Coastal Boulder Deposits as a Long-Lived Signature of Historical Wave Climate

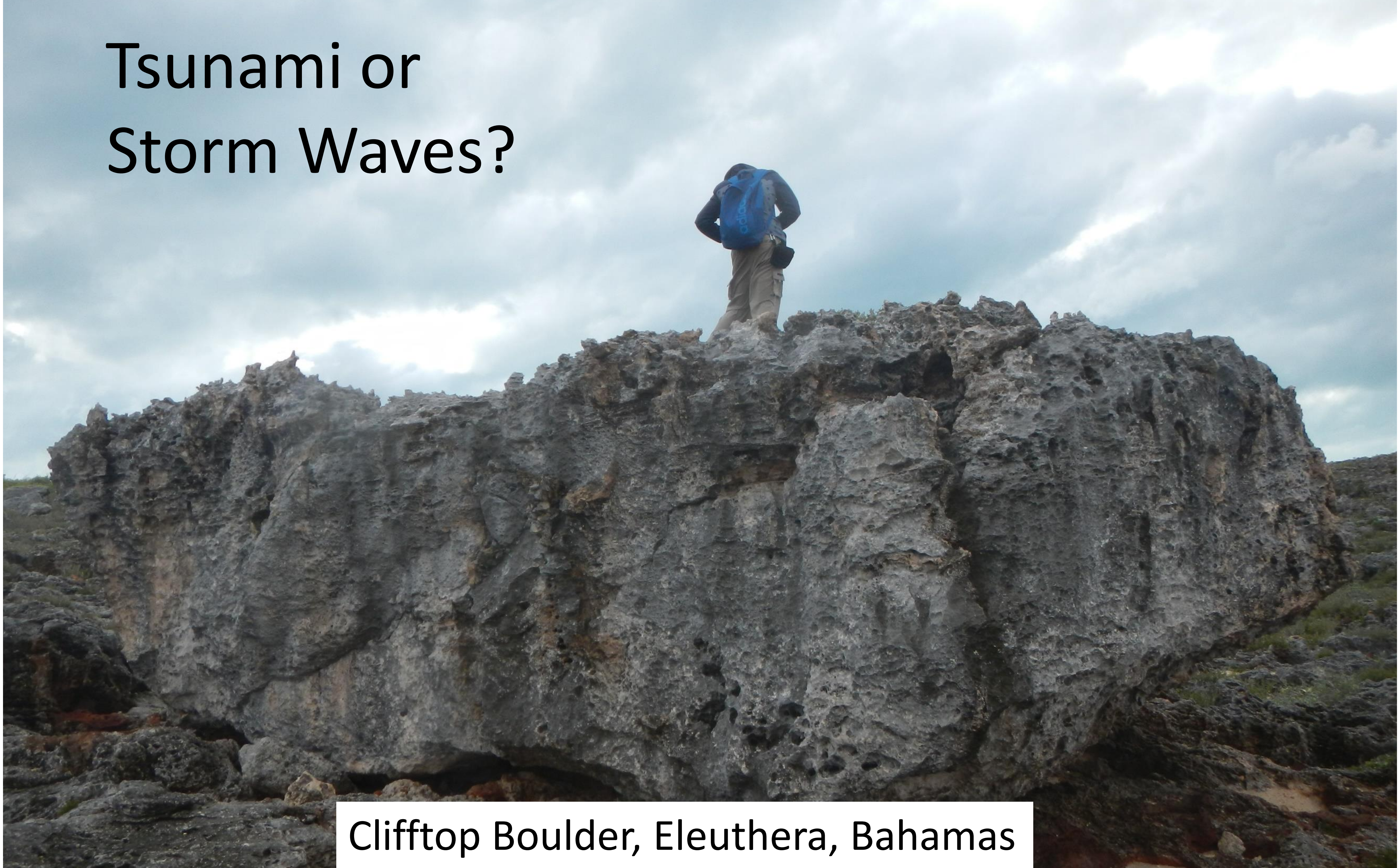
Andrew Kennedy and Melissa Berke, University of Notre Dame
Ronadh Cox, Williams College
Max Engel, Heidelberg University
Greg Guannel, University of the Virgin Islands
Annie Lau, Queensland University
Nobuhito Mori, Kyoto University

NSF

3RD INTERNATIONAL WORKSHOP ON
Waves, Storm Surges, and Coastal Hazards

THE NAUGHTON FOUNDATION

Tsunami or Storm Waves?



