

The Geological Record of Extreme Marine Inundation Events: Clues From Coastal Sediments and Boulders

Noelynna T. Ramos, Sheinna May D. Claro, Alec Benjamin G. Ramirez, Robelyn Z. Mangahas-Flores, Edrian M. Tubalado, Lyndon P. Nawanao Jr., Ace Matthew F. Cantillep, Jemimah Caryl C. Abalajon, Irene Fe D. Gepulla, Jennie Raika O. Taer, Patrick Sam M. Buenavista, Nichole Anthony D. Pacle, Daisuke Ishimura, Adam D. Switzer, Chuan-Chou Shen, Jessica Pilarczyk, and Kenji Satake

Department of Earth Sciences, National Central University, Taiwan 13 November 2026

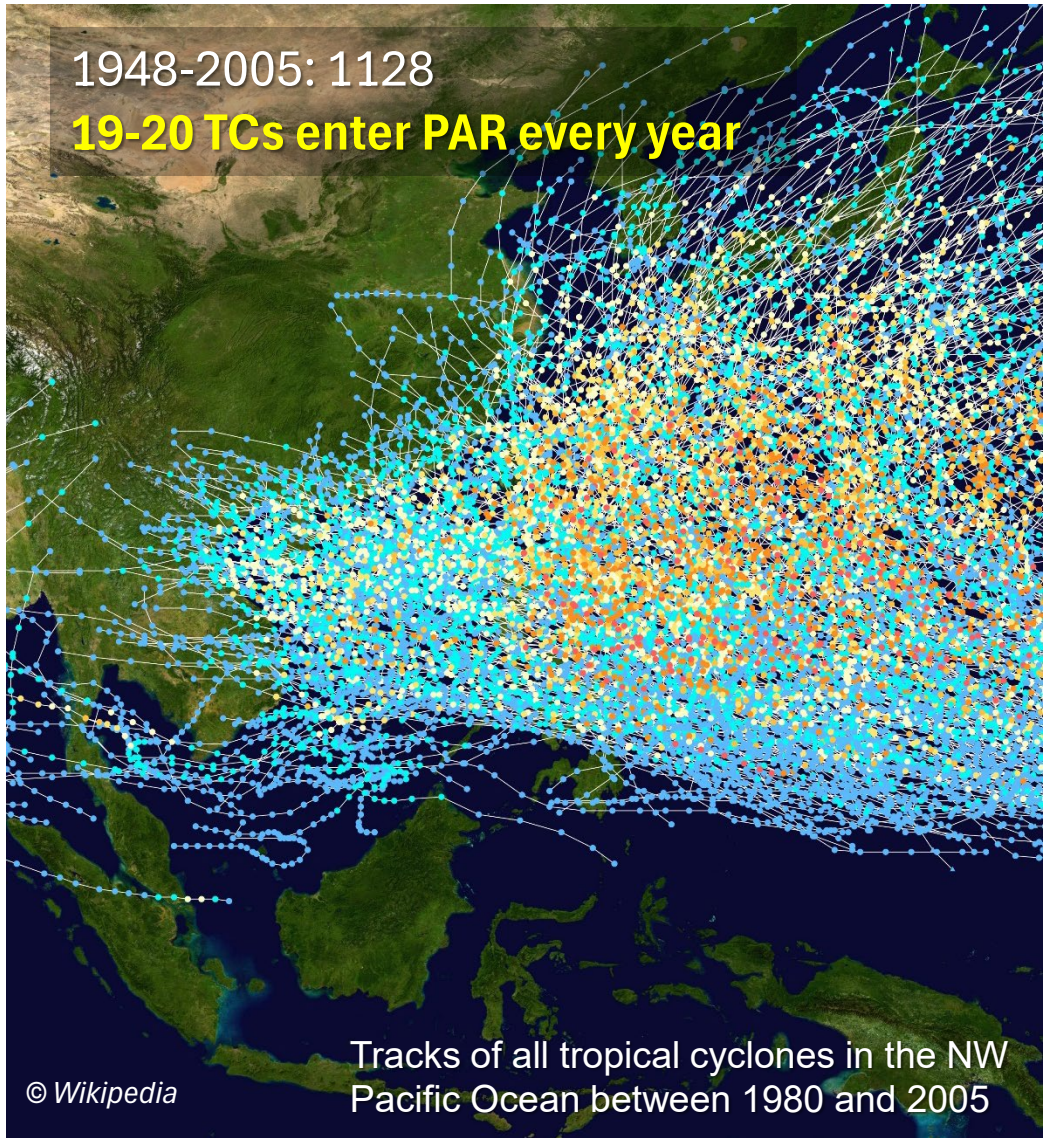
Coastal Hazard Setting of the Philippines



Population (2025):
116.8~117M (projected)

Languages: 130+

Coastline: ~36,000 km^2



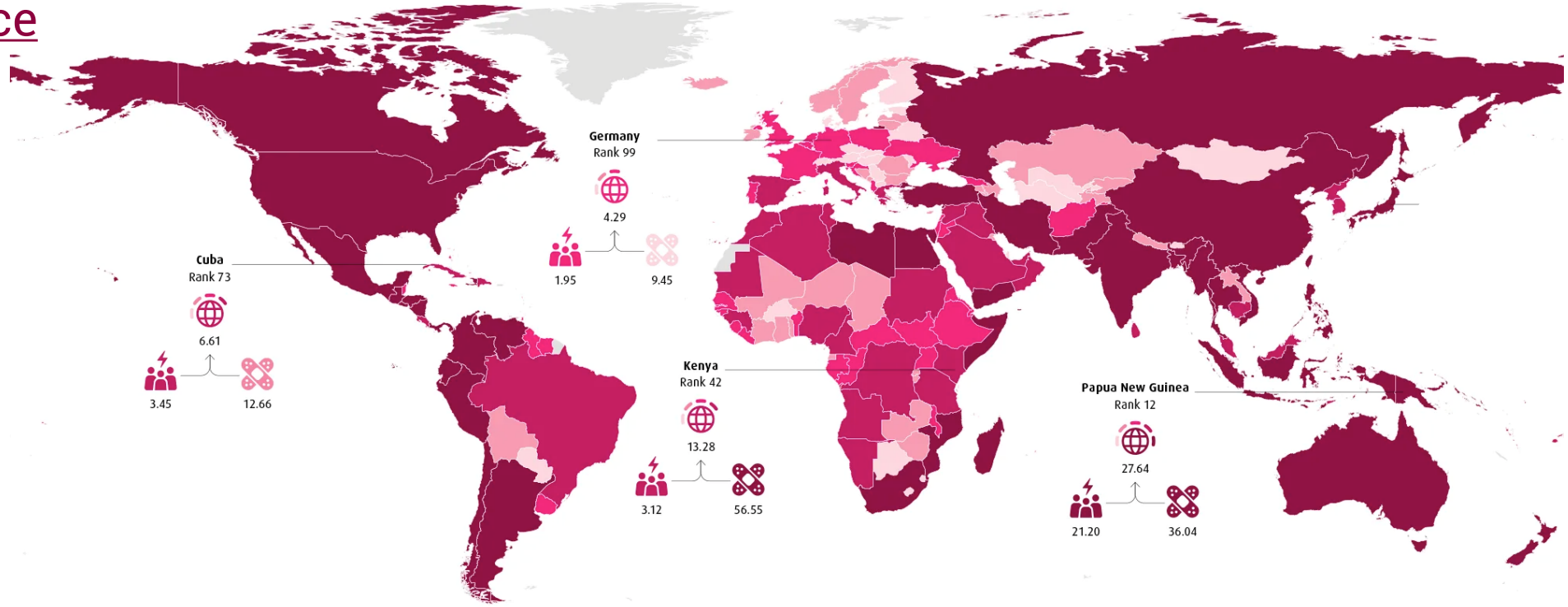


Data sources:
NASA, NGDC, PHIVOLCS, Tsutsumi and Perez (2013), PAGASA, Joint Typhoon Warning Center

The **World Risk Index** assesses the risk of disaster in consequence of extreme natural events for 193 (UN-recognized) countries and 99% of the world's population.

WorldRiskIndex 2026

Focus: Storms



THE 10 COUNTRIES WITH HIGHEST RISK

1	Philippines	46.69
2	India	44.97
3	Indonesia	44.63
4	Colombia	39.80
5	Mexico	39.18

2026: Storms
2025: Floods
2024: Multiple Crises
2023: Diversity
2022: Digitalization



WORLDRISKINDEX

very low	0.00 – 2.07
low	2.08 – 3.35
medium	3.36 – 6.31
high	6.32 – 13.72
very high	13.73 – 100.00
no data	

EXPOSURE

very low	0.00 – 0.22
low	0.23 – 0.74
medium	0.75 – 2.13
high	2.14 – 8.76
very high	8.77 – 100.00
no data	

VULNERABILITY

very low	0.00 – 10.09
low	10.10 – 15.97
medium	15.98 – 23.40
high	23.41 – 32.89
very high	32.90 – 100.00
no data	

Since 2022, fixed thresholds have been used to classify countries for the WorldRiskIndex and its components, enabling analyses of medium- and long-term trends. For each dimension and for the WorldRiskIndex, the medians of the quintile boundaries are calculated from the results of the past 20 years. Data sources: IFHV's own calculations based on CReSIS, EMDAT, FAO, GFDRR, IHME, IDMC, JRC, IMF, ILO, UCDP, UNESCO, UNHCR, UNDRR, WHO, World Bank, WorldPop, WID; additional information at https://weltrisikobericht.de/worldriskreport

THE 10 COUNTRIES WITH HIGHEST EXPOSURE

1	China	71.06
2	Mexico	50.69
3	Japan	43.35
4	India	40.83
5	Philippines	40.76
6	Indonesia	39.78
6	United States of America	39.78
8	Australia	32.11
9	Colombia	31.59
10	Russian Federation	28.37

THE 10 COUNTRIES WITH HIGHEST VULNERABILITY

1	Somalia	71.00
2	Central African Republic	70.89
3	Chad	69.34
4	Sudan	69.03
5	South Sudan	68.66
6	Democratic Republic of Congo	68.53
7	Yemen	67.75
8	Afghanistan	67.36
9	Niger	66.63
10	Ethiopia	66.33

Amidst the hazards, we find a silver lining…


ABS-CBN NEWS

Share

14 million Filipinos exposed to tsunami threat, warns Phivolcs

Aleta Nieva Nishimori, ABS-CBN News

Posted at Nov 05 2020 06:22 PM

Tsunami Hazard Map of NCR

EXPOSURE TO TSUNA

POPULATION

City	Male	Female	Total
Manila	574,632	592,182	1,166,814
Pasay	137,495	139,195	276,690
Navotas	126,563	122,746	249,309
Malabon	121,164	119,656	240,820

Building Use	
Residential	169,925
Mixed Residential and Commercial	95,331

DOST Renato …

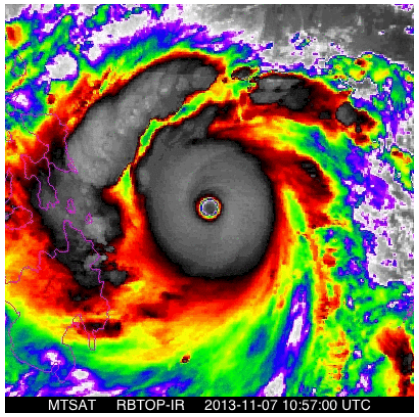
© news.abs-cbn.com


The New York Times

A Crisis Right Now: San Francisco and Manila Face Rising Seas

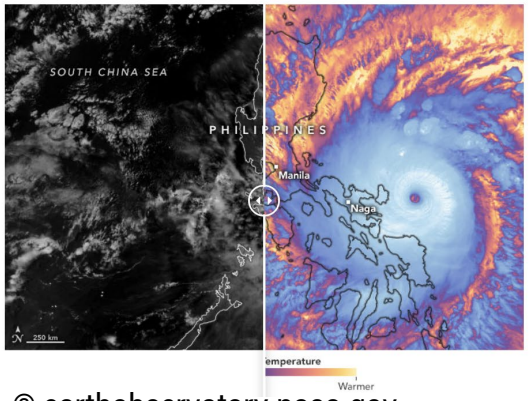
© www.nytimes.com


Images | Global Maps | Articles | Blogs | NASA earth observatory | EO Explorer | Topics


MTSAT RBTOP-IR 2013-11-07 10:57:00 UTC

© Japan Meteorological Agency

Devastating Storm Hits the Philippines



© earthobservatory.nasa.gov


View this area in EO Explorer

Super Typhoon Goni brought winds upwards of 300 kilometers (195 miles) per hour before making landfall on Catanduanes Island.

Super Typhoon Fung Wong (2025)
Super Typhoon Rai (2021)
Super Typhoon Goni (2020)
Super Typhoon Meranti (2016)
Super Typhoon Haiyan (2013)


The upside Philippines

Enduring the tide: the flooded Philippine islands that locals won't leave

Ben Doherty

@bendohertycorro

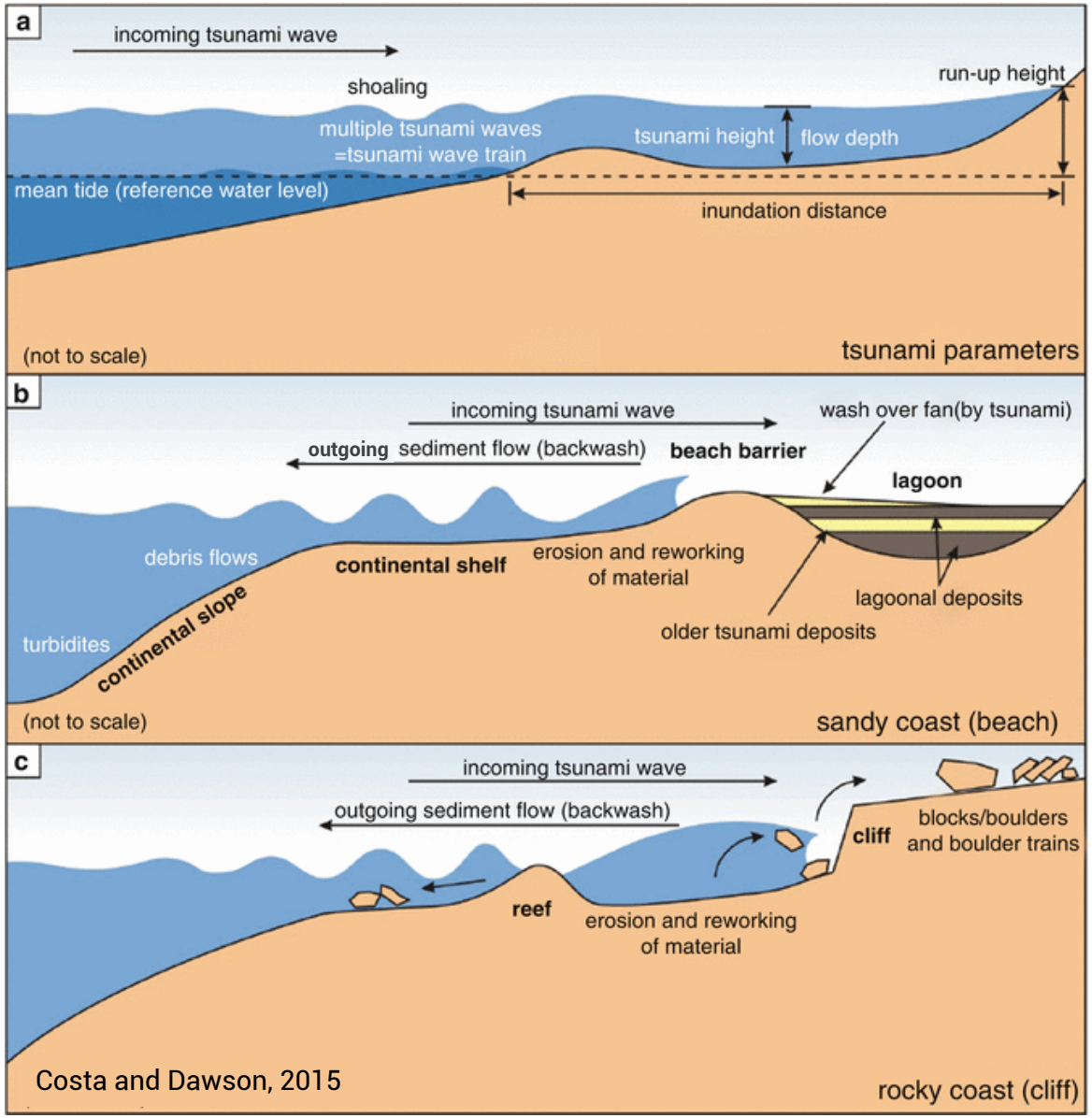
Fri 1 Feb 2019 01.00 GMT

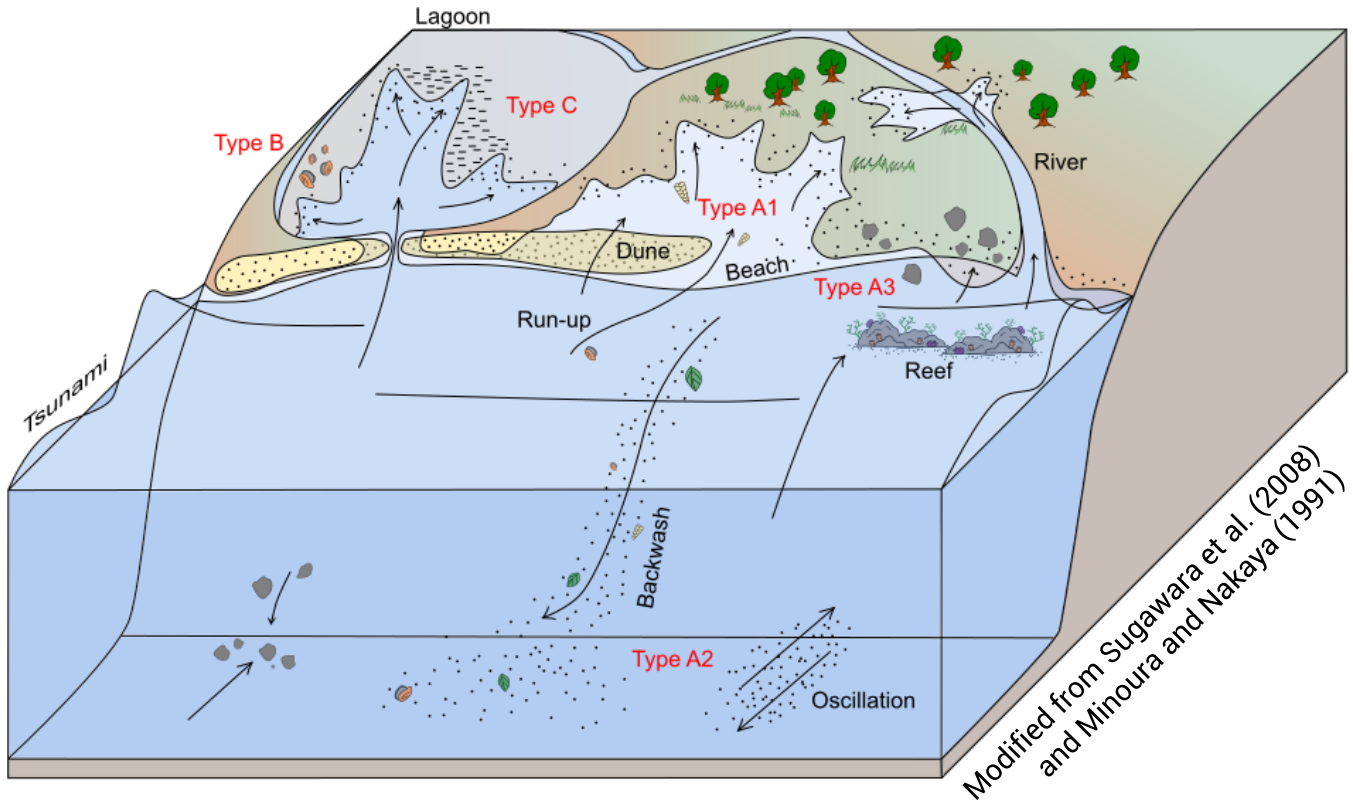
974 158

© www.theguardian.com

▲ Ubay island, which, following an earthquake, is entirely flooded on some tides. Photograph: Chris Chadwick/www.thehatch.tv

