California and Other Modern Basin Floor Seismo-Turbidite Sedimentology: Implications for Active Tectonic Margin Stratigraphy and Reservoirs*

Hans C. Nelson[1], Chris Goldfinger[2], and Julia Gutierrez Pastor[1]

Search and Discovery Article #50814 (2013)**
Posted July 22, 2013

*Adapted from oral presentation given at 2013 Pacific Section AAPG, SEG and SEPM Joint Technical Conference, Monterey, California, April 19-25, 2013

[1]CSIC Instituto Andaluz de Ciencias de la Tierra, University of Granada, Spain (hansnelsonugr@hotmail.com)
[2]COAS, Oregon State University, Corvallis, OR, USA

Abstract

Earthquakes generate mass transport deposits (MTDs) plus megaturbidite (MTD overlain by coeval turbidite), multi-pulsed, stacked, and mud homogenite seismo-turbidites. The strongest (Mw 9) earthquake shaking signatures appear to create multi-pulsed individual turbidites, where the number and character of multiple coarse-grained pulses for correlative turbidites generally remain constant both upstream and downstream in different channel systems. Multiple turbidite pulses, that correlate with multiple ruptures shown in seismograms of historic earthquakes (e.g. Chile 1960, Sumatra 2004 and Japan 2011), support this hypothesis. The weaker (Mw = or < 8) (e.g. northern California San Andreas) earthquakes generate dominantly upstream simple fining-up (uni-pulsed) turbidites in single tributary canyons and channels; however, downstream stacked turbidites result from synchronously triggered multiple turbidity currents that deposit in channels below confluences of the tributaries. Both multi-pulsed and stacked turbidites create potentially thick amalgamated-like reservoir sands. Petroleum reservoirs in unconfined basin settings of active tectonic margins may be enhanced because multiple great earthquakes cause seismic strengthening of margin sediment that result in minor MTDs in the turbidite system basin floor deposits (e.g. maximum run-out distances of MTDs across basin floors along active margins are an order of magnitude less than on passive margins). In contrast the MTDs, turbidites and reservoir deposits are equally intermixed on basin floors along passive margins such as the northern Gulf of Mexico. In confined or semi-confined basin settings, earthquake triggering results in potential reservoirs with coeval megaturbidites in proximal settings, thick stacked turbidites downstream, and ponded muddy homogenite turbidites in basin or sub-basin centers.

Selected References

Adams, J., 1990, Paleoseismicity of the Cascadia subduction zone; evidence from turbidites off the Oregon-Washington margin: Tectonics, v. 9/4, p. 569-583.

Anselmetti, F.S., R. Drescher-Schneider, H. Furrer, H.R. Graf, S.E. Lowick, F. Preusser, and M.A. Riedi, 2010, A nearly equal 180,000 years sedimentation history of a perialpine overdeepened glacial trough (Wehntal, N-Switzerland), *in* M. Fiebig, F. Preusser, K. Decker, and C. Schluechter, prefacers, Overdeepening of Alpine valleys: Swiss Journal of Geosciences, v. 103/3, p. 345-361.

Ashabranner, L.B., E.K. Tripsanas, and R.C. Shipp, 2010, Multi-direction flow in a mass-transport deposit, Santos Basin, offshore Brazil, *in* D.C. Mosher, R.C. Shipp, L. MOscardelli, J.D. Chaytor, C.D.P. Baxter, J.L. Homa, and R. Urgeles, eds., Submarine mass movements and their consequences; 4th international symposium: Advances in Natural and Technological Hazards Research, v. 28, p. 247-255.

Beck, C., J.-L. Reyss, F. Leclerc, E. Moreno, N. Feuillet, L. Barrier, F. Beauducel, G. Boudon, V. Clement, et. al., 2012, Identification of deep subaqueous co-seismic scarps through specific coeval sedimentation in Lesser Antilles: implication for seismic hazard: Natural Hazards and Earth System Sciences, v. 12, p. 1755-1767.

Goldfinger, C., 2012, Turbidite event history methods and implications for Holocene paleoseismicity of the Cascadia subduction zone: USGS, Reston, VA., Report # P 1661-F, internet resource.

Goldfinger, C., Y. Ideka, and R.S. Yeats, 2011, Superquakes and Supercycles: American Geophysical Union Fall Meeting, p. Abstract T11C-07.

Goldfinger, C., C.H. Nelson, J.E. Johnson, A. Morey, J. Patton, J. Gutierrez-Pastor, E.K. Grijalva, R. Burgmann, et. al., 2008, Plate boundary submarine paleoseismology, in Anonymous, ed., The next decade of the Seismogenic Zone Experiment; abstract volume: MARGINS Office United States, unpaginated.

Goldfinger, C., A.E. Morey, C.H. Nelson, J. Gutierrez-Pastor, J.E. Johnson, E. Karabanov, J. Chaytor, and A. Eriksson, 2007, Rupture lengths and temporal history of significant earthquakes on the offshore and north coast segments of the northern San Andreas Fault based on turbidite stratigraphy: Earth and Planetary Science Letters, v. 254/1-2, p. 9-27.

Goldfinger, C., C.H. Nelson, J.E. Johnson, D. Erickson, M. Winkler, P. Kalk, J. Pastor, A. Camarero, C. Morri, G. Dunhill, et. al., 2003, Holocene earthquake records from the Cascadia subduction zone and northern San Andreas Fault based on precise dating of offshore turbidites: Annual Review of Earth and Planetary Sciences, v. 31, p. 555-577.

Guttierez-Pastor, J., C.H. Nelson, C. Goldfinger, J.E. Johnson, C. Escutia, A. Eriksson, and A.E. Morey, 2009, Earthquake control of Holocene turbidite frequency confirmed by hemipelagic sedimentation chronology on the Cascadia and Northern California active continental margins, *in* B. Kneller, O.J. Martinsen, and B. McCaffrey, eds., External controls on deep-water depositional systems: Society for Sedimentary Geology, Special Publication, v. 92, p. 179-197.

Guttierez-Pastor, J., C.H. Nelson, C. Goldfinger, J.E. Johnson, C. Escutia, A. Eriksson, and A.E. Morey, 2009, Earthquake control of Holocene turbidite frequency confirmed by hemipelagic sedimentation chronology on the Cascadia and Northern California active continental margins, *in*

B. Kneller, O.J. Martinsen, and B. McCaffrey, eds., External controls on deep-water depositional systems: Society for Sedimentary Geology, Special Publication, v. 92, p. 179-197.

Gutierrez-Pastor, J., C.H. Nelson, C. Goldfinger, J.E. Johnson, C. Escutia, A. Ericsson, and A.E. Morey, 2009, Earthquake control of Holocene turbidite frequency confirmed by hemipelagic sedimentation chronology on the Cascadia and Northern California active continental margins, *in* B. Kneller, O.J. Martinsen, and B. McCaffrey, eds., External controls on deep-water depositional systems: Special Publication for Sedimentary Geology, v. 92, p. 179-197.

Gutierrez-Pastor, J., C.H. nelson, C. Goldfinger, and C. Escuita, 2013, Sedimentology of seismo-turbidites off the Cascadia and northern California active tectonic continental margins, Northwest Pacific Ocean: Marine Geology, v. 336, p. 99-119.

Kane, I.A., and D.M. Hodgson, 2011, Sedimentological criteria to differentiate submarine channel levee subenvironments; exhumed examples from the Rosario Fm. (Upper Cretaceous) of Baja California, Mexico, and the Fort Brown Fm. (Permian), Karoo Basin, S. Africa, *in* S.M. Hubbard, B.W. Romans, and A. Fidani, eds., The stratigraphic evolution of deep-water architecture: Marine and Petroleum Geology, v. 28/3, p. 807-823.

Kneller, B.C., and W.D. McCaffrey, 2003, The interpretation of vertical sequences in turbidite beds: The influence of longitudinal flow structure: Journal of Sedimentary Research, v. 73, p. 706-713.

Lowe, D.R., 1982, Sediment gravity flows; II, Depositional models with special reference to the deposits of high-density turbidity currents: Journal of Sedimentary Petrology, v. 52/1, p. 279-297.

Mulder, T., J.P.M. Syvitski, S. Migeon, J. Faugeres, and B. Savoye, 2003, Marine hyperpycnal flows; initiation, behavior and related deposits; a review: Marine Petroleum Geology, v. 20, p. 861-882.

Nelson, C.H., J. Gutierrez-Pastor, C. Goldfinger, and C. Escutia: 2012, Great earthquakes along the Western United States continental margin: implications for hazards, stratigraphy and turbidite lithology: Natural Hazards and Earth System Sciences, v. 12, p. 3191-3208.

Nelson, C.H., C. Escutia, J.E. Damuth, and D.C. Twichell, 2011, Interplay of mass-transport and turbidite-system deposits in different active tectonic and passive continental margin settings: external and local controlling factors: Society of Sedimentary Geology, v. 96, p. 39-66.

Nelson, C.H., C. Escutia, C. Goldfinger, E. Karabanov, J. Gutierrez-Pastor, and M. DeBatist, 2009, External Controls on Modern Clastic Turbidite Systems: Three Case Studies, Society of Sedimentary Geology, v. 93, p. 57-76.

Nelson, A.R., H.M. Kelsey, and R.C. Witter, 2006, Great earthquakes of variable magnitude at the Cascadia Subduction Zone: Quaternary Research, v. 65, p. 354-365.

Nelson, C.H., and C. Goldfinger, 2000, Variation of modern turbidite systems along the subduction zone margin of Cascadia Basin; implications for turbidite reservoir modeling: AAPG Annual Meeting Expanded Abstracts, p. 105.

Nelson, C.H., L.D. Kulm, P.R. Carlson, and J.R. Duncan, 1968, Mazama Ash in the Northeastern Pacific: Science, v. 161, p. 47-49.

Noda, A., T. TuZino, Y. Kanai, R. Furukawa, and J. Uchida, 2008, Paleoseismicity along the southern Kuril Trench deduced from submarine-fan turbidites: Marine Geology, v. 254/1-2, p. 73-90.

Patton, J.R., C. Goldfinger, A.E. Morey, C. Romsos, B. Black, Y. Djadjadihardja, and Udrekh, 2013, Seismoturbidite record as preserved at core sites at the Cascadia and Sumatr-Andaman subduction zones: Natural Hazards and Earth System Sciences, v. 13, p. 833-867.

Polonia, A., E. Bonatti, A. Camerienghi, R. G. Lucchi, G. Panieri, and L. Gasperini, 2013, Mediterranean megaturbidite triggered by the AD 365 Crete earthquake and tsunami: Scientific Reports, v. 3, Article 1285, 12 p.

Pouderoux, H., G. Larmarche, and J.-N. Proust, 2012, Building an 18,000-year-long paleo-earthquake record from detailed deep-sea turbidite characterization in Poverty Bay, New Zealand: Natural Hazards and Earth System Sciences NHESS, v. 12/6, p. 2077-2101.

St-Onge, G., E. Chapron, S. Mulsow, M. Salas, M. Biel, M. Debret, A. Foucher, T. Mulder, T. Winiarski, et. al., 2012, Comparison of earthquake-triggered turbidites from the Saguenay (Eastern Canada) and Reloncavi (Chilean margin) Fjords; implications for paleoseismicity and sedimentology: Sedimentary Geology, v. 243-244, p. 89-107.

Strasser, M., F.S. Anselmetti, D. Fah, D. Giardini, and M. Schnellmann, 2006, Magnitudes and source areas of large prehistoric Northern Alpine earthquakes revealed by slope failures in lake: Geology, v. 34, p. 1005-1008.

Tripsanas, E.K., D.J.W. Piper, and D.C. Campbell, 2008, Evolution and depositional structure of earthquake-induced mass movements and gravity flows: southwest Orphan Basin, Labrador Sea: Marine and Petroleum Geology, v. 25/7, p. 645-662.

Tripsanas, E.K., W.R. Bryant, and B.A. Phaneuf, 2004, Depositional processes of uniform mud deposits (unifites), Hedberg Basin, northwest Gulf of Mexico; new perspectives, *in* W.W. Sager, W.R. Bryant, and E.H. Doyle, prefacers, High-resolution studies of continental margin geology and geohazards: AAPG Bulletin, v. 88/6, p. 825-840.

Twichell, D.C., C.H. Nelson, N. Kenyon, and W. Schwab, 2009, The influence of external processes on the Holocene evolution of the Mississippi Fan, *in* B. Kneller, O.J. Martinsen, and B. McCaffrey, eds., External controls on deep-water depositional systems: Special Publication for Sedimentary Geology, v. 92, p. 145-157.

Van Daele, M., V. Cnudde, P. Duyck, M. Pino, R. Urrutia, and M. De Batist, in press, Multidirectional, synchronously-triggered seismo-turbidites and debrites revealed by X-ray computed tomography (CT): Sedimentology.

CALIFORNIA AND OTHER MODERN BASIN FLOOR SEISMO-TURBIDITE SEDIMENTOLOGY: IMPLICATIONS FOR ACTIVE TECTONIC MARGIN STRATIGRAPHY AND RESERVOIRS

C. HANS NELSON
TRG, CSIC
JULIA GUTIÉRREZ PASTOR
Instituto Andaluz Ciencias de la Tierra
CSIC

CHRIS GOLDFINGER
COAS, Oregon State University

SHIPBOARD SCIENTIFIC PARTY 1999 & 2002

•**Funding Sources:**
National Science Foundation, Division of Earth Sciences
U.S. Geological Survey, NEHRP program
TRG Turbidite Research Group, University

PSAAPG APRIL 23, 2013

TODAYS TOPICS

SEISMO-TURBIDITES :

MULTIPULSED (e.g. Cascdia, Chile 1960, Sumatra, 2004, Japan, 2011)

STACKED (e.g. North San Andreas, New Zealand, Japan Sea 1983, Algeria 2003, Chile 2007, Haiti, 2010, Lakes Biwa & Lucerne 2200 yr BP)

MEGABEDS (e.g. Labrador Sea, Chile, Lake Lucerne, Marmara Sea)

HOMOGENITE/UNIFITE SAND/MUD (e.g. Ionian Sea 365 A.D., Lucerne 1601 A.D., Marmara Sea 1912, Lesser Antilles 1974, Chile 2007, Haiti 2010)

SEICHE SILT LAMINA e.g. Chile 2007, Haiti 2010, Marmara Sea 1912)

TSUNAMITE (e.g. Ionian Sea 365 A.D., Japan, 2011)

IMPLICATIONS OF TURBIDITE PALEOSEISMIC HISTORY:

- ACTIVE TECTONIC MARGIN TURBIDITES MAINLY SEISMICALLY TRIGGERED
- UNCONFINED BASIN FLOOR SEISMO-TURBIDITE SYSTEMS HAVE LIMITED MTDs BECAUSE OF SEISMIC STRENGTHENING
- CONFINED BASIN FLOOR SEISMO-TURBIDITES HAVE THICK MEGABED DEBRITE AND HOMOGENITE SANDS OR MUDS
- BASIN SETTING & SEISMO-TURBIDITE DEPOSITION IMPORTANT FOR RESERVOIRS

SEISMO-TURBIDITE DEFINITIONS FOR TALK

- **MULTI-PULSED –** INDIVIDUAL TURBIDITE WITH MULTIPLE COARSE-GRAINED PULSES - RESULT FROM A SURGING TURBIDITY CURRENT CREATED BY ~*Mw* 9 EARTHQUAKE RUPTURE PATTERN

- **STACKED -** MULTIPLE TURBIDITES DEPOSITED ON A BASIN FLOOR OR BELOW CANYON AND CHANNEL CONFLUENCES - RESULT FROM MULTIPLE TURBIDITY CURRENTS TRIGGERED SYNCRONOUSLY ALONG A BASIN MARGIN BY AN ~ =/< *Mw* 8 EARTHQUAKE

- **MEGABED -** (Haughton et al., 2009 definition) INDIVIDUAL BED CONTAINING DEBRITE OVERLAIN BY TURBIDITE - RESULT FROM EARTHQUAKE TRIGGERED DEBRIS FLOW THAT EVOLVES INO A TURBIDITY CURRENT

- **HOMOGENITE/UNIFITE -** PONDED MASSIVE, THICK (up to 10s of m) SAND OR MUD OVERLYING STRUCTURED TURBIDITE BASAL SAND OR DEBRITE - RESULT FROM MULTIPLE TURBIDITY CURRENTS TRIGGERED SYNCRONOUSLY ALONG A CONFINED BASIN MARGIN BY AN EARTHQUAKE

- **SEICHE DEPOSITS -** SEISMO-TURBIDITE CAP OF LAMINATED SILTS OR MUDS WITH OPPOSING PALEOCURRENT DIRECTIONS

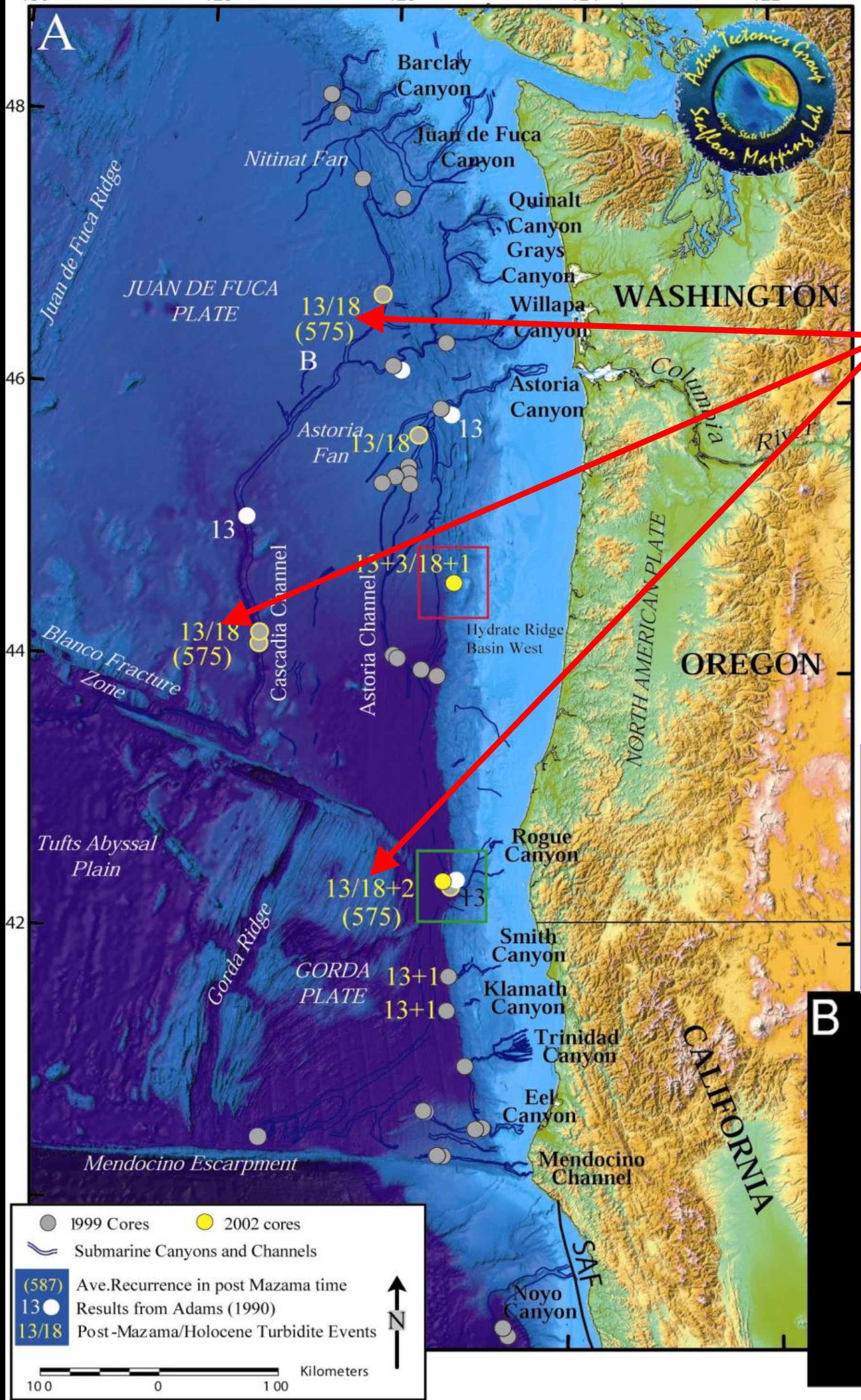
- **TSUMAMITES –** SHALLOW WATER CLAY CAP FROM TSUNAMI BACKWASH

-SEISMO-TURBIDITE DEFINITIONS FOR TALK SHOWN IN PREVIOUS SLIDE

-SEISMO-TURBIDITE HISTORICAL EXAMPLES SHOWN IN INTRODUCTION SLIDE

-CASCADIA (see slides 5-8) AND SAN ANDREAS MARGIN (see slides 17-21) SEISMO-TURBIDITES SHOWN BY SYNCHRONOUS TRIGGERING EVIDENCE :