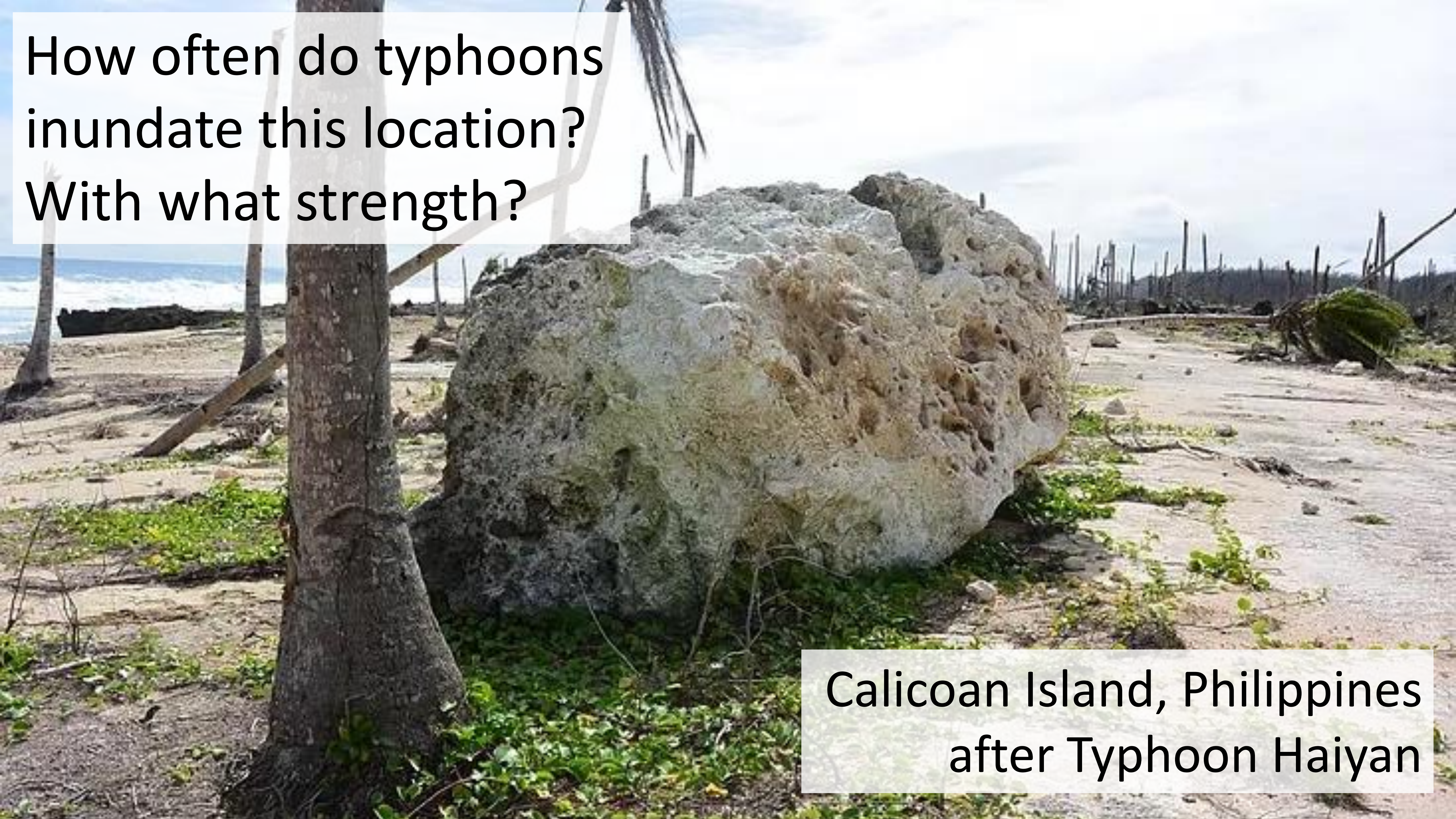
Clifftop Boulder, Eleuthera, Bahamas

How is this deposit related to wave climate?