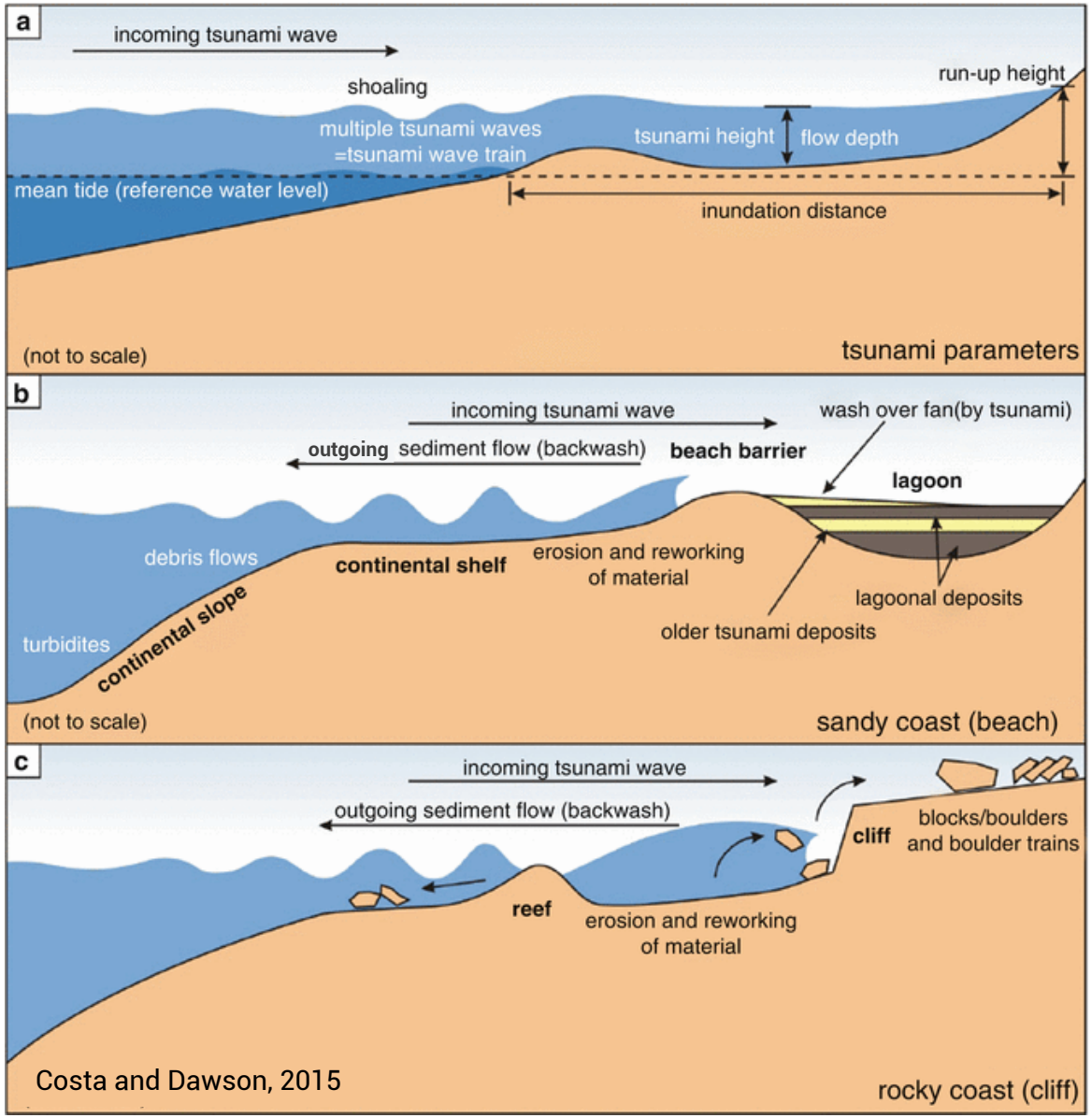
Overwash and washover? What is the difference? 🤔



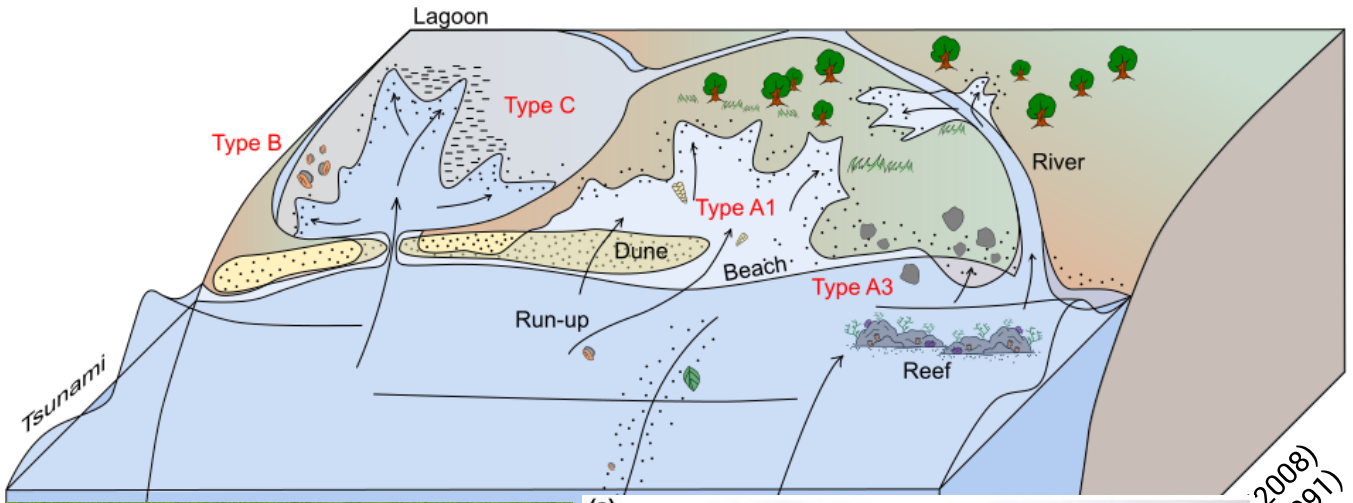


Washover deposits are accumulations of sand, gravel, and shell debris transported by high-energy waves during storm surges or tsunamis that flow over ("overwash") coastal barriers (e.g., dunes or beaches).

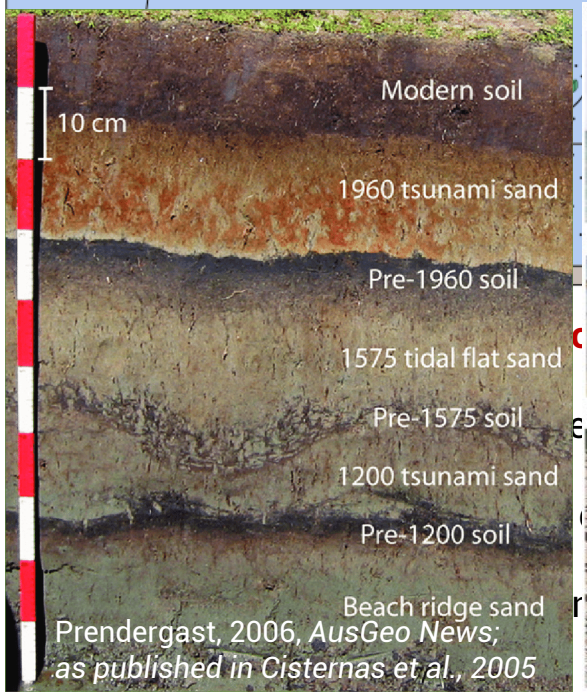
Washover Deposits (Tsunami and Storm Surge)



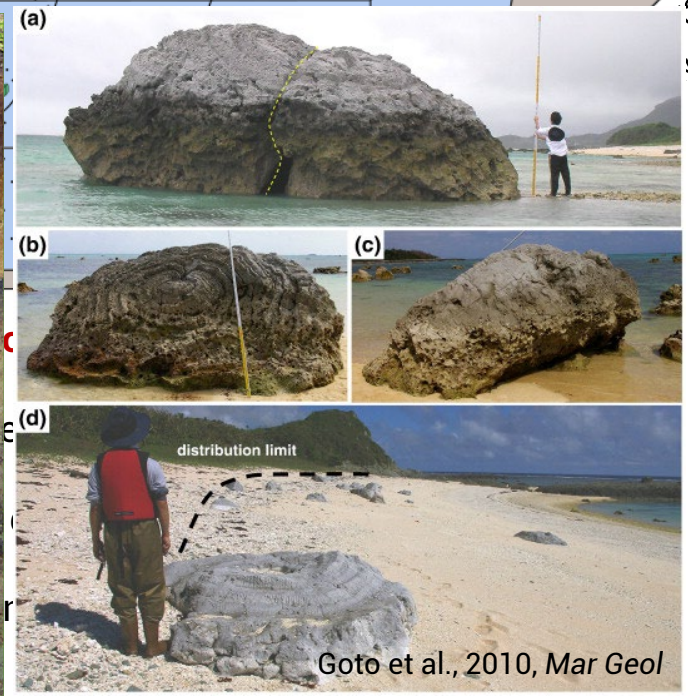
Costa and Dawson, 2015



(2008)
ya (1991)