- 13 TURBIDITES (T1-T13) ABOVE FIRST SEISMO-TURBIDITE MARKER BED CONTAINING MAZAMA ASH (MA) FROM CRATER LAKE ERUPTION & 18 SEISMO-TURBIDITES ABOVE HOLOCENE/PLEISTOCENE BOUNDARY IN CHANNELS OF ALL TYPES OF CASCADIA TURBIDITE SYSTEMS (see next slide 5) (Nelson et al., 2000, Goldfinger et al., 2003; 2008; 2012)
- CONFLUENCE TEST WITH SAME NUMBER OF POST MA AND HOLOCENE TURBIDITES UPSTREAM AND DOWNSTREAM FROM CHANNEL CONFLUENCES PROVES SYNCHRONOUS TRIGGERING (Adams, 1990)
- SAME 14C AND HEMIPELAGIC SEDIMENT (thickness/sedimentation rate) AGES FOR CORRELATIVE SEISMO-TURBIDITES IN DIFFERENT TURBIDITE SYSTEMS OF CASCADIA MARGIN (Guttierez Pastor et al., 2009) (see slide 8)
- CORRELATION OF TURBIDITE PALEOSEISMIC RECORDS WITH ONSHORE CASCADIA & SAN ANDREAS PALEOSEISMIC RECORDS (Goldfinger et al. 2007; 2008; 2012)
- SAME DENSITY AND MAGNETIC SUSCEPTIBILITY LOG SIGNATURES FOR CORRELATIVE SEISMO-TURBIDITES (e.g. number of coarse grained pulses & layer thickness- see slides 10 & 11) (Goldfinger et al. 2008; 2012)
- BELOW SAN ANDREAS CHANNEL CONFLUENCES, STACKED TURBIDITES WITH SEPARATE MINERALOGY FROM DIFFERENT TRIBUTARY CANYON SOURCES PROVES SYNCHRONOUS TRIGGERING (Goldfinger et al, 2007)



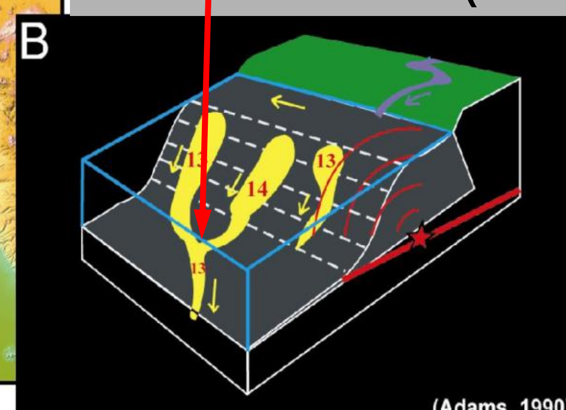
CASCADIA MARGIN

MULTI-PULSED TURBIDITES

CORES SHOW REGIONAL CORRELATION OF TURBIDITES

i.e. regional synchroneity shown by = numbers of turbidites (13 post-Mazama and 18 Holocene) in widely separated channels on the Cascadia margin. and by the “confluence test” (see B - same number of turbidites above and below channel confluences, ie. if turbidites triggered randomly, **number below confluence = 27, not 13**

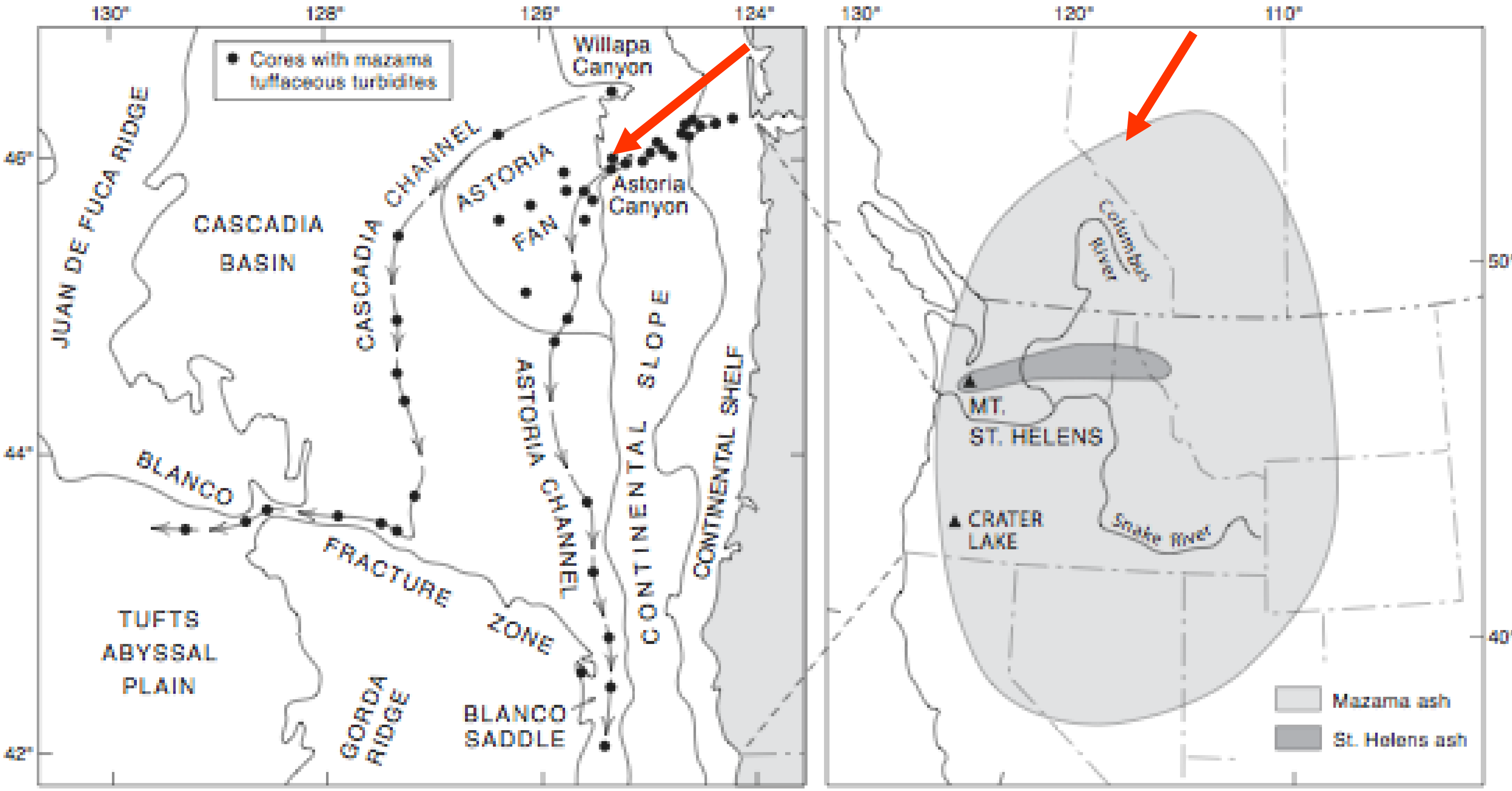
CORRELATION FOR 800 km IN CASCADIA BASIN INDICATES TRIGGERING BY GREAT EARTHQUAKES (*Mw* >8-9)



NOTE: DIFFERENT TYPES OF TURBIDITE SYSTEMS (e.g. DEEP SEA CHANNELS, SUBMARINE FANS, BASE OF SLOPE APRONS)

Goldfinger et al., 2003; 2012)

DISTRIBUTION OF MAZAMA ASH IN AIRFALL AND DEPOSITED IN CANYON & CHANNEL TURBIDITES FIRST OCCURRENCE IN T13 = CASCADIA MARKER BED



MOUNT MAZAMA (CRATER LAKE) ERUPTION 7626 yr BP- GREENLAND ICE CORE 100X GREATER THAN ST. HELENS ERUPTION IN 1980

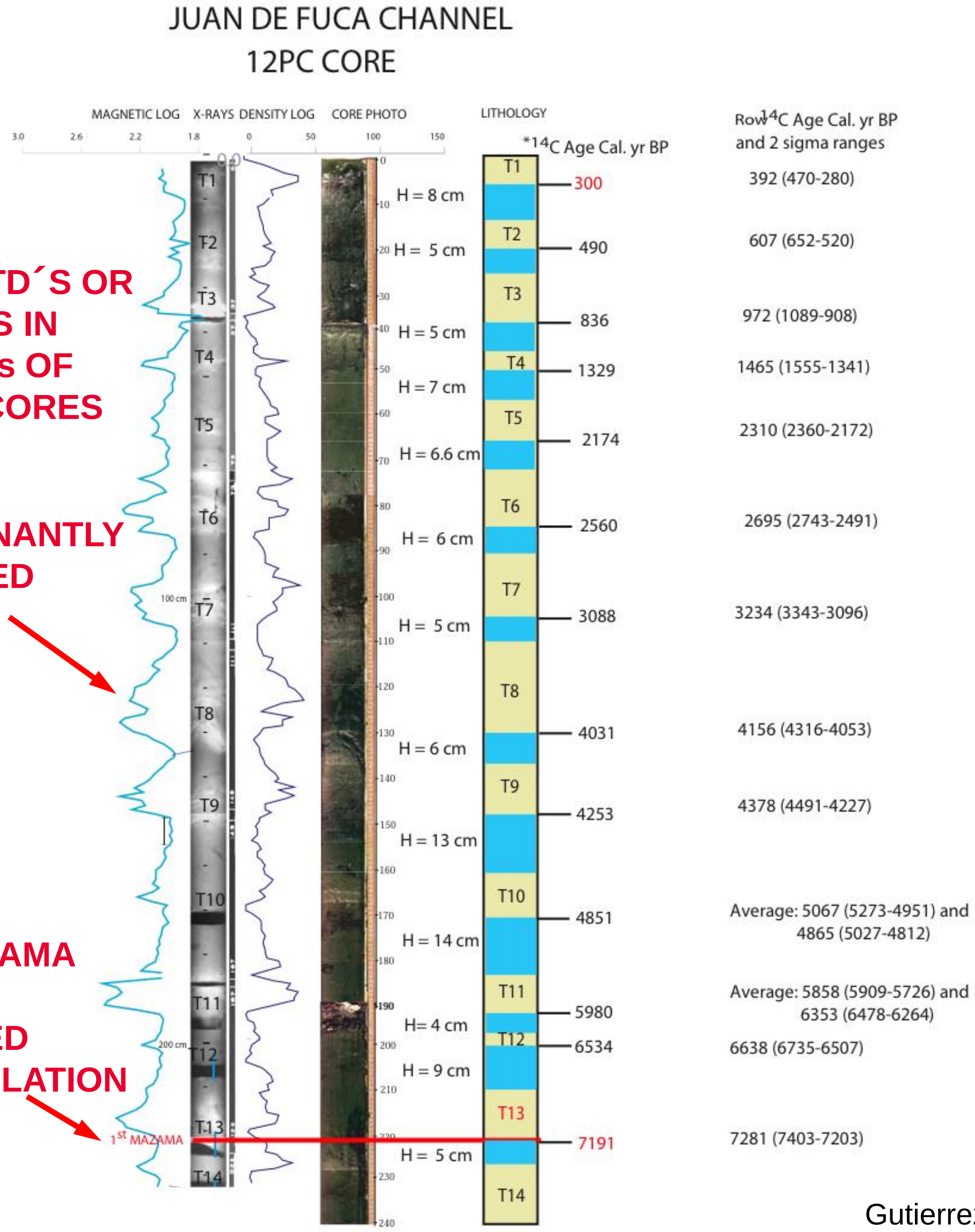
Nelson et al., 1968; 2009

13 POST MAZAMA ASH TURBIDITES (T1 - T13) IN CASCADIA BASIN CHANNELS USED TO DEFINE PALEOSEISMIC HISTORY

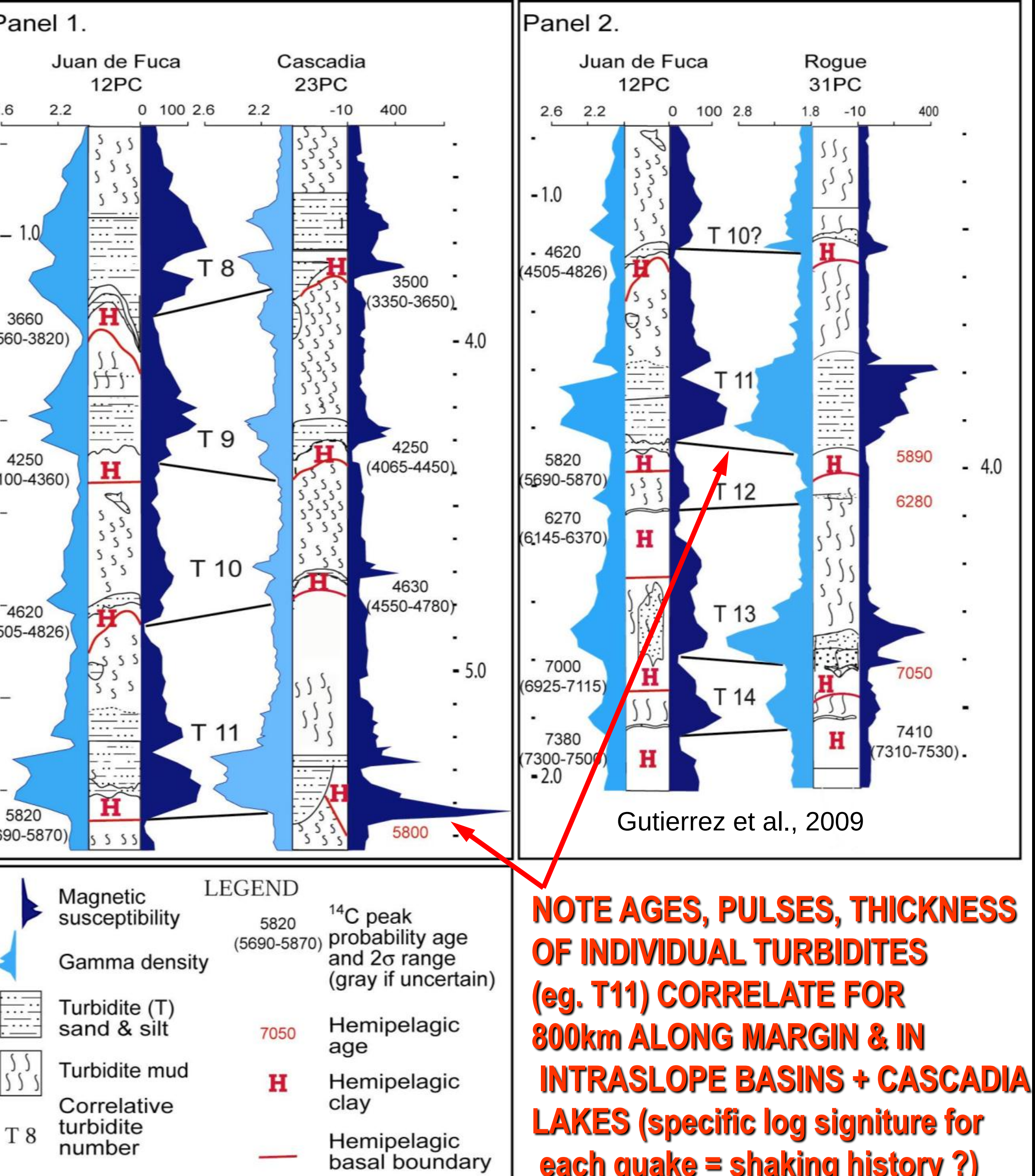
NOTE NO MTD´S OR TSUNAMITES IN THIS OR 100s OF CASCADIA CORES

NOTE DOMINANTLY MULTIPULSED TURBIDITES

T13 1st MAZAMA TURBIDITE MARKER BED FOR CORRELATION



Gutierrez et al., 2009



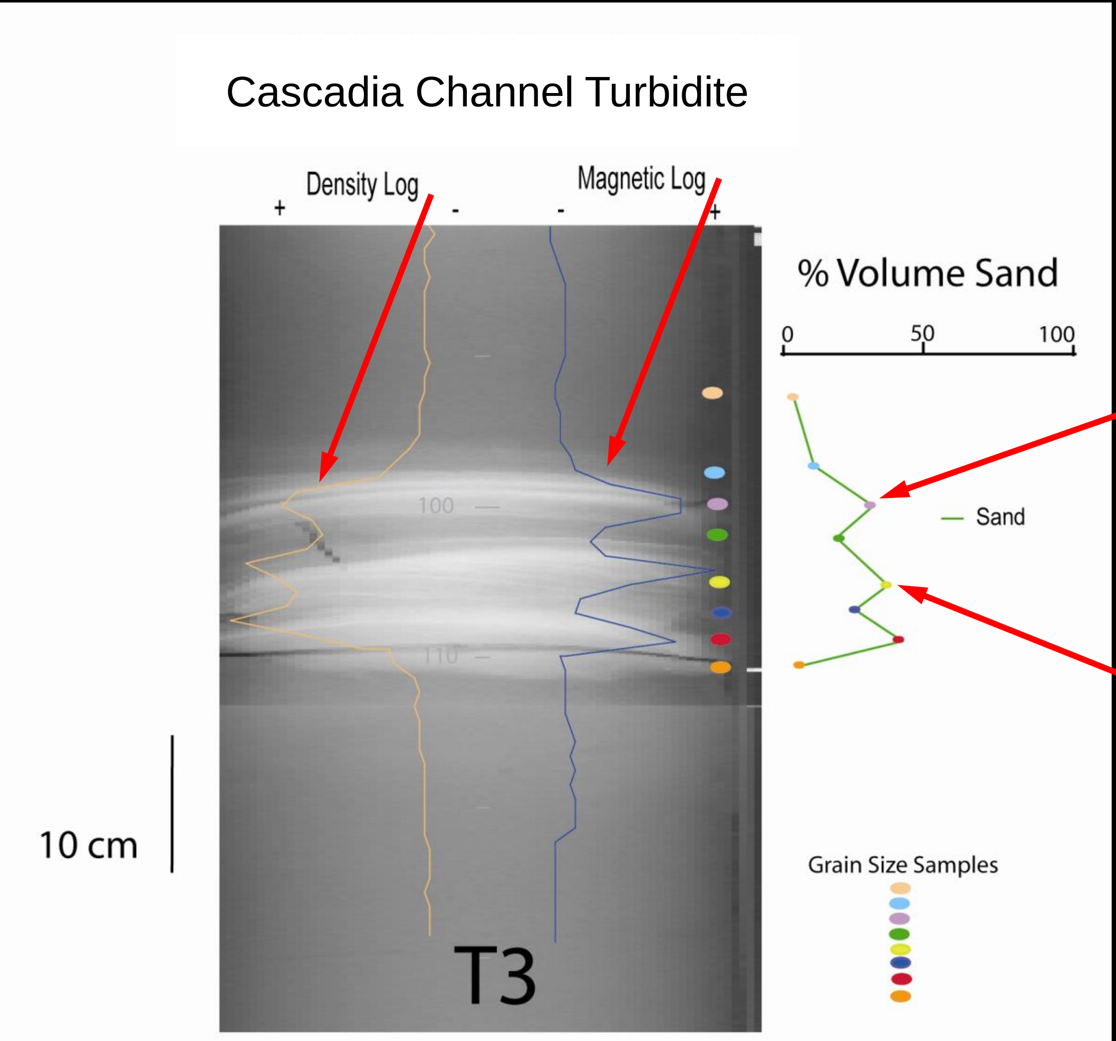
CORRELATION OF CASCADIA BASIN MULTI-PULSED TURBIDITES

BASED ON:

