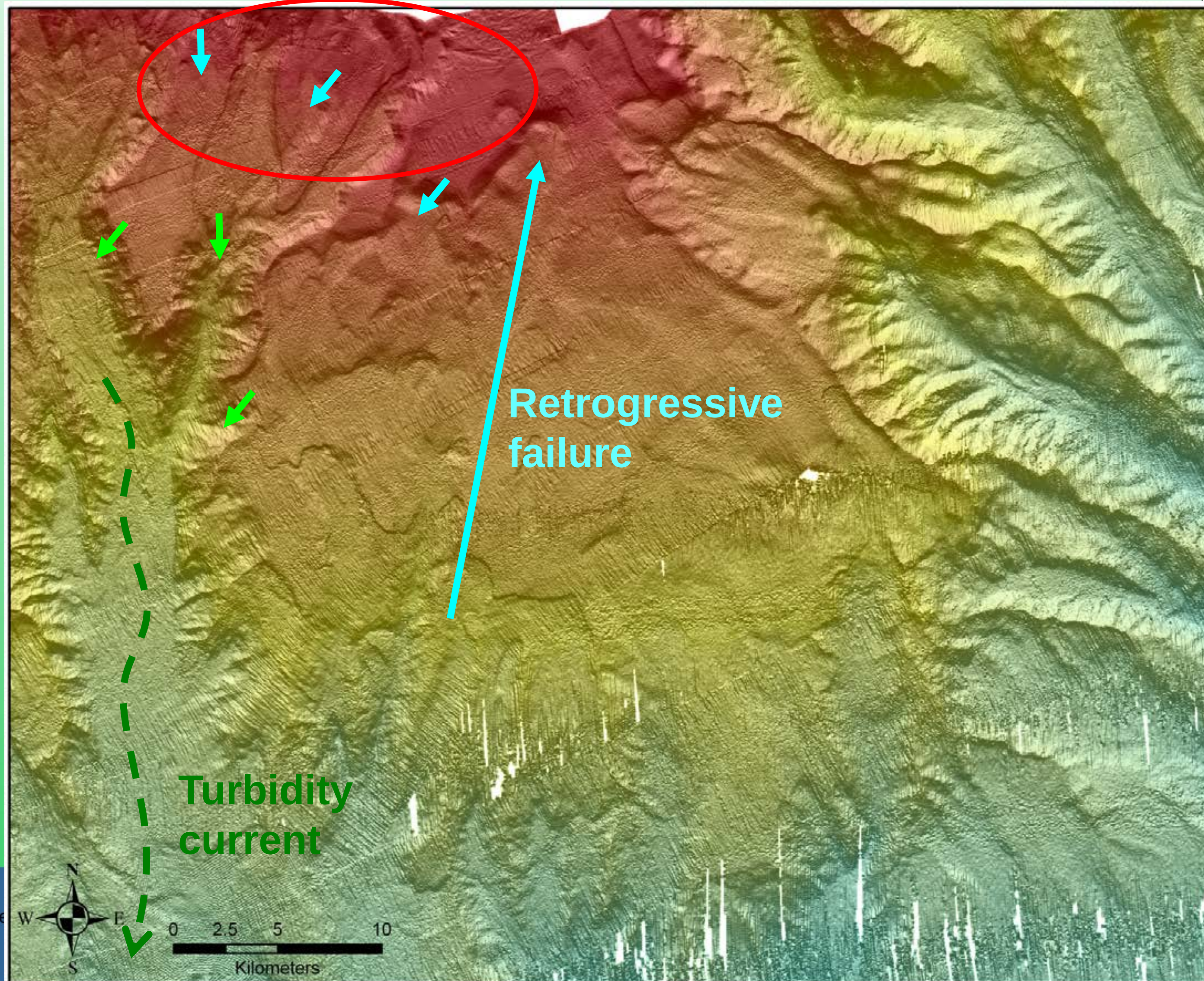




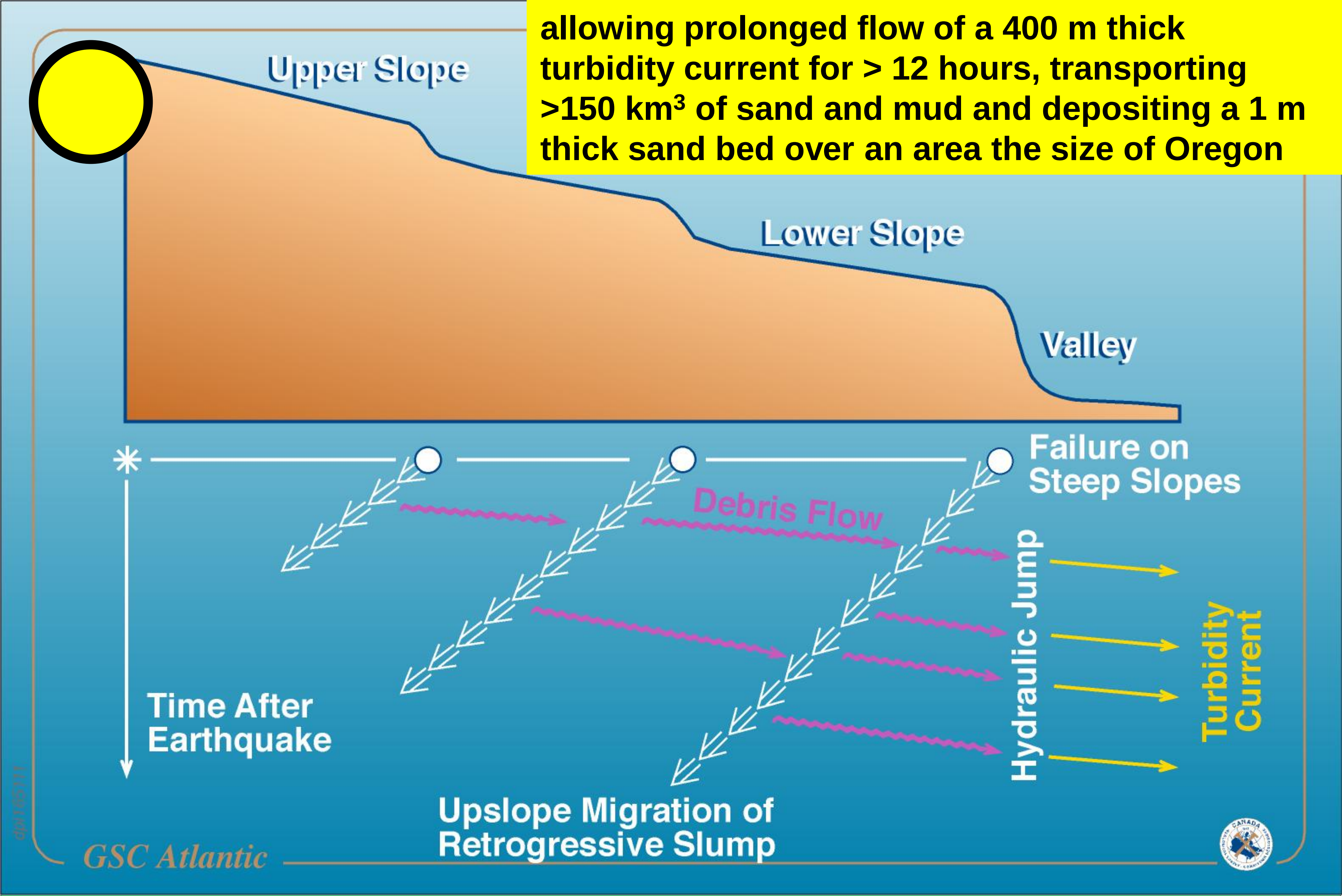
- Initiated on steep slopes
  - controlled by salt tectonics on the lower slope
  - and on walls of slope valleys
- retrogressive failure back up to the upper slope