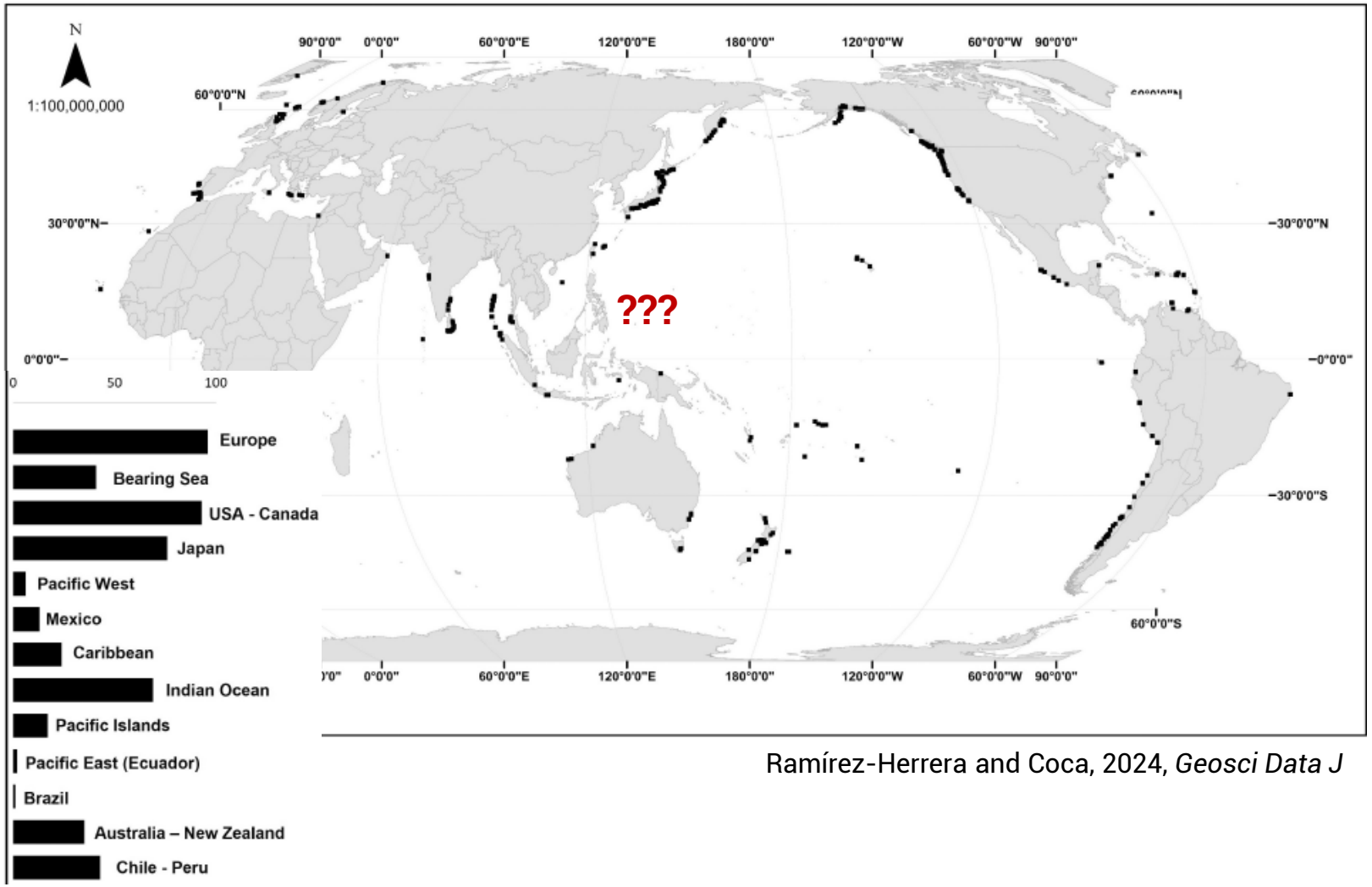


Prendergast, 2006, *AusGeo News;*
as published in Cisternas et al., 2005



Goto et al., 2010, *Mar Geol*

Global Distribution of Tsunami Deposit Sites



Ramírez-Herrera and Coca, 2024, *Geosci Data J*

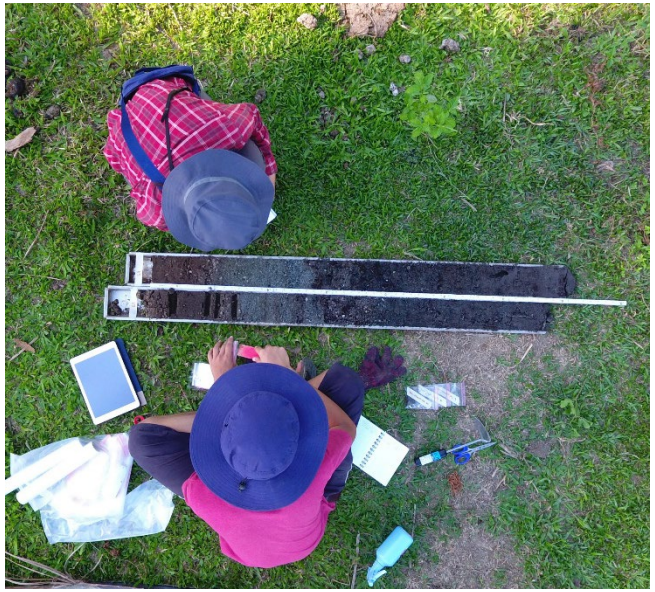


Wallis et al., 2017, *Geol Soc Spec Publ*



© AIST as published in Jankaew et al., 2008, *Nature*

Examination and Analysis of Washover Deposits

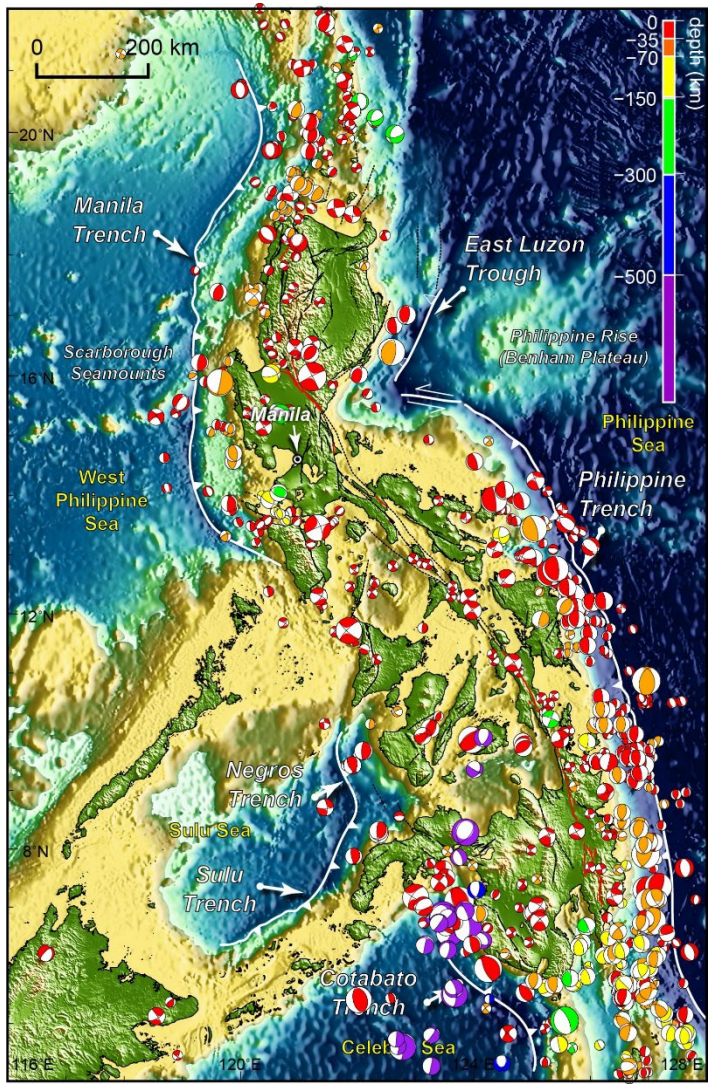






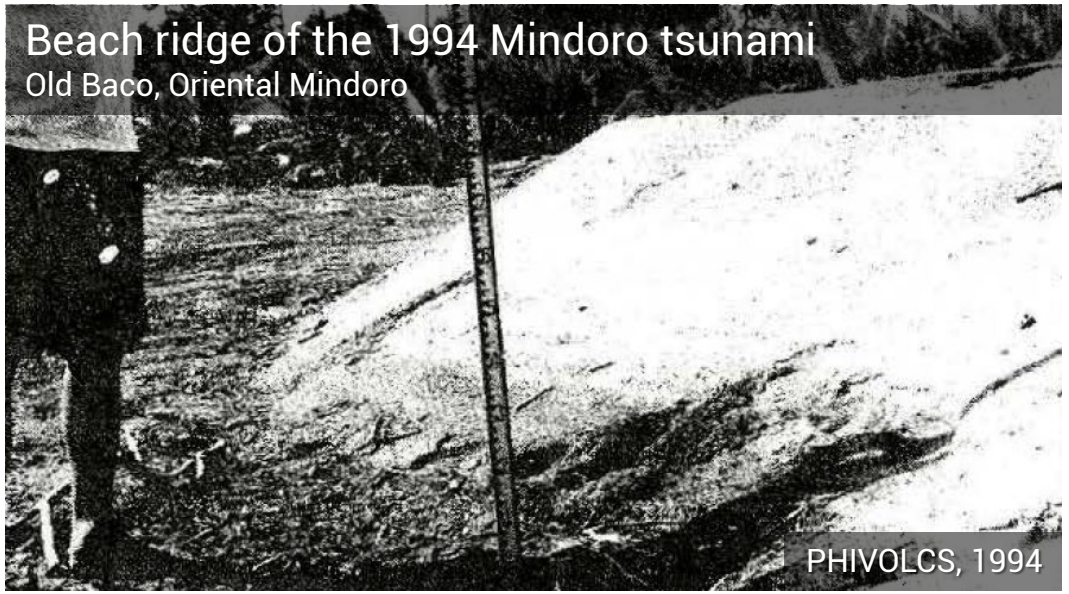
iPhone LIDAR rendering by ZT Aguas

EQ-induced Tsunamis in the Philippines

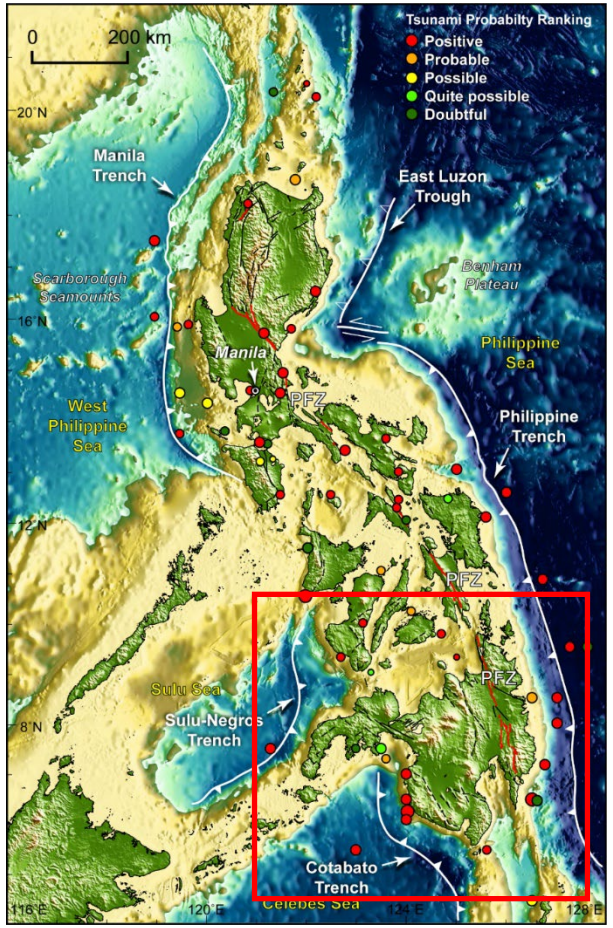


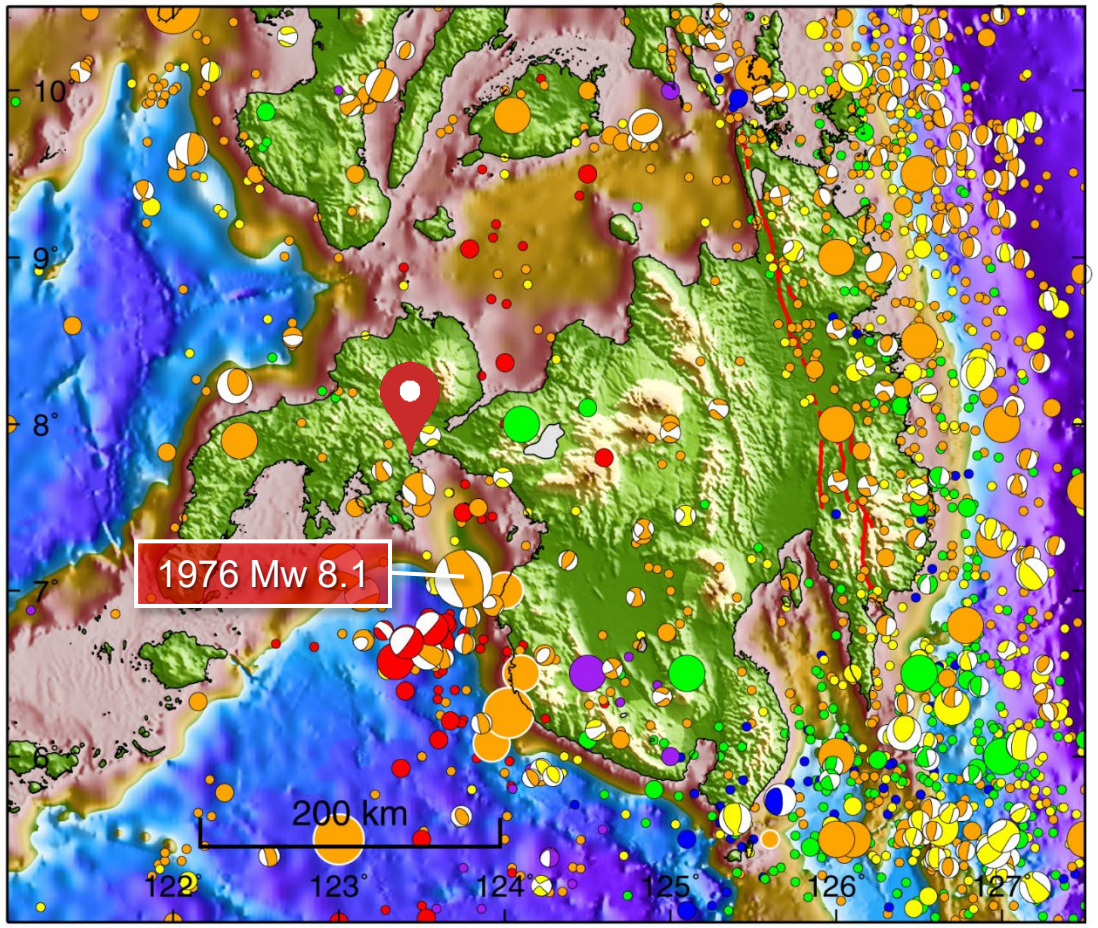


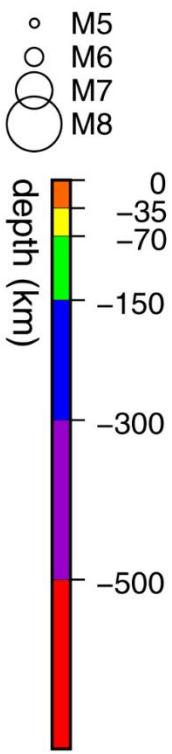




1976 Moro Gulf Earthquake and Tsunami





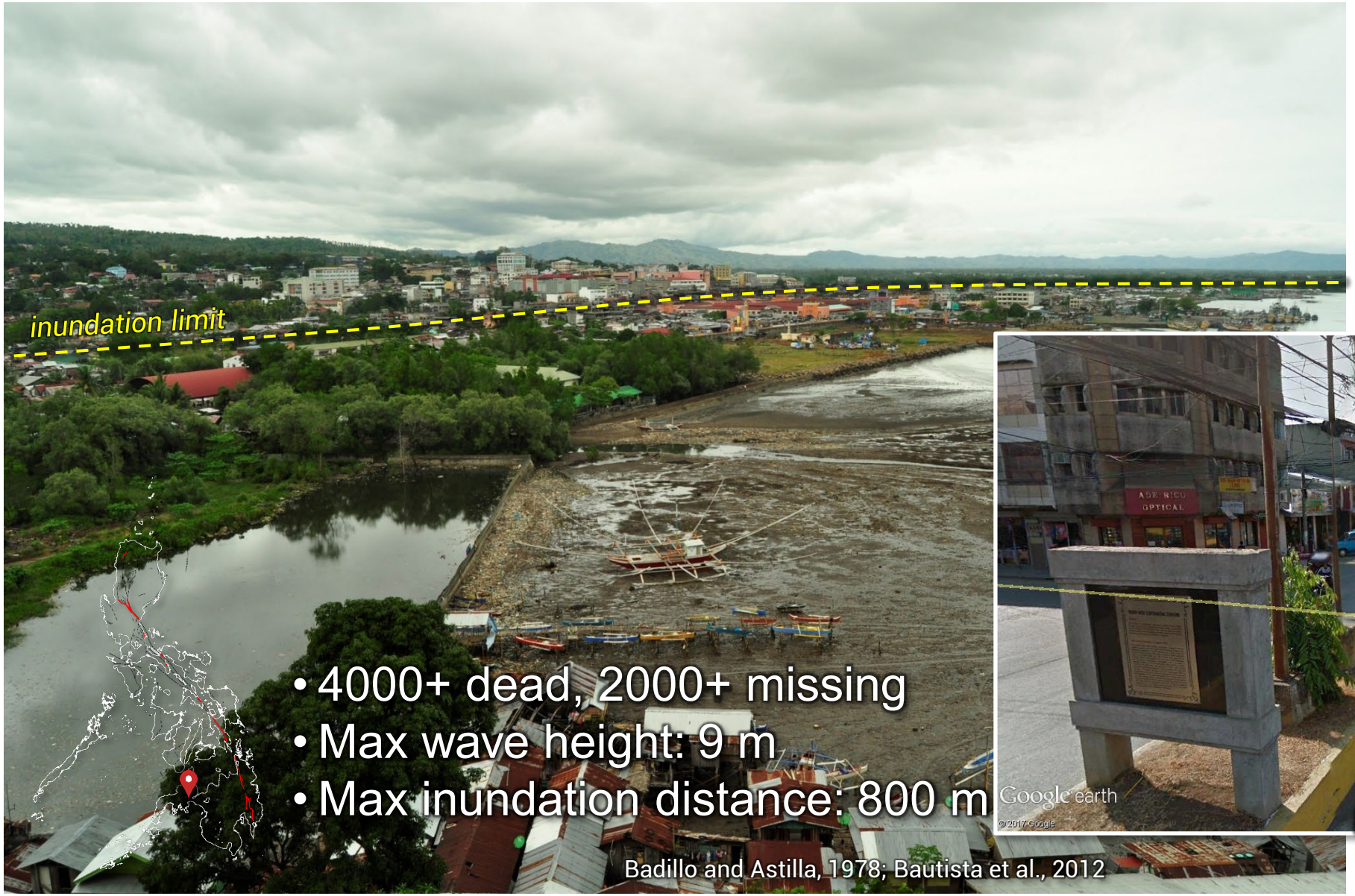


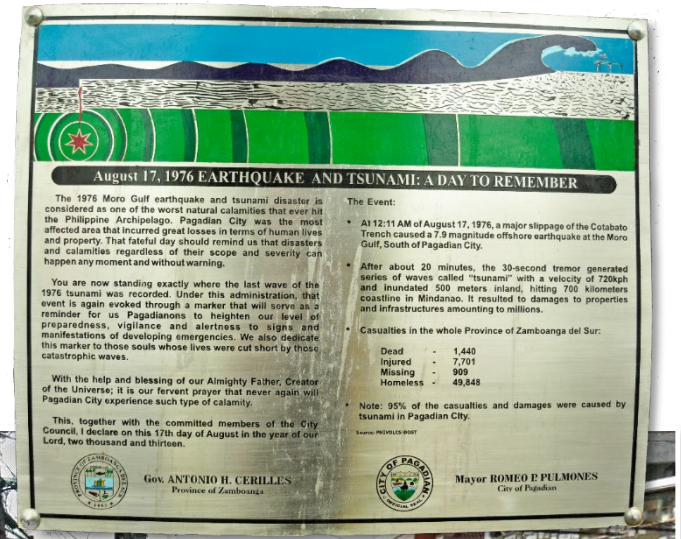


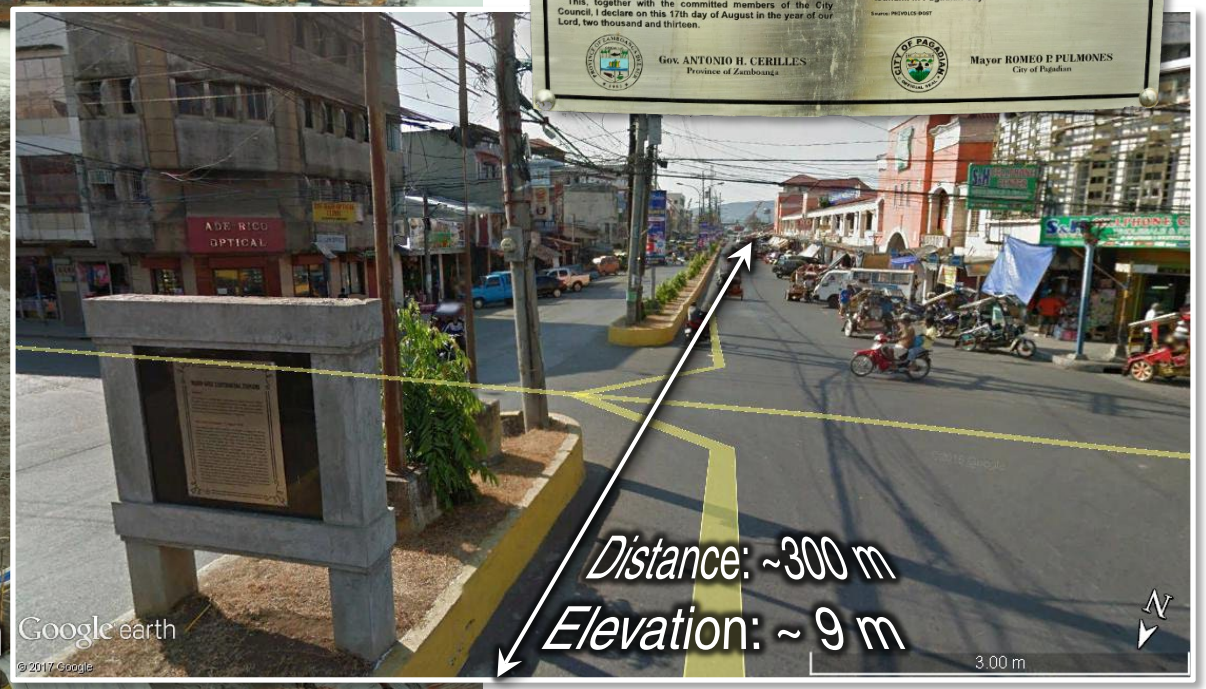
Claro et al., 2021, *Mar Geol*

17 August 1976 at 12:11 AM (GMT+8)
Mw 8.1 megathrust EQ (Bautista et al., 2012)

1976 Moro Gulf Earthquake and Tsunami

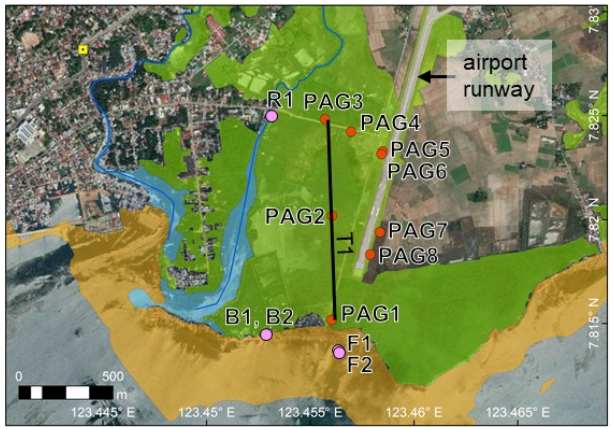






1976 Moro Gulf Tsunami Deposits

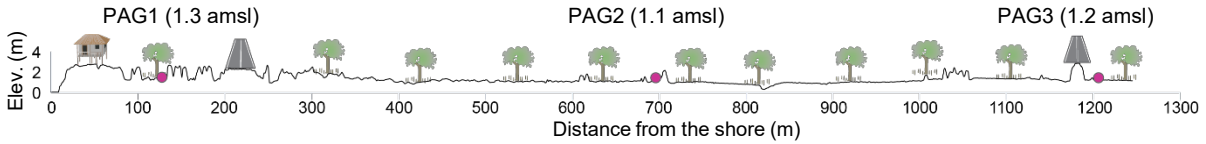


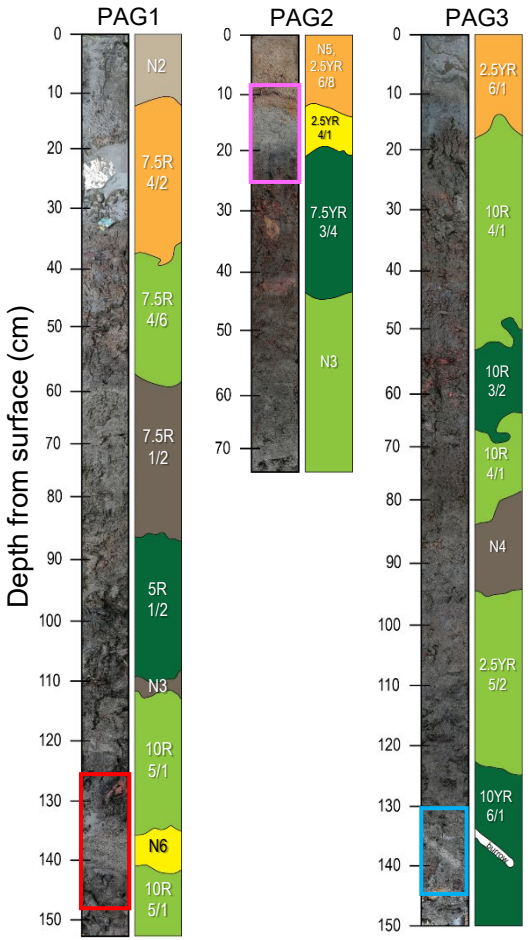