- POST- MAZAMA
  T 1-13 TURBIDITE #
- C14 AGES
- PHYSICAL PROPERTIES

(DENSITY AND
MAGNETIC SUSCEPTIBILITY
PEAK # AND THICKNESS OF EACH
CORRELATIVE T 1-13 TURBIDITE)

GRAIN SIZE VERIFIES PHYSICAL PROPERTIES LOGS (DENSITY & MAGNETIC) AS PROXIES FOR MULTIPLE TEXTURAL PULSES OF INDIVIDUAL CASCADIA SEISMO-TURBIDITES



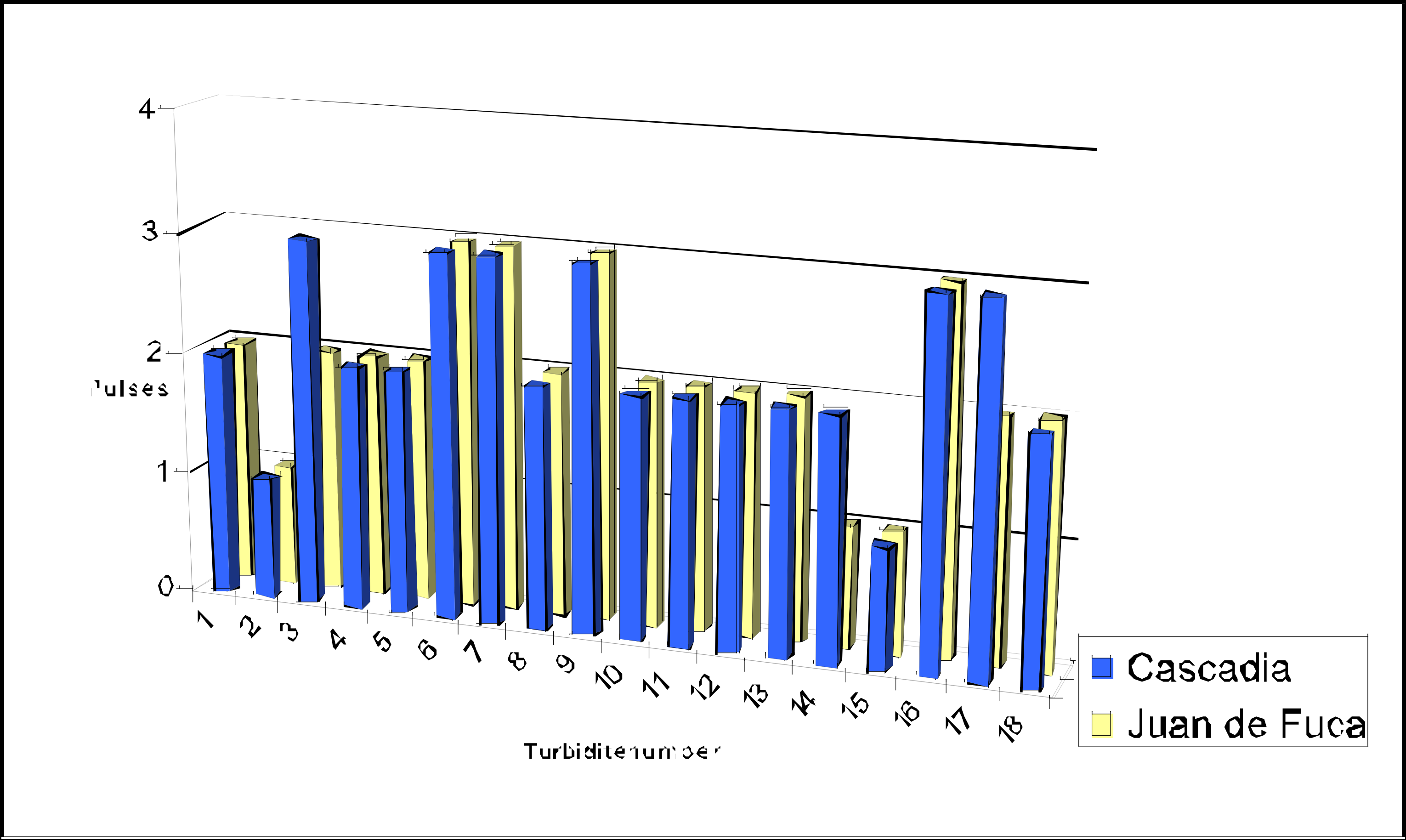
X-RAY RADIOGRAPH OF CORE

3 GRAIN SIZE PULSES IN AN INDIVIDUAL TURBIDITE

T3 PULSES GRADE UPWARD, BUT OTHER TURBIDITES SHOW REVERSE GRADING OF PULSES

GUTIERREZ ET AL., 2013

DOMINANT MULTI-PULSED TURBIDITES IN JUAN DE FUCA TRIBUTARY CHANNEL & CASCADIA CHANNEL BELOW CONFLUENCE



Gutierrez Pastor et al., 2013

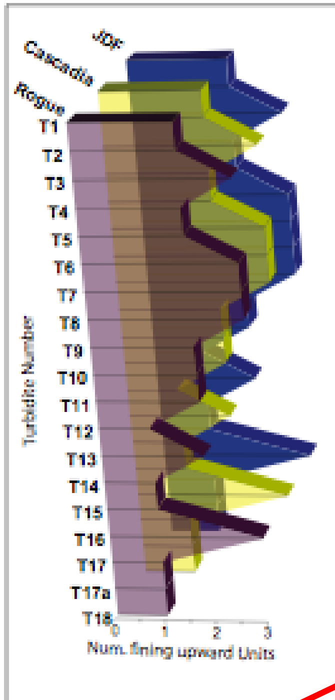
- PROXIMAL TRIBUTARY AND DISTAL PULSES BELOW CONFLUENCES = SAME IN CASCADIA BASIN
- ~ 10 % UNI-PULSED AND ~ 90 % MULTI-PULSED TURBIDITES IN CASCADIA BASIN
- INDICATES THAT ~ *Mw* 9 EARTHQUAKE SHAKING IS MAIN CAUSE OF PULSES IN CASCADIA BASIN

HIGH CORRELATION OF TURBIDITE PULSES & THICKNESS

A

Number of fining upward units

#	JDF	Cascadia	Rogue
T1	2	2	2
T2	2	2	2
T3	3	3	3
T4	2	2	2
T5	2	2	2
T6	3	3	3
T7	3	3	3
T8	3	3	3
T9	3	2	2
T10	2	2	2
T11	2	2	2
T12	1	1	1
T13	2	2	2
T14	1	1	1
T15	1	1	1
T16	3	3	3
T17	1	1	1
T17a	1	1	1
T18	1	1	1

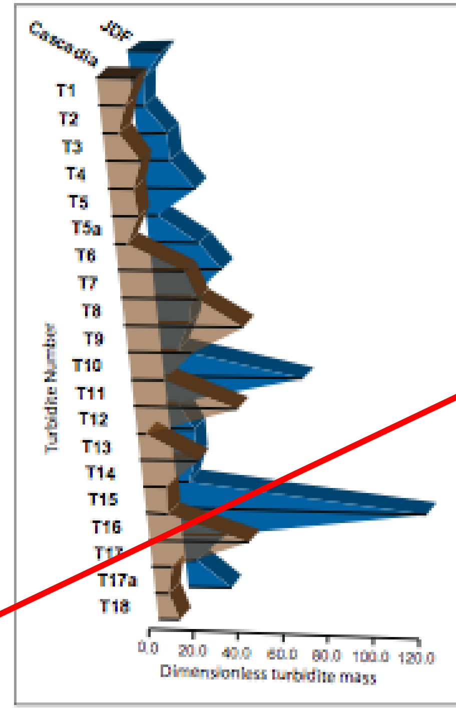


Pearson correlation matrix.:
fining upward units per event

	JDF	Cascadia	Rogue
JDF	1		
Cascadia	0.96	1	
Rogue	0.96	1	1

Goldfinger et al., 2011

B

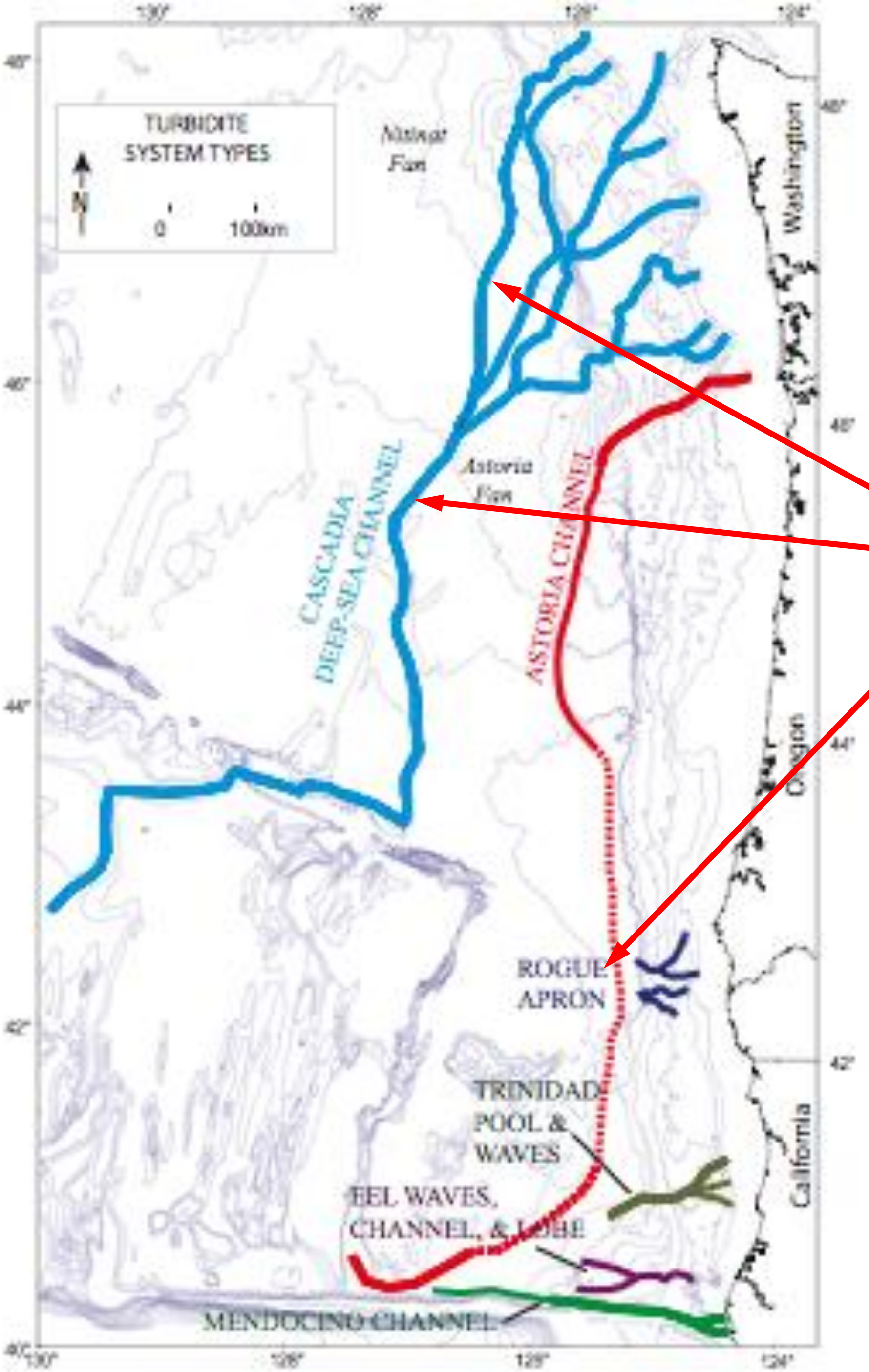


	12PC mass	23PC mass
12PC mass	1	
23PC mass	0.658306	1
avg. mass	0.913635	0.883491

Goldfinger et al., 2012

SHOWS CORRELATIVE TURBIDITES HAVE:

- SAME PULSE TYPE IN 3 DIFFERENT CHANNELS FOR 800 km
- SAME THICKNESS
- BOTH INDICATE THAT ~ Mw 9 EARTHQUAKE SHAKING IS MAIN CAUSE OF PULSES IN CASCADIA BASIN



CAUSE OF DOMINANT MULTI-PULSED TURBIDITES FROM ~*Mw* 9 EARTHQUAKES IN THE UNCONFINED CASCADIA BASIN MARGIN

UNIQUE SEISMIC SIGNATURE
OF EACH ~ *Mw* 9 EARTHQUAKE
~ 1,000 km RUPTURE PATTERN
CHARACTERIZE MULTI-PULSED
CORRELATIVE TURBIDITES
ABOVE & BELOW
CHANNEL CONFLUENCES
IN VARIOUS TURBIDITE SYSTEMS
CASCADIA INTRASLOPE BASINS & LAKES

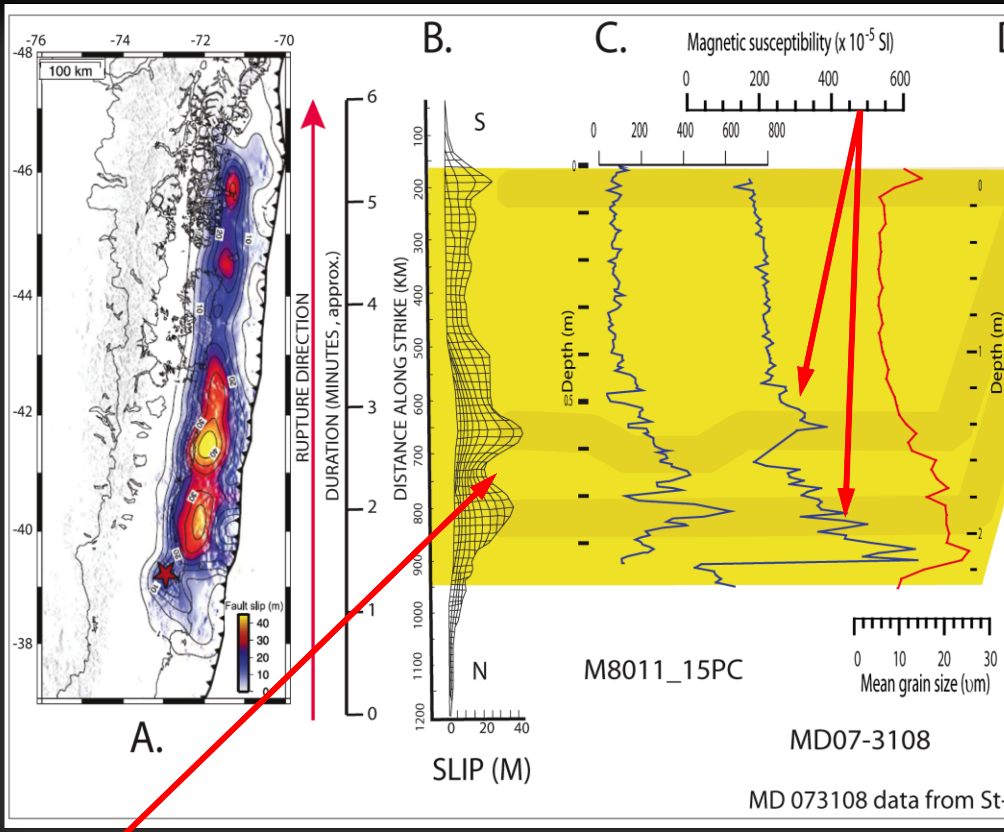
(shown in previous slide
by correlation of individual turbidite
physical properties & thickness)

Nelson et al., 2012

CHILE, 1960 *Mw* 9.5 STRONGEST HISTORIC EARTHQUAKE

Multipulsed ~ *Mw* 9 seismo-turbidites like Cascadia that correlate with historic seismograph slip pulses are found in other subduction zone localities, like Chile, Sumatra, Kurile & Japan,

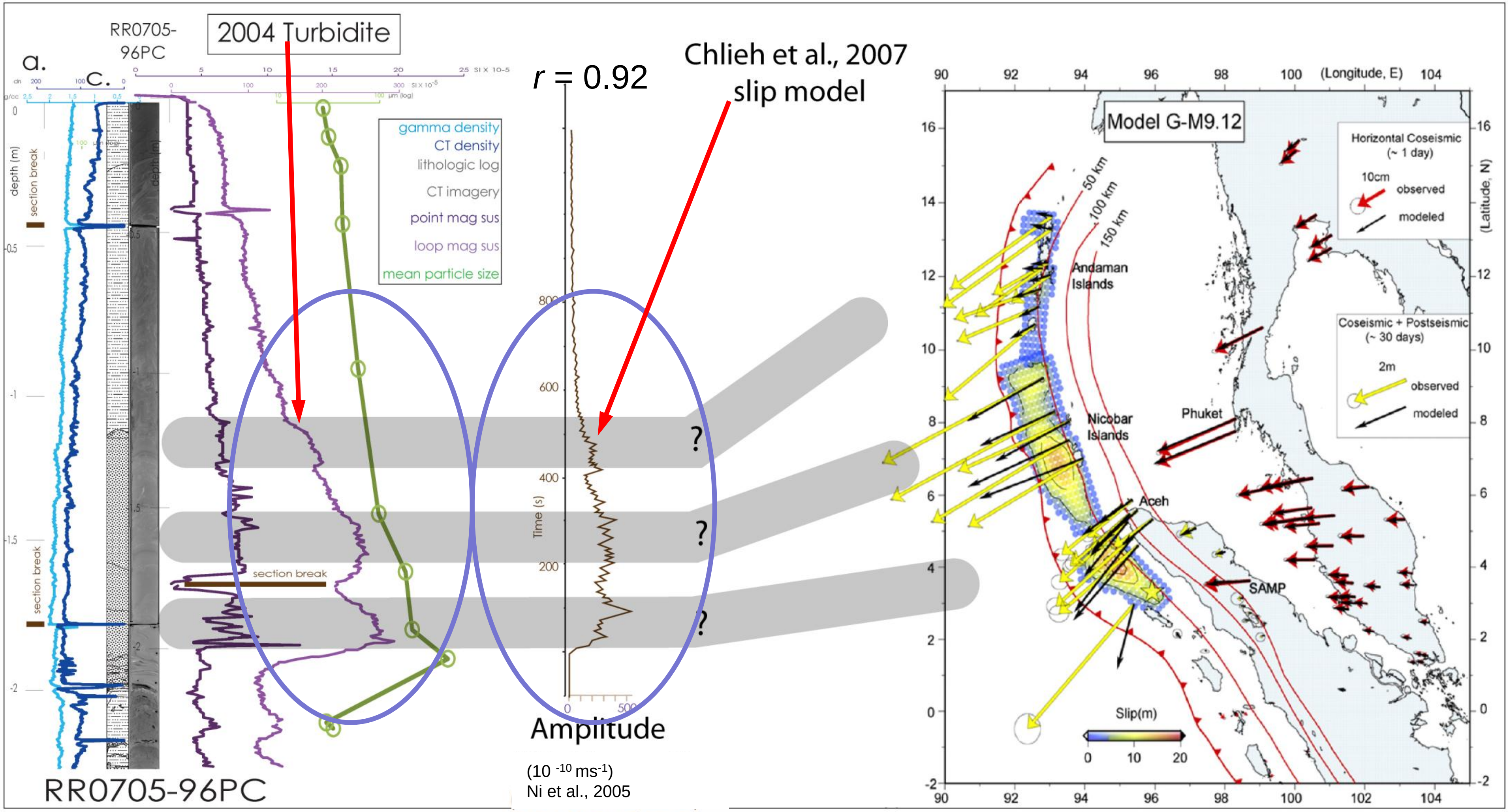
St Onge et al., 2012 ; Patton et al., 2013; Noda et al., 2008; Goldfinger and Ikehara, 2012



NOTE B SHOWS 2 SLIP PULSES FROM EARTHQUAKE RUPTURE

The 1960 Chile turbidite appears in numerous cores in the trench and in fjords as a two pulse sandy event at the seafloor -note C arrows to 2 sand pulses Pb210 and Cs 137 confirm the ~1960 age (St Onge et al., 2012).