Transformation of the flow

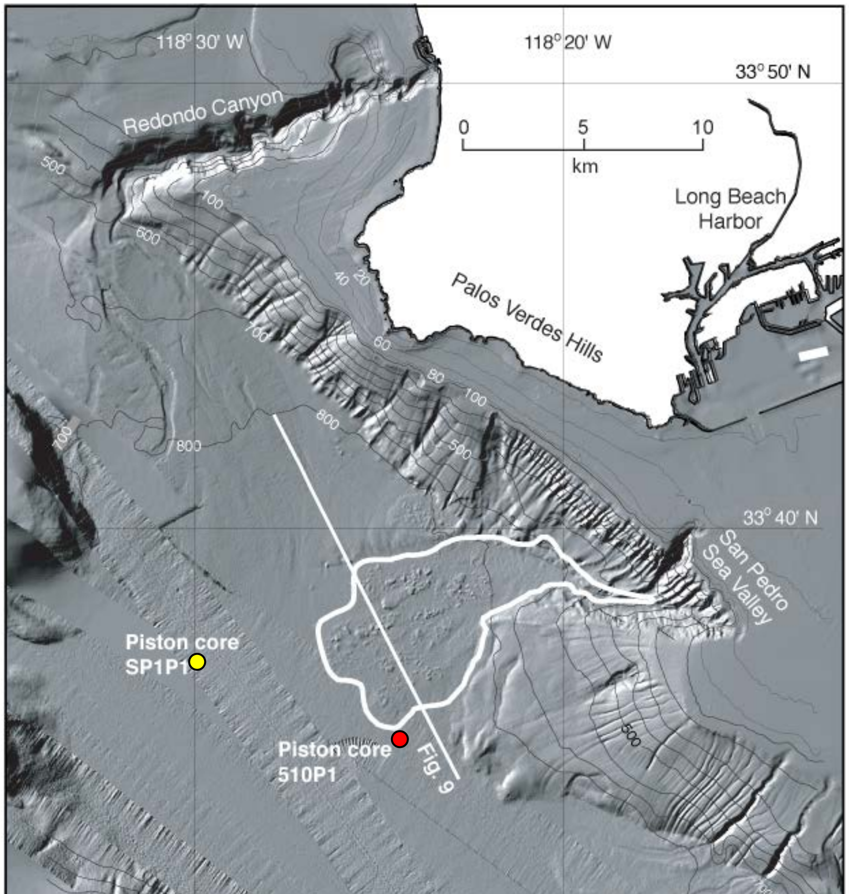
- Rotational slumps
- Converted to debris flows on local steep slopes
- Debris flows went through hydraulic jumps on steep valley walls
- Occurred progressively during retrogressive failure



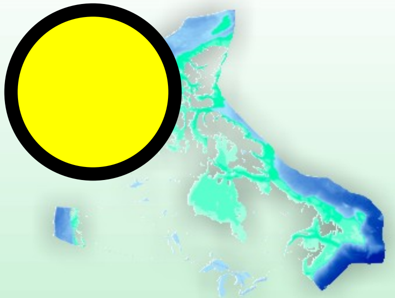
allowing prolonged flow of a 400 m thick turbidity current for > 12 hours, transporting >150 km^3 of sand and mud and depositing a 1 m thick sand bed over an area the size of Oregon



NOT ALL SUBMARINE LANDSLIDES FORM TURBIDITY CURRENTS



- **San Pedro slide (Holocene) off Los Angeles**
- thin turbidite only in proximal piston core
- similar experience elsewhere
- need a steep gradient, and perhaps confinement by a conduit, to form a turbidity current



3. Nature of the flow

- How do flows behave in submarine canyons ?
  - Know something of the velocity and thickness where cables were broken. 1929 M=7.2 Grand Banks was 65 km/hr, 400 m thick.
  - Turbulent flows on a gradient steeper than 1:100 (0.6°) may accelerate and erode
  - high-density surges may deposit and die

Supercritical flow in turbidity currents

- *Likely at gradients >1:100 (0.6°), certainly at gradients of 1:50 (1.2°)*
- *Supercritical flows down submarine canyons tend to be unsteady*
- *Head is thicker than the body, body moves faster, head entrains water through waves breaking at the back of the head and returns this to the body, thickening and diluting the body*

“Ignition” in turbidity currents

Autosuspension: bottom drops away faster than sediment can settle out

$\omega/u < \tan \beta$ where ω is settling velocity

for fine sand, $\omega = 1$ cm/s

$\beta = 6^{o}$, then $u_{crit} = 10$ cm/s

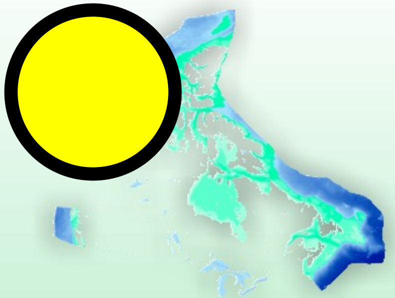
$\beta = 0.6^{o}$, then $u_{crit} = 1$ m/s (2 knots)

under conditions of autosuspension, the bed is eroded, more material in suspension, increasing density and driving the flow - ***ignition***

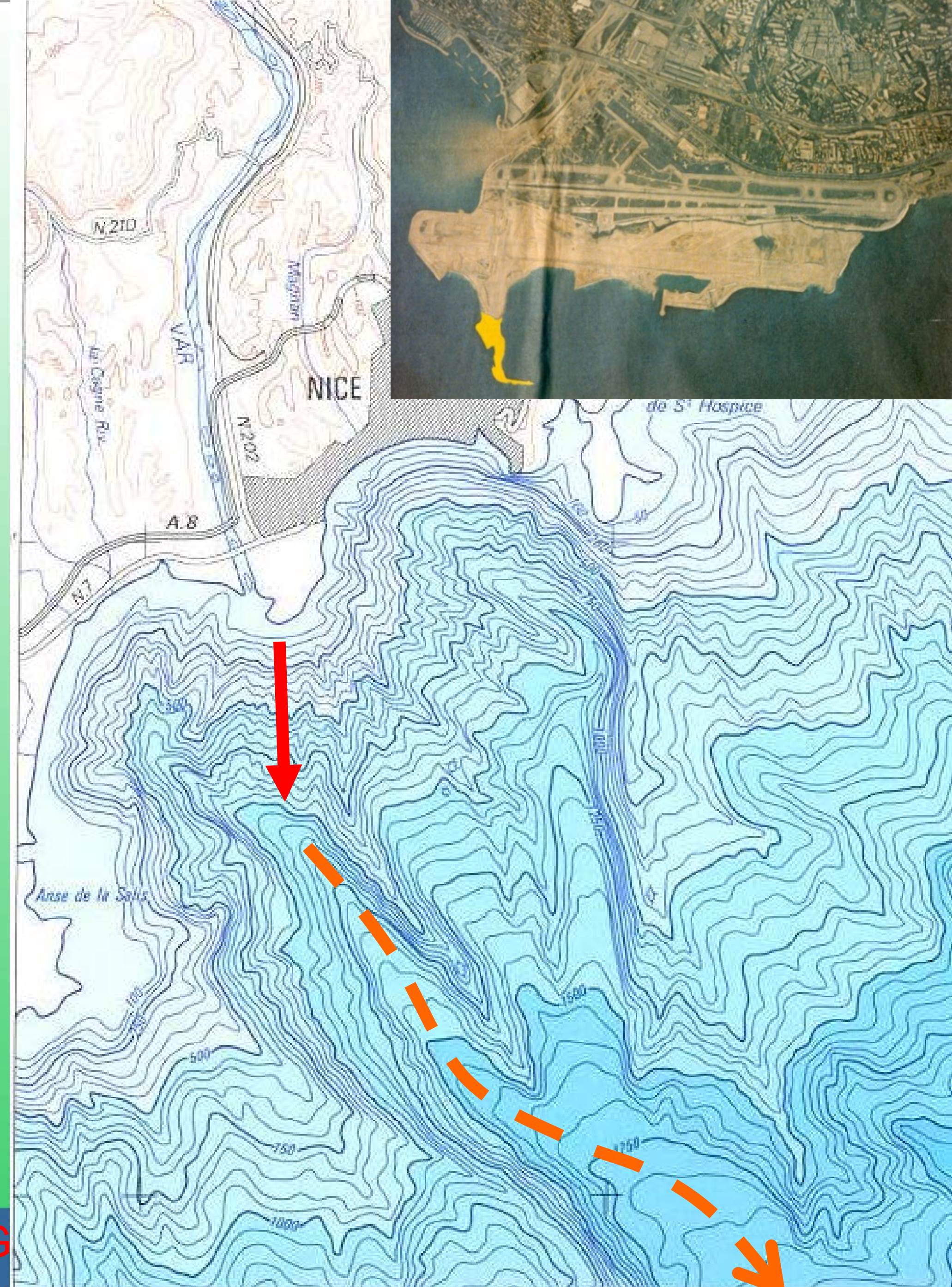
Hydraulic jumps in turbidity currents

- *may occur at abrupt decrease in slope or with flow expansion at end of a canyon*
- *known from underflows in lakes*
- *efficient entrainment of ambient seawater*
- *break up a debris flow or other high-density flow into a turbidity current*