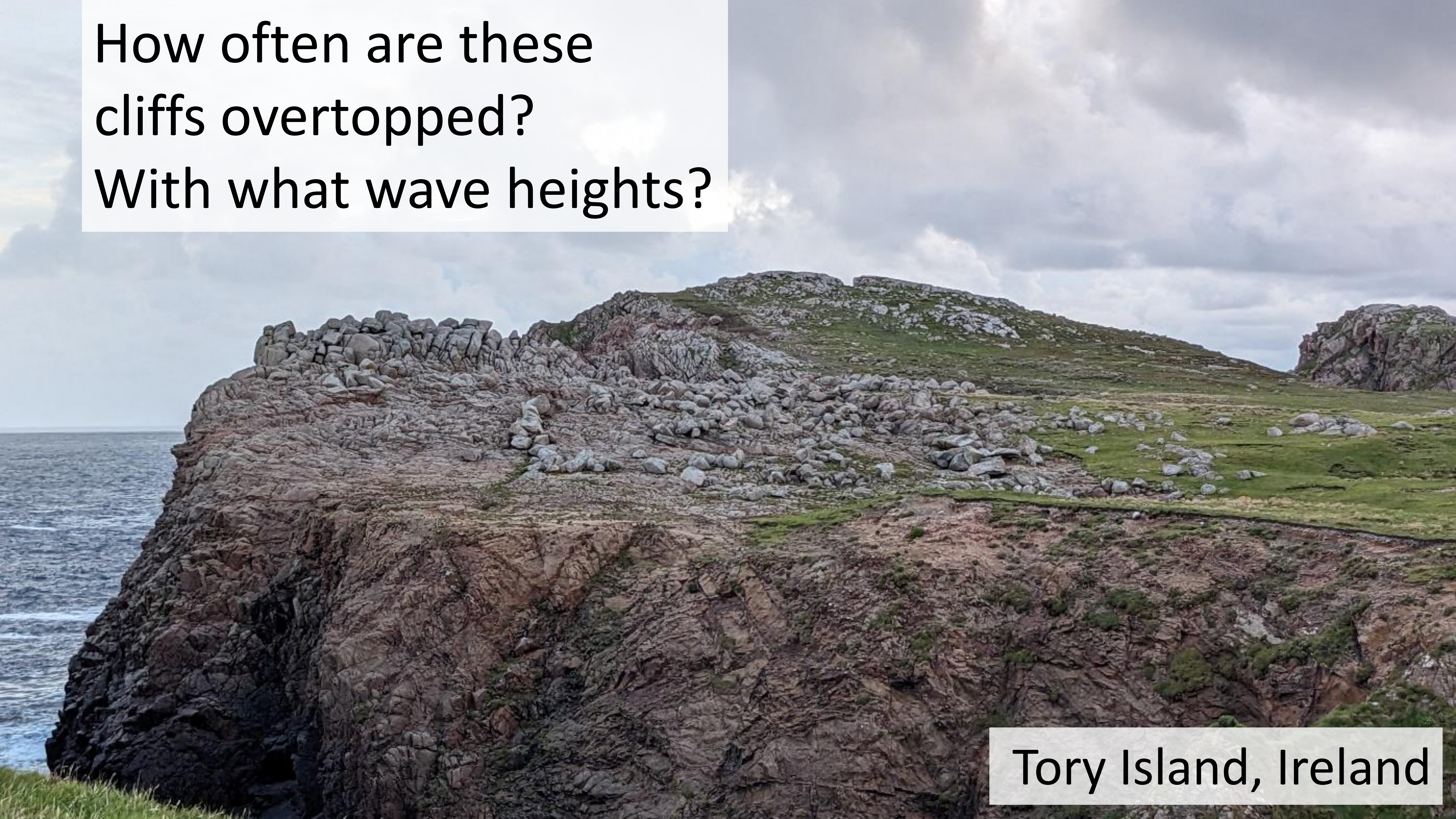
Inishmore, Ireland


What is the hurricane wave climate here?
Eleuthera, Bahamas

How often do typhoons inundate this location? With what strength?



Calicoan Island, Philippines after Typhoon Haiyan


How often are these cliffs overtopped?
With what wave heights?
Tory Island, Ireland

What is the inundation history of this location?
What was the wave climate?

Also Tory Island

The Fundamental Questions

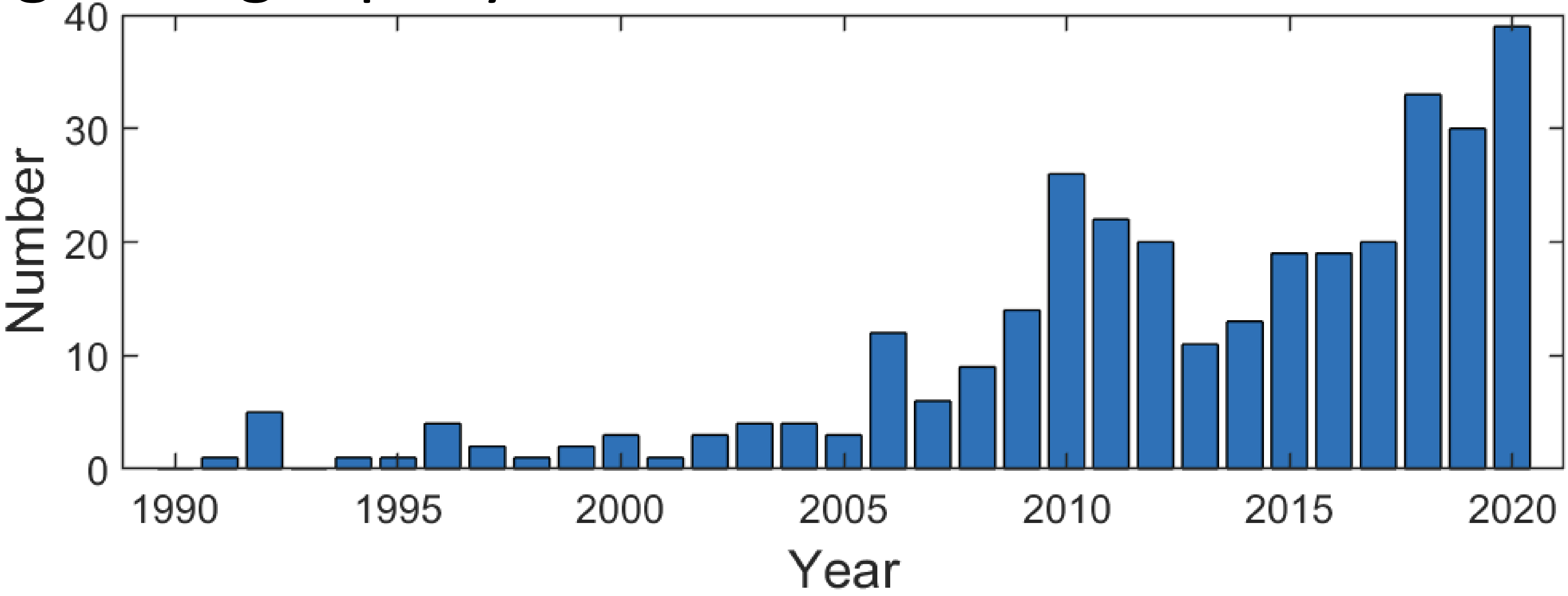
Given a Coastal Boulder Deposit with no direct observations or historical record:

- Was it generated by a tsunami, storm wave, or other?
  - What was the event magnitude?
  - How often did (do) these events occur?
- What does this tell us about the climatology and paleoclimatology in this area?
- How can we apply these lessons at other sites?

The Fundamental Answers

We cannot answer with confidence, to varying degrees

- Coastal Boulder Deposit studies are a new field, and growing rapidly



We need objective, general criteria that can be proven to characterize deposits and the storms or tsunamis generating them

Balearic Islands, Mediterranean

Photo from Roig-Munar et al. (2019) J. Marine Sci. Eng.

How does Wave Climate Enter Into This Problem?