SUMATRA 2004 *Mw* 9.1 EARTHQUAKE WITH 3 SLIP RUPTURES DEPOSITED TURBIDITES WITH 3 COARSE-GRAINED PULSES



Goldfinger et al., 2012; Patton et al., 2013

“Surging flows are likely to contain corresponding repetitions of grading and structure divisions”

Lowe, 1982

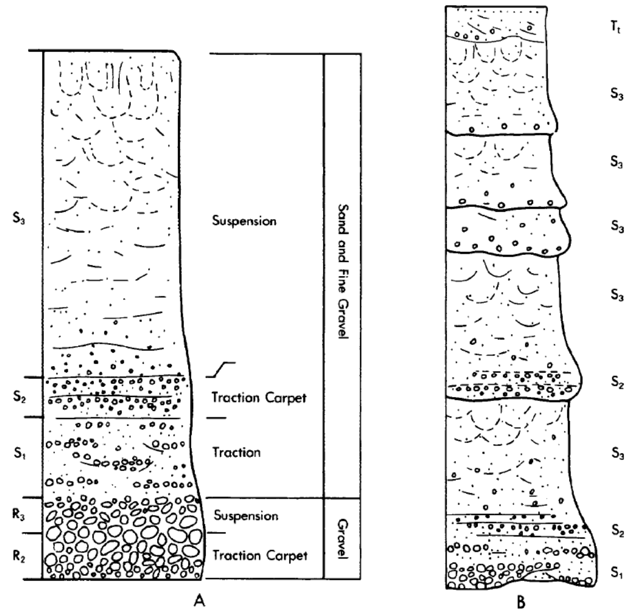
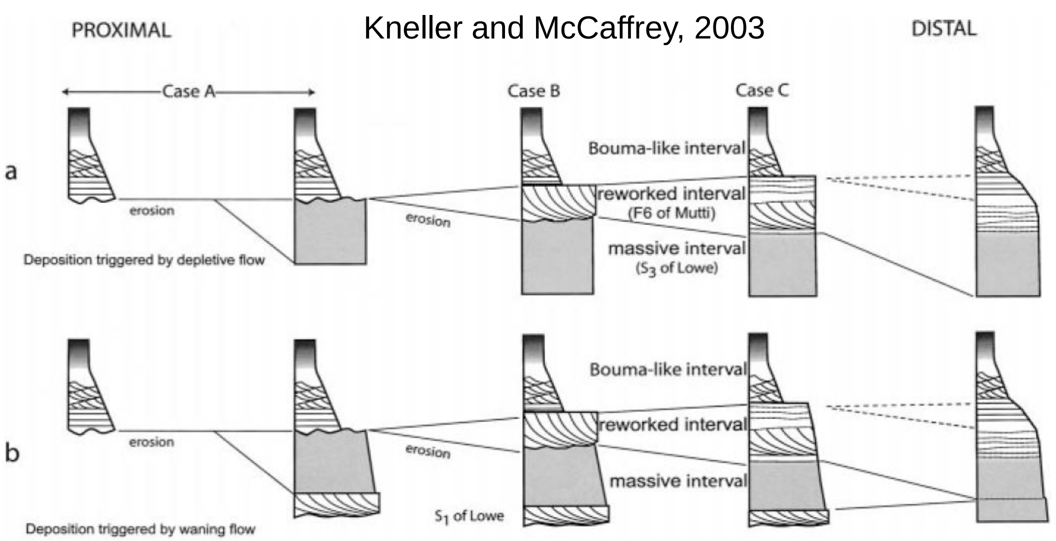


FIG. 11.—A) Ideal sequence of divisions deposited by a single high-density turbidity current declining through discrete gravelly and sandy sedimentation waves. Because of downslope separation of gravel and sand depositional stages, complete high-density sedimentation units such as this are rarely formed. B) Complex sedimentation unit deposited by surging sandy high-density turbidity current.

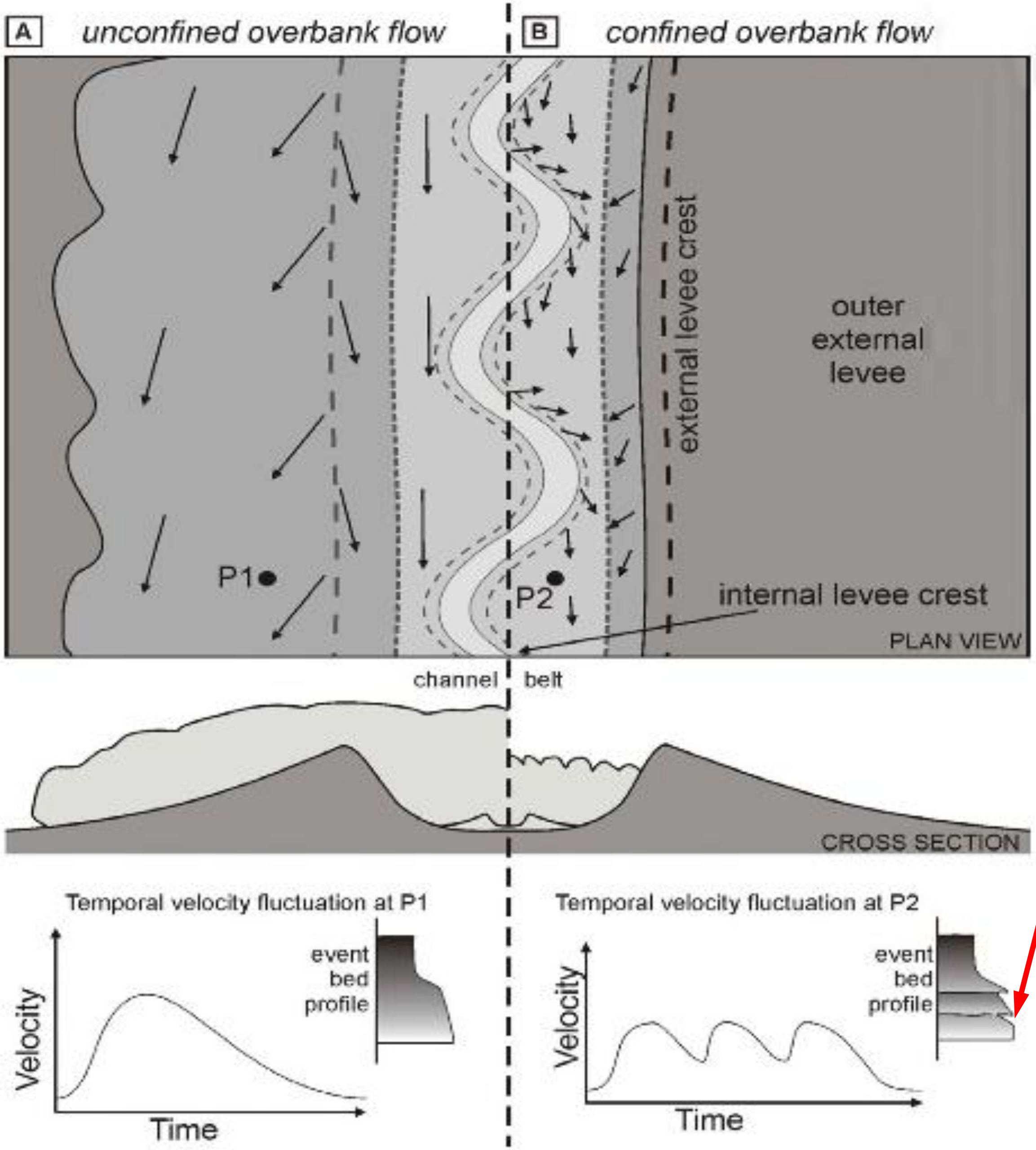
PREVIOUS STUDIES OBSERVED AND PREDICTED COMPLEX PATTERNS THAT ARE FOUND IN MULTI- PULSED SEISMO- TURBIDITES

LOGICAL THAT ~ *Mw* 9 EARTHQUAKE RUPTURE SLIP PATTERN CAN CAUSE TURBIDITY CURRENT SURGING FLOWS THAT DEPOSIT INDIVIDUAL MULTI-PULSED SEISMO-TURBIDITES (e.g. Sumatra 2004 earthquake had energy to cause earth to wobble on its axis)



COMPLEX HYPOTHETICAL DEPOSITS FROM UNSTEADY FLOW

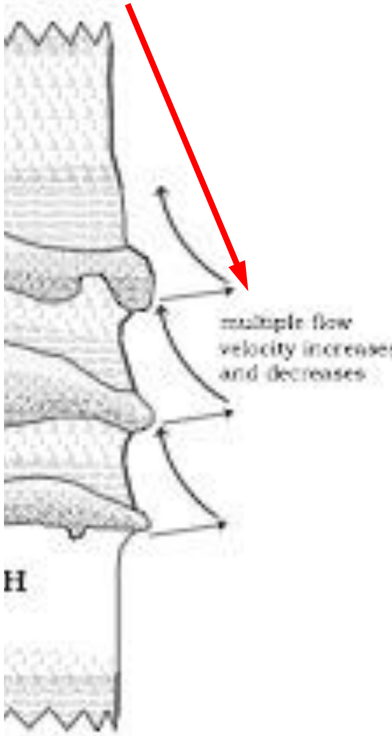
MULTI-PULSED TURBIDITES IN INTRACHANNEL LEVEES & FLOOD HYPERPICNITES



LEVEE MODELS (Kane & Hodgson, 2011)

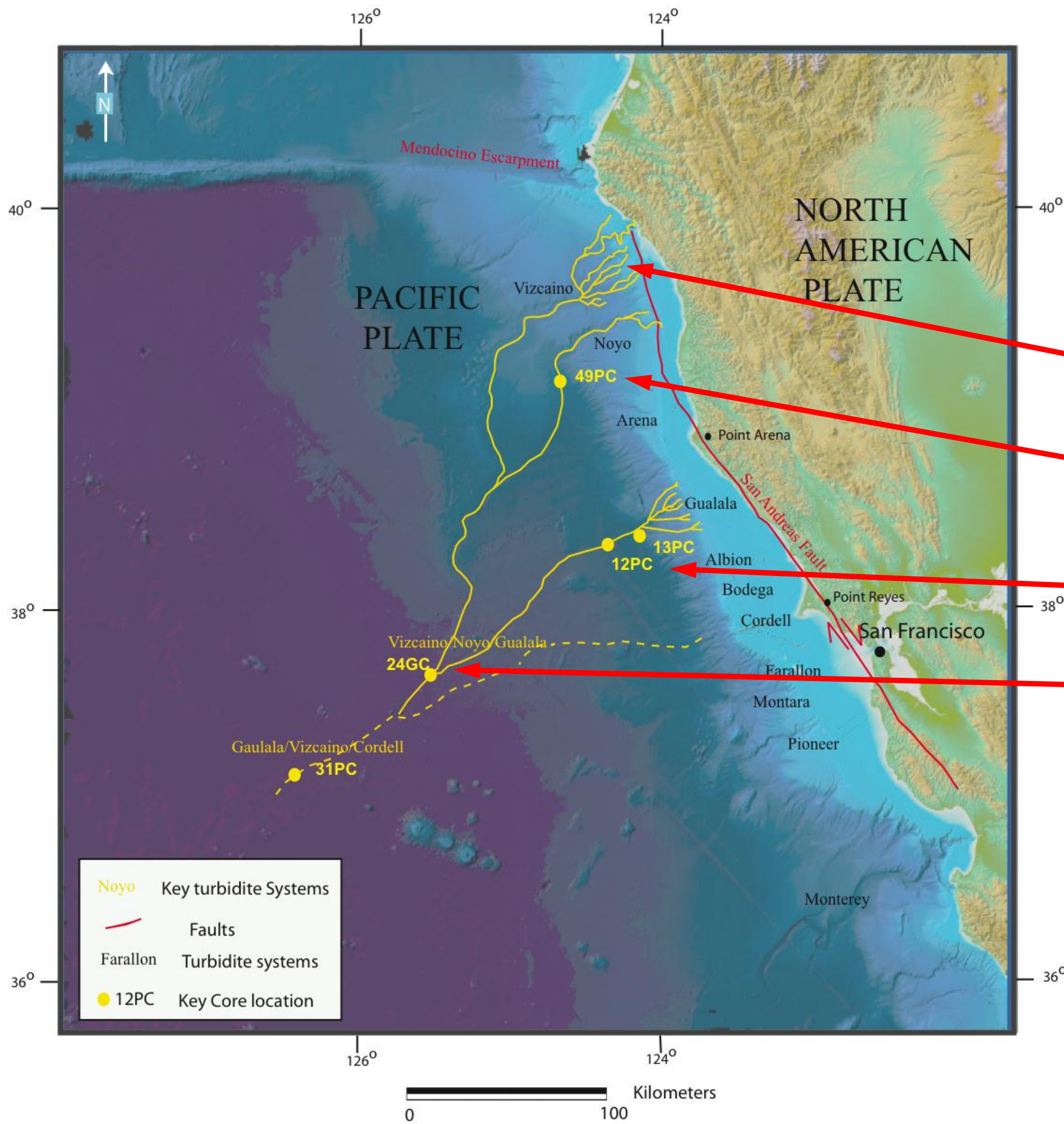
NOTE MULTI-PULSED SEISMO-TURBIDITES ARE NOT UNIQUE !

MULTI-PULSED TURBIDITE



Mulder et al., 2003

Figure. 2



Gutierrez Pastor et al., 2013

LOCATION OF CALIFORNIA SAN ANDREAS MARGIN CORES IN UNCONFINED BASIN

VISCAINO

NOYO (next slide)

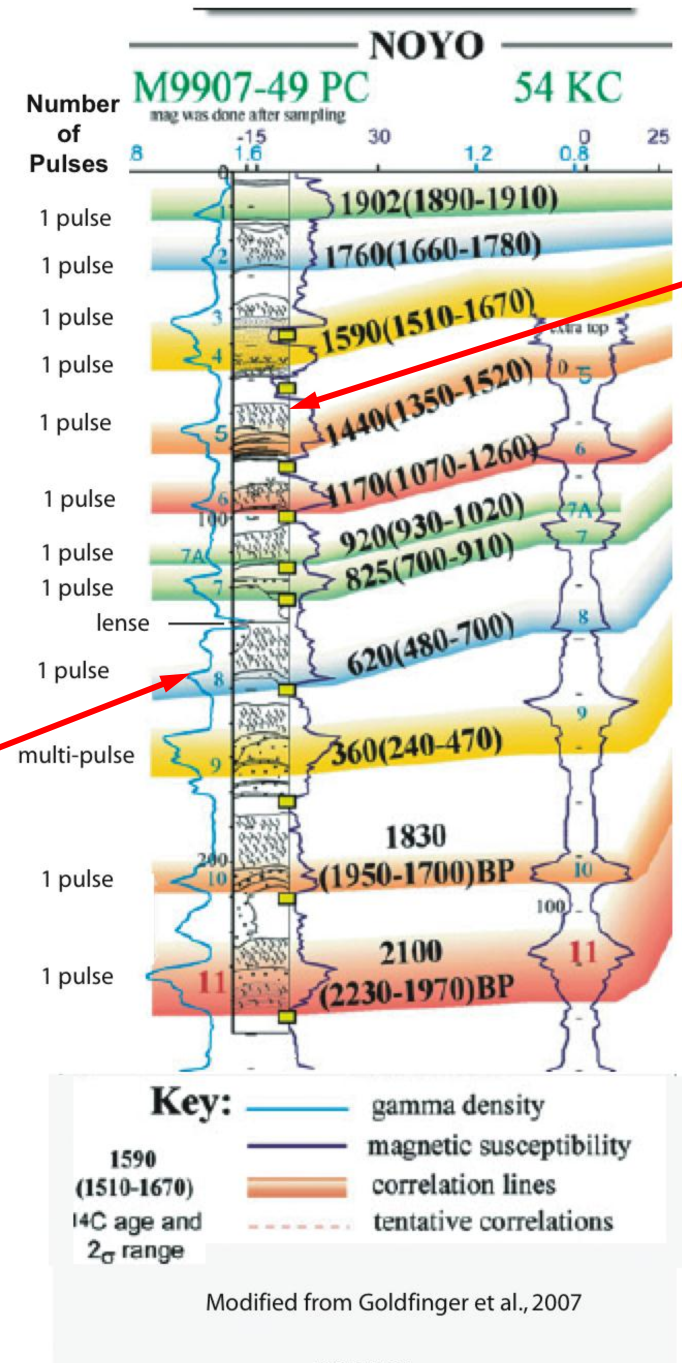
GUALALA

CONFLUENCE
WITH 24GC CORE

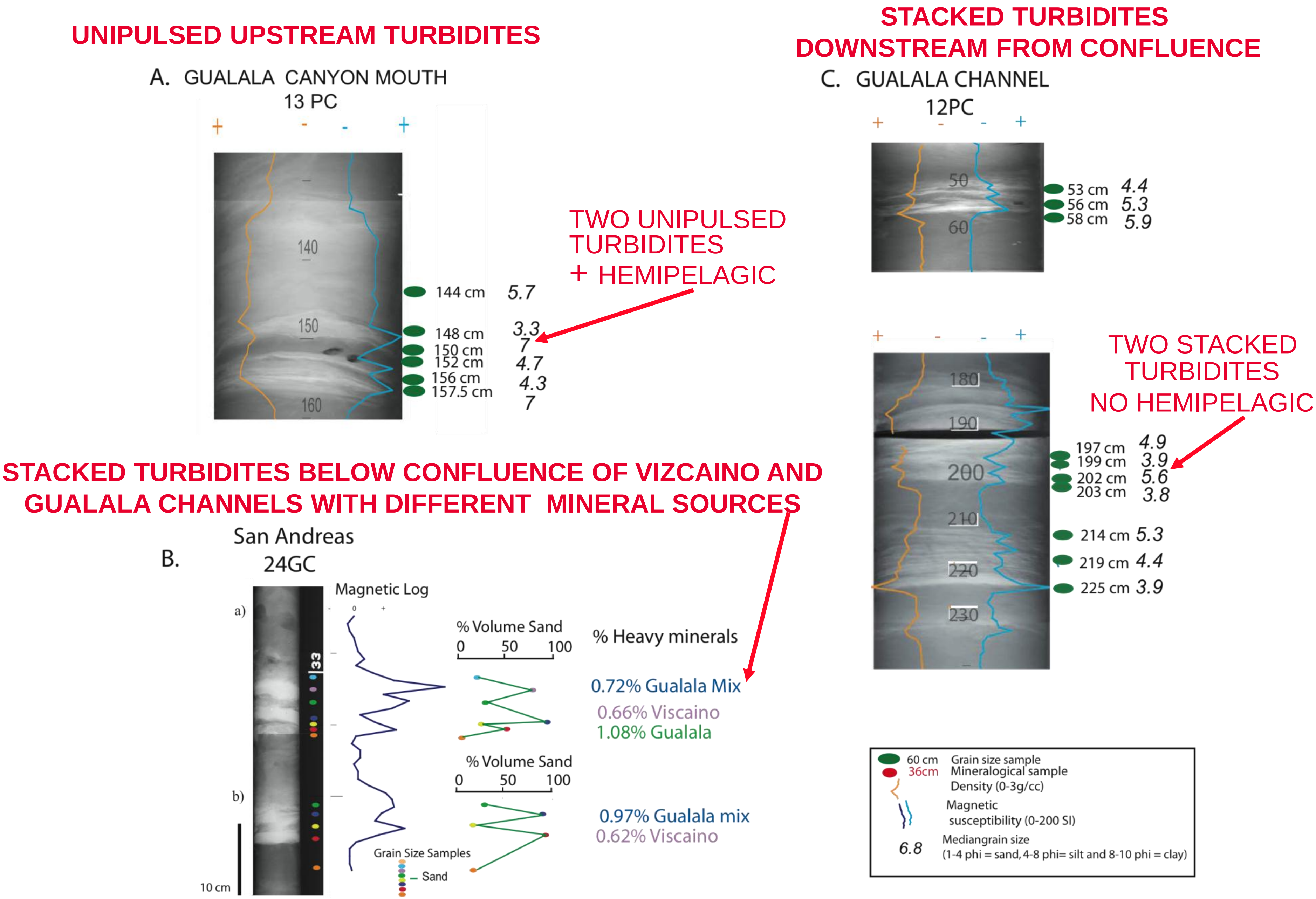
EXAMPLE OF STACKED SEISMO-TURBIDITES FROM ~ *Mw* 8 EARTHQUAKES WITH 300 km RUPTURE

DOMINANCE OF UPSTREAM UNIPULSED TURBIDITES IN NOYO 49PC CORE

10 OF 11 turbidites
(~ 90 %) are uni-pulsed
(classic fining
up turbidites) in contrast to
multi-pulsed turbidites of
upstream Cascadia
channels