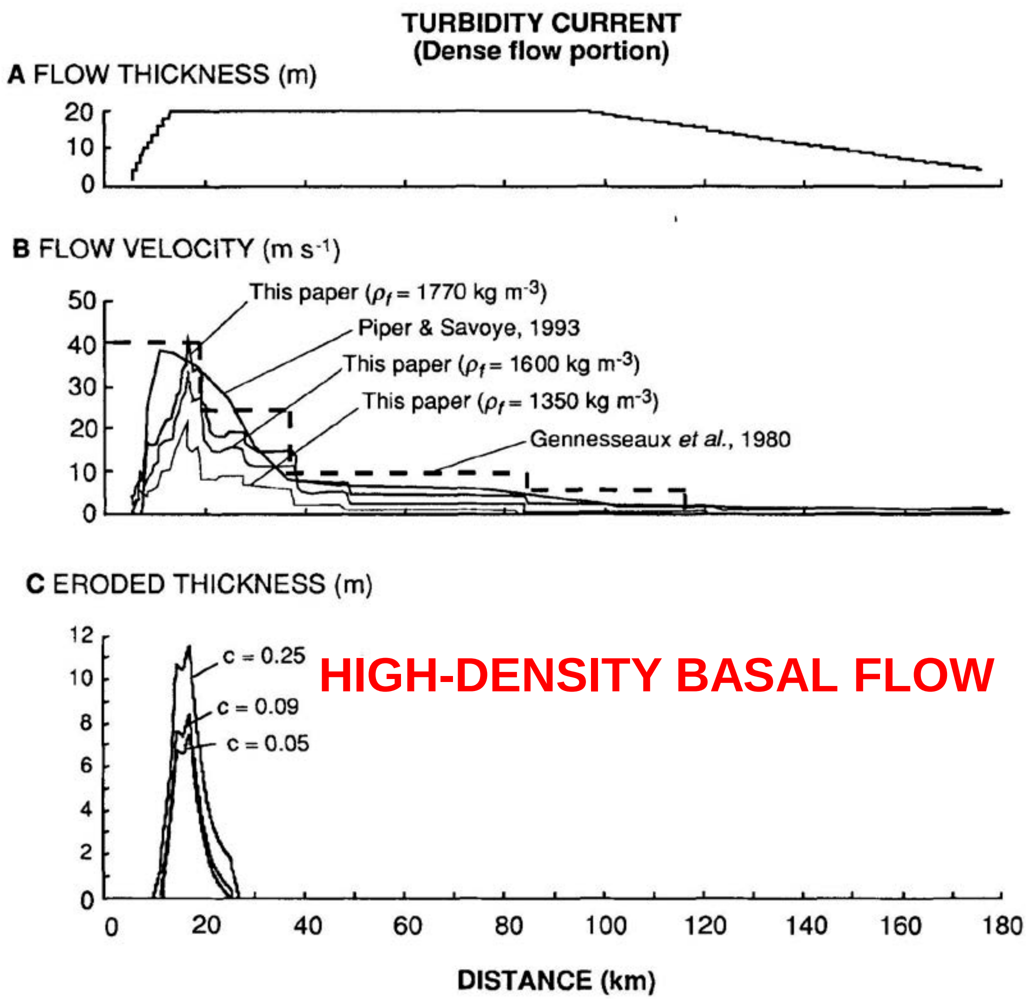
Hydraulic jump at the end of a spillway -source unknown; from http://www.iahrmedialibrary.net

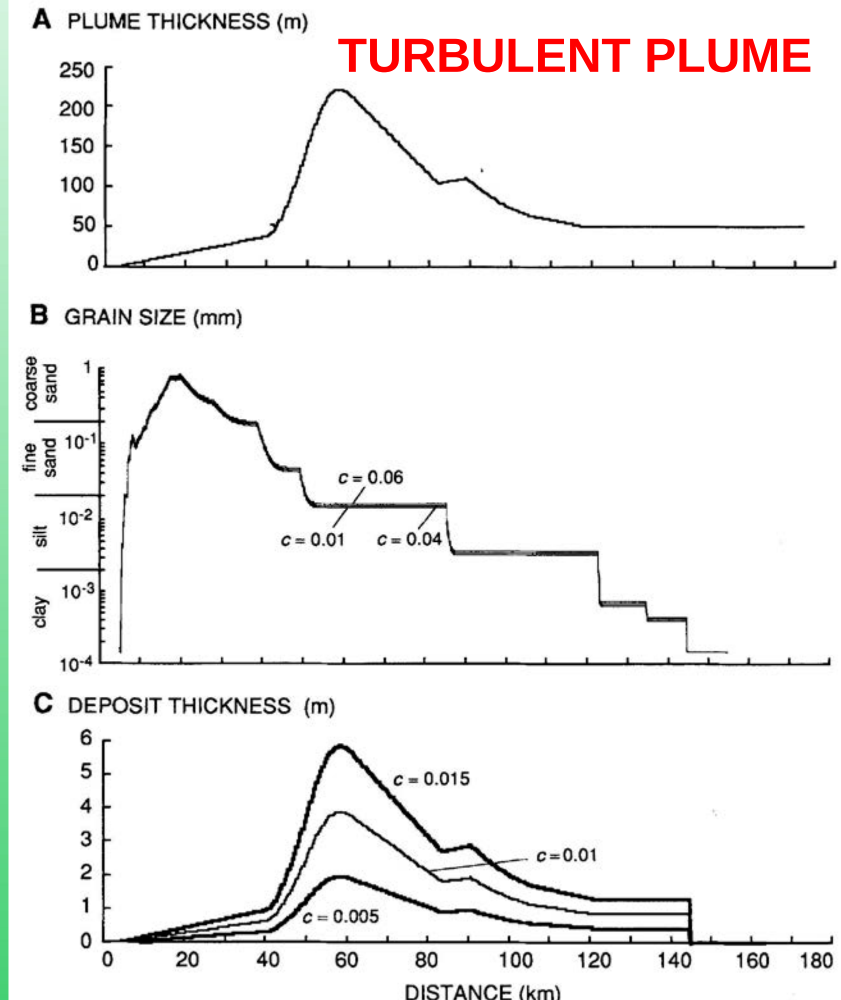


- **1979 anthropogenic failure at Nice airport**:
  - break up of mixed sand - mud failed material on canyon wall with 12° gradient
  - acceleration down canyon, eroding sand from canyon floor
  - rapid deposition of sand with flow expansion at mouth of canyon: likely a high-concentration base to the flow