Claro et al., 2021, *Mar Geol*

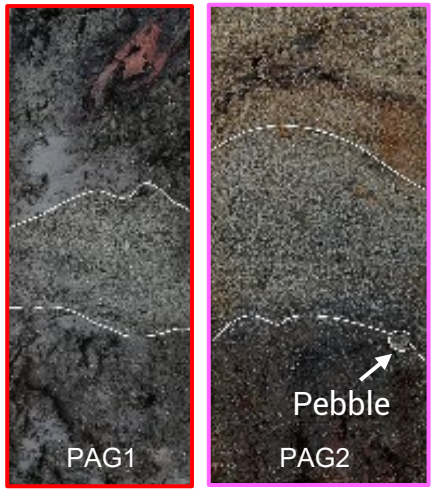
◄ South (shore)

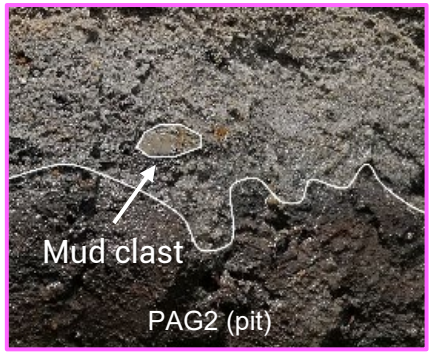
Topographic Profile (T1)



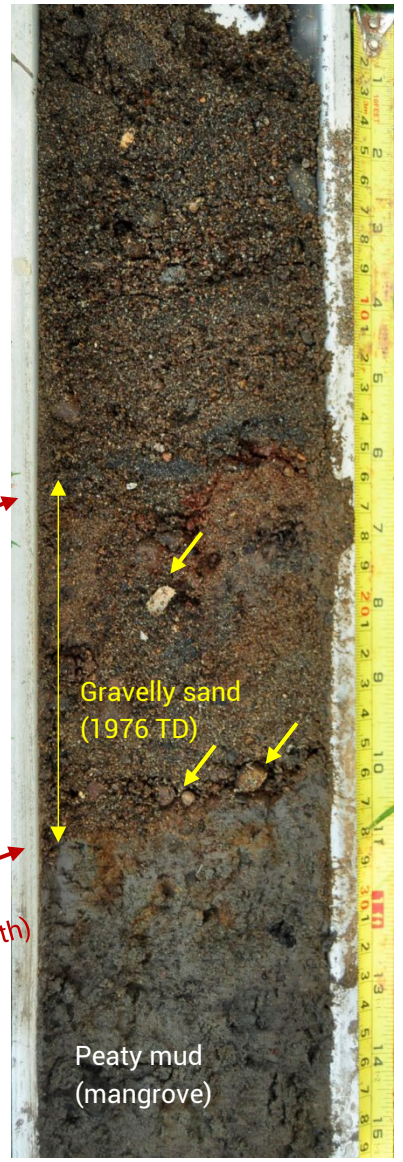


Close-up photos





- Soil
- Peaty mud
- Sand I
- Sand II
- Mangrove peat
- Peaty sand
- Silty sand



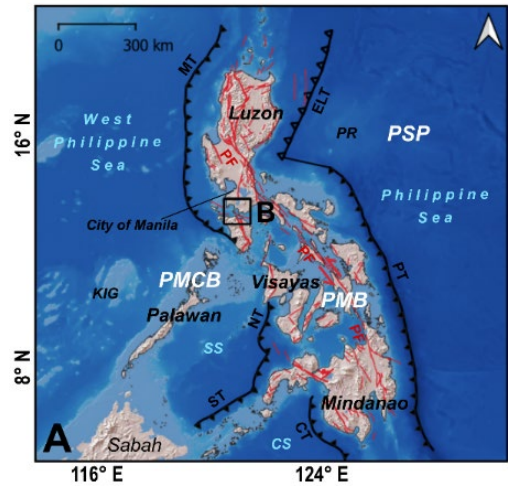
1994 Mindoro Earthquake & Tsunami

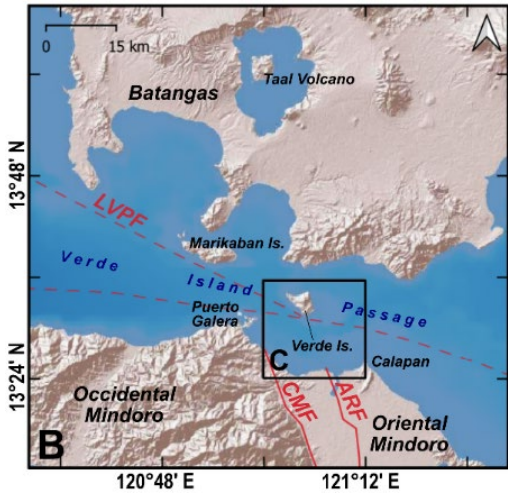


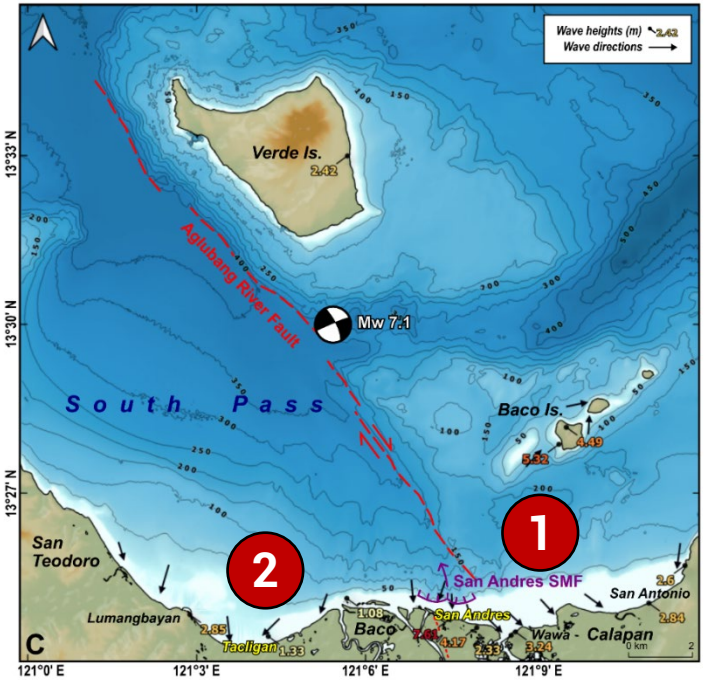
- 78 dead
- Max wave height: 8 m
- Max inundation distance: 250 m

PHIVOLCS (1994)

1994 Mindoro Tsunami Deposits



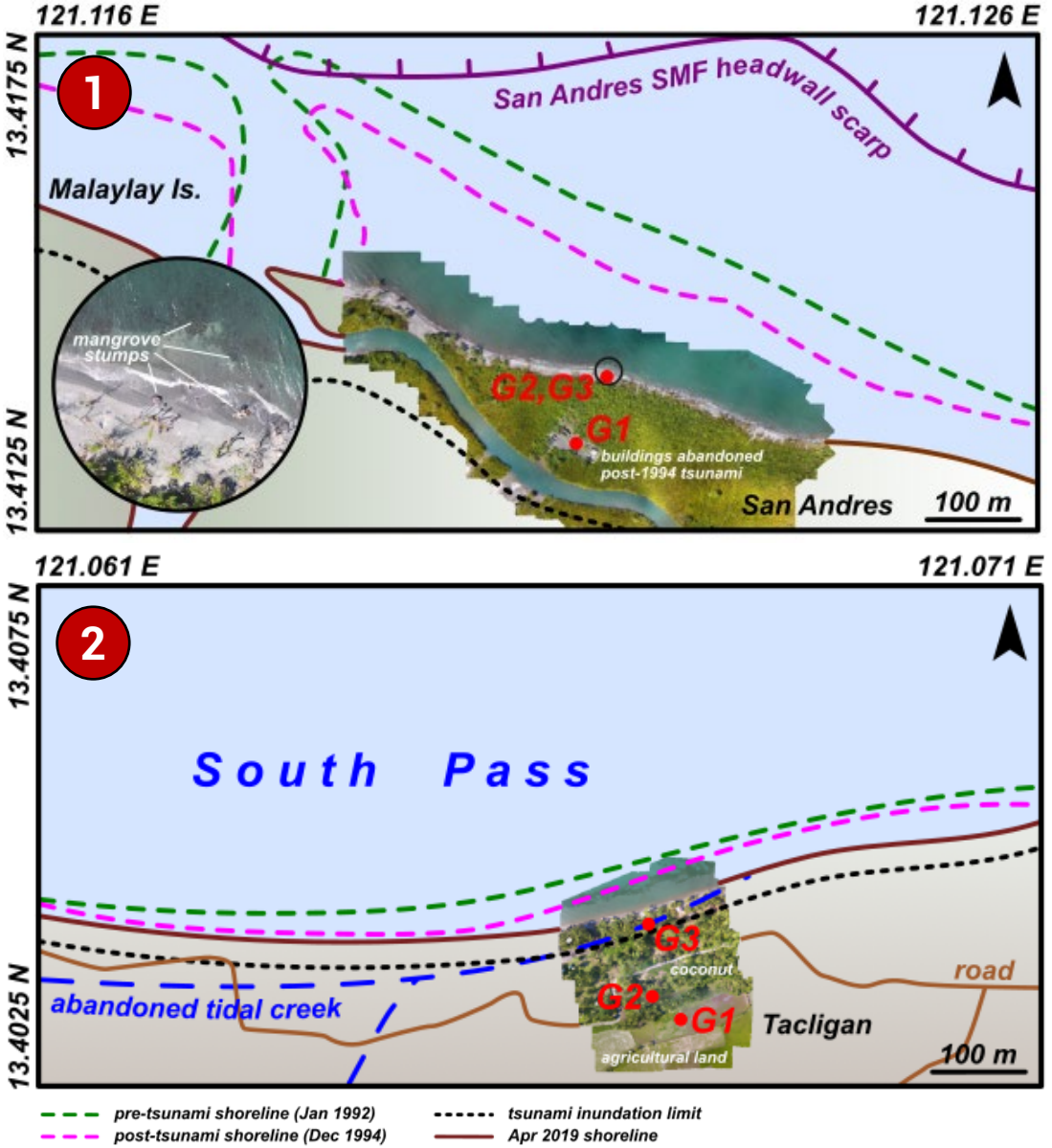




1 San Andres, Baco
<1 km S of the SASMF

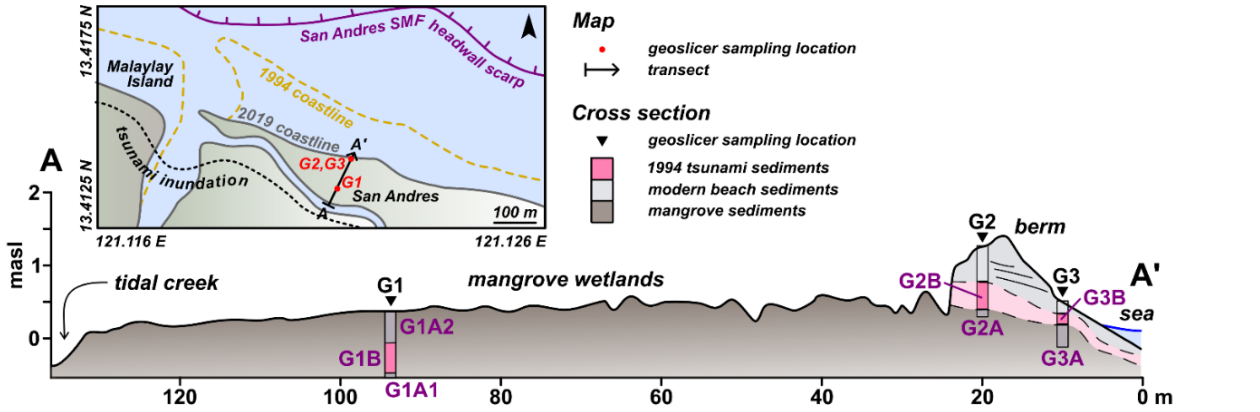
2 Tacligan, San Teodoro
~6 km WSW of the SASMF

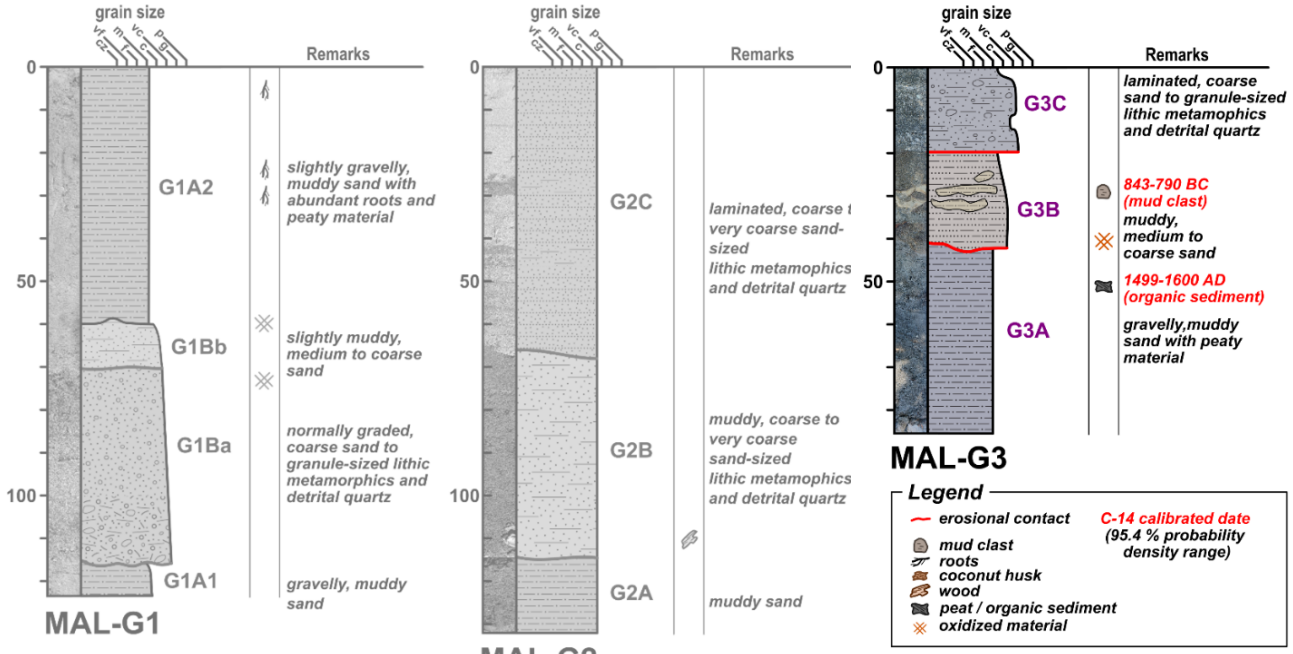
15 November 1994 at 3:15 AM (GMT+8)
Mw 7.1 strike-slip EQ (PHIVOLCS, 1994)
EQ-triggered submarine mass failure (Ramirez et al., 2022)



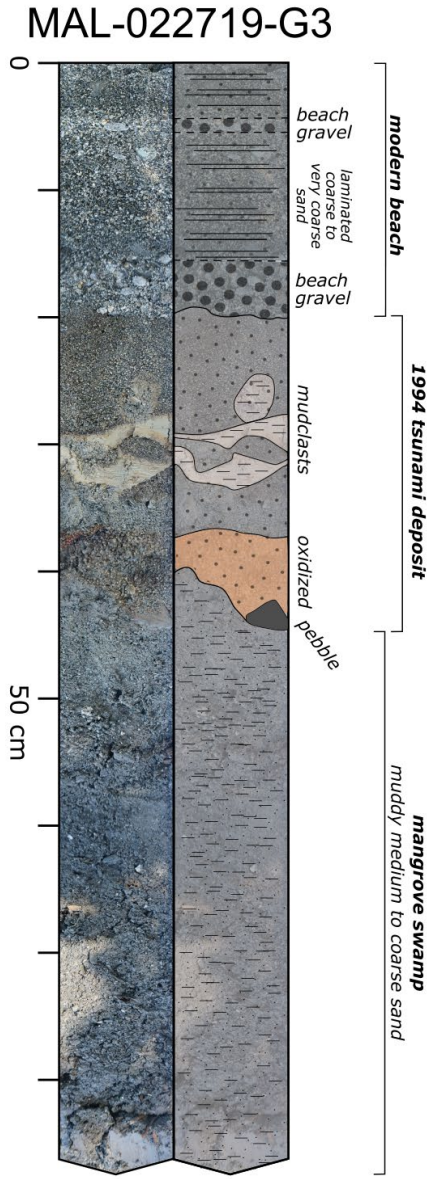
Ramirez et al., 2023, SCSTW-12

1994 Mindoro Tsunami Deposits





Ramirez et al., *In preparation*



Post-tsunami sediments
modern beach: *laminated, coarse to very coarse sand-sized lithic metamorphics and detrital quartz*