NOTE ONLY TURBIDITES & NO MTD LAYERS OR TSUNAMITES IN ANY SAN ANDREAS CORES



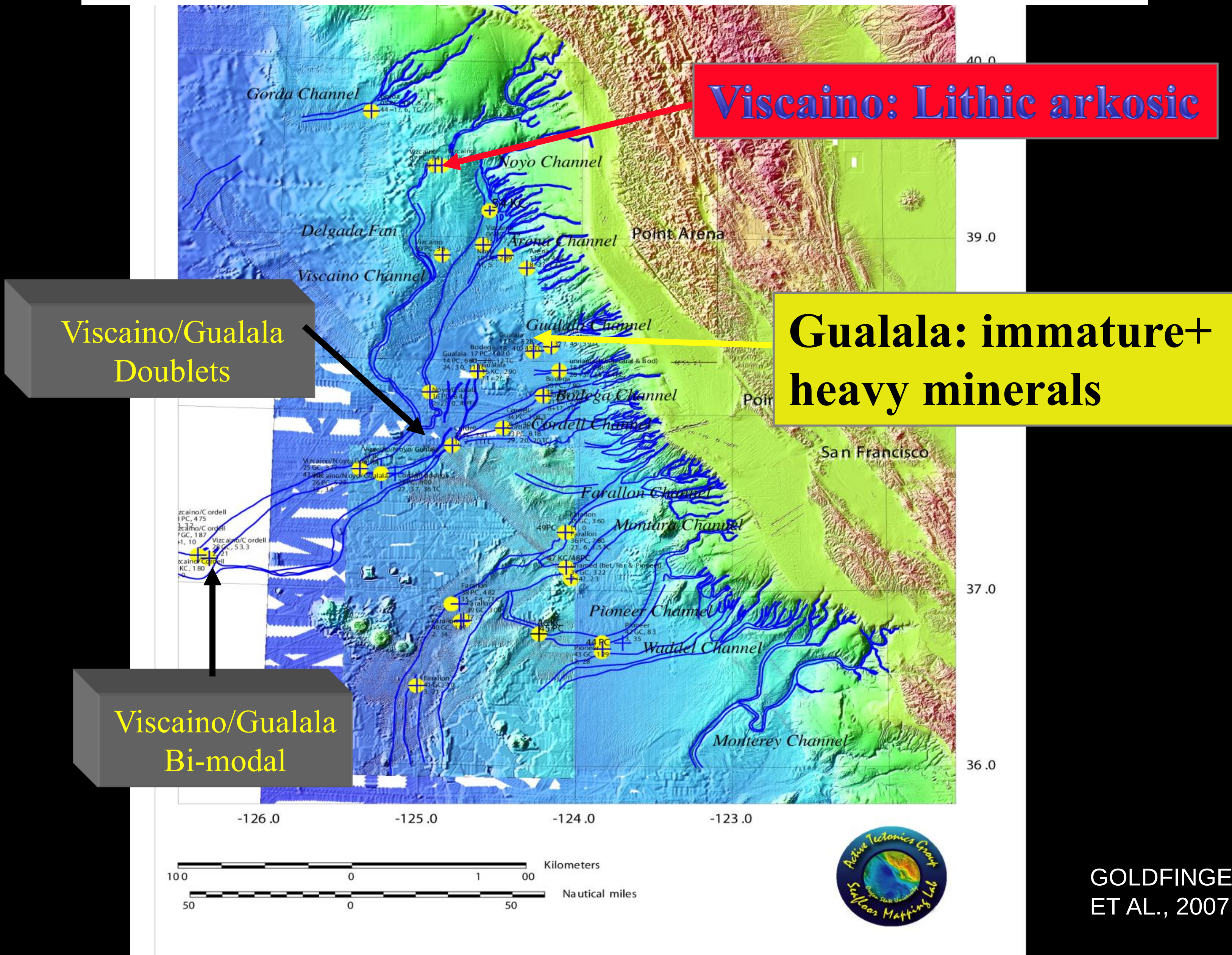
Gutierrez Pastor et al., 2013

Nelson et al., 2012

~ *Mw* 8 EARTHQUAKES OF SAN ANDREAS MARGIN RESULT IN UPSTREAM UNIPULSED & DOWNSTREAM STACKED SEISMO-TURBIDITES BELOW TRIBUTARY CONFLUENCES

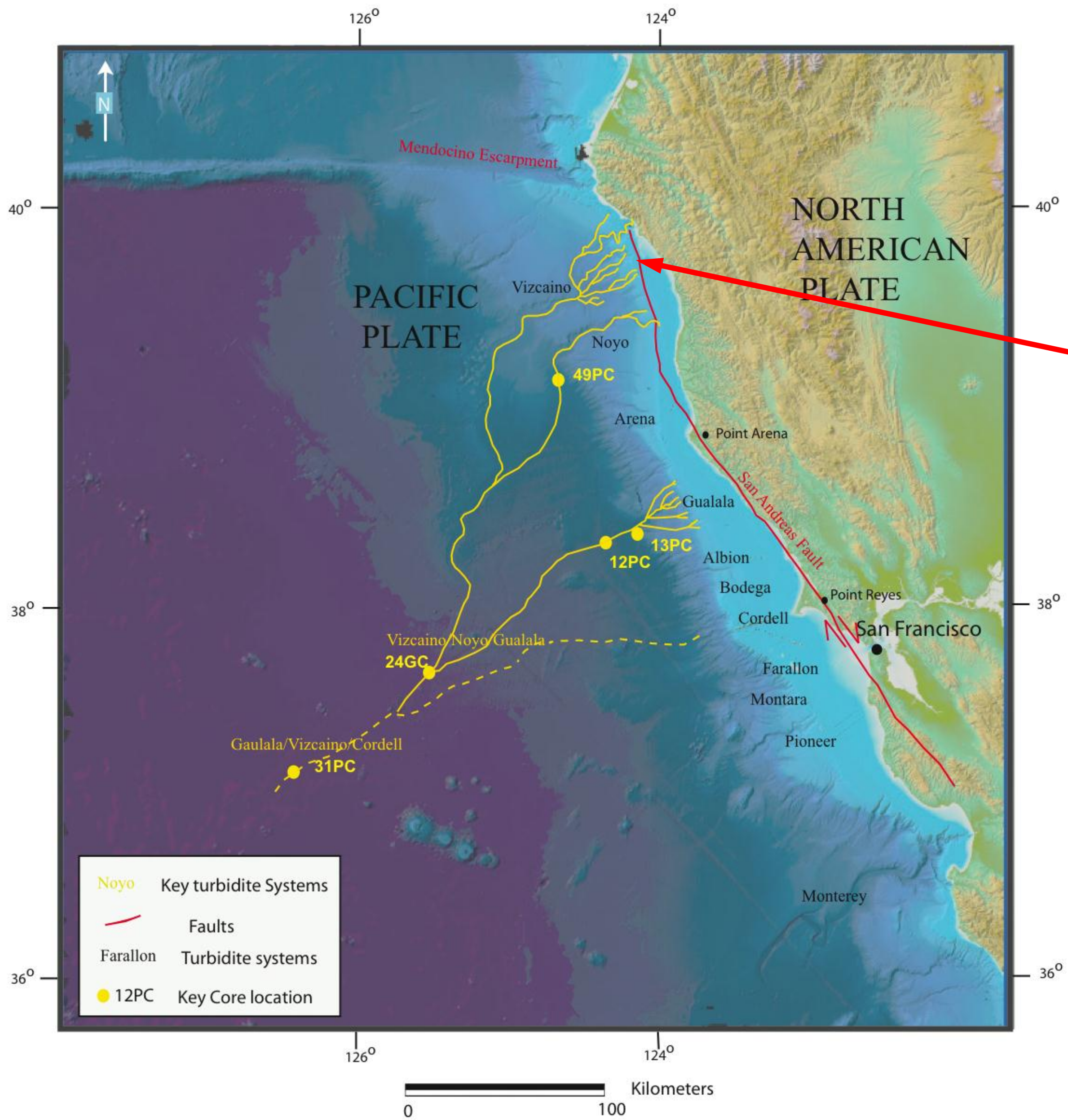
- UPSTREAM UNIPULSED TURBIDITES (classic fining up turbidites) CHARACTERIZE THE SAN ANDREAS MARGIN COMPARED TO UPSTREAM MULTI-PULSED TURBIDITES THAT CHARACTERIZE CASCADIA MARGIN & RESULT FROM STRONGER SHAKING OF ~ *Mw* 9 EARTHQUAKES (see slides 7, 8,10 and 11)
- NOTE THAT BOTH UPSTREAM SINGLE NOYO CANYON/CHANNEL (core 49PC) & GUALALA SINGLE CANYON (core 13 PC) MAINLY CONTAIN UNIPULSED TURBIDITES (see slides 18 and 19)
- DOWNSTREAM FROM MULTIPLE GUALALA TRIBUTARY CANYON (core 12 PC) AND NOYO/VISCANO/GUALALA CHANNEL CONFLUENCES (core 24 BC) STACKED TURBIDITES ARE CHARACTERISTIC (see slide 19)
- STACKED TURBIDITES FROM A SINGLE EARTHQUAKE EVENT RESULT FROM MULTIPLE TURBIDITY CURRENTS THAT ARE SYNCHRONOUSLY TRIGGERED IN NUMEROUS TRIBUTARY CANYONS AND THEN DEPOSIT RAPIDLY ONE ON TOP OF ANOTHER BECAUSE OF VARYING TRAVEL DISTANCES & VELOCITIES
- SYNCHRONOUS TRIGGERING AND STACKING ARE PROVED BY THE DIFFERENT MINERALOGY OF EACH TURBIDITE UNIT OF THE STACK (see slides 19B and 23B)

BELOW TRIBUTARY CHANNEL CONFLUENCES STACKED TURBIDITE BEDS WITH DIFFERENT MINERAL CONTENT RESULT FROM SYNCHRONOUS EARTHQUAKE TRIGGERING IN PROXIMAL CHANNELS WITH DIFFERENT MINERAL SOURCES



GOLDFINGER ET AL., 2007

Figure. 2



Nelson et al., 2012; Gutierrez Pastor et al., 2013

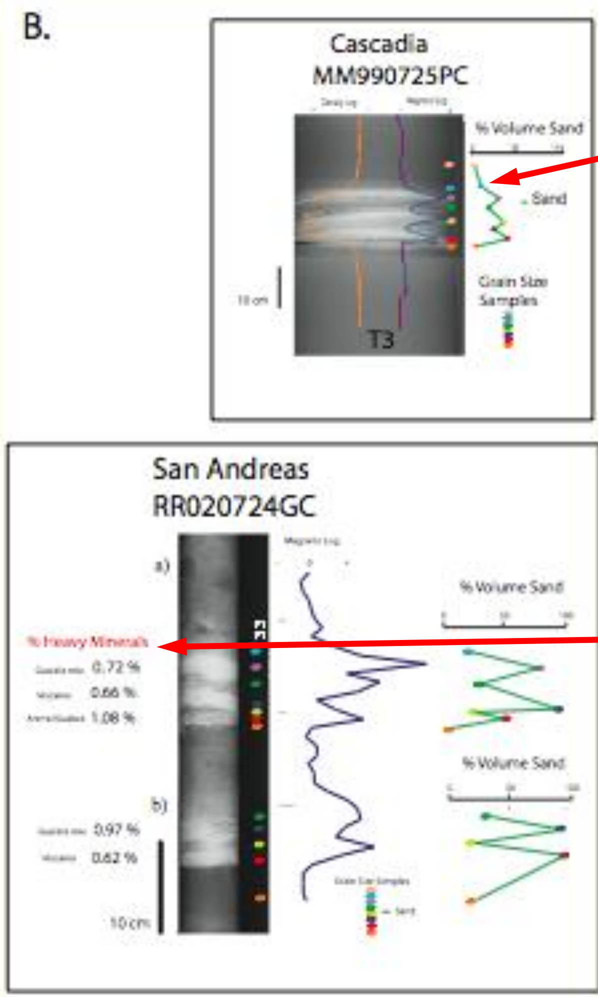
CAUSE OF DOMINANT STACKED TURBIDITES FROM WEAKER ~ *Mw* 8 EARTHQUAKES IN THE UNCONFINED SAN ANDREAS MARGIN

EARTHQUAKE WITH ~ 300 km RUPTURE TRIGGERS SYNCHRONOUS TURBIDITY CURRENTS WITH VARYING TRAVEL DISTANCE IN MULTIPLE TRIBUTARY CANYONS TO CAUSE STACKED TURBIDITES BELOW CONFLUENCES

(SHOWN BY MINERALOGY OF DIFFERENT CANYON SOURCES OR DIFFERENT PALEOCURRENT DIRECTIONS OF SEDIMENTARY STRUCTURES)

(Van Daele et al., in press)

COMPLEX MULTI-PULSED (CASCADIA) AND STACKED (SAN ANDREAS) SEISMO-TURBIDITES



X-RAY RADIOGRAPH OF CORES

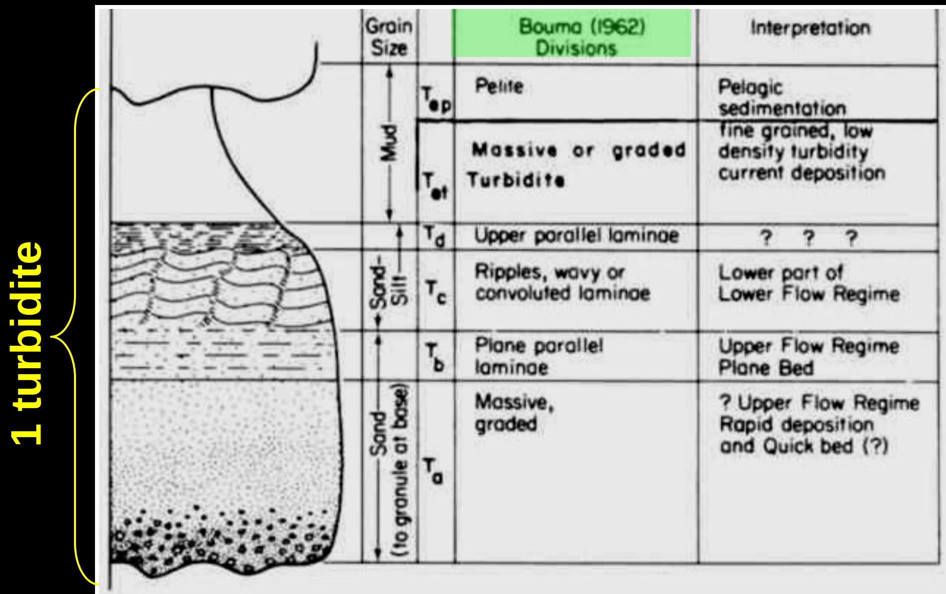
INDIVIDUAL MULTI-PULSED TURBIDITES ABOVE AND BELOW CONFLUENCES SHOWN BY RADIOGRAPHS, TEXTURE, DENSITY, AND MAGNETIC SUSCEPTIBILITY, TRIGGERED BY ~*Mw* 9 EARTHQUAKES

UNIPULSED ABOVE & STACKED TURBIDITES BELOW CHANNEL CONFLUENCES SHOWN BY MINERALS, RADIOGRAPHS, TEXTURE, DENSITY, AND MAGNETIC SUSCEPTIBILITY, TRIGGERED BY ~ *Mw* 8 EARTHQUAKES

GUTIERREZ ET AL., in review

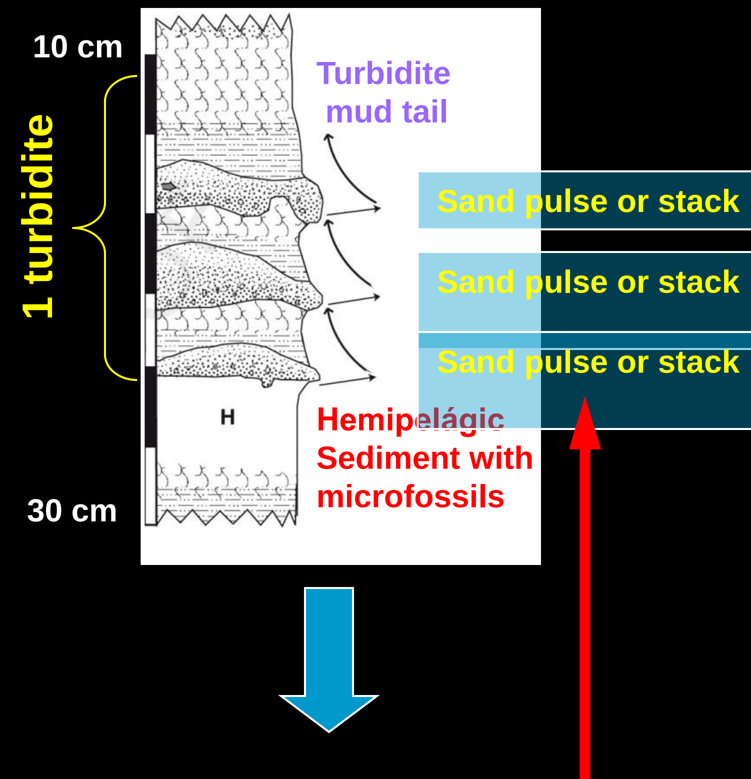
INDIVIDUAL TURBIDITE EVENT BEDS

CLASSIC TURBIDITE



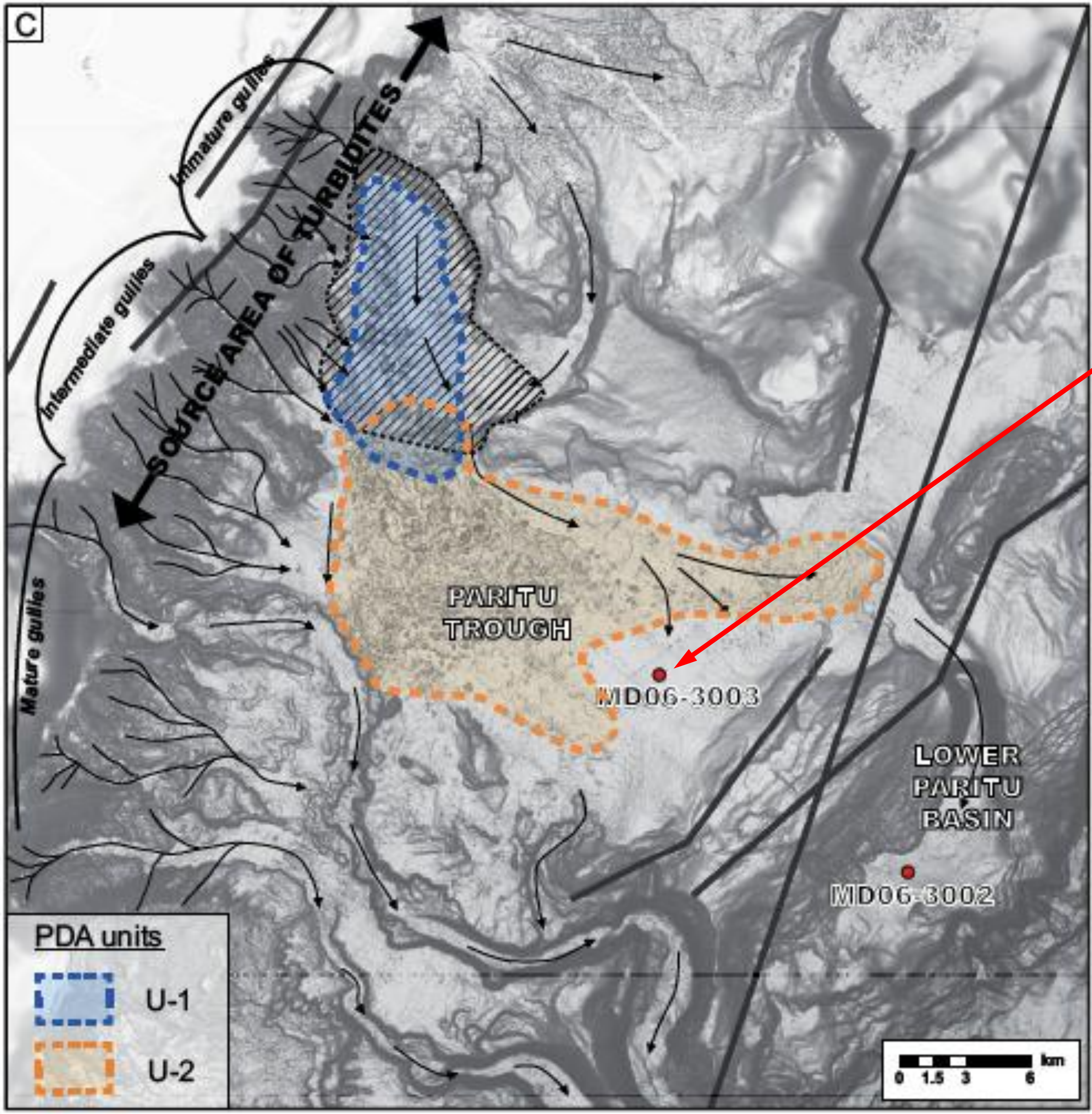
CONTINUOUS UPWARD GRADATION OF SAND TEXTURE & INTERNAL SEDIMENTARY STRUCTURES

PALEOSEISMIC TURBIDITE



MULTIPLE PULSES OR STACKS OF SAND TEXTURE & IRREGULAR GRADATION OF TEXTURE & SEDIMENTARY STRUCTURES + ALSO CREATES PSUDO-AMALGAMATION