1979 Nice event: mix of geological constraints and modelling. *Mulder et al. 1997*





4. What else happens in the conduit ?

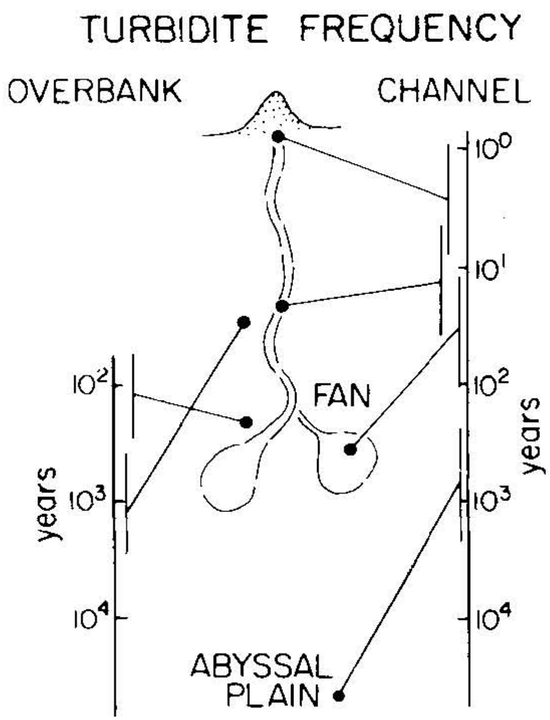
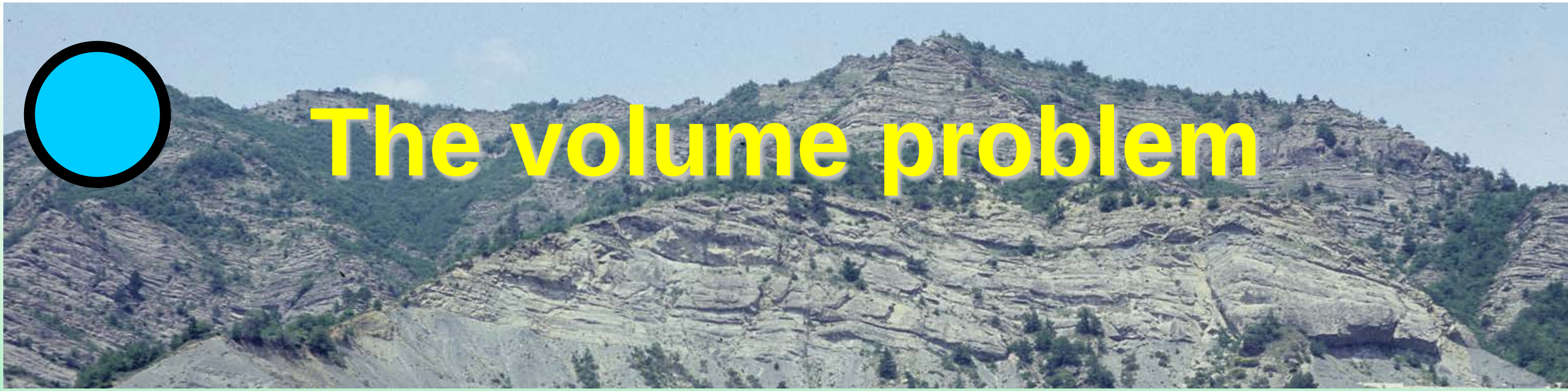


Fig. 9. Turbidity current frequency in different environments of *active* fans. (Based primarily on our own data from Holocene La Jolla, Pleistocene Navy and Laurentian Fans and Sohm, Wilkes, Alaska and Baffin Bay Abyssal Plains.)

- sand-transport events are common in canyons but rare in deep-water depocentres
- many examples
  - La Jolla
  - Monterey
  - Gulf of Corinth



The volume problem

- A single turbidity current can transport over 100 km^3 of sediment: > 10 x combined total annual sediment load of all rivers in the world [ancient record, 1929]
- Most observed slumps are either muddy or smaller than 1 km^3 (e.g. on sandy prodeltas)
- Observed river floods are smaller than 1 km^3
- Need a prolonged turbulent flow to get a large volume onto and across a basin floor

Navy Fan off NW Mexico

Conduit flushing

- Small, frequent initiating events deposit sand proximally within canyons and fan valleys
- Rare larger initiating events erode sand stored in canyons and even levees

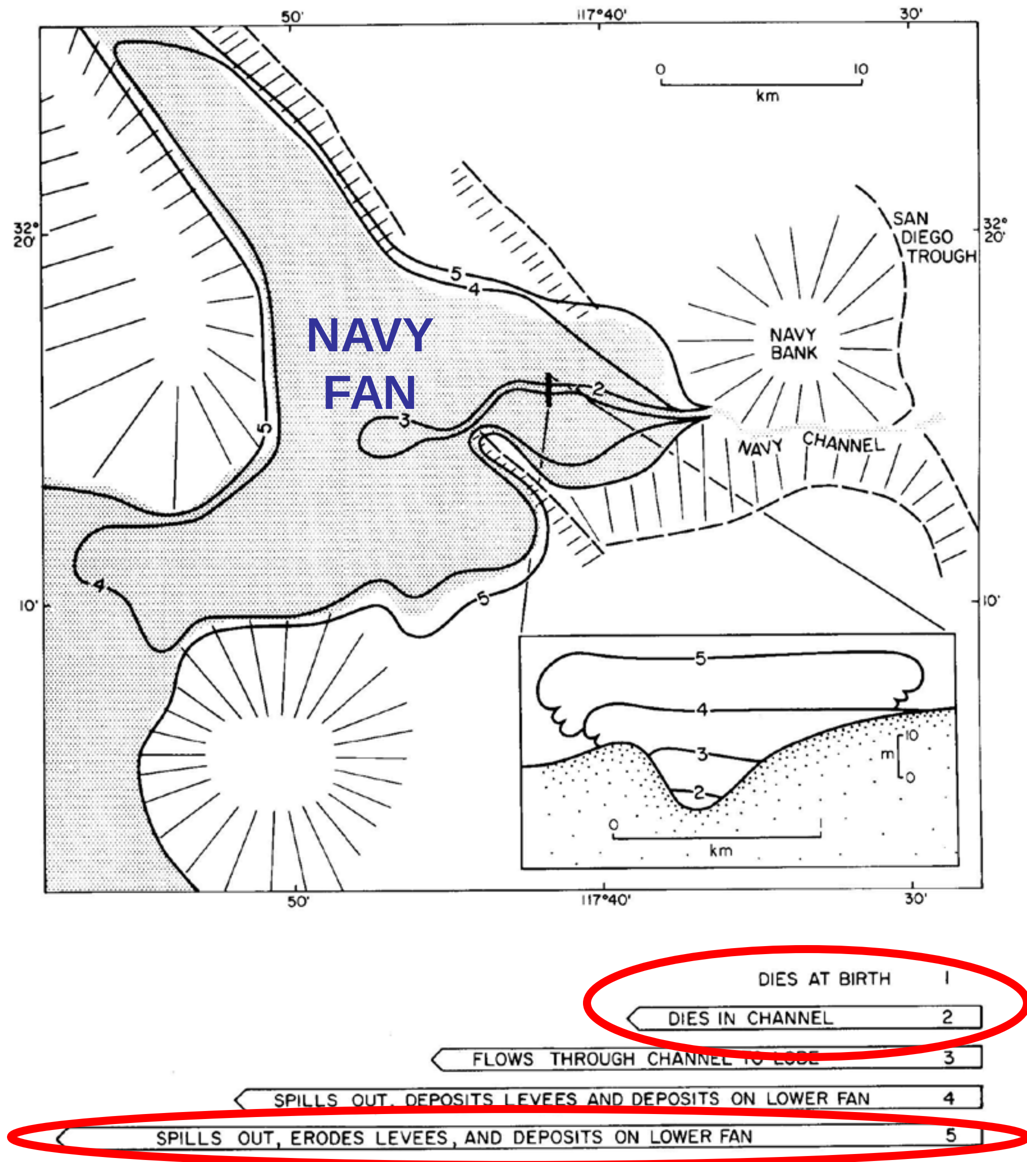
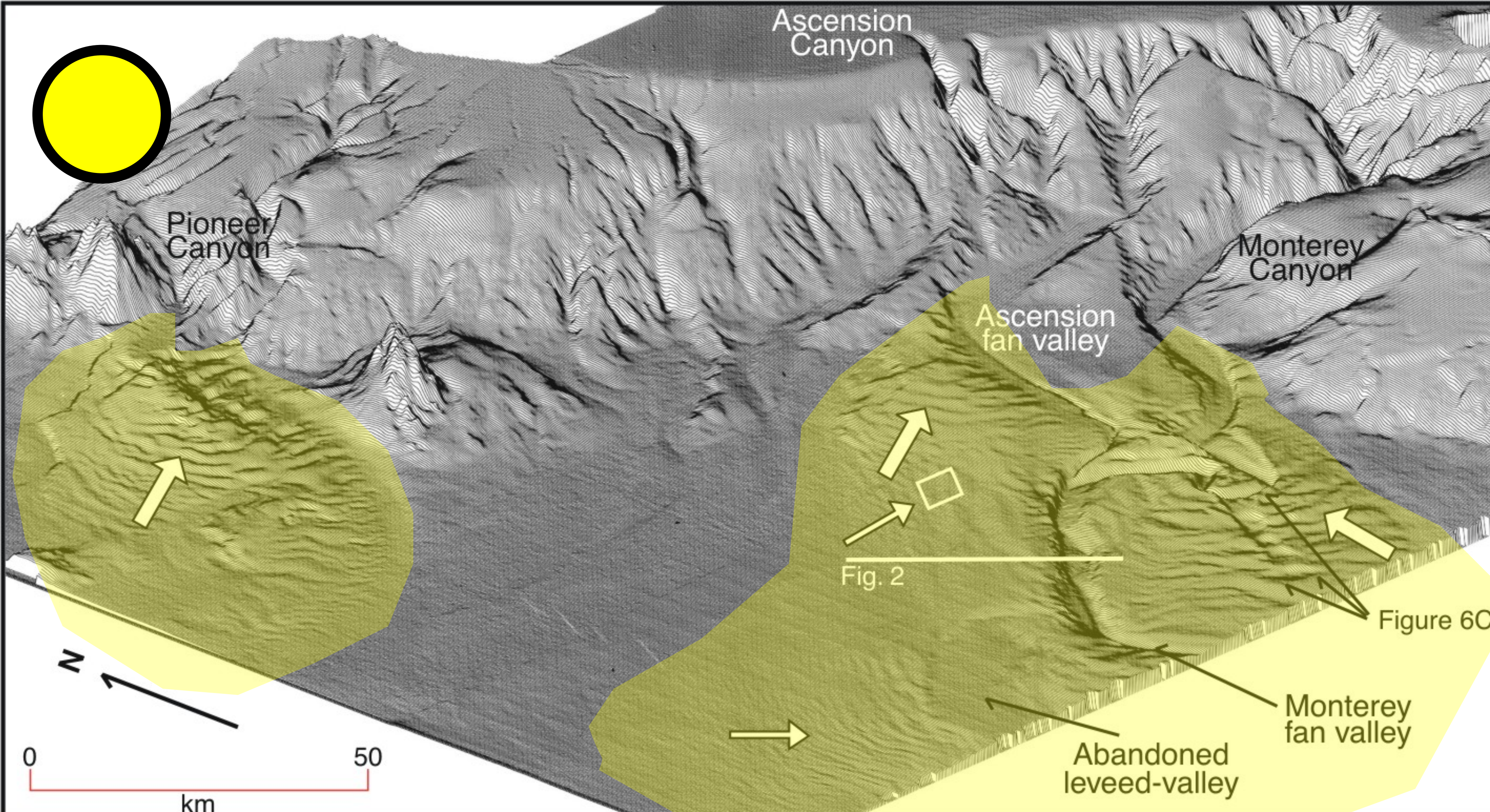