1994 tsunami deposit
~20-50 cm thick, normally graded, coarse sand to granule-sized lithic metamorphics and detrital quartz capped by slightly muddy, medium to coarse sand layer; contains mud clasts (mud clast is older than underlying mangrove sediments)

Background sediments mangrove wetland deposits: *gravelly and muddy, medium to coarse sand*

1994 Mindoro Tsunami Deposits

1 ***San Andres***

A: *Contact between the 1994 tsunami sediments (G1Ba) and underlying mangrove wetland deposits (G1A1)*

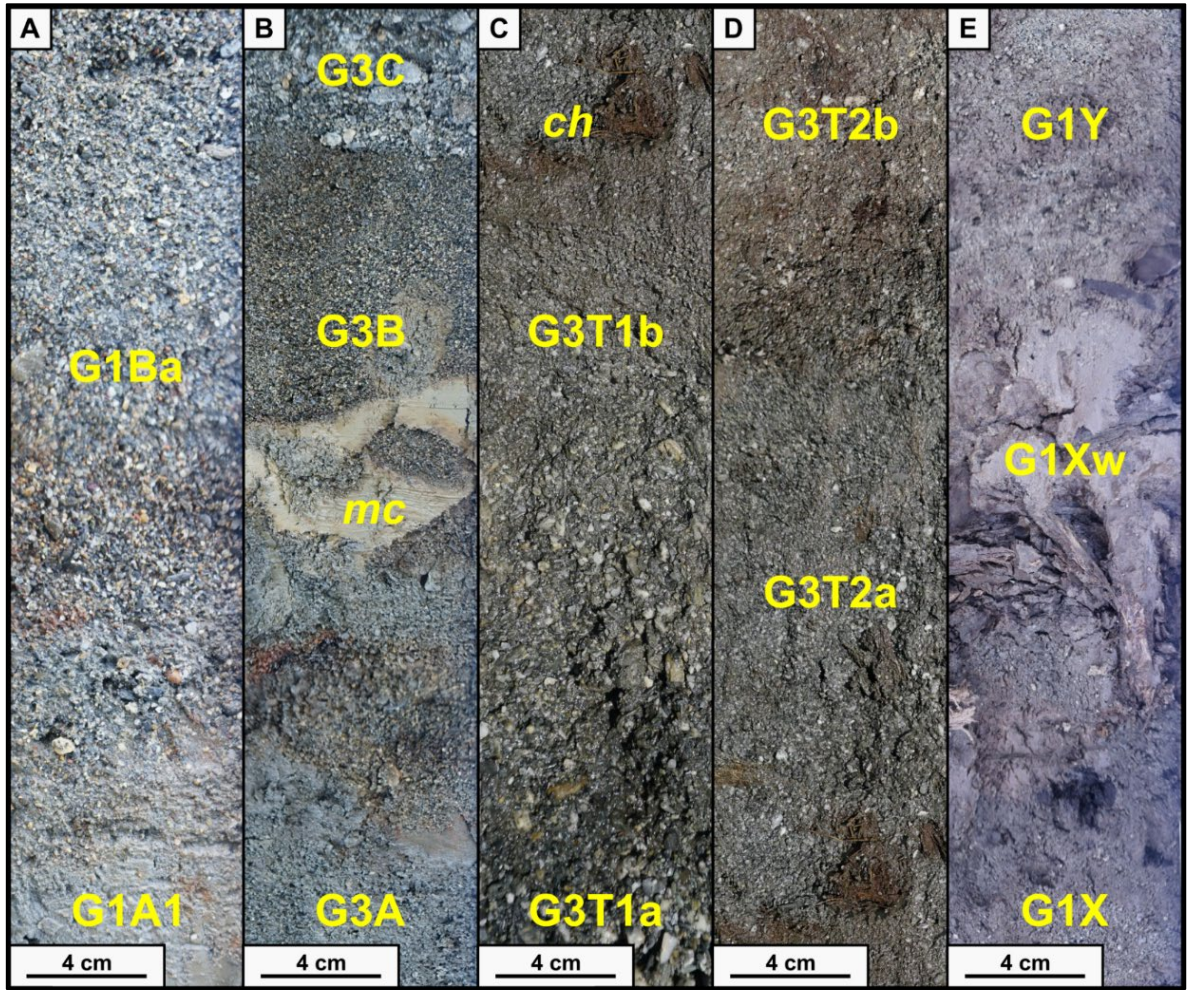
B: *The 1994 tsunami deposit with mud clasts (G3B), underlain by mangrove wetland deposits (G3A) and truncated by modern beach deposits (G3C)*

2 ***Tacligan***

C: *Couplet representing the 1st tsunami wave incursion*

D: *Couplet representing the 2nd tsunami wave incursion*

E: *Possible older extreme wave event deposit (G1Xw), ~130 m inland of present shoreline*

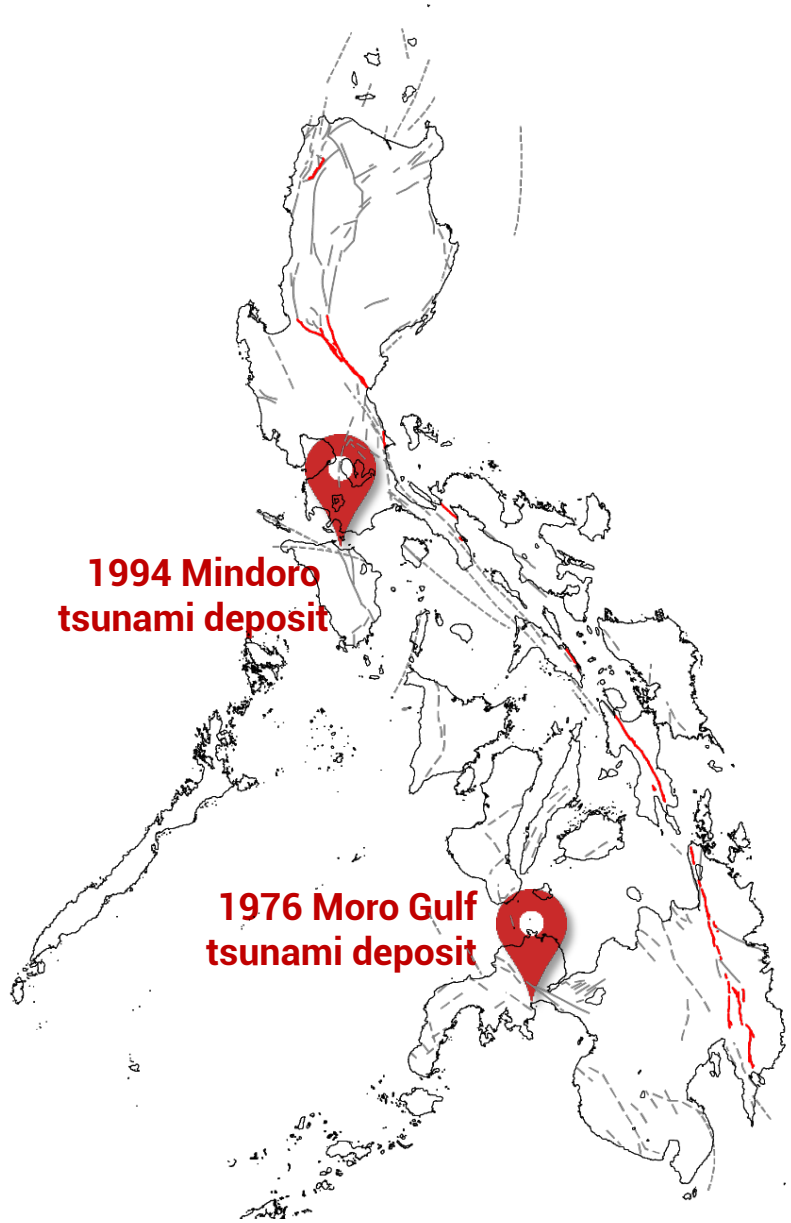


1994 tsunami deposits*: poorly sorted; slightly muddy (~1-10%) coarse sand to granule-sized lithic metamorphics and detrital quartz*

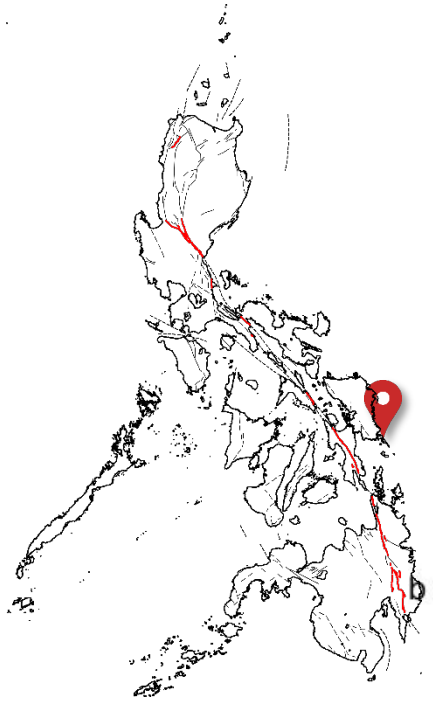
Ramirez et al., *In preparation*

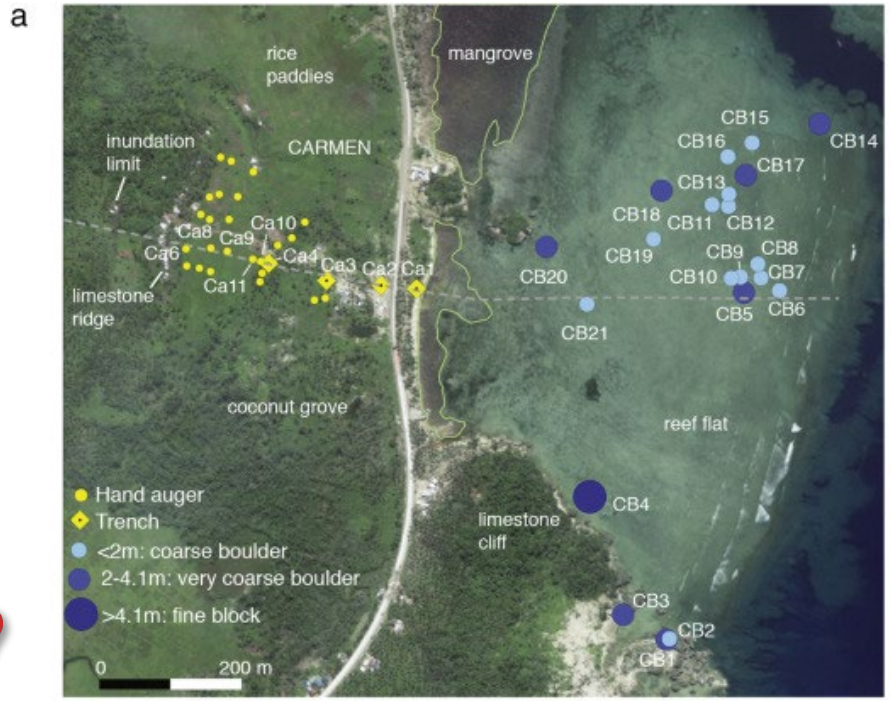
Washover Deposits of EMI Events in the Philippines

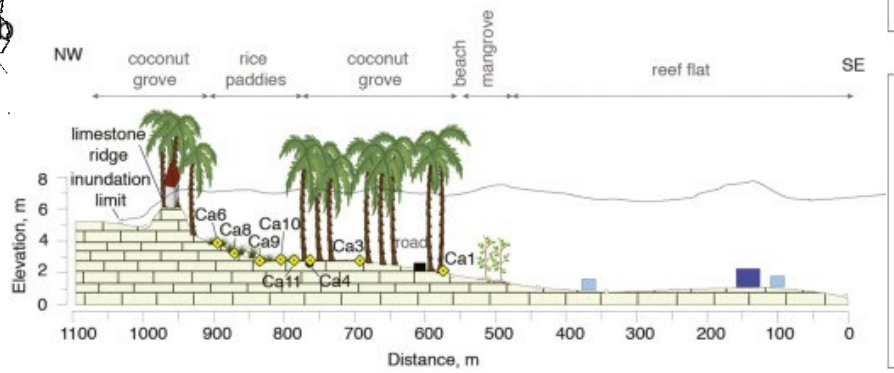
- Tsunami deposits at the two study sites are characterized by
  a) *poor sorting and coarser grain size than pre-event surface sediments (e.g., mangrove sediments, soil);*
  b) *basal erosional contacts;*
  c) *mud clasts; and*
  d) *sedimentary features of wave incursions.*

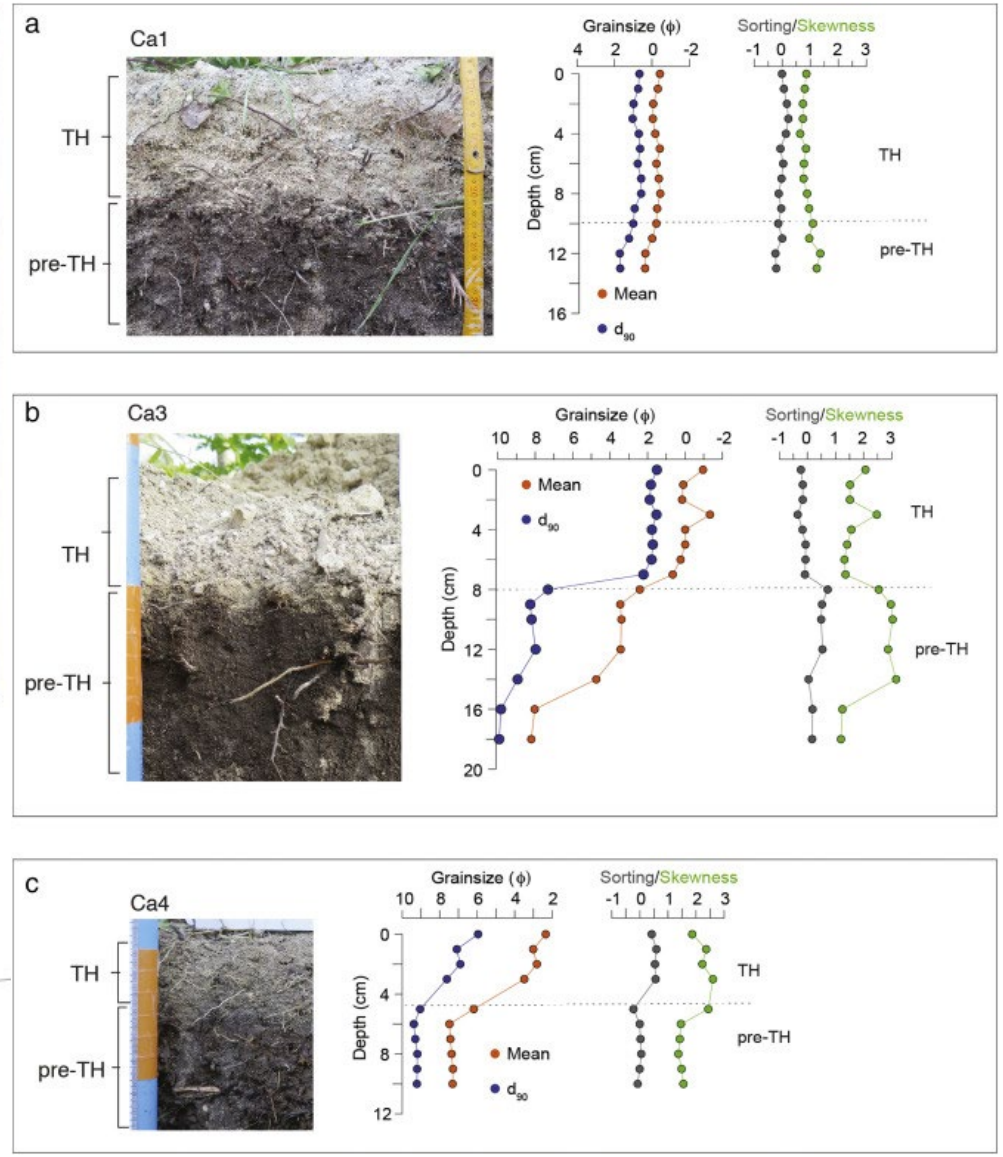


2013 TY Haiyan Storm Deposits









Soria et al., 2018, *Mar Geol*

Siargao Island Protected Landscape and Seascape



- largest marine protected area in the Philippines, covering approximately 278,914 hectares of terrestrial, wetland, and marine environments
- home to the largest continuous mangrove forest in the Philippines (notably in Del Carmen, recognized as a Ramsar Wetland of International Importance)

2021 Typhoon Rai (Odette)



https://science.nasa.gov

https://www.philstar.com AFP / Ferdinand Cabrera



ABS-CBN

News Entertainment Lifestyle Sports Metro.Style More BINI Sudoku

News

'It's no more': Philippine surfing paradise wiped out by typhoon

Ferdinandh Cabrera, Agence France-Presse

Published December 22, 2021 02:34 PM PHT | Updated December 22, 2021 08:30 PM PHT