- Storm waves (and tsunamis) provide the driving force that generates boulder deposits (height, period, return interval)
- Combines with setting (elevation, topography, bathymetry, shoreline distance) and boulder properties (size, density, shape, lithology) to give a very complex problem

Dimensional Analysis

- Dimensional analysis offers a methodology to link wave climate to boulder properties

$$\frac{U^2}{gl\left(\rho_s / \rho_w - 1\right)} = f\left(\text{shape,coefficients,setting}\right)$$

Dimensional Analysis

- Dimensional analysis offers a methodology to link wave climate to boulder properties

$$\frac{U^2}{gl\left(\rho_s/\rho_w - 1\right)} = f\left(\text{shape,coefficients,setting}\right)$$

Fluid velocity at boulder leading to motion

Dimensional Analysis

- Dimensional analysis offers a methodology to link wave climate to boulder properties

$$\frac{U^2}{gl\left(\rho_s / \rho_w - 1\right)} = f\left(\text{shape,coefficients,setting}\right)$$

Gravitational acceleration

Dimensional Analysis

- Dimensional analysis offers a methodology to link wave climate to boulder properties

$$\frac{U^2}{gl\left(\rho_s / \rho_w - 1\right)} = f\left(\text{shape,coefficients,setting}\right)$$

Boulder length scale

Dimensional Analysis

- Dimensional analysis offers a methodology to link wave climate to boulder properties

$$\frac{U^2}{gl\left(\rho_s / \rho_w - 1\right)} = f\left(\text{shape,coefficients,setting}\right)$$

Rock and fluid densities

Dimensional Analysis

- Dimensional analysis offers a methodology to link wave climate to boulder properties

$$\frac{U^2}{gl\left(\rho_s / \rho_w - 1\right)} = f\left(\text{shape,coefficients,setting}\right)$$

Unknown function

Dimensional Analysis

- Dimensional analysis offers a methodology to link wave climate to boulder properties

$$\frac{U^2}{gl\left(\rho_s / \rho_w - 1\right)} = f\left(\text{shape,coefficients,setting}\right)$$

- Combine with link between velocity and wave height

$$U^2 = gH_s f_2\left(Z / H_s, X / H_s, \text{topobathy,L}_0 / H_s\right)$$

Dimensional Analysis

- Dimensional analysis offers a methodology to link wave climate to boulder properties

$$\frac{U^2}{gl\left(\rho_s / \rho_w - 1\right)} = f\left(\text{shape,coefficients,setting}\right)$$

- Combine with link between velocity and wave height

$$U^2 = gH_s f_2\left(Z / H_s, X / H_s, \text{topobathy,} \mathrm{L}_0 / H_s\right)$$

A significant wave height

Dimensional Analysis

- Dimensional analysis offers a methodology to link wave climate to boulder properties

$$\frac{U^2}{gl\left(\rho_s / \rho_w - 1\right)} = f\left(\text{shape,coefficients,setting}\right)$$

- Combine with link between velocity and wave height

$$U^2 = gH_s f_2\left(Z / H_s, X / H_s, \text{topobathy,}\mathrm{L}_0 / H_s\right)$$

Elevation above high tide

Dimensional Analysis

- Dimensional analysis offers a methodology to link wave climate to boulder properties

$$\frac{U^2}{gl\left(\rho_s / \rho_w - 1\right)} = f\left(\text{shape,coefficients,setting}\right)$$

- Combine with link between velocity and wave height

$$U^2 = gH_s f_2\left(Z / H_s, X / H_s, \text{topobathy,L}_0 / H_s\right)$$

Inland distance

Dimensional Analysis

- Dimensional analysis offers a methodology to link wave climate to boulder properties

$$\frac{U^2}{gl\left(\rho_s / \rho_w - 1\right)} = f\left(\text{shape,coefficients,setting}\right)$$

- Combine with link between velocity and wave height

$$U^2 = gH_s f_2\left(Z / H_s, X / H_s, \text{topobathy}, \mathrm{L}_0 / H_s\right)$$

Details important for wave transformation

Dimensional Analysis

- Dimensional analysis offers a methodology to link wave climate to boulder properties

$$\frac{U^2}{gl\left(\rho_s / \rho_w - 1\right)} = f\left(\text{shape,coefficients,setting}\right)$$

- Combine with link between velocity and wave height

$$U^2 = gH_s f_2\left(Z / H_s, X / H_s, \text{topobathy,} \mathrm{L}_0 / H_s\right)$$

Function

Dimensional Analysis

- Dimensional analysis offers a methodology to link wave climate to boulder properties

$$\frac{U^2}{gl\left(\rho_s / \rho_w - 1\right)} = f_1\left(\text{shape,coefficients,setting}\right)$$

- Combine with link between velocity and wave height

$$U^2 = gH_s f_2\left(Z / H_s, X / H_s, \text{topobathy}, \mathrm{L}_0 / H_s\right)$$

to get $$\frac{H_s}{gl\left(\rho_s / \rho_w - 1\right)} = f_3\left(Z / H_s, X / H_s, \text{shape,etc.}\right)$$

Dimensional Analysis

- Dimensional analysis offers a methodology to link wave climate to boulder properties

$$\frac{U^2}{gl\left(\rho_s/\rho_w-1\right)}=f\left(\text{shape,coefficients,setting}\right)$$

- Combine with link between velocity and wave height

$$U^2=gH_s f_2\left(Z/H_s, X/H_s, \text{topobathy}\right)$$

to get $$\frac{H_s}{gl\left(\rho_s/\rho_w-1\right)}=f_3\left(Z/H_s, X/H_s, \text{shape,etc.}\right)$$

Use c/b axis ratios

Dimensional Analysis

- Dimensional analysis offers a methodology to link wave climate to boulder properties

$$\frac{U^2}{gl\left(\rho_s/\rho_w-1\right)}=f\left(\text{shape,coefficients,setting}\right)$$

- Combine with link between velocity and wave height

$$U^2=gH_s f_2\left(Z/H_s, X/H_s, \text{topobathy}\right)$$

to get $$\frac{H_s}{gl\left(\rho_s/\rho_w-1\right)}=f_3\left(Z/H_s, X/H_s, \text{shape,etc.}\right)$$