Fig. 8. Schematic map of Navy Fan and cross-section of upper-fan valley, showing thickness and extent of turbidites of size classes 2–5.

5. Pathways of flows

- Entrainment of water leads to thickening of flows, commonly hundreds of metres thick
- Head of the flow driven by pressure differential, flows down regional topography
- Flows will thin over topographic obstacles but may overtop them



Sediment waves indicating widespread supercritical flow below the mouths of canyons

Navy Fan off NW Mexico

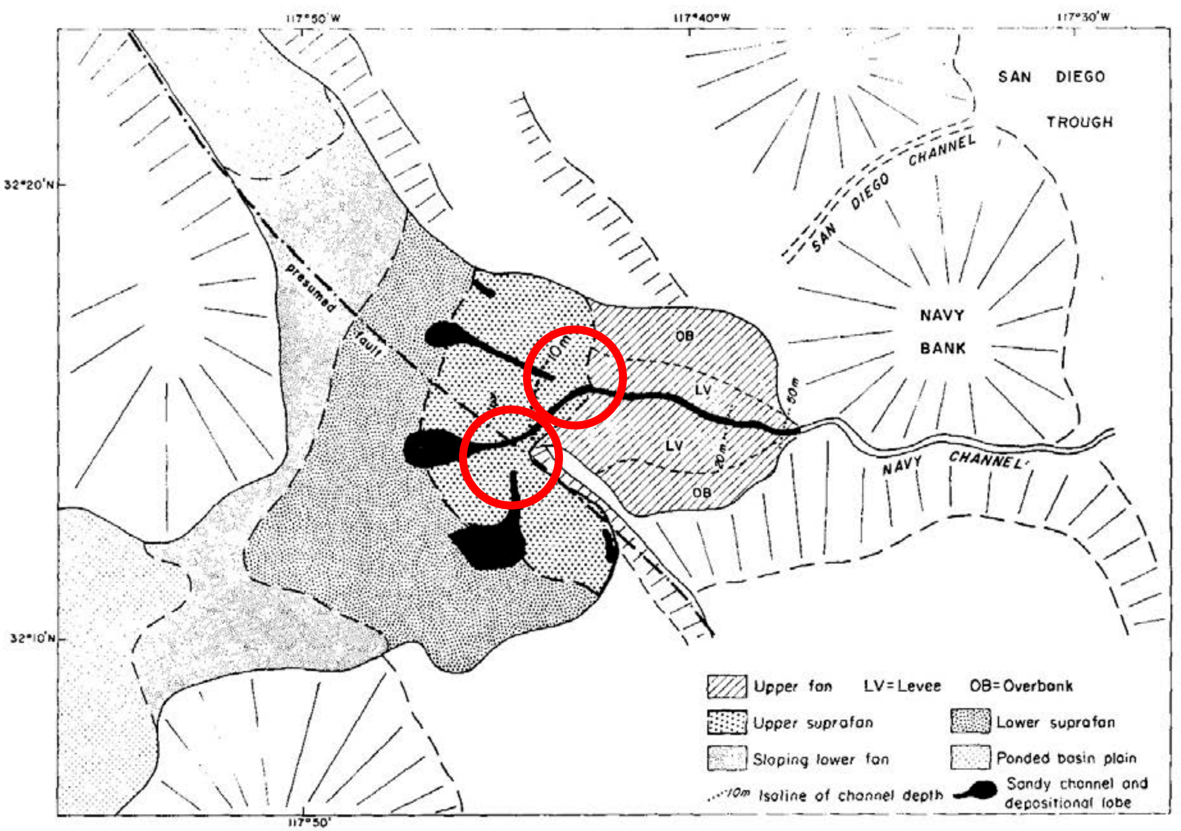
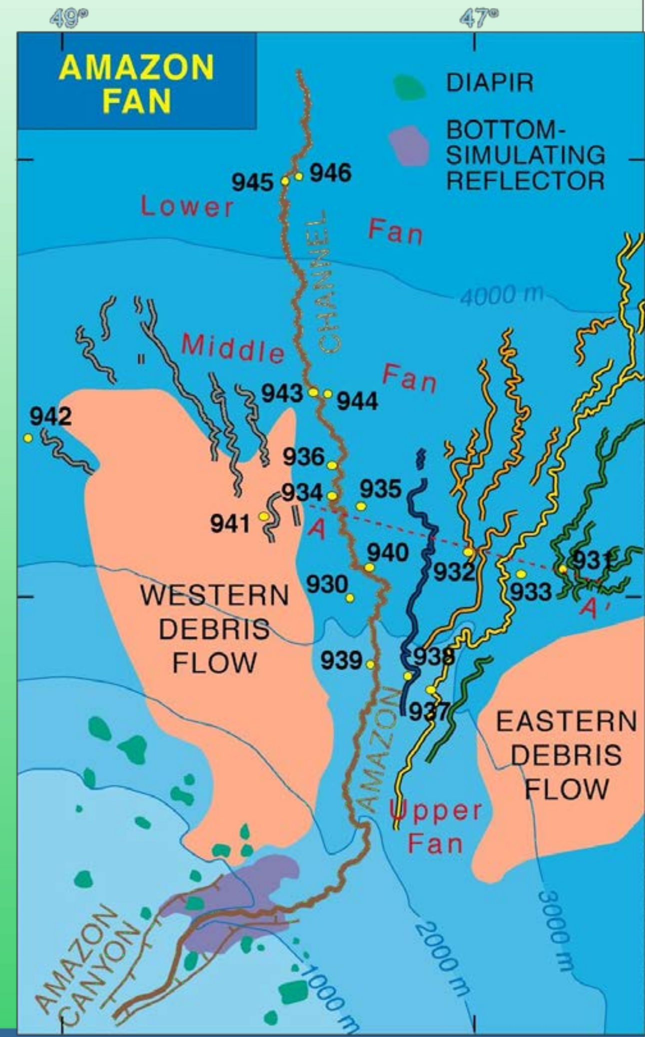