Julia Gutiérrez Pastor, 2009



NEW ZEALAND MARGIN WITH 18 kyr of ~ *Mw* 8 EARTHQUAKES & STACKED TURBIDITES

NOTE:

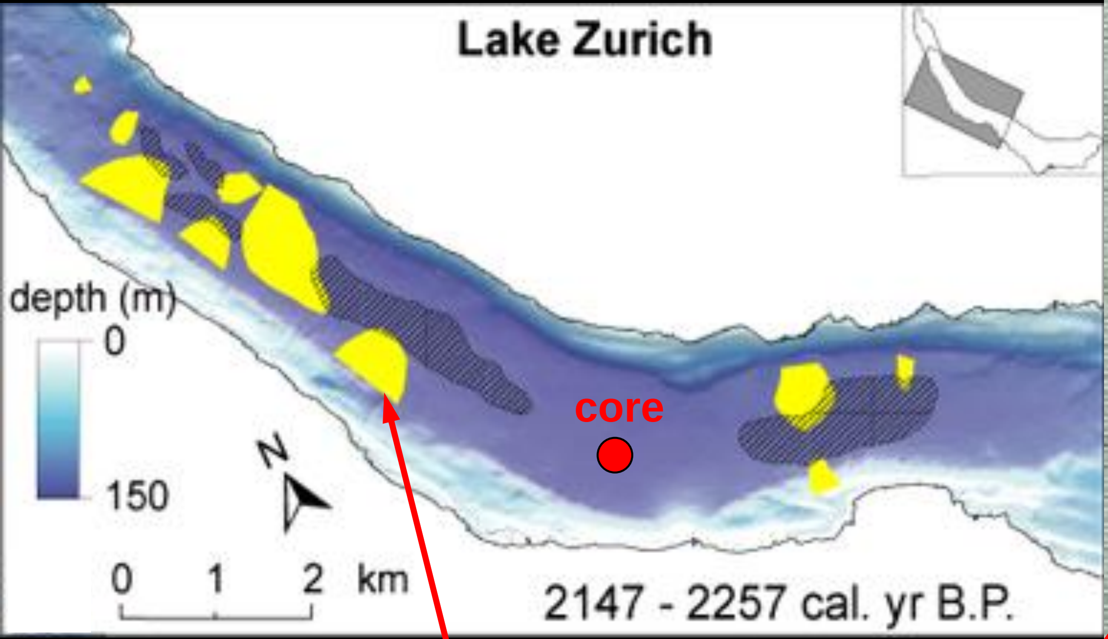
1. DOMINANCE OF SEISMO-TURBIDITES (75 OF 77 Holocene & Pleistocene sand beds with slope forams from earthquake failures)

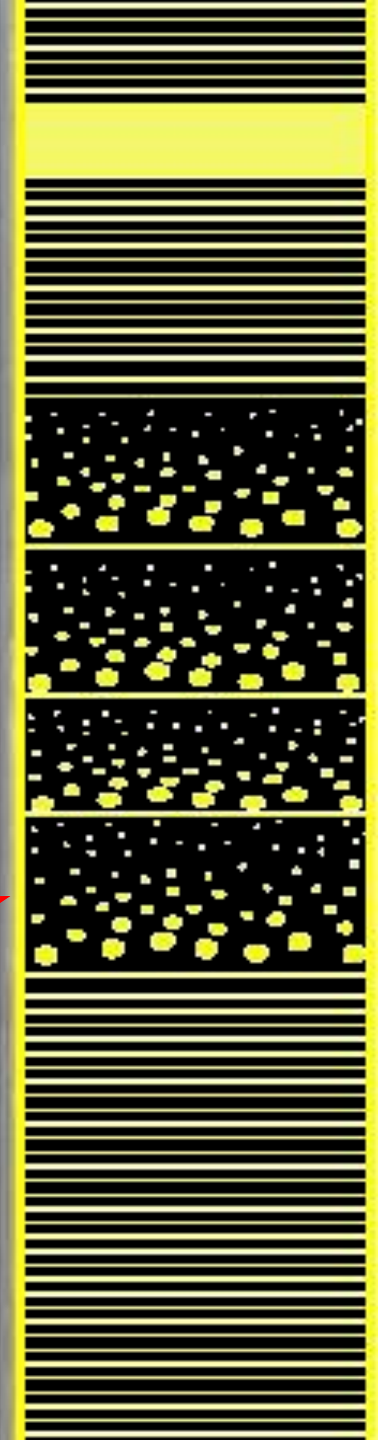
2. ONLY 2 HYPER-PYCNITES (with inshore & shelf forams

3. NO EVIDENT TSUNAMITES

Pouderoux et al., 2012

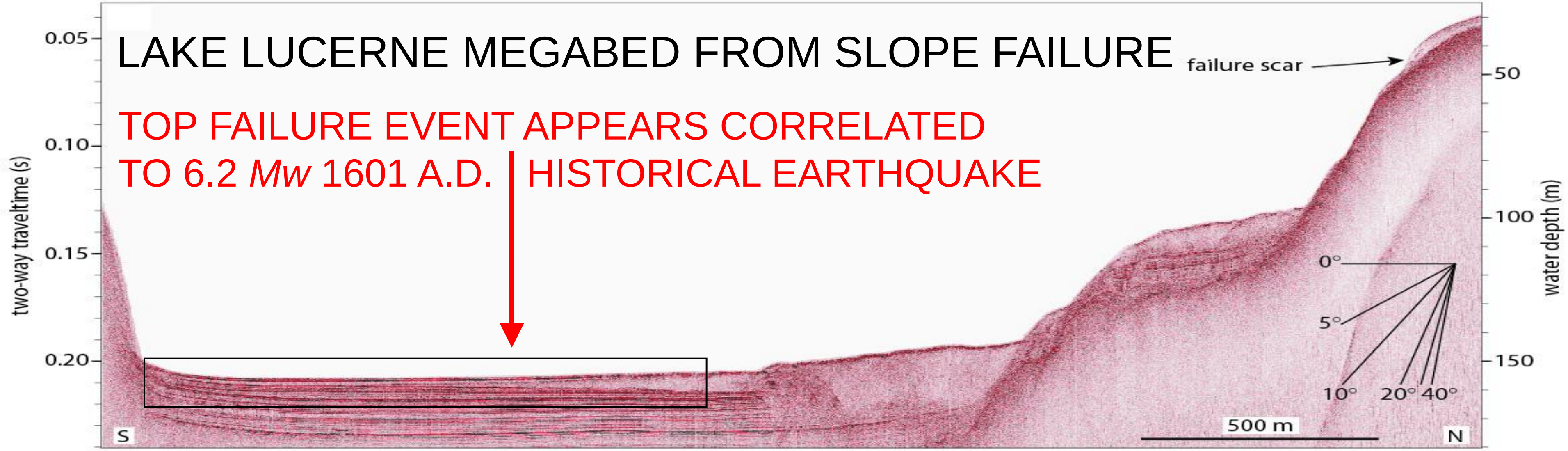
STACKED TURBIDITES IN CONFINED BASIN CENTER OF LAKE ZURICH RESULT FROM SYNCHRONOUS LANDSLIDES TRIGGERED BY AN EARTHQUAKE

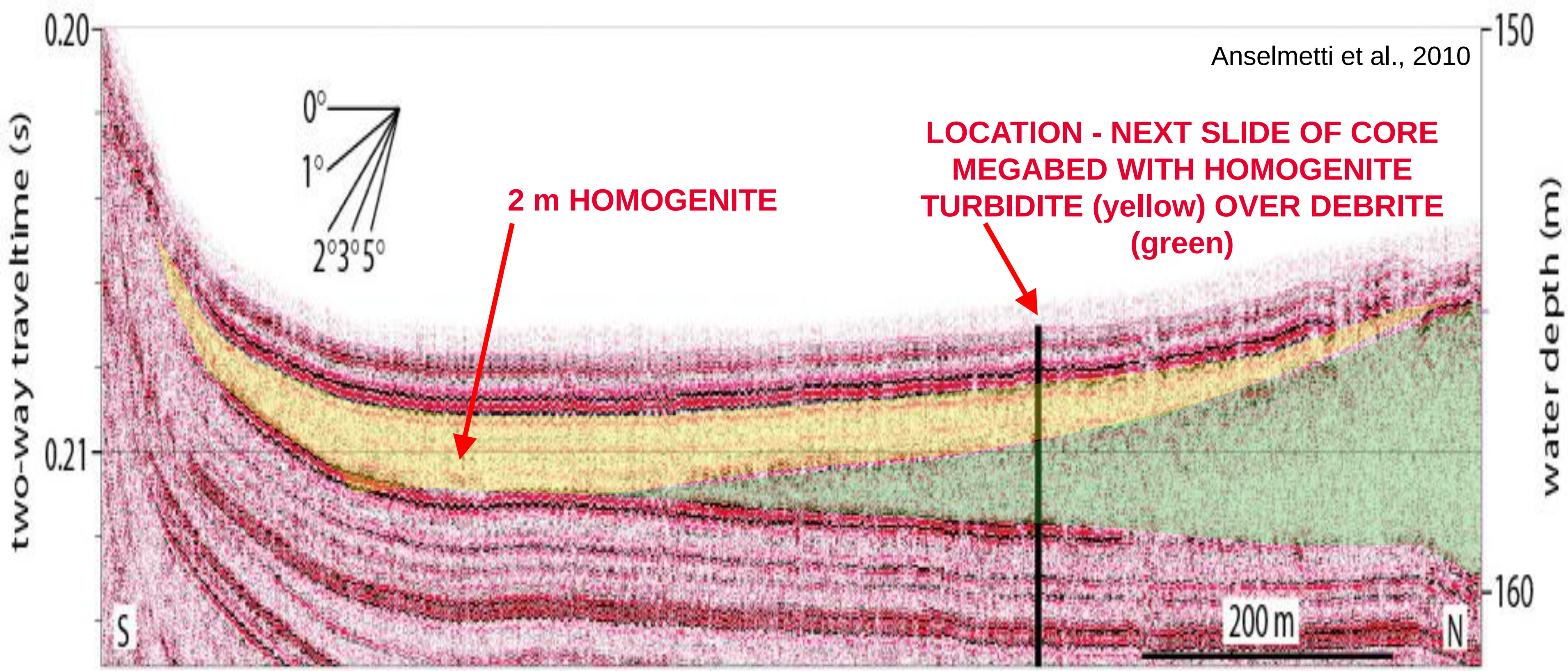




OTHER CONFINED BASINS WITH HISTORICAL STACKED TURBIDITES OFF ALGERIA, CHILE, HAITI, NEW ZEALAND, & JAPAN

STACKED TURBIDITES RESULT FROM VARIABLE ARRIVAL TIMES OF TURBIDITY CURRENTS ORIGINATING FROM COEVAL SLOPE FAILURES CAUSED BY ~ 2000 yr B.P. EARTHQUAKE





Anselmetti et al., 2010

BASE OF LUCERNE MUDDY HOMOGENITE MEGABED OVER DEBRITE

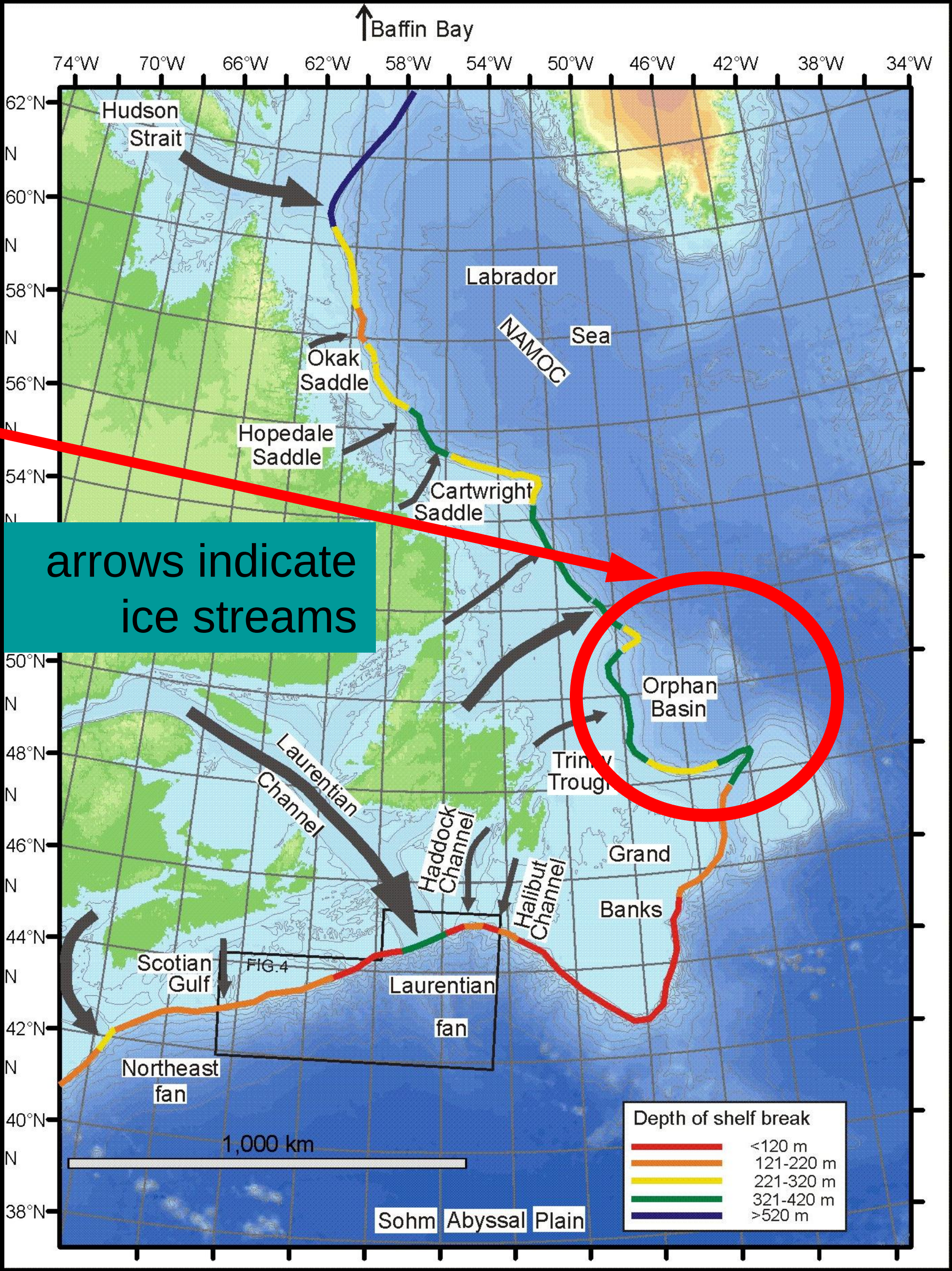
OTHER CONFINED BASINS WITH SIMILAR EARTHQUAKE TRIGGERED FAILURES FROM BASIN WALLS DEPOSIT MEGABEDS (turbidites over debrites) ON BASIN FLOORS (e.g. Marmara Sea, Chile lakes & fjords Labrador Sea – see next slide)

SEISMO-TURBIDITE SANDY MEGABEDS IN CONFINED BASIN

Orphan Basin
Newfoundland
NOTE: sand-rich glacial source

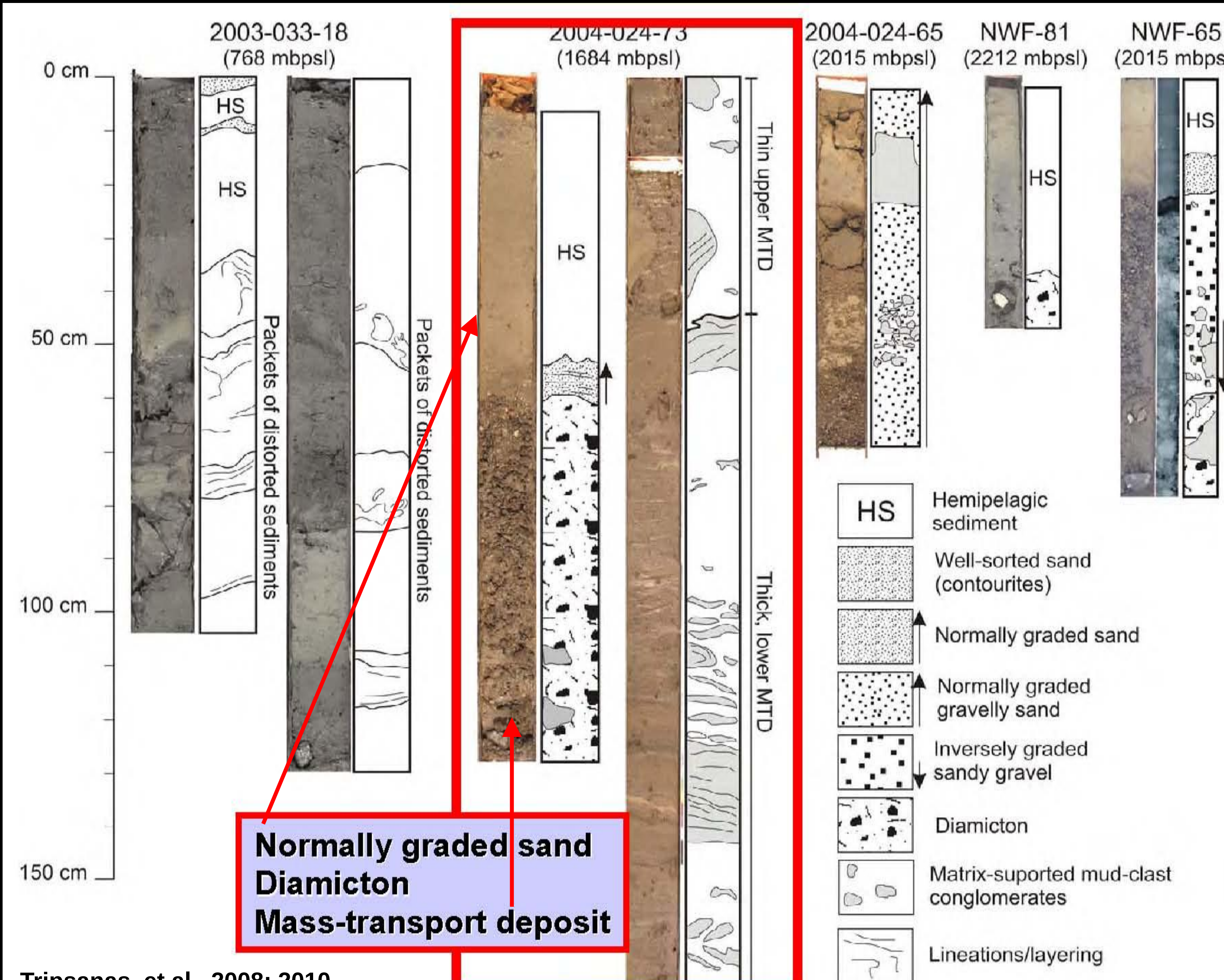
Canadian Passive Margin Earthquakes

- 1931 Baffin Bay *Mw* = 7.3
- 1929 Grand Banks *Mw* = 7.2
- 1809, 1836 felt on Labrador coast, epicenter unknown
- Evidence for earthquakes = synchronous MTDs in multiple canyons