Future work

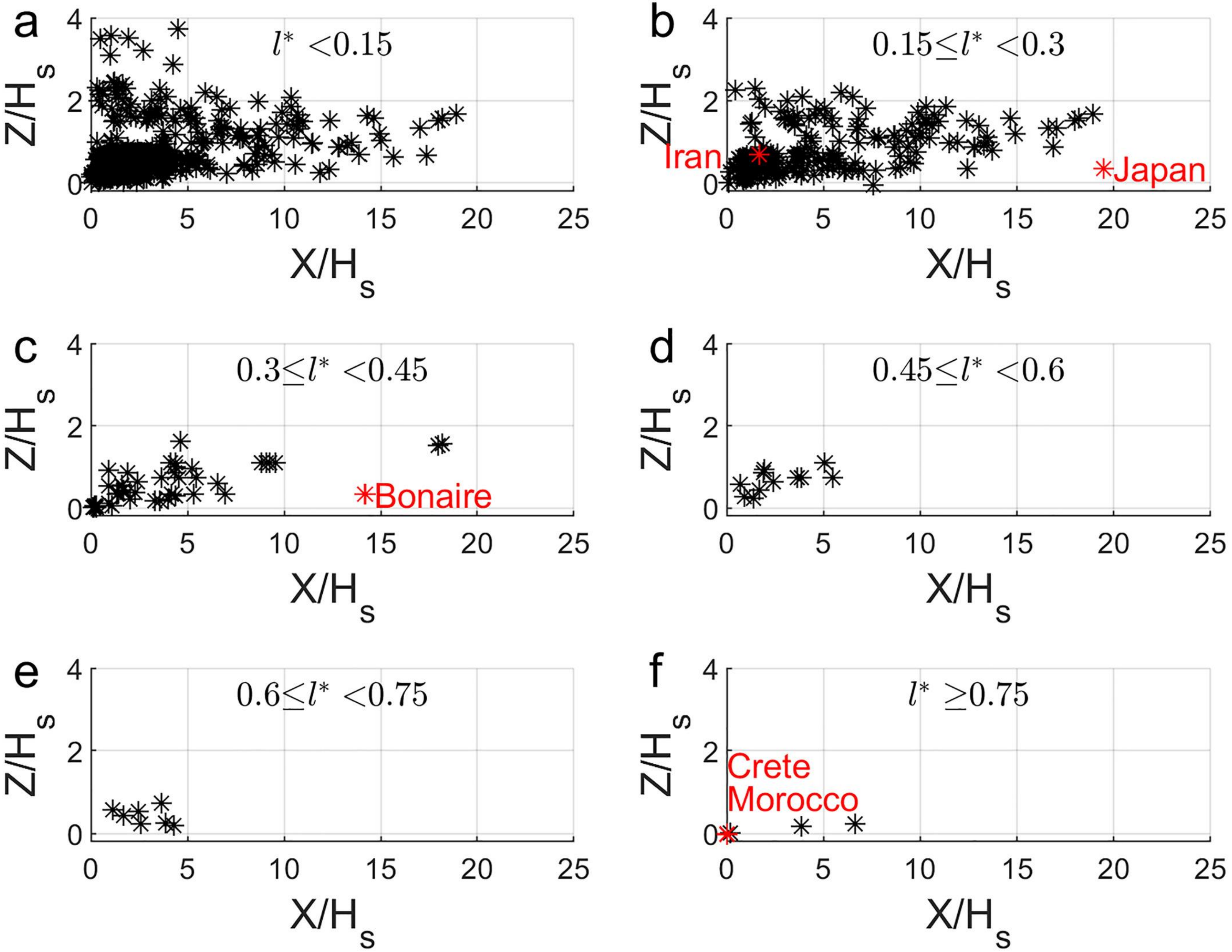
Which Hs to Use?