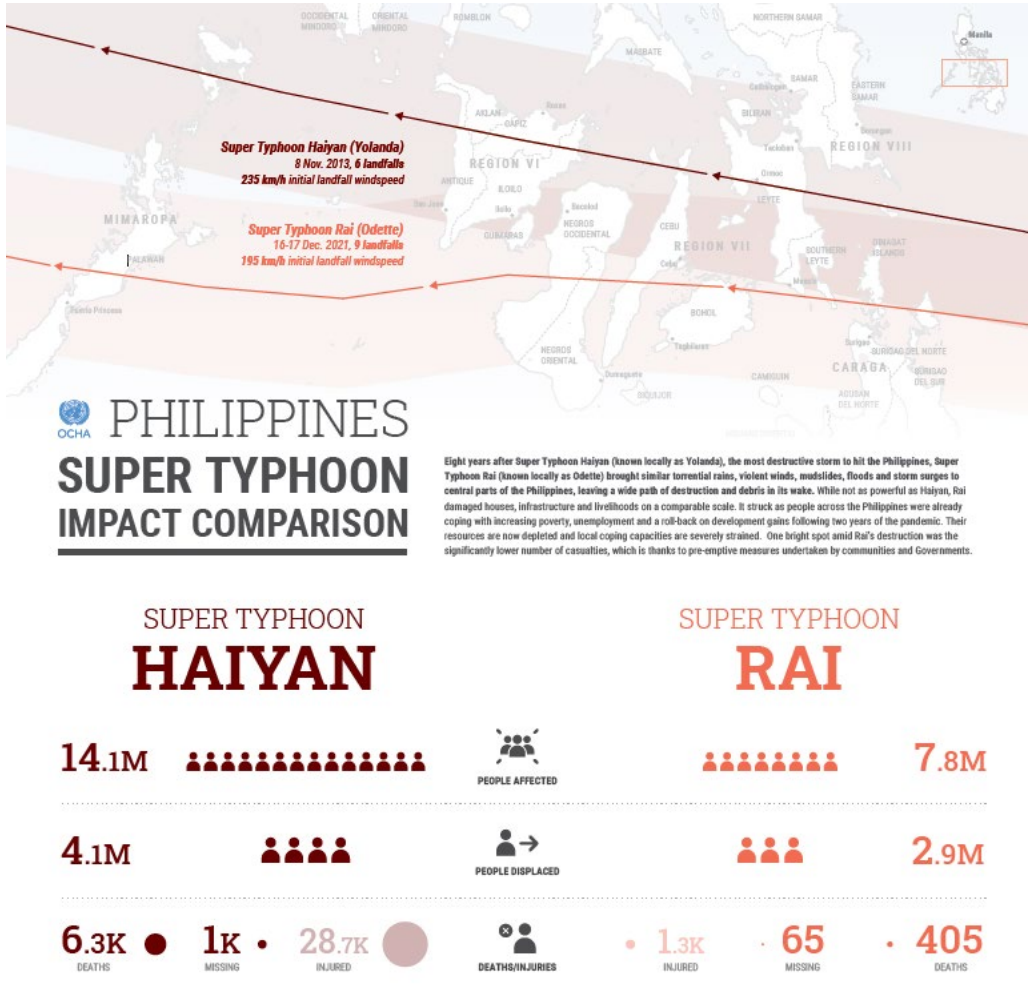


2021 Typhoon Rai (Odette)

2nd costliest typhoon in Philippine history behind TY Haiyan in 2013

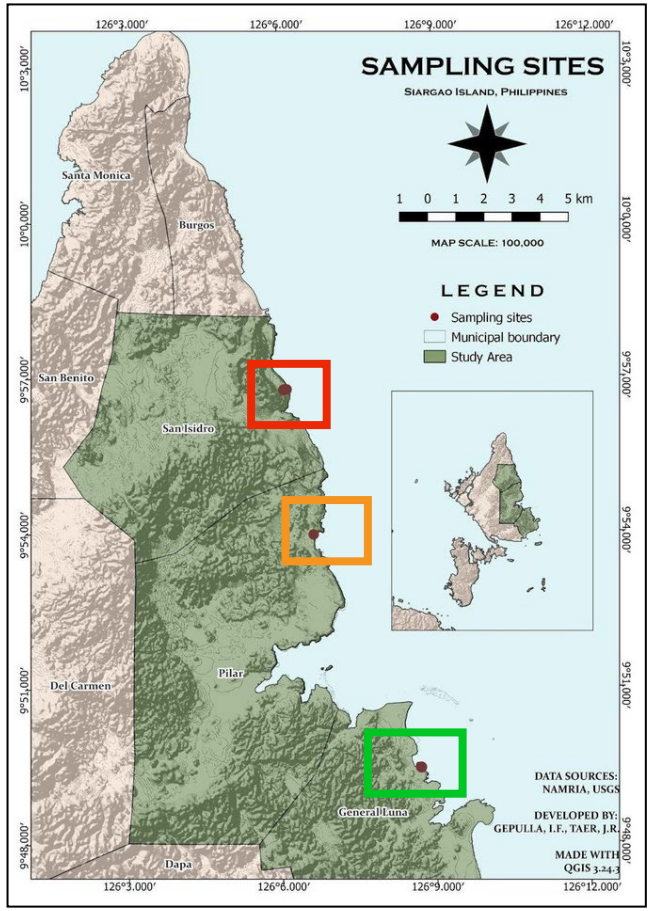


https://science.nasa.gov



UN Office for the Coordination of Humanitarian Affairs

Geomorphic Impacts of Typhoon Overwash



Taer and Gepulla, 2026,
Undergraduate thesis



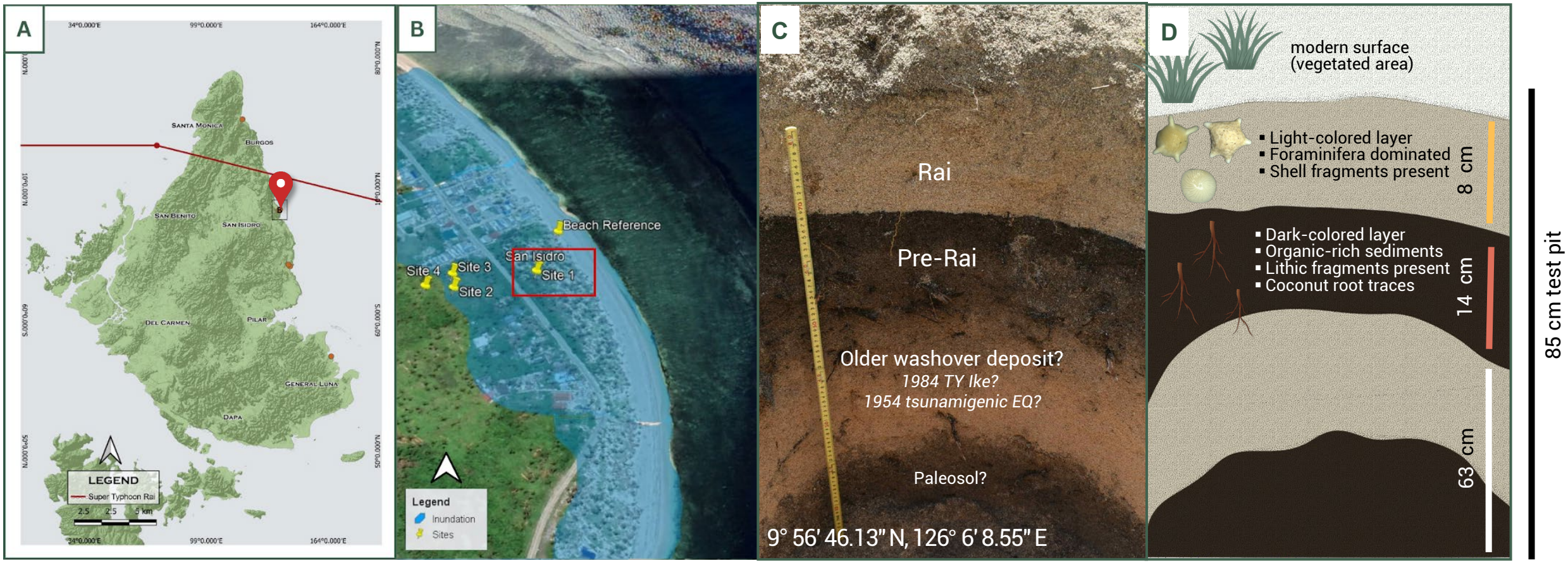
Geomorphic Impacts of Typhoon Overwash





2021 TY Rai (Odette) Washover Sediments

Site 1: SAN ISIDRO



Map of Siargao Island showing the (A) track of Typhoon Rai; (B) inundation map of the study site; (C) excavated test pit of the washover deposit; and (D) schematic section of the excavated test pit.

2021 TY Rai (Odette) Washover Sediments

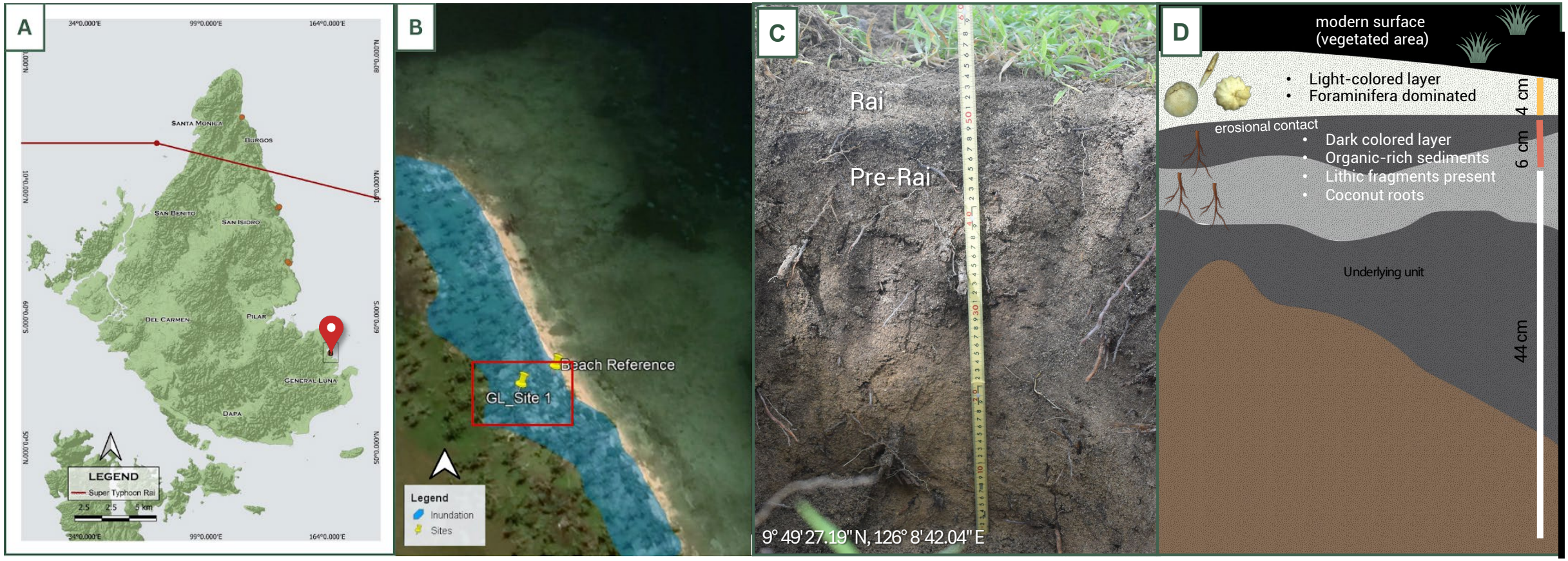
Site 2: PILAR



Map of Siargao Island showing the (A) track of Typhoon Rai; (B) inundation map of the study site; (C) excavated test pit of the washover deposit; and (D) schematic section of the excavated test pit.

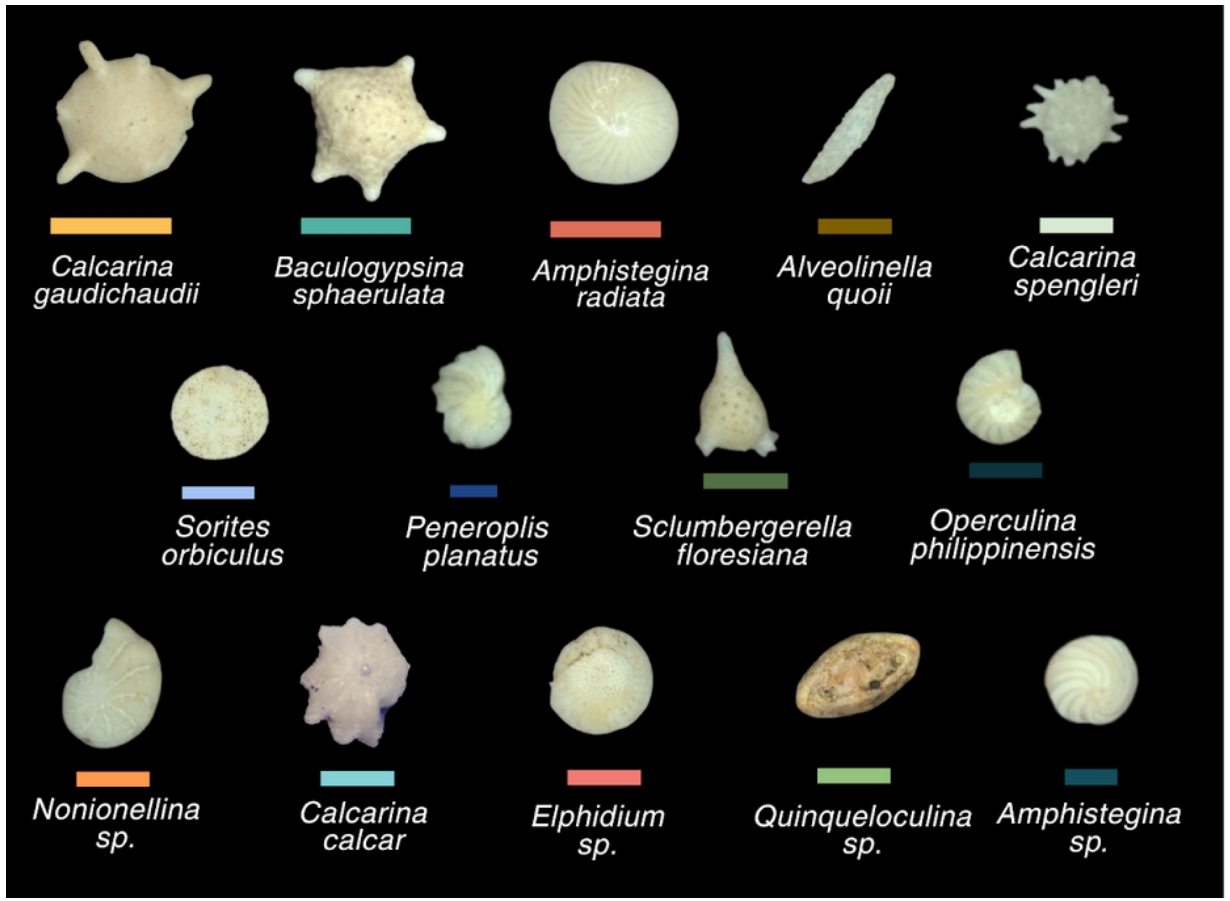
2021 TY Rai (Odette) Washover Sediments

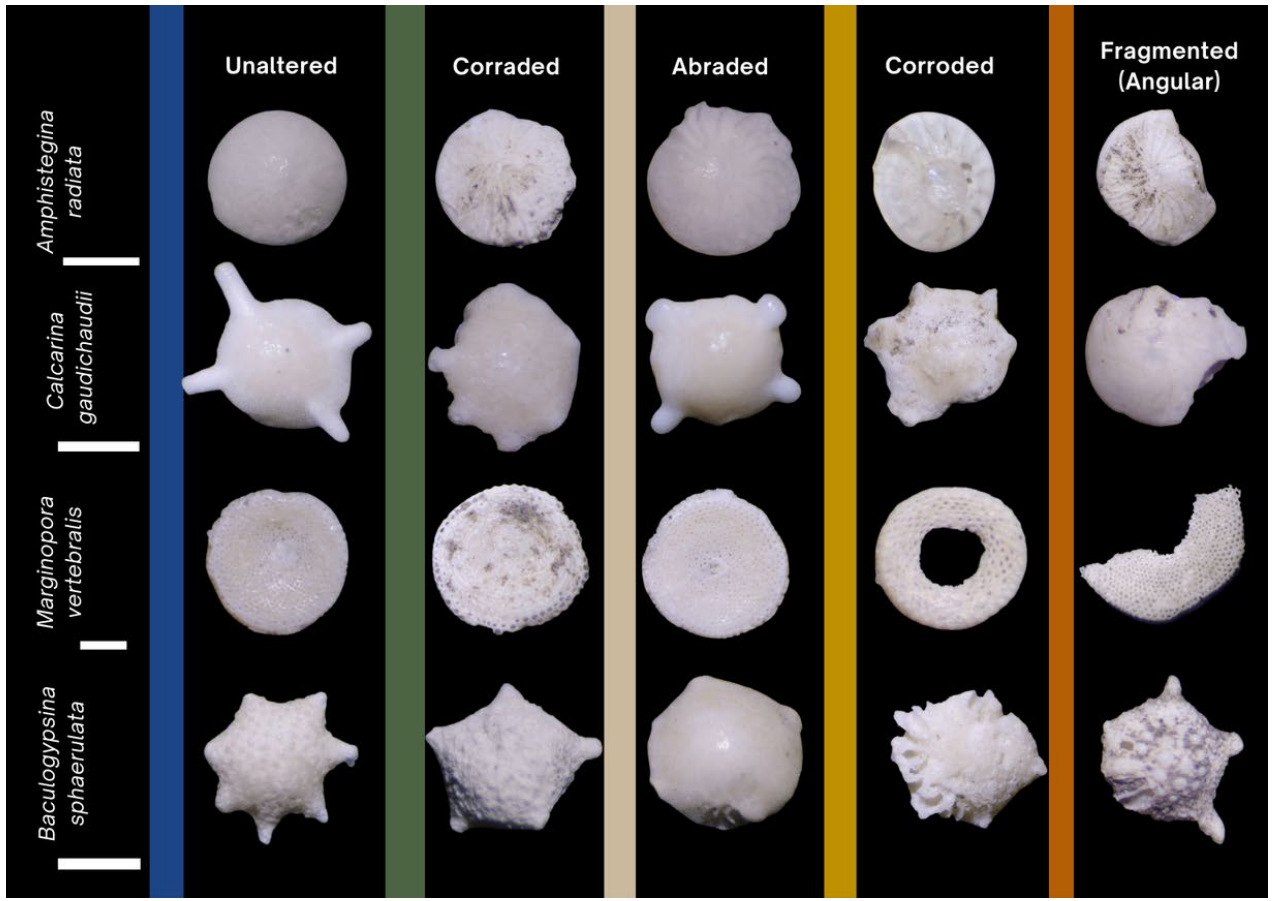
Site 3: GENERAL LUNA



Map of Siargao Island showing the (A) track of Typhoon Rai; (B) inundation map of the study site; (C) excavated test pit of the washover deposit; and (D) schematic section of the excavated test pit.