Fig. 14. Regional setting and major subdivisions of Navy Fan.

- at sharp bends, turbidity currents spill over levees that are 10-20 m high and then re-form a new channel

Amazon fan

- Main flow down active channel
- Fine sand to silt turbidites in some abandoned channels, by spillover of main levees



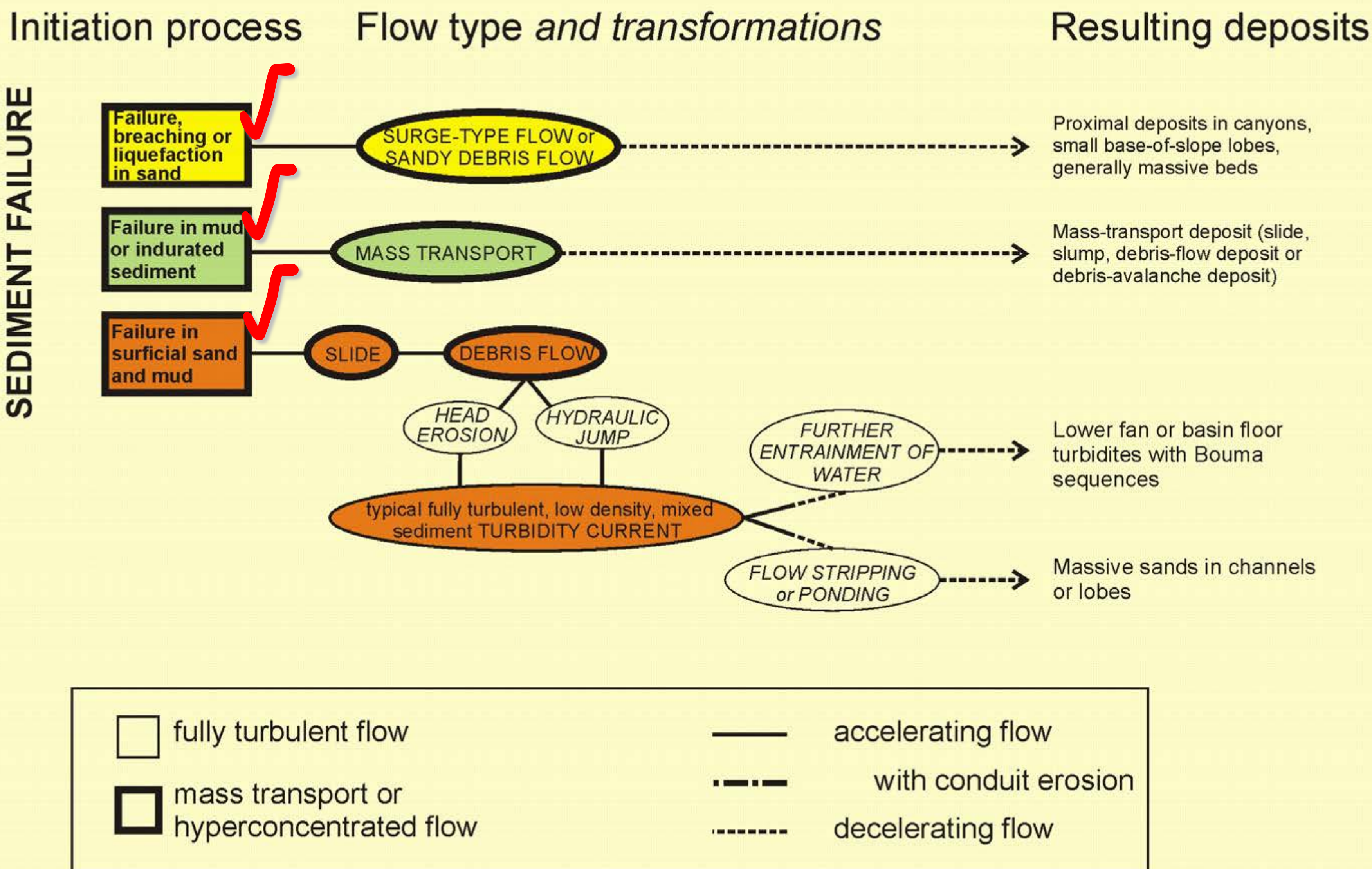
I don't know of a good example on an accretionary margin, where spillover is well documented

6. Other processes that initiate turbidity currents

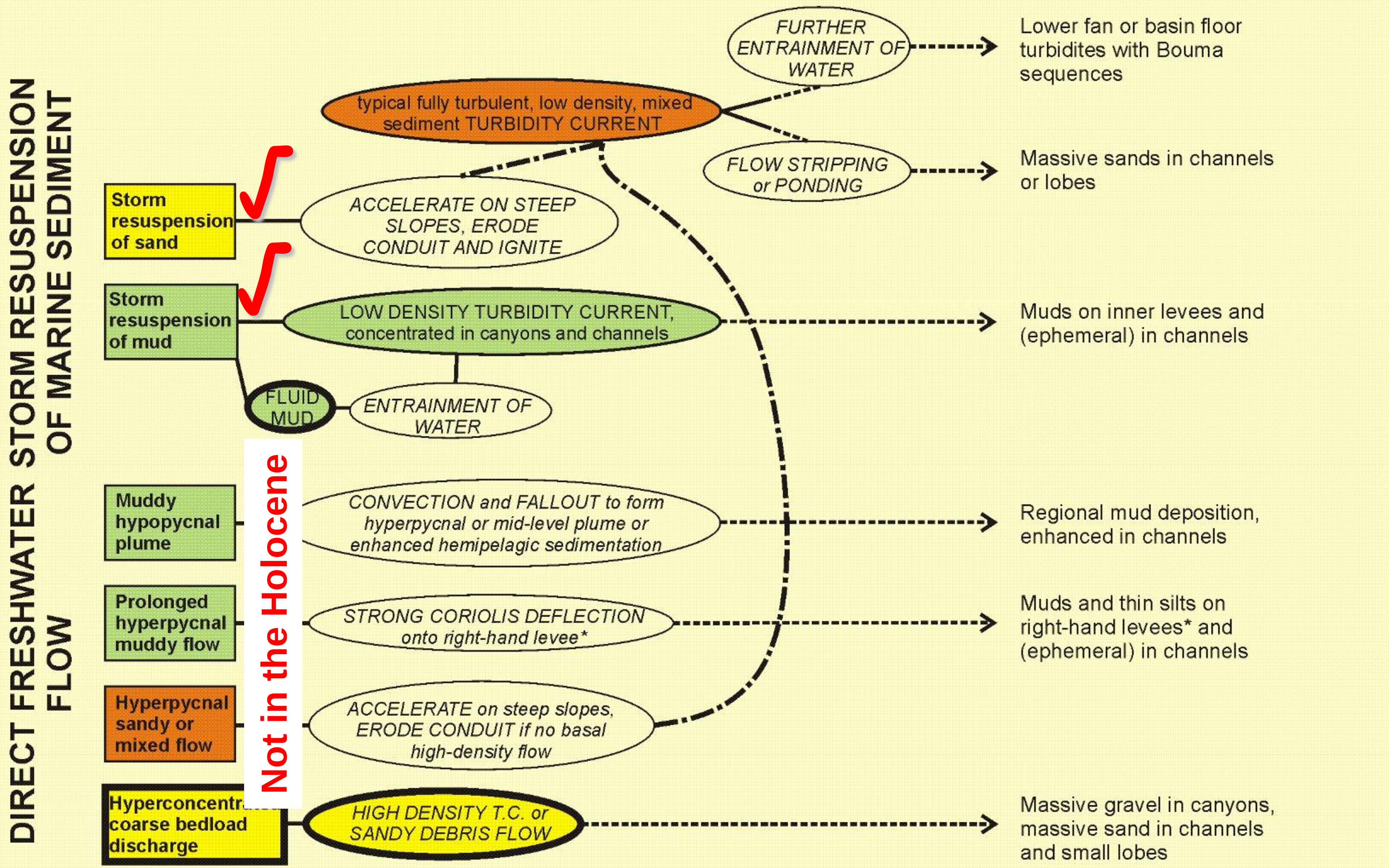
- Transformation of failed sediment
- Resuspension of outer shelf sediments by "oceanographic" processes
- Hyperpycnal flows from rivers or ice margins