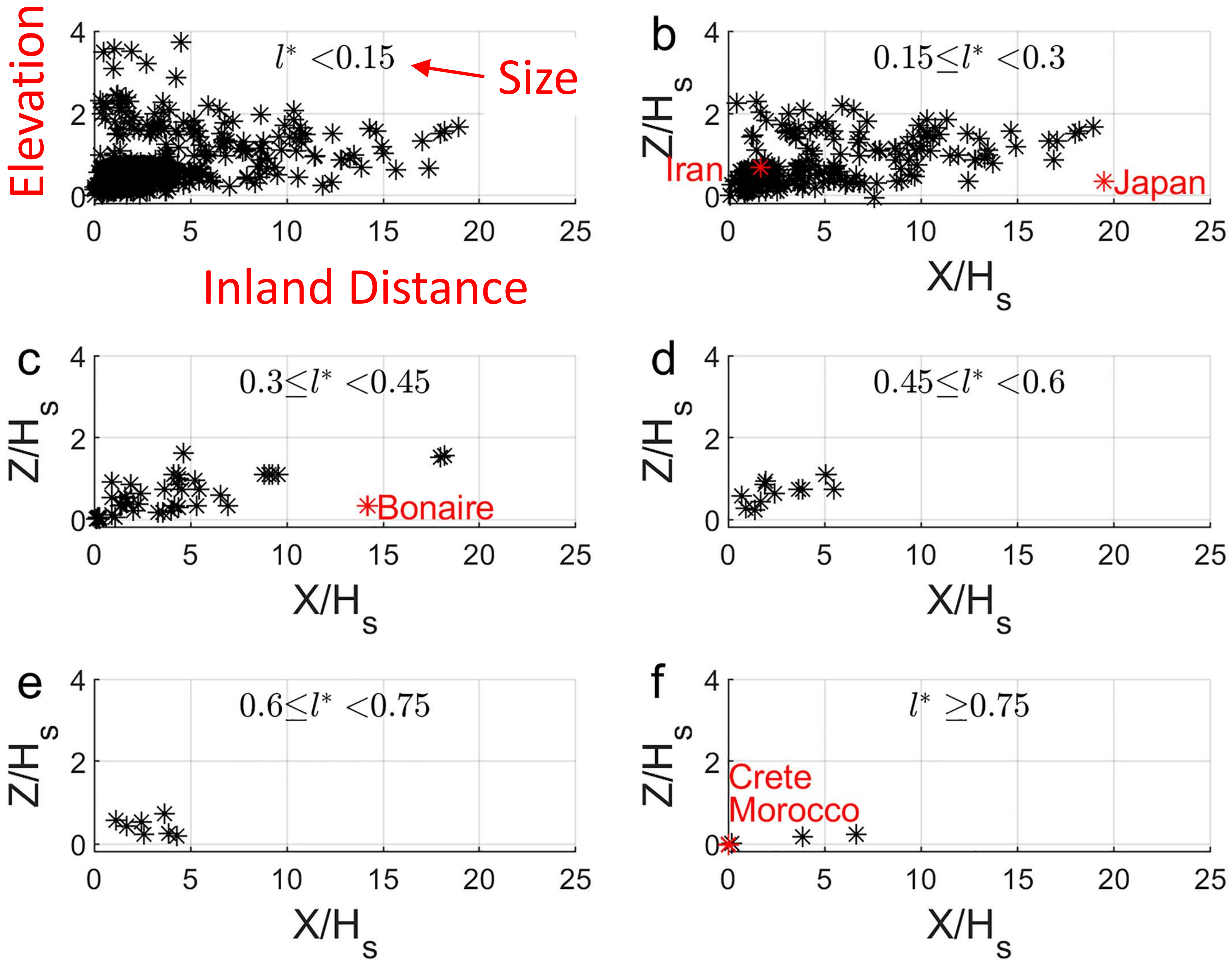
- Application of representative Hs gives much freedom to choose
  - Location of max Hs for specific storms
  - Location, return period of Hs for climate
- Choose 100 year return period for climatology
- Choose 1.5km from shoreline for Hs location
  - Out of surf zone where Hs changes rapidly
  - Can be computed by Regional/Global models

Which Hs to Use?

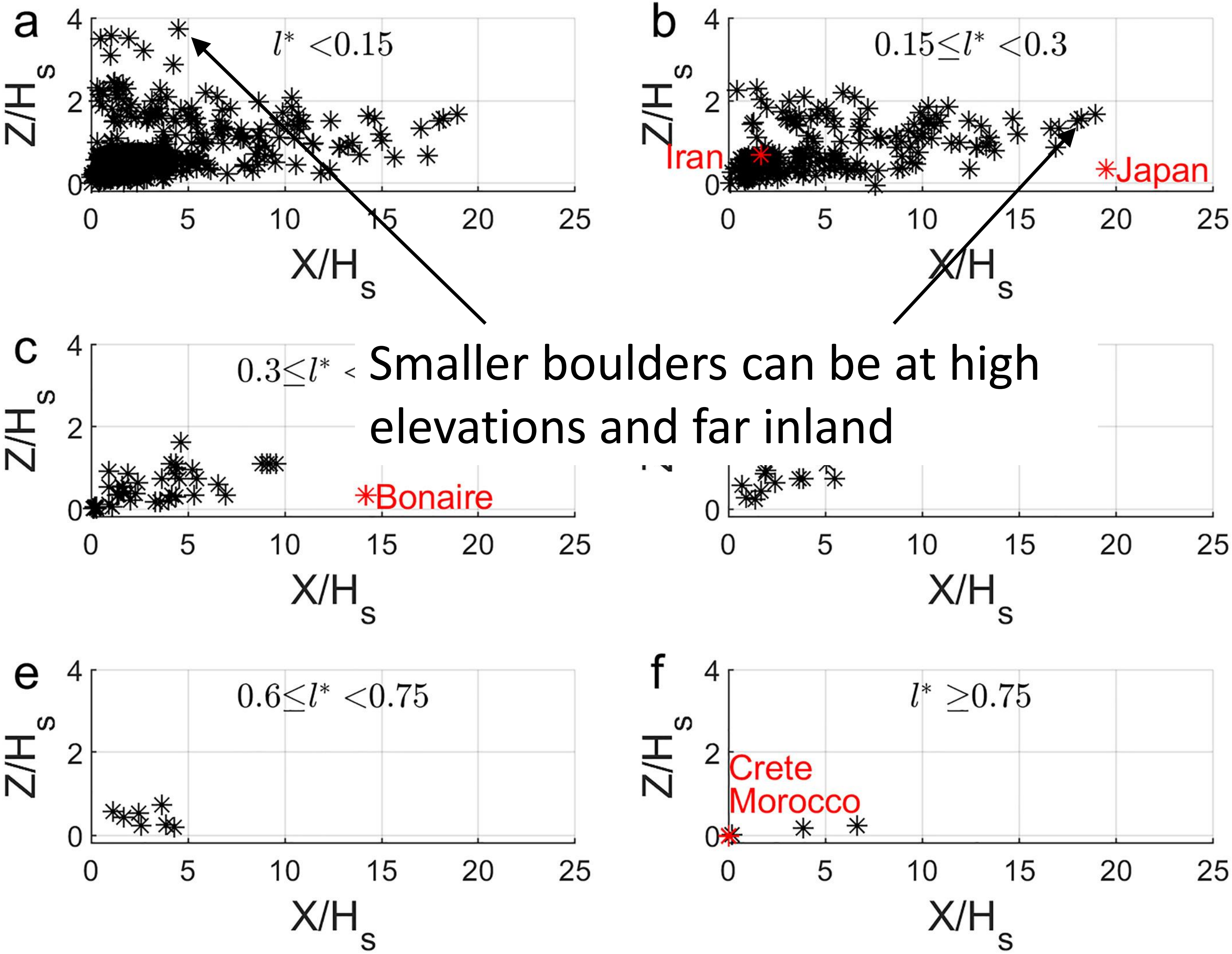
- Application of representative Hs gives much freedom to choose
  - Location of max Hs for specific storms
  - Location, return period of Hs for climate
- Choose 100 year return period for climatology
- Choose 1.5km from shoreline for Hs location
  - Out of surf zone where Hs changes rapidly
  - Can be computed by Regional/Global models