2021 TY Rai (Odette) Washover Sediments





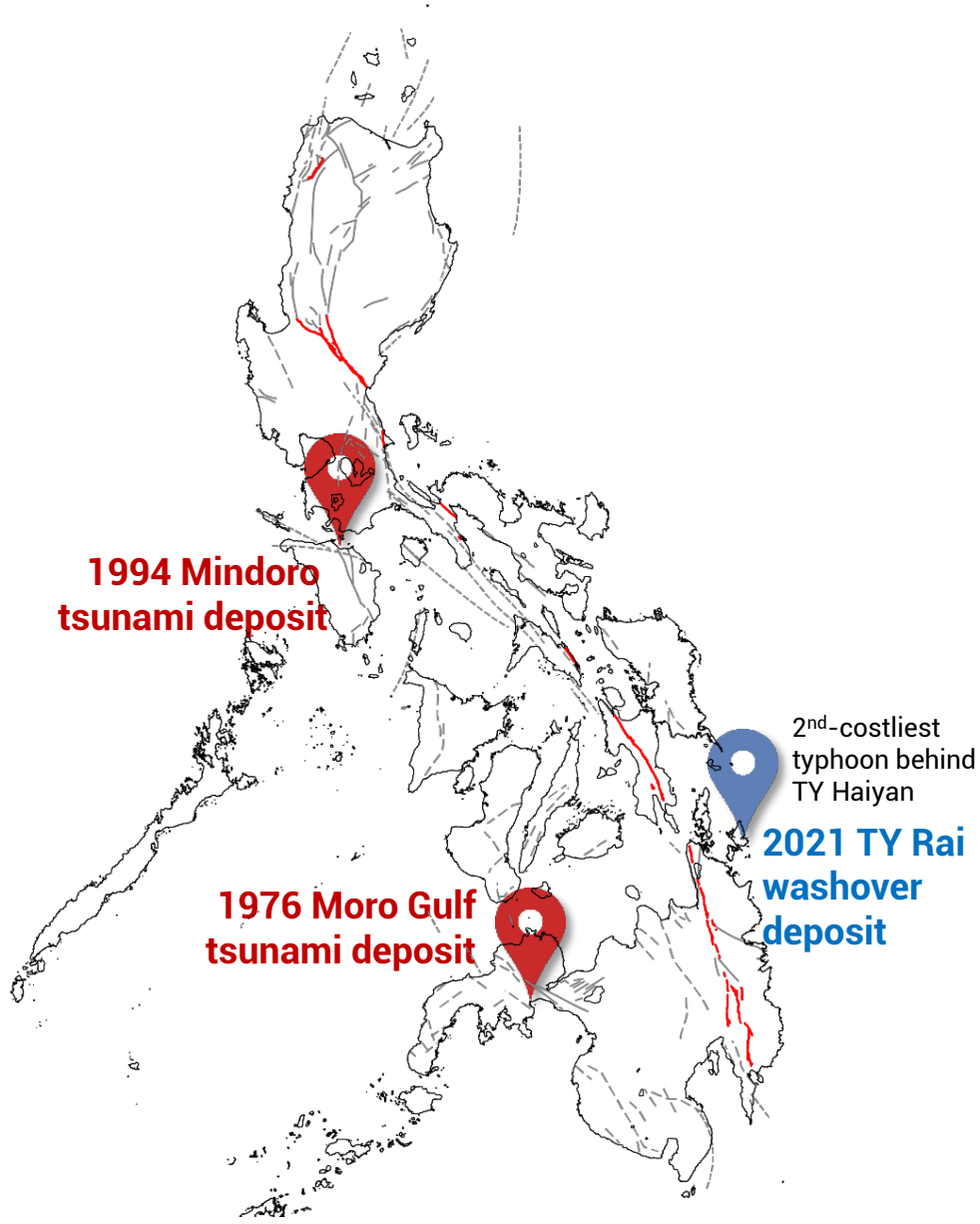
Foraminiferal assemblage suggests a primary source from the **nearshore environment** and reflects high-energy marine transport during overwash events.

Typhoon Rai forams are generally **abraded and fragmented tests**, while pre-Rai forams are **corraded and corroded**. Unaltered tests are found in TY Rai and beach sediments.

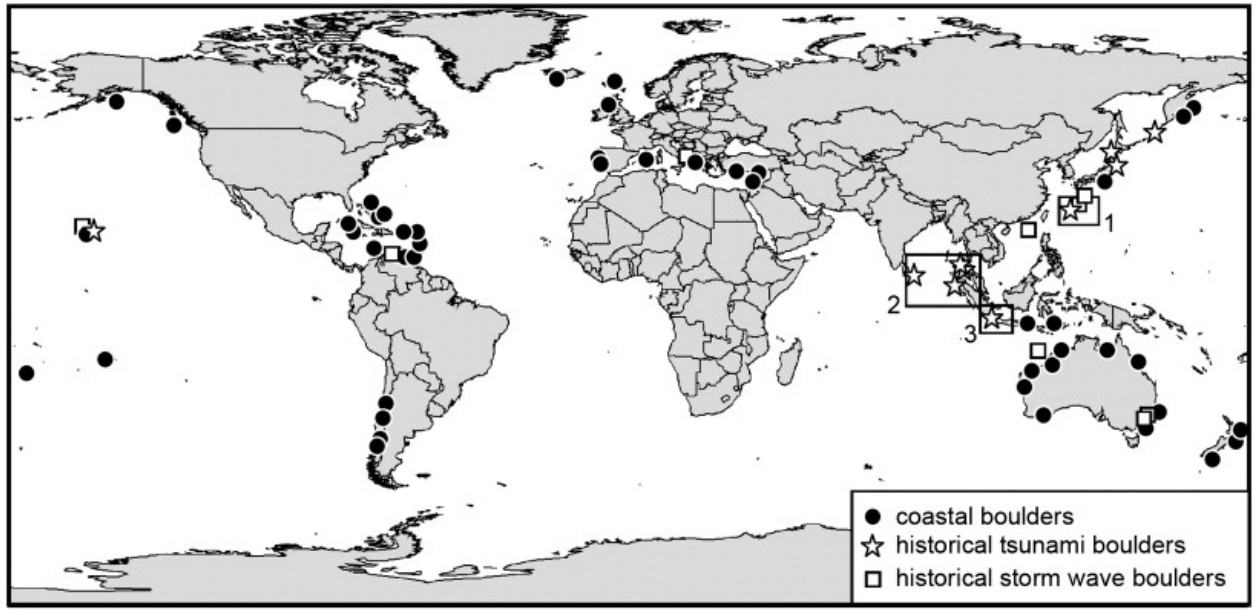
Washover Deposits of EMI Events in the Philippines

- Tsunami deposits at the two study sites are characterized by
  a) *poor sorting and coarser grain size than pre-event surface sediments (e.g., mangrove sediments, soil);*
  b) *basal erosional contacts;*
  c) *mud clasts; and*
  d) *sedimentary features of wave incursions.*

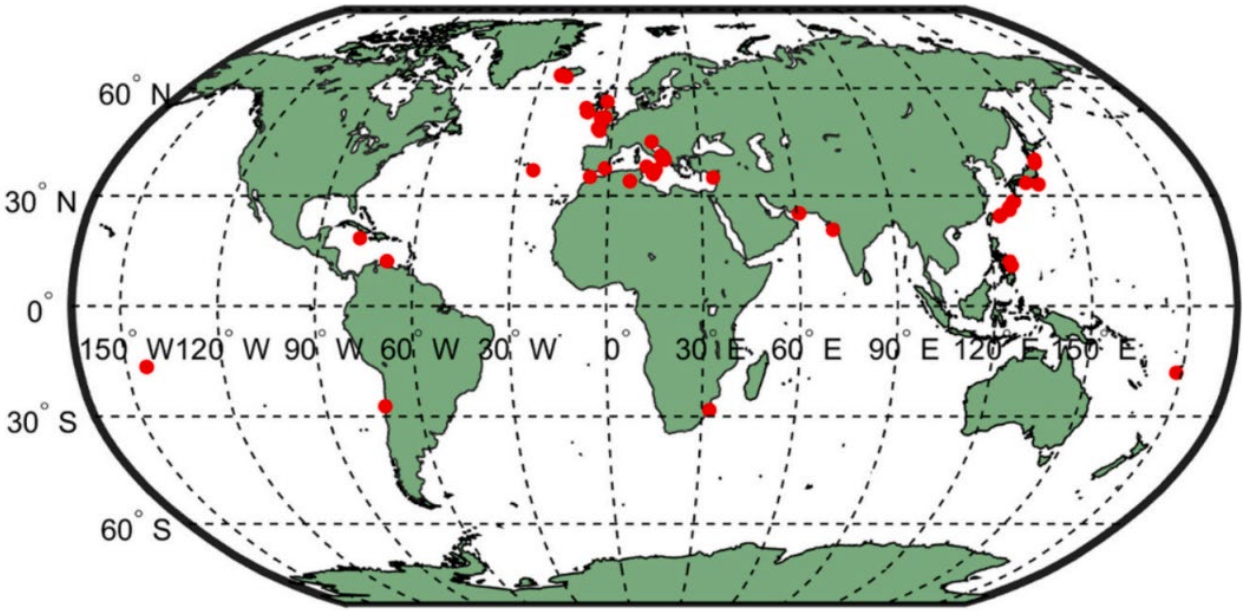
- Washover deposits of Typhoon Rai are generally coarse-grained, poorly sorted, and in sharp contact with the underlying soil. Foram assemblages are from the nearshore source.



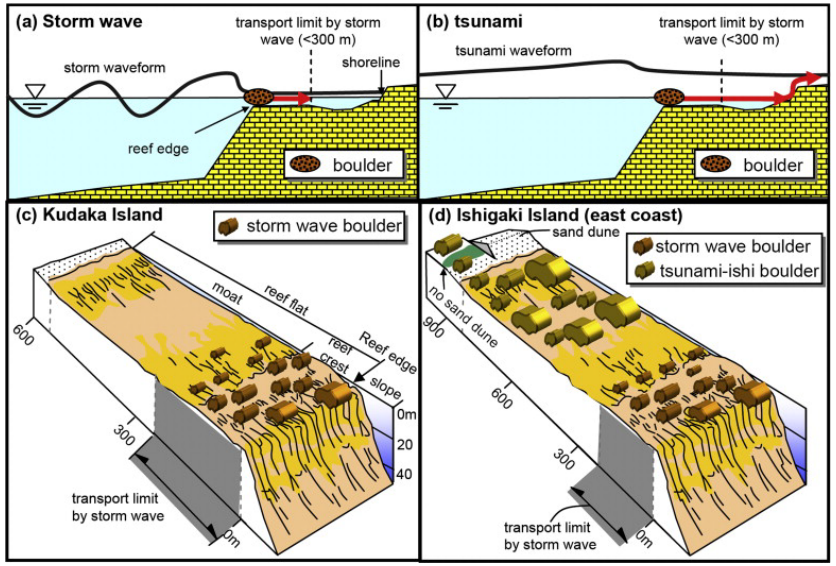
Coastal Boulders



Inundation Signatures on Rocky Coastlines Global Database (ISROC-DB)



Kennedy et al., 2026, *Mar Geol*

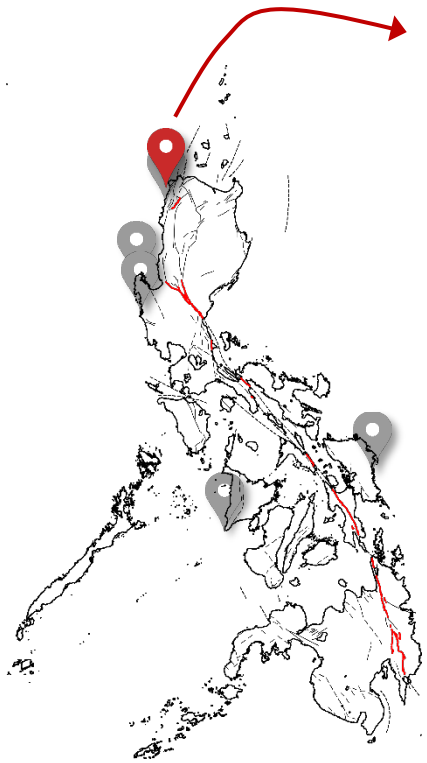


Goto et al., 2010, *Earth Sci Rev*



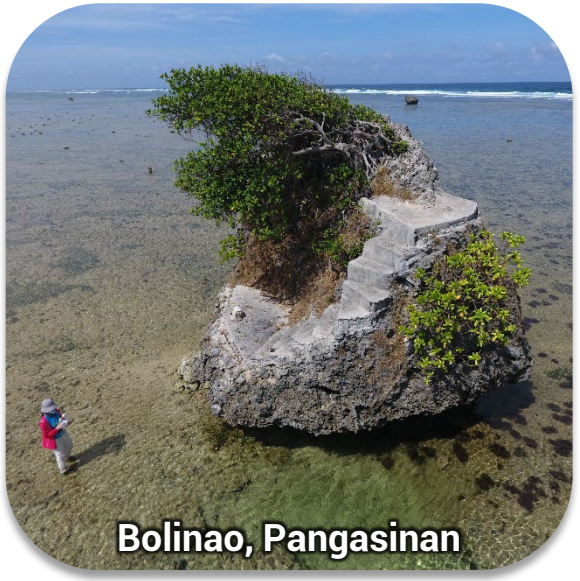


Coastal Boulders




Pasuquin, Ilocos Norte


Cabugao, Ilocos Sur


Bolinao, Pangasinan

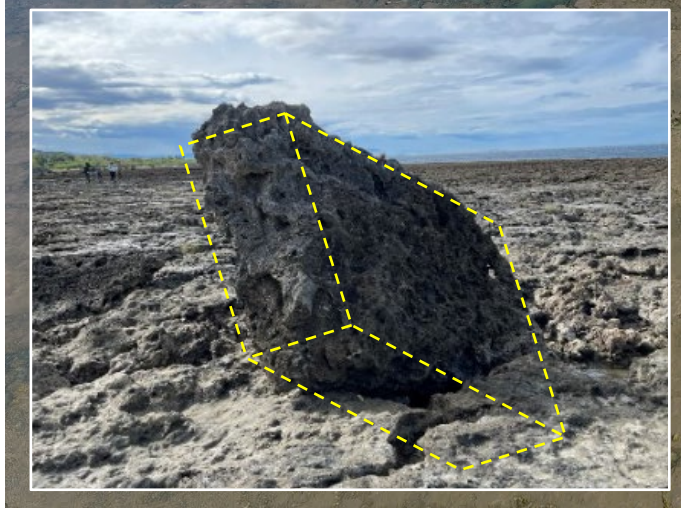

Sta. Cruz, Zambales


San Joaquin, Iloilo

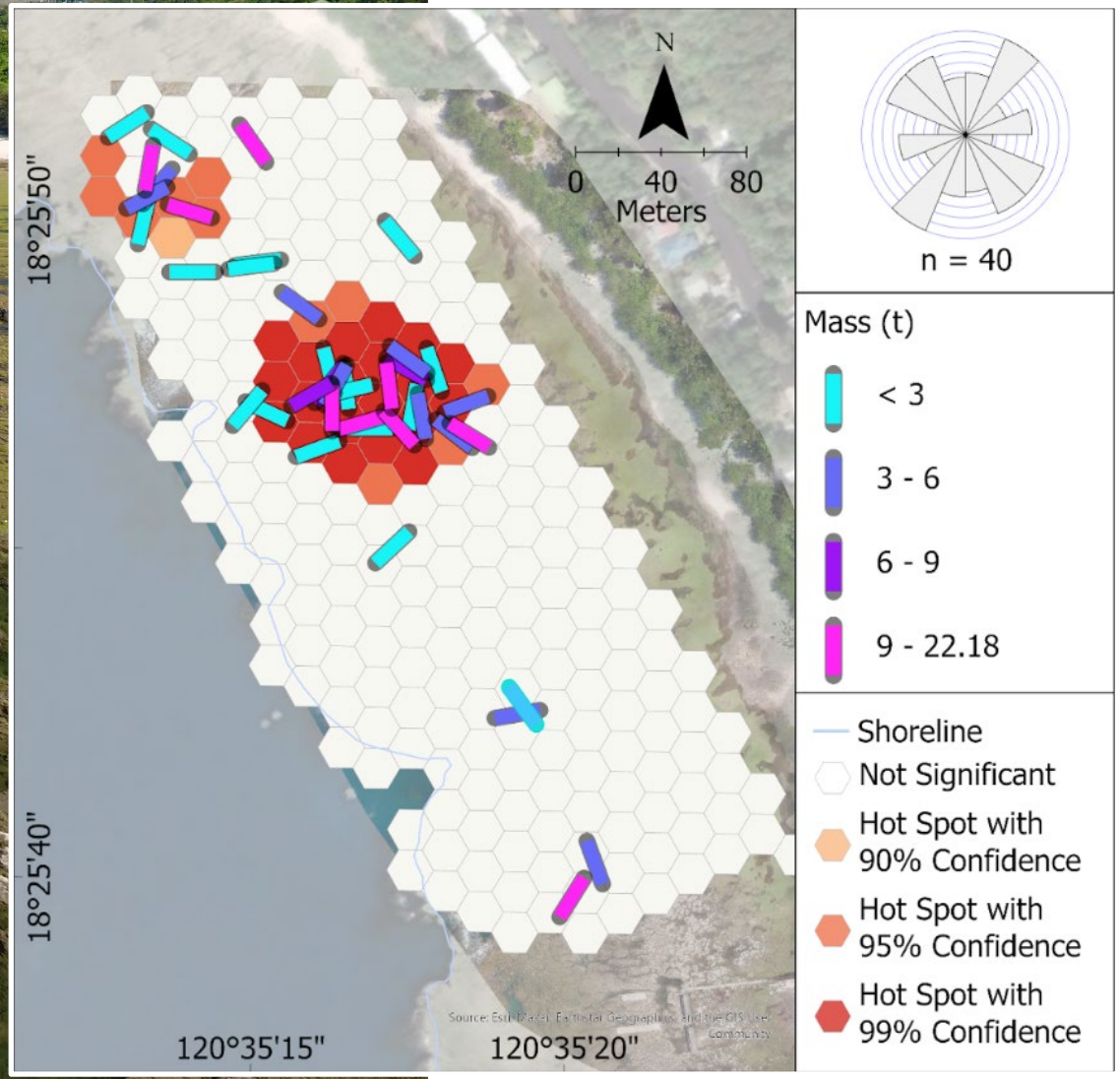

San Julian, Eastern Samar

Storm surge and tsunami(?) boulders

n=198 (flat block 30%, slab 24%)
Largest: a-axis ~5 m (31 tons)
Farthest distance from intertidal (fossil) reef edge: ~ 280 m