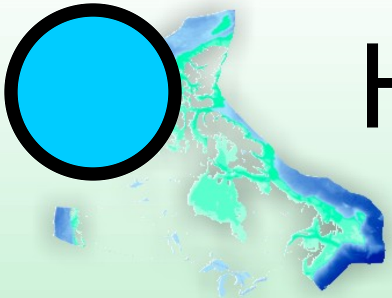
MANY FLOWS LAST FOR DAYS –
THEY ARE NOT SHORT-LIVED SURGES

Sediment failure and resulting deposits



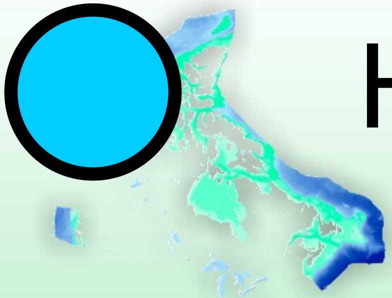
Other processes





High-concentration vs. fully turbulent dichotomy

- “**Sandy debris flows**”
  - – hyperpycnal supply of hyperconcentrated bedload
  - – fluidization/liquefaction/breaching of coarse-grained sediment
- deposit in
  - – slope conduits (canyons, channels, proximal “fans” on deltas)
  - – gradients $< 0.5^\circ$ at base of slope, on mid fan



High-concentration vs. fully turbulent dichotomy

- **Fully turbulent flows**
  - – transformation of retrogressive failures
  - – “oceanographic processes”
  - – suspension load of hyperpycnal flows
- erode deposits of “sandy debris flows” in slope conduits
- deposit on low gradients of the basin plain

7. How easy is it to correlate turbidites ?

- The fewer the data and the fewer the turbidites, the easier it is
- Depositional processes, or bioturbation, or sampling may produce a discontinuous record
- Easier on lobes and basin floor, more difficult in channels and levees

Navy Fan – EASY !

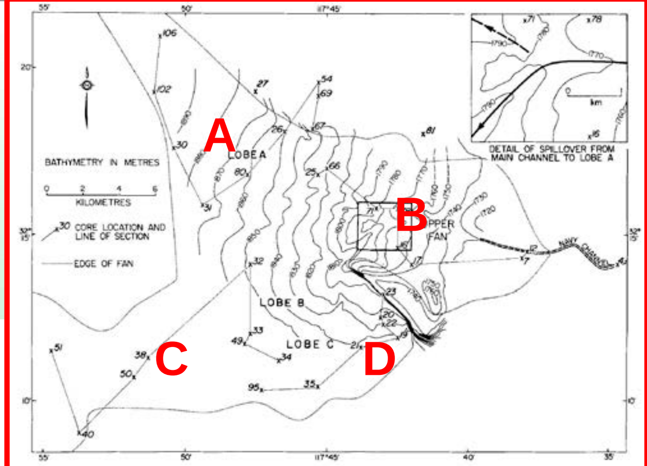


Fig. 2. Detailed bathymetry (based on deep-tow survey of Normark *et al.*, 1979) of Navy Fan with location of cores illustrated in Fig. 4. Inset shows detailed bathymetry of first main bend in distributary channel.