Wave Modelers!!!!

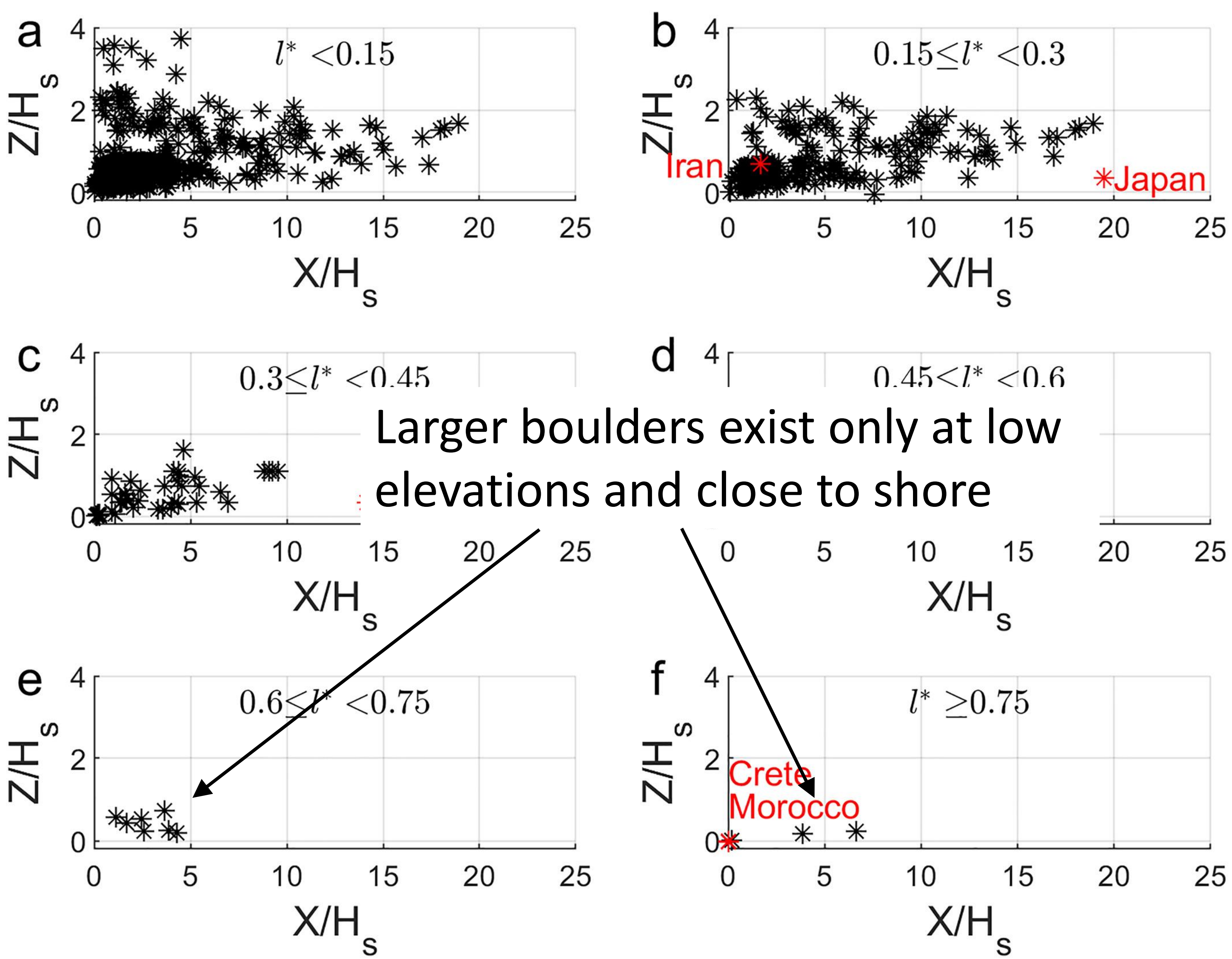

a
$l^* < 0.15$
b
$0.15 \leq l^* < 0.3$
Iran
Japan
c
$0.3 \leq l^* < 0.45$
Bonaire
d
$0.45 \leq l^* < 0.6$
e
$0.6 \leq l^* < 0.75$
f
$l^* \geq 0.75$
Crete
Morocco
Z/H_s
X/H_s
0
2
4
5
10
15
20
25