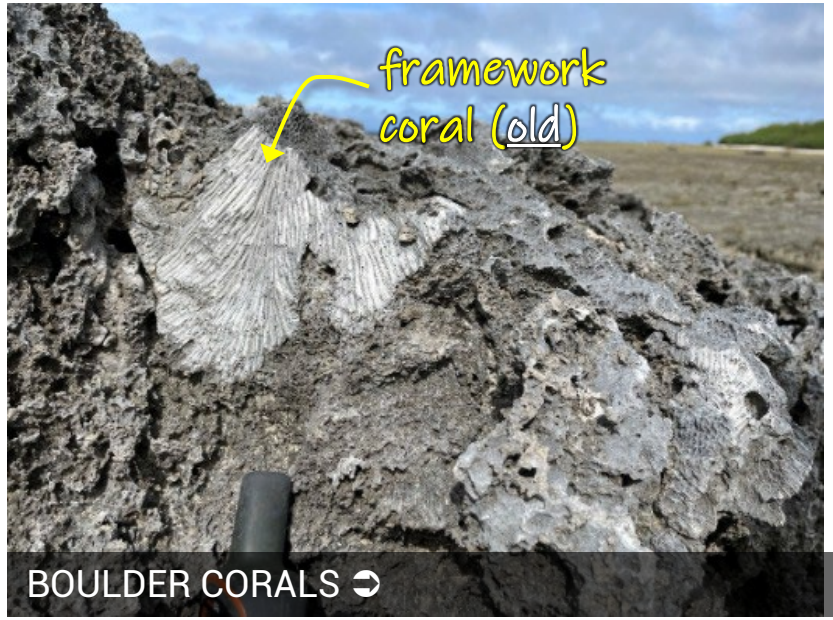


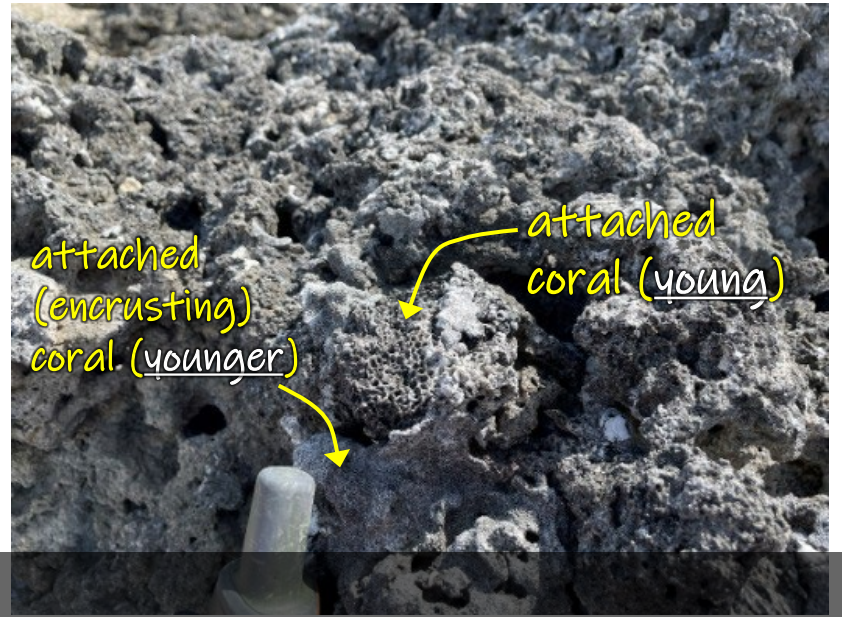
MFV rolling: 1.62–4.41 m/s
MFV lifting: 1.75–6.9 m/s
MWH: 2.25–3.96 m



Tubalado et al., 2026, *Mar Geol*

Coral Sampling and Dating







BOULDER CORALS ➲







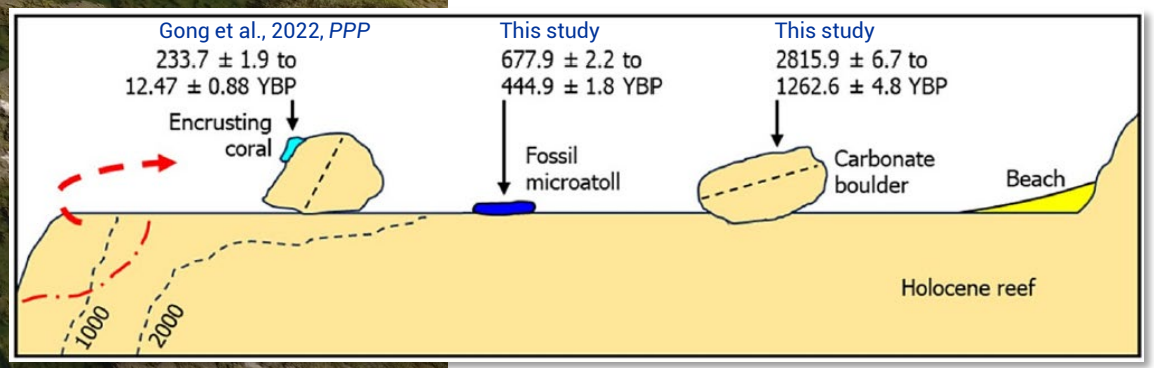
PLATFORM CORALS ➲

Storm surge and tsunami(?) boulders

n=198 (flat block 30%, slab 24%)
Largest: a-axis ~5 m (31 tons)
Farthest distance from intertidal (fossil) reef edge: ~ 280 m

444.9 ±1.8
522.9 ±2.0
1262.6 ±4.8
575.3 ±2.2
1668 ±12
492.3 ±2.5
677.9 ±2.2
1932.7 ±5.5
1933 ±15; 2542.9 ±5.7
1934.4 ±9.1
477.3 ± 1.6
2401.3 ±7
2207.6 ±6.4
2815.9 ± 6.7



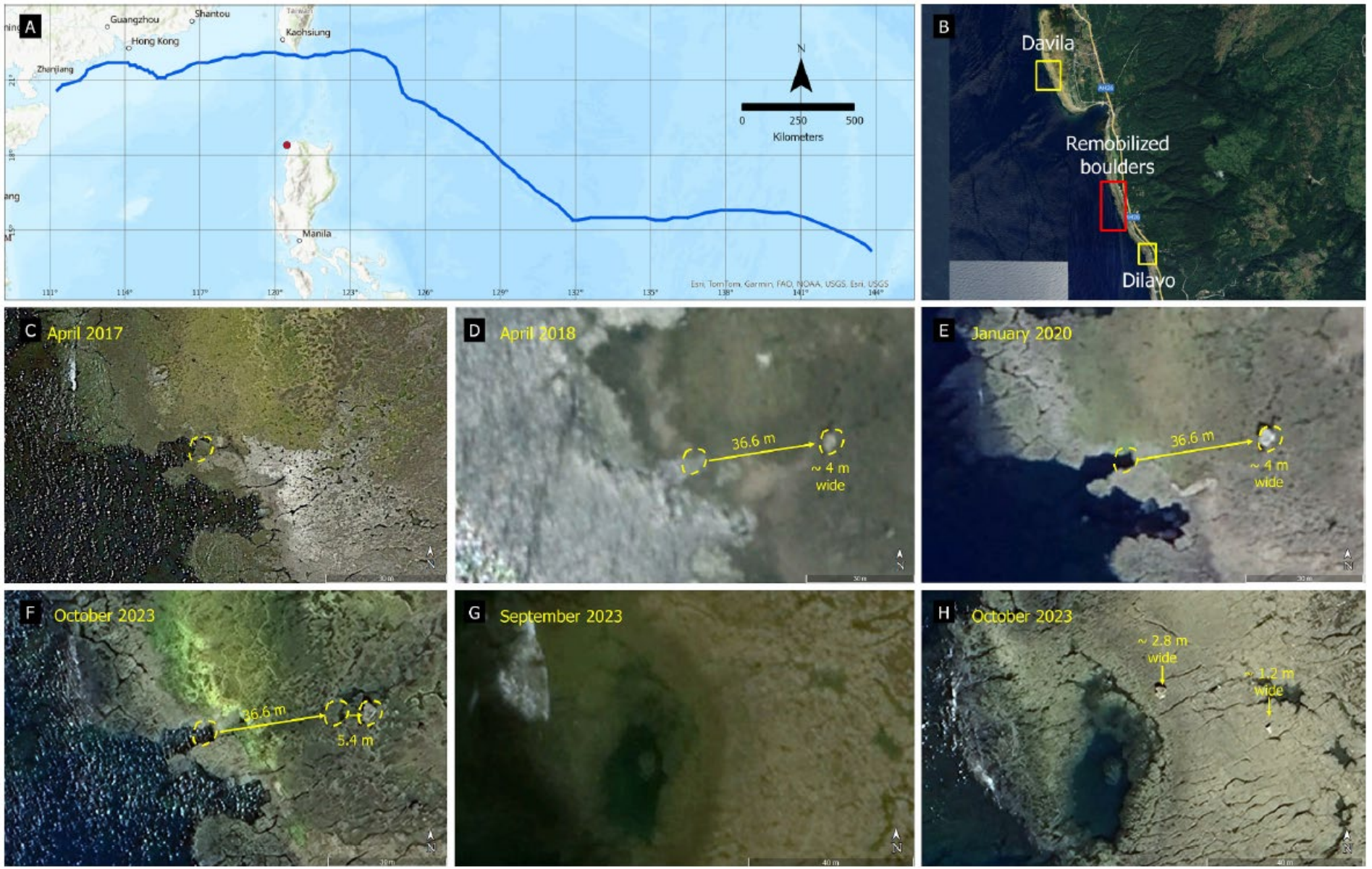


- Ages correlate with coral samples collected on nearby emergent platforms
- Uplift of reef platform between 440~680 years ago

*Thorium-230 ages are in 'yr BP'

Tubalado et al., 2026, *Mar Geol*

Boulder Remobilization by Typhoons



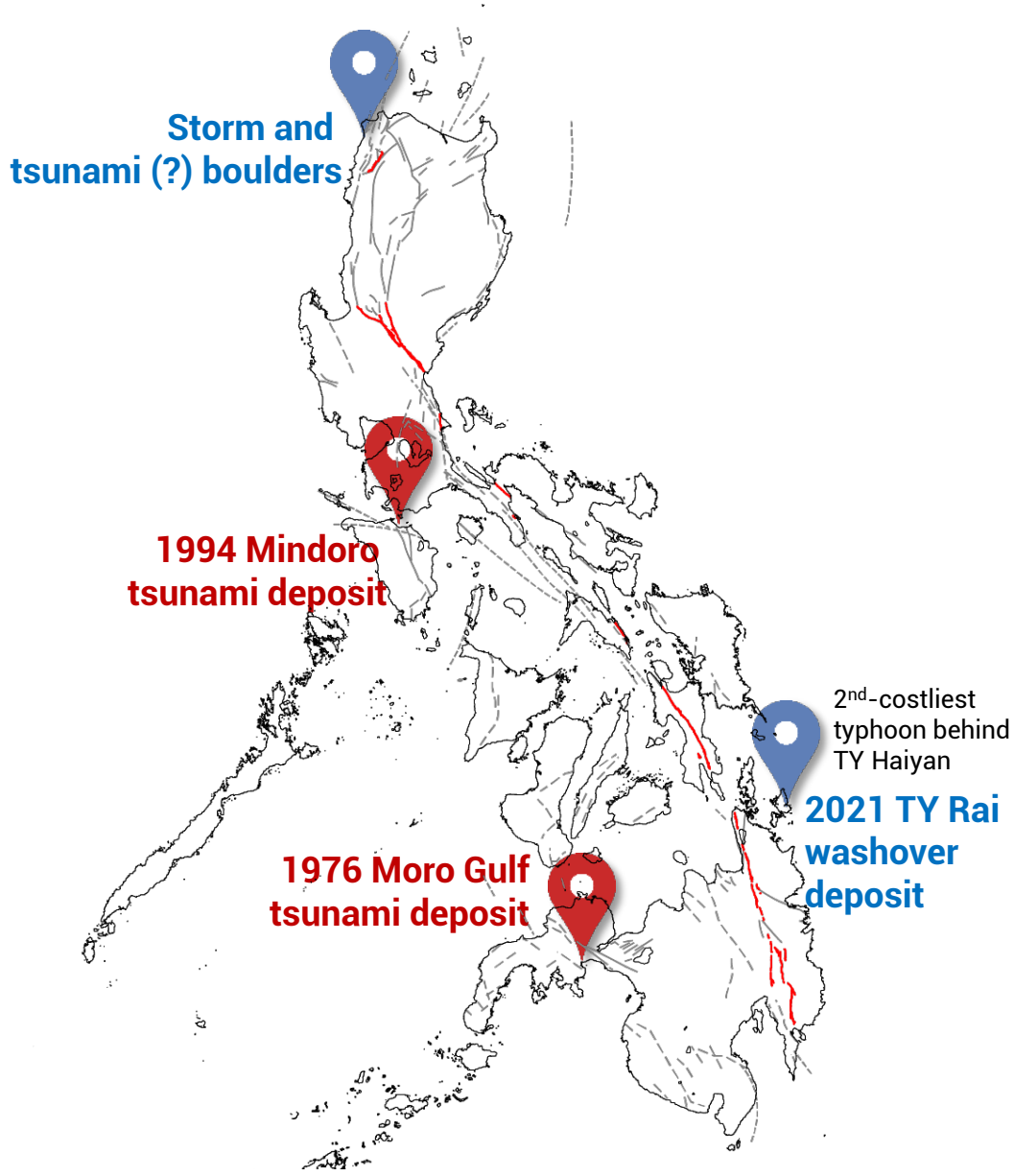
Tubalado et al., 2026, *Mar Geol*

Washover Deposits of EMI Events in the Philippines

- Tsunami deposits at the two study sites are characterized by
  a) *poor sorting and coarser grain size than pre-event surface sediments (e.g., mangrove sediments, soil);*
  b) *basal erosional contacts;*
  c) *mud clasts; and*
  d) *sedimentary features of wave incursions.*

- Washover deposits of Typhoon Rai are generally coarse-grained, poorly sorted, and in sharp contact with the underlying soil. Foram assemblages are from the nearshore source.

- Large carbonate boulders can be emplaced by both tsunami and storm surge. Recent typhoons have remobilized the boulders, posing challenges in modeling emplacement mechanisms.



Challenges in Washover Deposit Research

- **Distinguishing tsunami vs. storm surge deposits**
  - overlapping characteristics of processes and deposits; proxy limitations
- **Geographic variability; preservation bias**
  - geologic and climate setting; selective preservation/erosion; taphonomic effects
- **Sampling bias; site accessibility (e.g., private access, land disputes)**
  - sampling density
- **Temporal resolution; dating uncertainties**
  - limited availability of dateable material; reworking of sediments
- **Process modeling (hydrodynamics, sediment transport)**
  - parameterization; scarce validation data

Washover deposit research remains an active and evolving field, requiring continued development of new techniques and approaches to improve our understanding of coastal hazards and their geological records.

Summary

- Fine (sand) and coarse (boulder) washover deposits provide insights into the characteristics of extreme (high-energy) marine inundation events. *Detailed observations are important.*

- Distinguishing tsunami and storm surge deposits remains a challenge, but integrating multiple proxies and modeling techniques improves our ability to differentiate their washover sediments. *Establish baseline data.*

- Determining the emplacement mechanism of large coastal boulders is a complex process. Radiometric dating is limited by coral availability, while process modeling faces fundamental challenges (e.g., disputed equations). *Models rely on good input data.*

Thank You!

- Prof. Kenji Satake and the Department of Earth Sciences, National Central University
- Department of Science and Technology
- University of the Philippines
- All our collaborators!

The Geological Record of Extreme Marine Inundation Events: Clues From Coastal Sediments and Boulders

Noelynna T. Ramos, Sheinna May D. Claro, Alec Benjamin G. Ramirez, Robelyn Z. Mangahas-Flores, Edrian M. Tubalado, Lyndon P. Nawanao Jr., Ace Matthew F. Cantillep, Jemimah Caryl C. Abalajon, Irene Fe D. Gepulla, Jennie Raika O. Taer, Patrick Sam M. Buenavista, Nichole Anthony D. Pacle, Daisuke Ishimura, Adam D. Switzer, Chuan-Chou Shen, Jessica Pilarczyk, and Kenji Satake

Thank You!


1976 Moro Gulf tsunami
1994 Mindoro tsunami


Eastern Samar washover


2021 Typhoon Rai deposits
2021 Typhoon Rai deposits