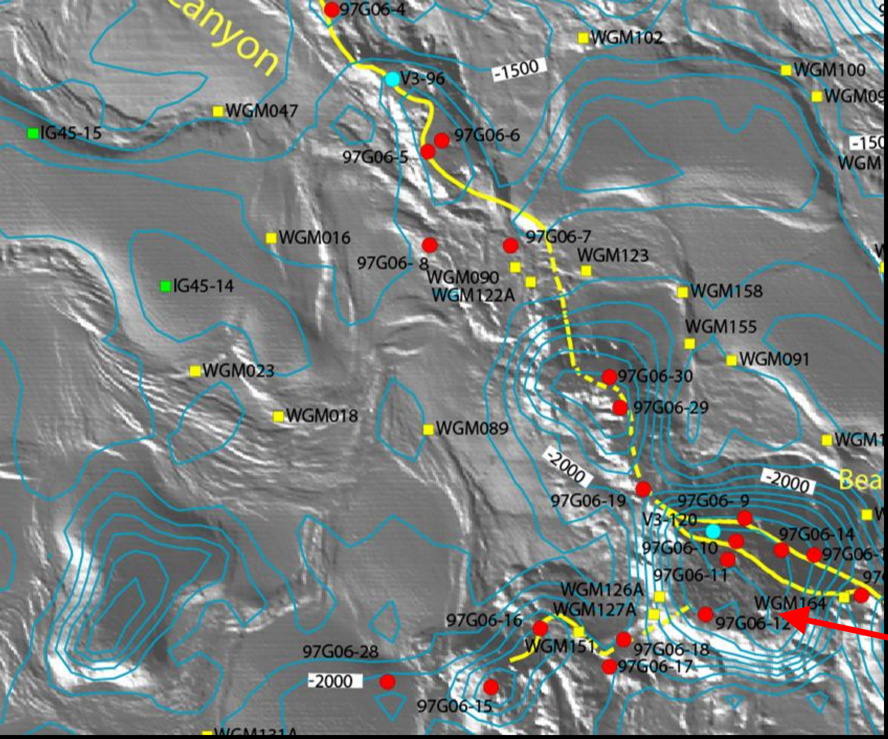


Tripsanas et al., 2008; 2010

CANADIAN SANDY TURBIDITE MEGABED OVER DEBRITE MTD



Tripsanas et al., 2008; 2010

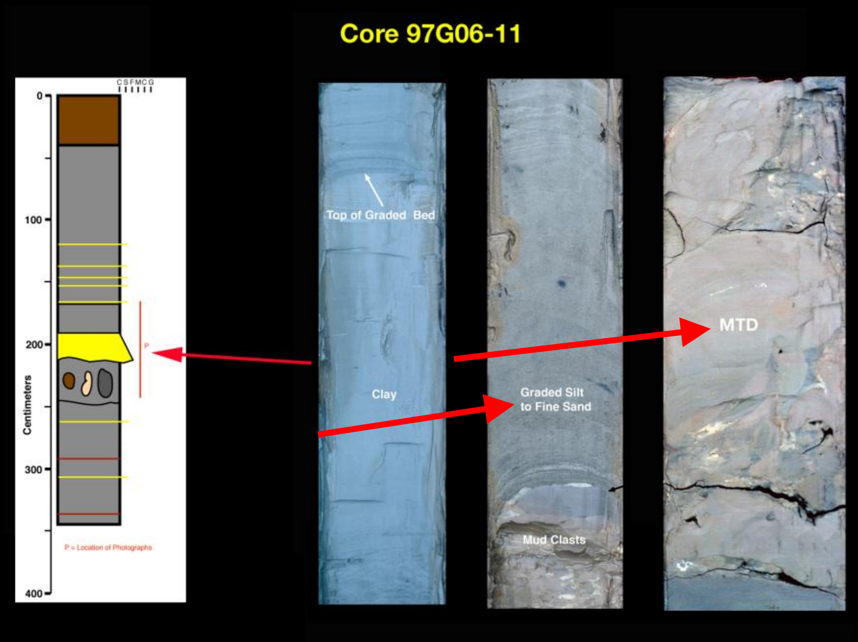


SEISMO-TURBIDITE MEGABEDS ARE NOT UNIQUE

i.e. other confined & unconfined basin floors have megabeds

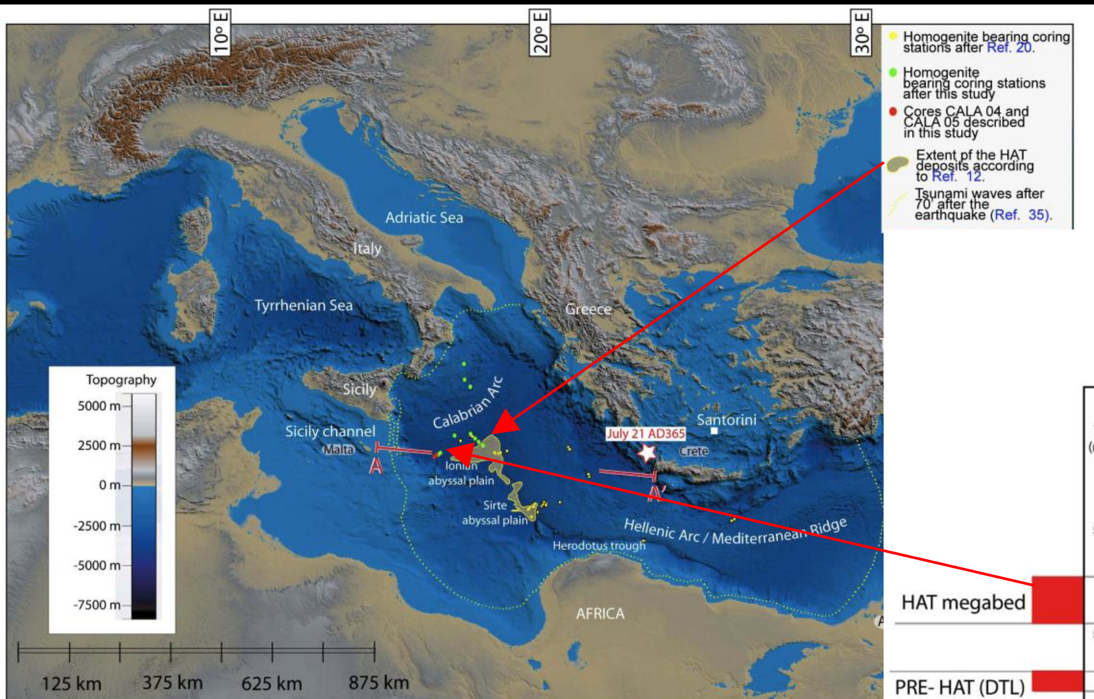
BEAUMONT SALT WITHDRAWAL MINI-BASIN ON BRYANT CANYON PATHWAY IN GULF OF MEXICO

Turbidite Overlying Mass-Transport Deposit
Beaumont Basin Floor



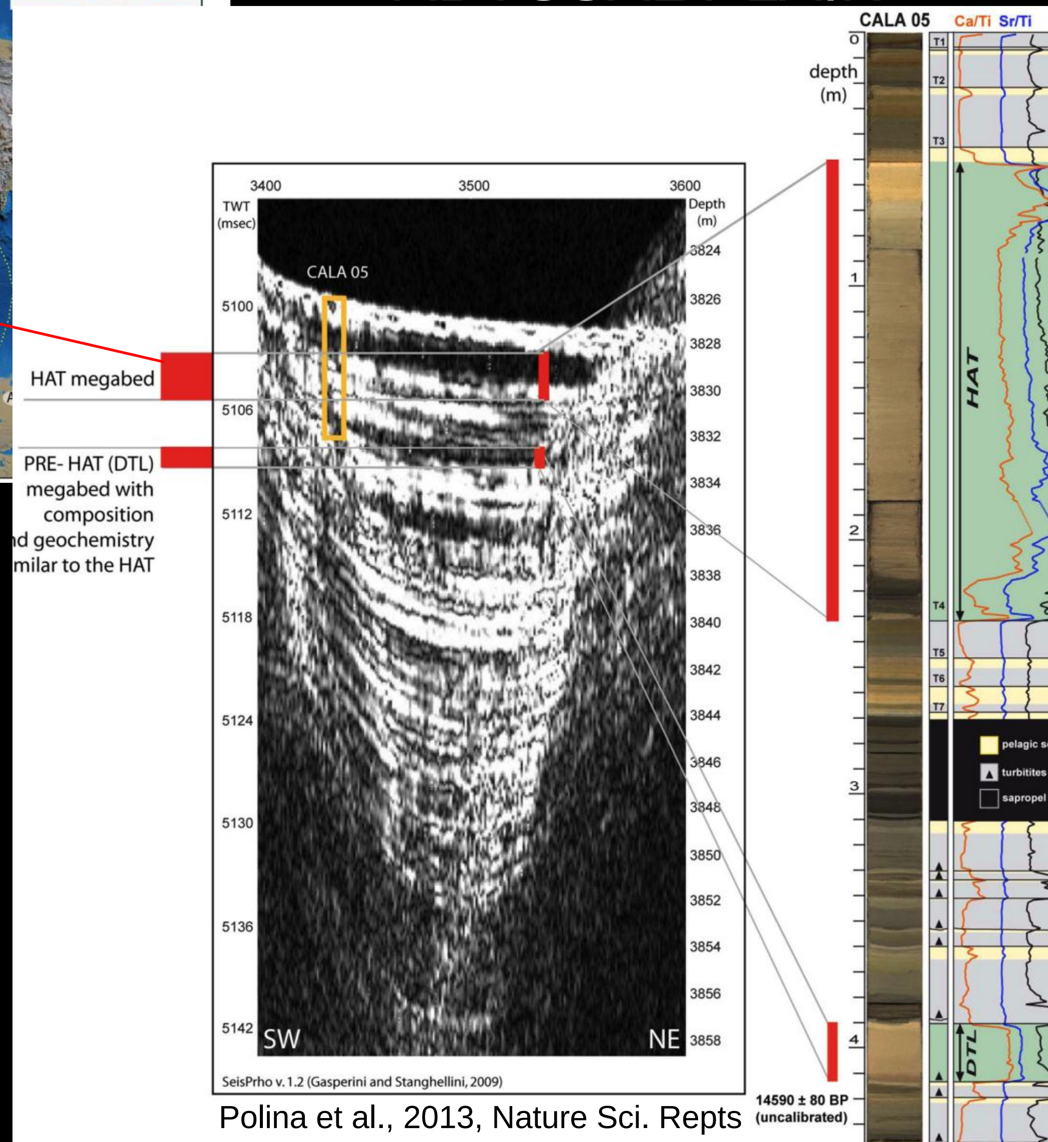
Nelson et al., 2006

THICK MUDDY HOMOGENITE FROM IONIAN SEA ABYSSAL PLAIN



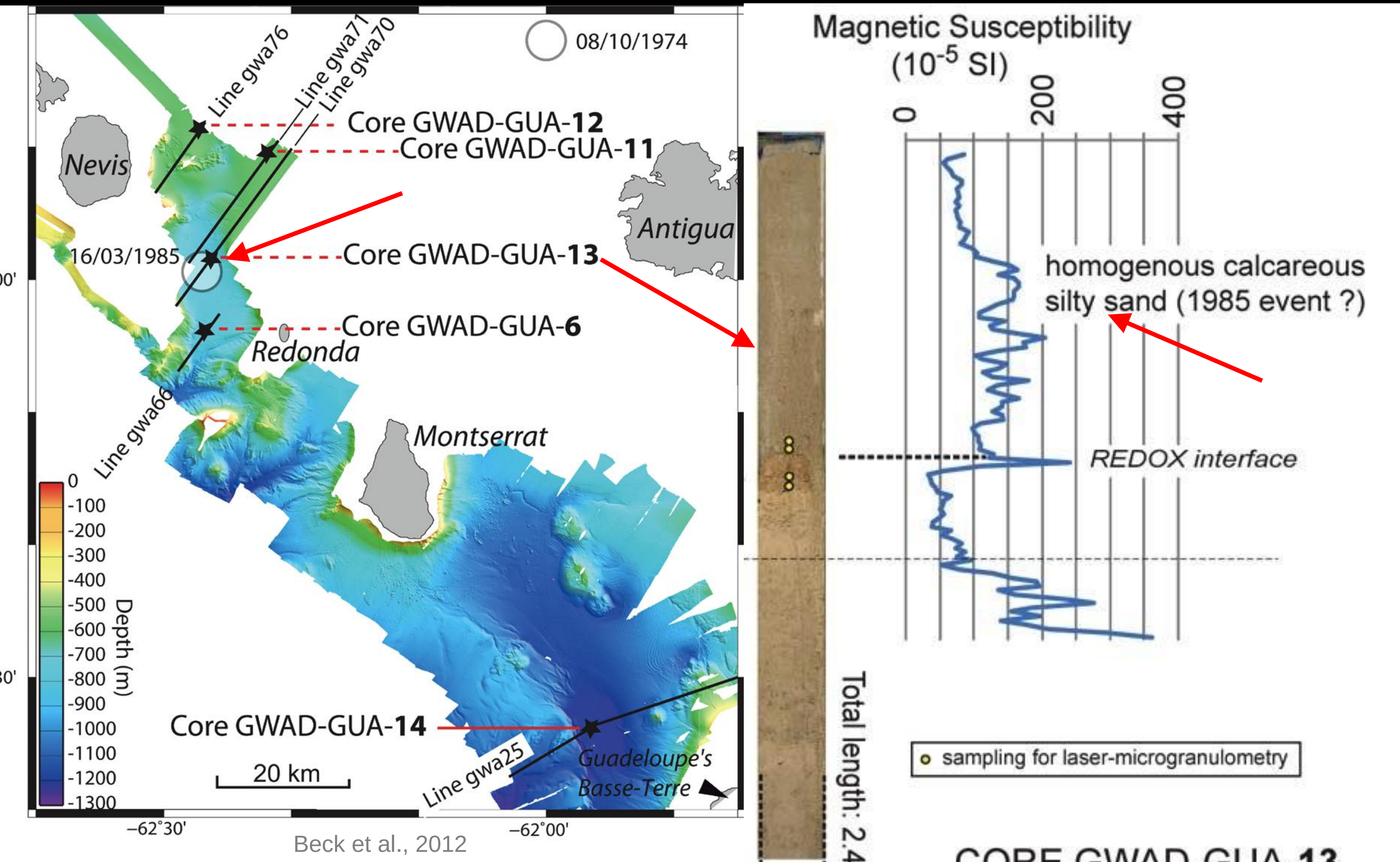
PONDED HAT HOMOGENITE DEPOSITED BY 365 A.D. CRETE *Mw* 8.3-8.5 EARTHQUAKE

- 45 cm graded sand base (50-100%)
- 135 cm homogenite mud (80% silt, 20 % clay) above sand base
- Maximum HAT thickness 20-25 m in seismic profiles



Polina et al., 2013, Nature Sci. Repts

LESSER ANTILLES 1.3 m SANDY HOMOGENITE IN BASIN FLOOR CENTER FROM 1985? *Mw* 6.3 QUAKE



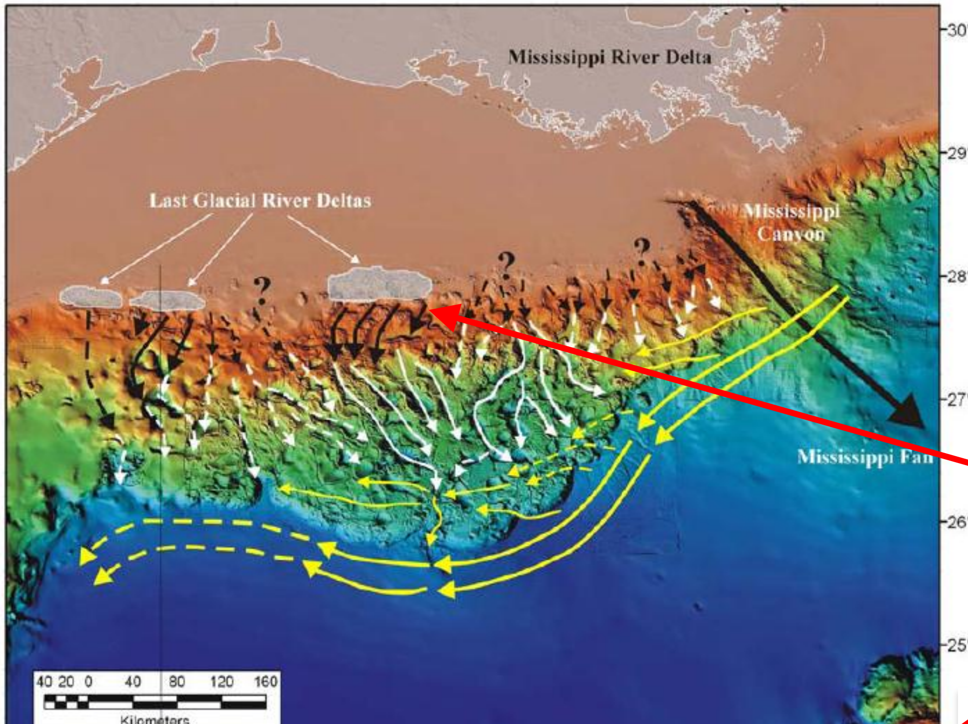
Beck et al., 2012

SEISMO-TURBIDITE PONDED HOMOGENITE/UNIFITES **ARE NOT UNIQUE**

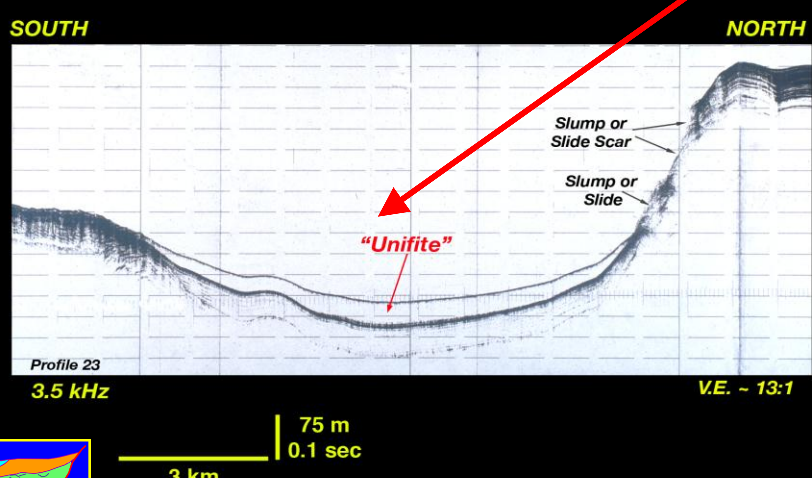
i.e. other closed or semi-closed basin floors have homogenite/unifites

UNIFITE SOURCE,

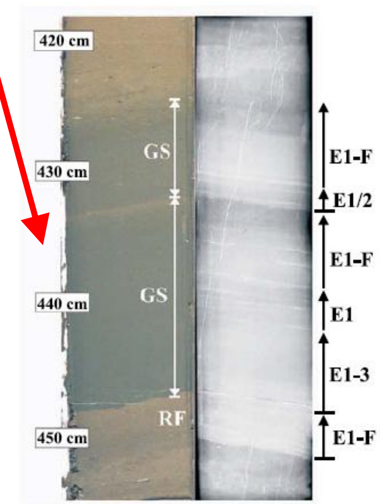
HOMOGENITE CORE LITHOLOGY



Mud Turbidite or "Unifite" in Intraslope Basin



Olson and Damuth (2000)