D. J. W. Piper and W. R. Normark

Depositional lobes

Overbank

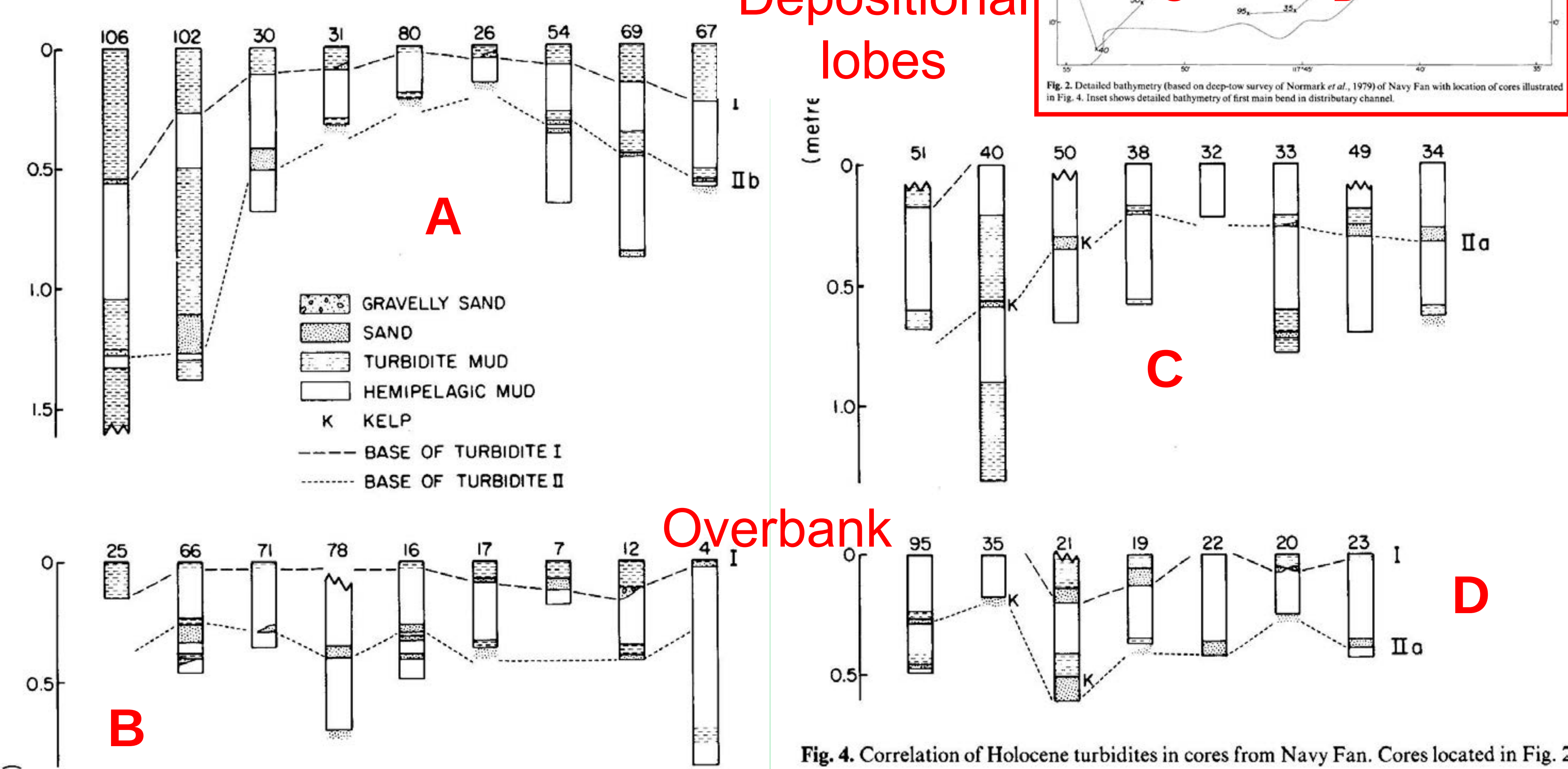
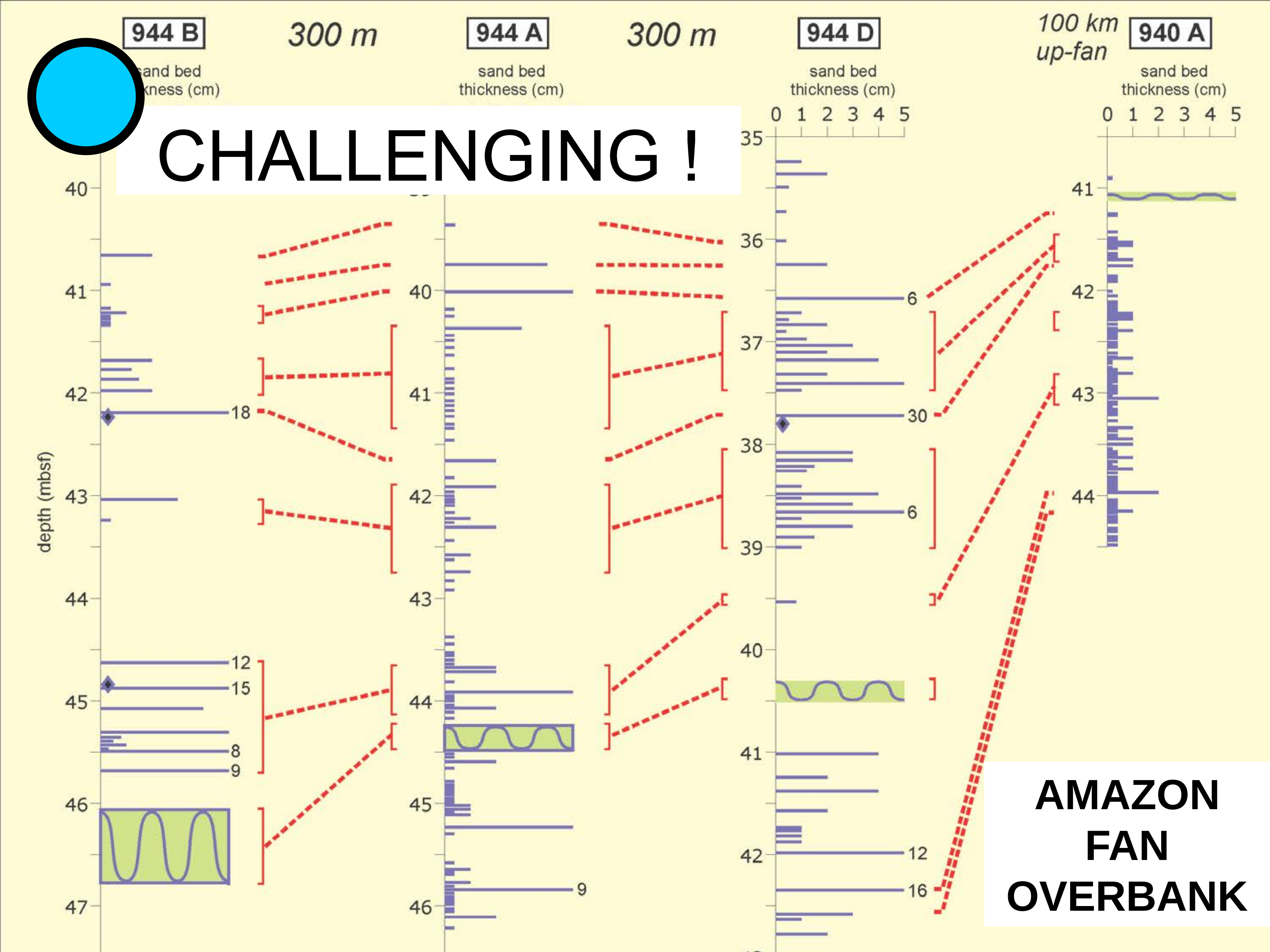
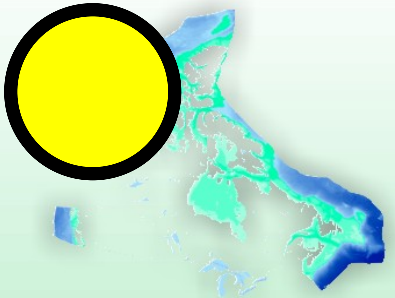


Fig. 4. Correlation of Holocene turbidites in cores from Navy Fan. Cores located in Fig. 2



CHALLENGING !
944 B
300 m
944 A
300 m
944 D
100 km up-fan
940 A
sand bed thickness (cm)
depth (mbsf)
18
12
15
8
9
6
30
6
12
16
9
AMAZON FAN OVERBANK

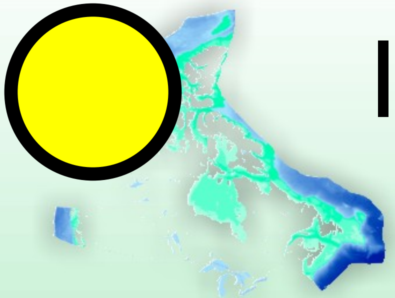


8. Are there turbidite features diagnostic of earthquake-triggering ?

- despite claims, the literature says no
  - depends on whether proximal or distal
  - depends how flows evolve
  - multiple amalgamated turbidites of different petrology
- microfossils in muddy turbidites used to distinguish hyperpycnal vs. coastal vs. upper slope sources of sediment

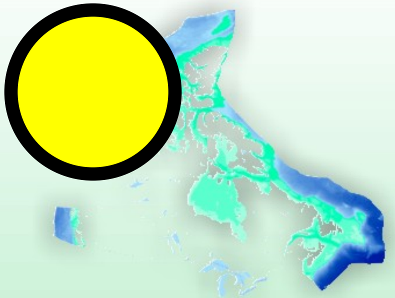
An outsider's view of the Cascadia margin

- Remarkably strong understanding of relatively few cores
- Demonstration of synchronous supply through multiple conduits – important !
- Poor understanding of history of failure in the source area
- Poor understanding of the behaviour of flows in the conduits (thickness, spillover)



I have polite scepticism about

- Depositional settings on channel floors as an unbiassed monitor of flows
- Correlations based on physical property wiggles
- Simple turbidite size vs. earthquake magnitude correlations (although the empirical evidence seems good on Cascadia margin – perhaps because of cyclic loading and liquefaction)
- Meaning of thin mud layers between sands
  - fluid mud deposition
  - Kelvin-Helmholtz waves
  - floc/muscovite accretion
  - tail of a turbidity current



What do we need to know ?

- thickness and pathways of flows, *derived from distribution of turbidites*
  - focus on critical events
- character and record of failure in the source area, mechanism of transformation of failures

Questions ?

- I would like to thank Julia Guttiérez-Pastor, Brian Atwater and Hans Nelson for providing unpublished material
- the organisers for inviting me to this very interesting workshop
- and the GSC for supporting, sometimes unwittingly, my turbidite research over the past 30 years