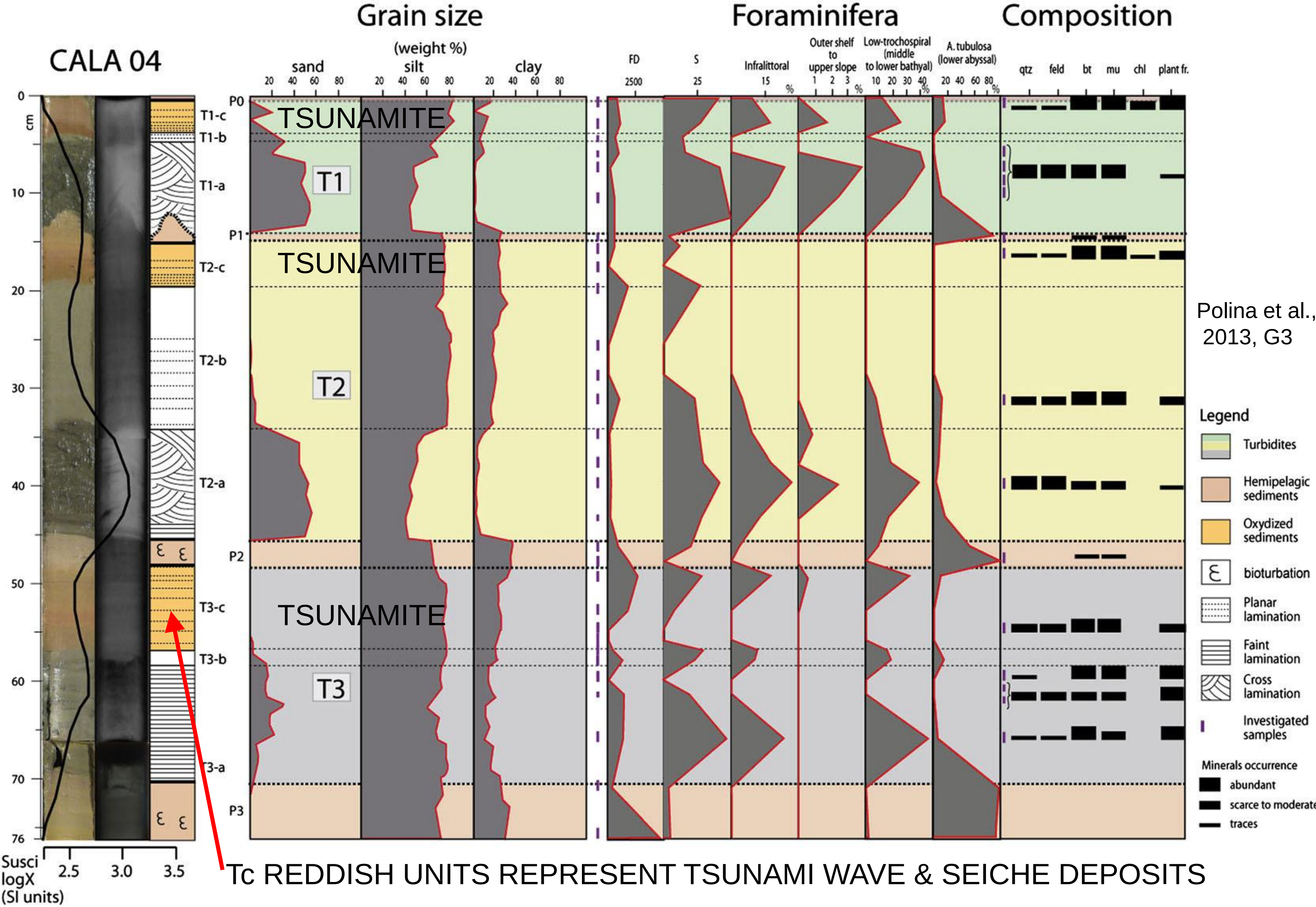


Tripsanas et al., 2004

SEICHE & TSUNAMITE SEISMO-TURBIDITES

- SEICHE DEPOSITS – OBSERVED IN HISTORICAL EARTHQUAKE CAPPING DEPOSITS OF CHILE, HAITI, MARMARA SEA & DETERMINED BY MULTIPLE CROSS BED SETS WITH OPPOSING PALEOCURRENT DIRECTIONS - Van Daele et al., in press)
- TSUNAMITE DEPOSITS – ORIGINALLY POSTULATED FOR THICK IONIAN SEA HOMOGENITES IN 1980s & FOR SOME OTHER THICK HOMOGENITE DEPOSITS (see slide 32)
- HOWEVER – RECENTLY TSUNAMITES OBSERVED AS ONLY THIN CAPPING DEPOSITS IN IONIAN SEA HOMOGENITES (see slide 36) & AS THIN CAPPING DEPOSITS IN < 1000 m WATER DEPTH FROM JAPAN 2011 QUAKE (identified by shallow water biota & Fukashima power plant isotopes – K. Ikehara personal communication, 2013)
- ALSO – NONE OBSERVED IN UNCONFINED BASIN SETTINGS OFF CASCADIA, SAN ANDREAS & NEW ZEALAND + LAKE LUCERNE WITH COEVAL SLIDES & NO TSUNAMIS HAS HOMOGENITES (see slide 27)
- ?? – DO THICK PONDED HOMOGENITES IN CONFINED BASINS RESULT FROM MULTIPLE COEVAL EARTHQUAKE FAILURES AROUND BASIN ? - SUCH AS THOSE OBSERVED IN LAKE LUCERENE & CHILE AYEN FJORD (see slide 41)

THIN TSUNAMITE CAP ON HOMOGENITES FROM IONIAN SEA



Polina et al., 2013, G3

Tc REDDISH UNITS REPRESENT TSUNAMI WAVE & SEICHE DEPOSITS

COMPARISON OF BASIN FLOOR MTD RUNOUT DISTANCES

ACTIVE TECTONIC MARGIN MTDs

LOCATION	MAX RUN OUT DISTANCE (km)	NUMBER OF MTD SHEETS
CASCADIA	5 TO 35	7
NORTH CALIFORNIA	80	1

PASSIVE MARGIN MTDs

LOCATION	MAX RUN OUT DISTANCE (km)	NUMBER OF MTD SHEETS
AMAZON FAN	140 - 255	4
ALEUTIAN BASIN	250 - 400	15
MISSISSIPPI FAN	350 - 600	20
ISSLER ET AL. (2005)	800	45
WYNN ET AL. (2009)	1,000	1

COMPARISON INDICATES:

- **MAXIMUM RUN OUT DISTANCES ARE 10X LESS ON ACTIVE MARGINS**
- **SEISMIC STRENGTHENING IS THE CAUSE**

Nelson et al., 2011

ACTIVE TECTONIC CASCADIA MARGIN EXAMPLE WITH LARGE SLIDES BUT SHORT MTD RUN-OUT OF 25 km

25 km WIDTH SLIDE
ca. 11,000yr BP

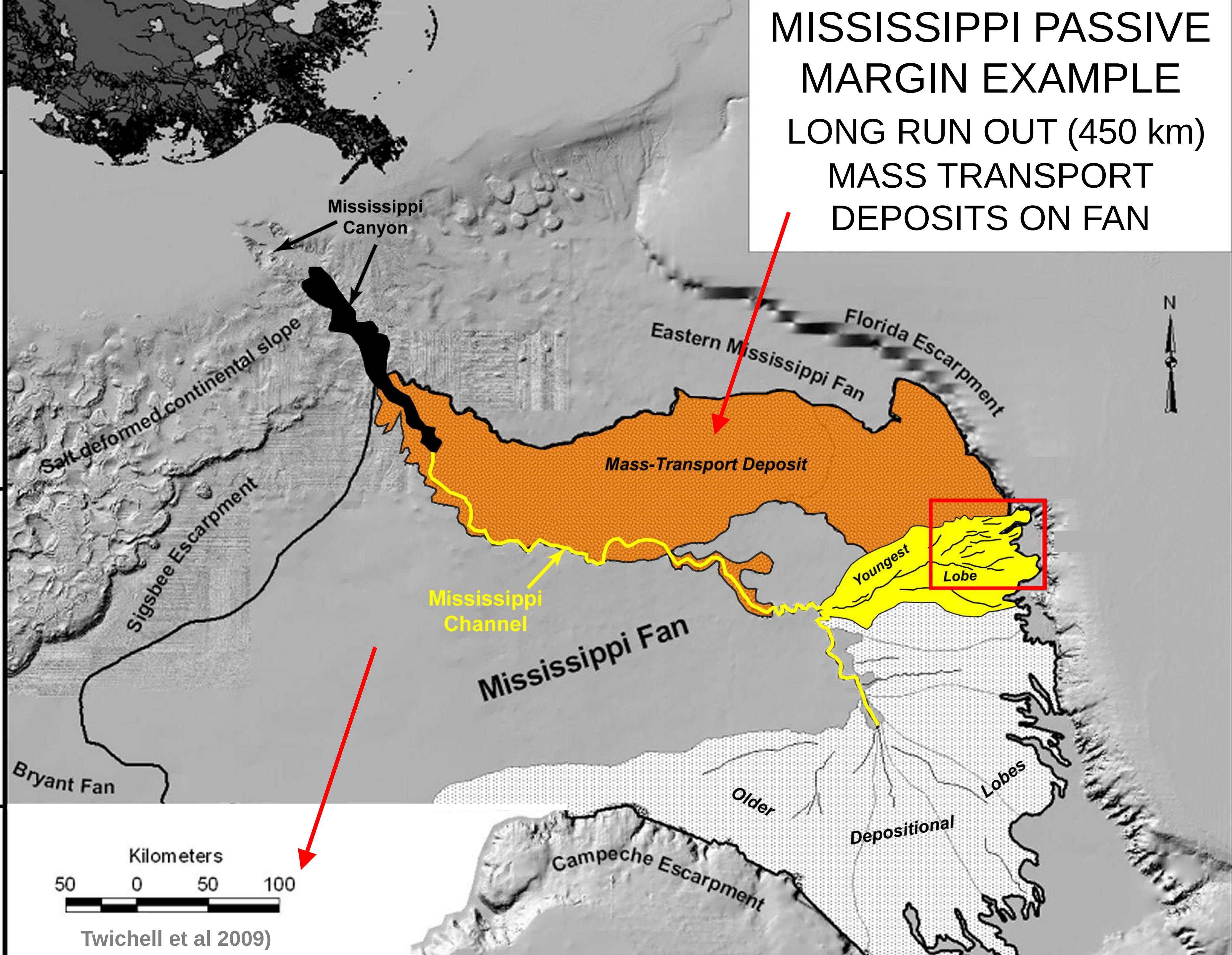
100 km WIDTH SLIDE
ca. 25,000yr BP

MTD RUN OUT DISTANCE FROM BASE OF SLOPE

Nelson et al., 2011

MISSISSIPPI PASSIVE MARGIN EXAMPLE

LONG RUN OUT (450 km) MASS TRANSPORT DEPOSITS ON FAN



Twichell et al 2009)

MTDS IN UNCONFINED BASINS OF ACTIVE TECTONIC MARGINS WITH GREAT EARTHQUAKE SEISMICITY COMPARED TO PASSIVE MARGINS

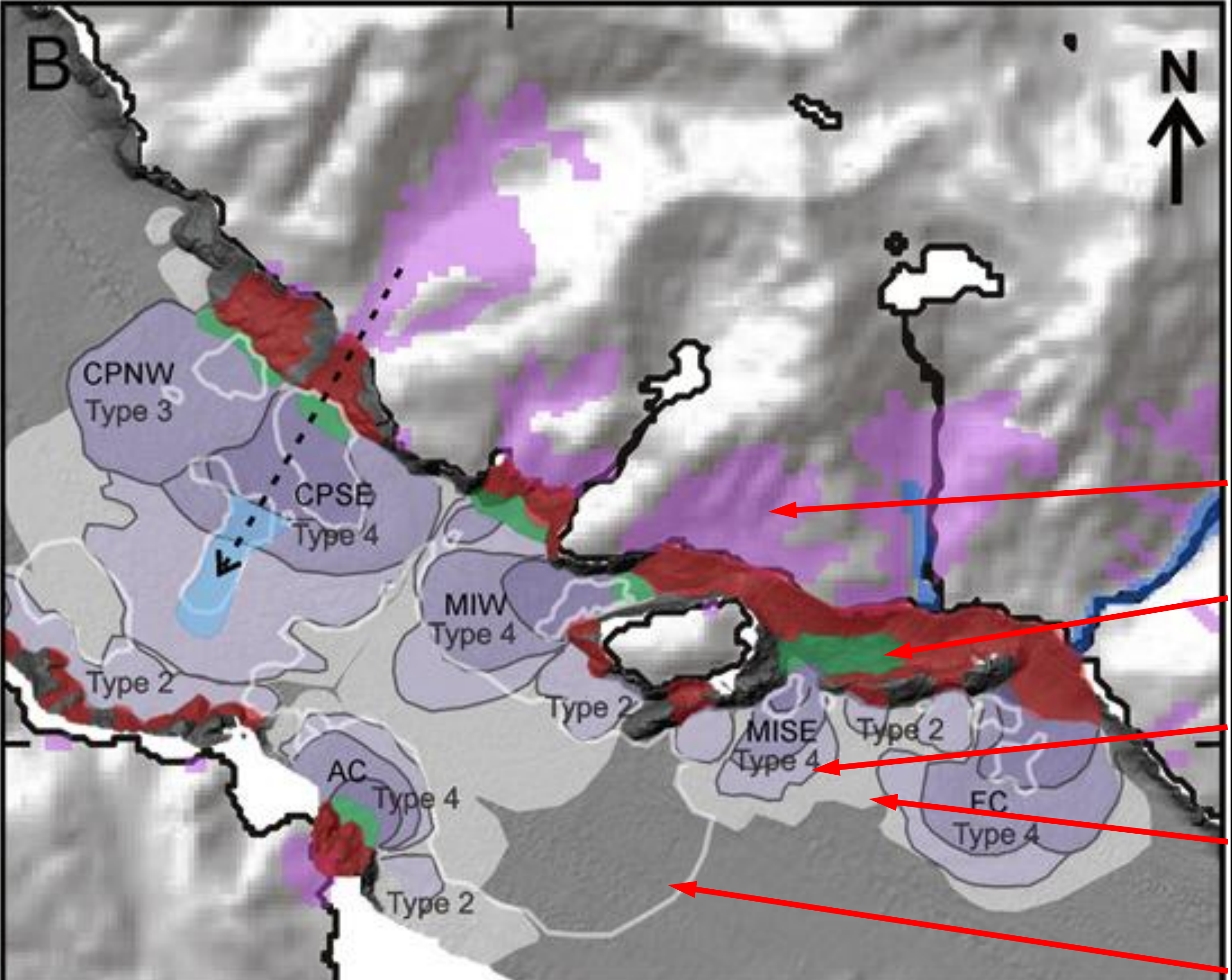
- **ACTIVE TECTONIC MARGINS:**
  - »FEW SURFACE AND SUBSURFACE MTD ACROSS BASIN FLOORS
  - »MAXIMUM MTD RUNOUTS <100 km ONTO UNCONFINED BASIN FLOORS
  - »TURBIITES DOMINANT, FEW MTDs

- **ACTIVE MARGINS HAVE SEISMIC STRENGTHENING:**
  - »REPEATED EARTHQUAKES DENSIFY SEDIMENT
  - »DENSIFIED SEDIMENT DOES NOT MOBILIZE WELL INTO DEBRIS FLOWS
  - »SURFACE MORPHOLOGY, MEASURED SEDIMENT STRENGTH AND EXPERIMENTS ALL SUBSTANTIATE PROCESS ON ACTIVE MARGIN SLOPES (Lee et al., 1992; 2004)

- **PASSIVE MUDDY MARGINS:**
  - »MTD SHEETS COVER SUBMARINE FAN SURFACES
  - »MAXIMUM MTD RUNOUTS = 1,000 km ON BASIN FLOOR
  - »EQUAL AMOUNTS OF MTDs AND TURBIDITES AT ALL SCALES

NELSON ET AL., 2011

PATTERN OF DEPOSITS FROM 2007 *Mw* 6.2 EARTHQUAKE IN AYEN FJORD CHILE



LANDSLIDES

PROXIMAL MTDs

MEGABEDS

STACKED TURBIDITES

PONDED HOMOGENITE MUD & SEICHE SEISMO- TURBIDITES IN DEEP BASIN CENTER

Van Daele et al., 2013; in press

CONCLUSIONS

- GREAT EARTHQUAKES (Mw 6-9) RESULT IN CHARACTERISTIC MULTI-PULSED, STACKED, MEGABED & HOMOGENITE SEISMO-TURBIDITES WHICH DOMINATE DEPOSITION ON ACTIVE TECTONIC MARGINS; ONLY STACKED MAY BE UNIQUE

- TYPES AND PATTERNS OF SEISMO-TURBIDITES VARY DEPENDING ON EARTHQUAKE STRENGTH & MORPHOLOGIC SETTING; *Mw* 9 = MULTI-PULSED DOMINANT THROUGHOUT SYSTEMS; *Mw* 6-8 EARTHQUAKES = PROXIMAL UNI-PULSED DOMINANT & STACKED BELOW CONFLUENCES & ON CONFINED BASIN FLOORS

- EARTHQUAKES IN CONFINED BASINS RESULT IN MEGABED, PONDED HOMOGENITE, & THIN SEICHE + TSUNAMITE DEPOSITS ON DEEP BASIN FLOORS; SANDY SYSTEMS = POTENTIAL THICK RESERVOIR SANDS; MUDDY SYSTEMS = BAFFLES OR SEALS

- ACTIVE TECTONIC MARGINS HAVE THE POTENTIAL FOR THICK SAND RESERVOIR BEDS BECAUSE OF AMALGAMATED-LIKE MULTI-PULSED, STACKED, MEGABED & HOMOGENITE SEISMO-TURBIDITES; + SEISMIC STRENGTHENING LIMITS AMOUNT OF MTDs IN UNCONFINED BASINS

- SEISMO-TURBIDITE SYSTEMS MAY HAVE PREDICTABLE PATTERNS OF RESERVOIRS; UNCONFINED BASINS = MULTIPULSED OR UNIPULSED + STACKED SANDS IN CHANNELS & LOBES; CONFINED BASINS = MTDs ON SLOPES, PROXIMAL MEGABEDS & PONDED HOMOGENITES + STACKED TURBIDITES IN DEEP BASIN CENTERS (e.g. IN SANDY SYSTEMS THICK MEGABEDS & HOMOGENITES = POTENTIAL RESERVOIRS)

-SEISMO-TURBIDITE DEFINITIONS FOR TALK SHOWN IN PREVIOUS SLIDE

-SEISMO-TURBIDITE HISTORICAL EXAMPLES SHOWN IN INTRODUCTION SLIDE

-CASCADIA (see slides 5-8) AND SAN ANDREAS MARGIN (see slides 17-21) SEISMO-TURBIDITES SHOWN BY SYNCHRONOUS TRIGGERING EVIDENCE :

- 13 TURBIDITES (T1-T13) ABOVE FIRST SEISMO-TURBIDITE MARKER BED CONTAINING MAZAMA ASH (MA) FROM CRATER LAKE ERUPTION & 18 SEISMO-TURBIDITES ABOVE HOLOCENE/PLEISTOCENE BOUNDARY IN CHANNELS OF ALL TYPES OF CASCADIA TURBIDITE SYSTEMS (Nelson et al., 2000, Goldfinger et al., 2003; 2008; 2012)
- CONFLUENCE TEST WITH SAME NUMBER OF POST MA AND HOLOCENE TURBIDITES UPSTREAM AND DOWNSTREAM FROM CHANNEL CONFLUENCES PROVES SYNCHRONOUS TRIGGERING (Adams, 1990)
- SAME 14C AND HEMIPELAGIC SEDIMENT (thickness/sedimentation rate) AGES FOR CORRELATIVE SEISMO-TURBIDITES IN DIFFERENT TURBIDITE SYSTEMS OF CASCADIA MARGIN (Guttierez Pastor et al., 2009) (see slide 8)
- CORRELATION OF TURBIDITE PALEOSEISMIC RECORDS WITH ONSHORE CASCADIA & SAN ANDREAS PALEOSEISMIC RECORDS (Goldfinger et al. 2008; 2012)
- SAME DENSITY AND MAGNETIC SUSCEPTIBILITY LOG SIGNATURES FOR CORRELATIVE SEISMO-TURBIDITES (e.g. number of coarse grained pulses & layer thickness- see slides 10 & 11) (Goldfinger et al. 2008; 2012)
- BELOW SAN ANDREAS CHANNEL CONFLUENCES, STACKED TURBIDITES WITH SEPARATE MINERALOGY FROM DIFFERENT TRIBUTARY CANYON SOURCES PROVES SYNCHRONOUS TRIGGERING (Goldfinger et al, 2007)