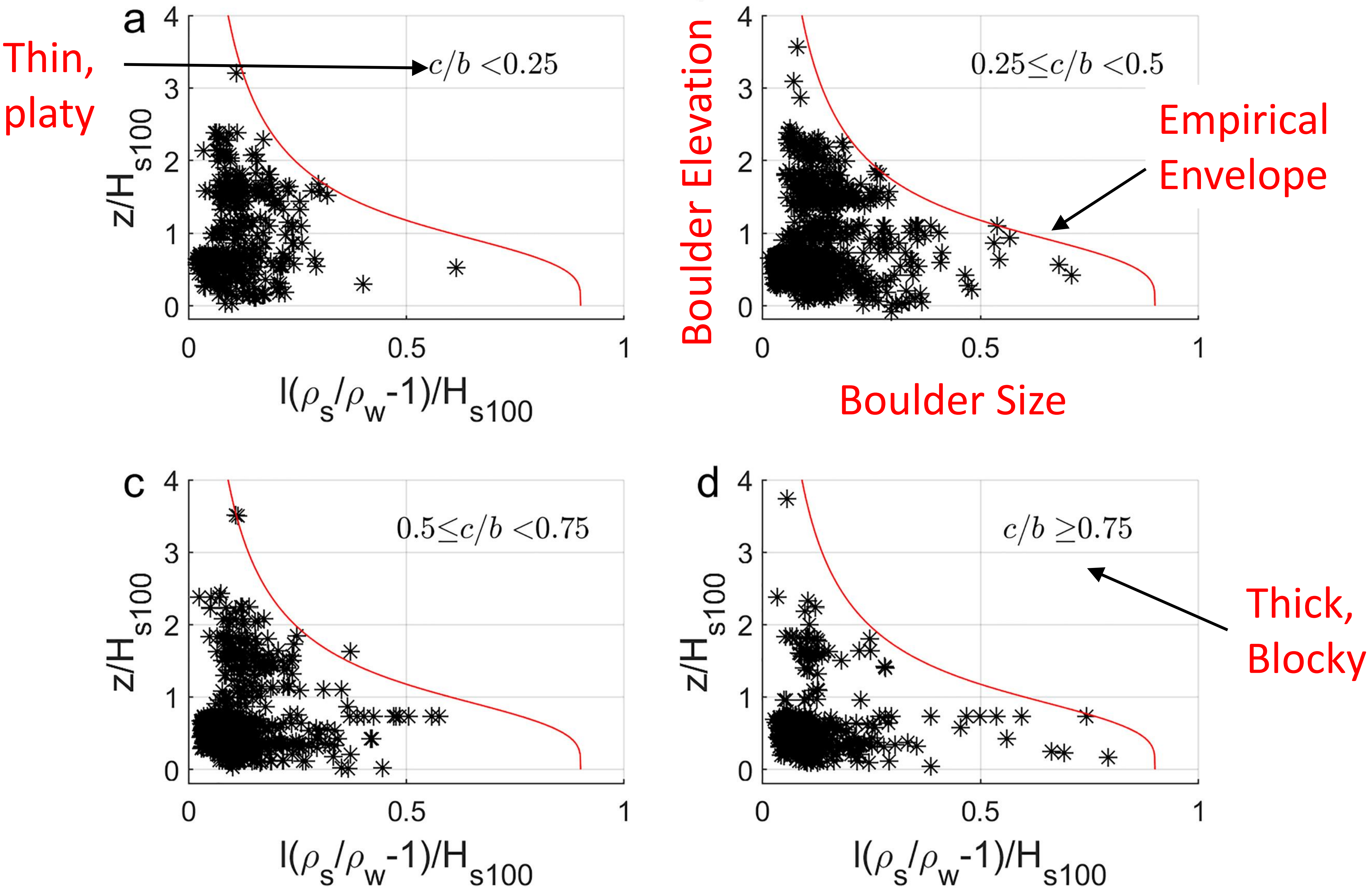


Elevation
Size
Inland Distance
$l^* < 0.15$
b
$0.15 \le l^* < 0.3$
Iran
Japan
c
$0.3 \le l^* < 0.45$
Bonaire
d
$0.45 \le l^* < 0.6$
e
$0.6 \le l^* < 0.75$
f
$l^* \ge 0.75$
Crete
Morocco
Z/H_s
X/H_s



Smaller boulders can be at high elevations and far inland
a
$l^* < 0.15$
b
$0.15 \leq l^* < 0.3$
Iran
Japan
c
$0.3 \leq l^*$
Bonaire
e
$0.6 \leq l^* < 0.75$
f
$l^* \geq 0.75$
Crete
Morocco
Z/Hs
X/Hs


a
b
c
d
e
f
Z/Hs
X/Hs
l* <0.15
0.15≤l* <0.3
0.3≤l* <0.45
0.45≤l* <0.6
0.6≤l* <0.75
l* ≥0.75
Iran
Japan
Crete
Morocco
Larger boulders exist only at low elevations and close to shore



a
Thin,
platy
c/b <0.25
z/H$_{s100}$
l(ρ_s/ρ_w-1)/H$_{s100}$
Boulder Elevation
$0.25 \leq c/b$ <0.5
Empirical
Envelope
Boulder Size
c
$0.5 \leq c/b$ <0.75
d
$c/b \geq 0.75$
Thick,
Blocky

Wave Modeling

- **The greatest void in this field is the lack of representative wave heights to characterize boulder deposits and transport**
- Both individual storms (e.g. Typhoon Haiyan) and climatological wave properties (H_{s100}) are lacking at most boulder sites
- Lack of wave climate at known storm wave CBD hurts interpretation at sites with unknown histories
- What was Hs for unknown storms?
- Storm vs tsunami CBD?

Urgent Wave Modeling Needs

1. Simulations of the Historical Hurricane/Typhoon record at fine scale (~500m) around rocky coastlines
2. Climatological wave height exceedance probabilities at fine scales around rocky coastlines
3. Simulations of storm seasons (e.g. Winter 2023-24)

- **All can be addressed by people here!**

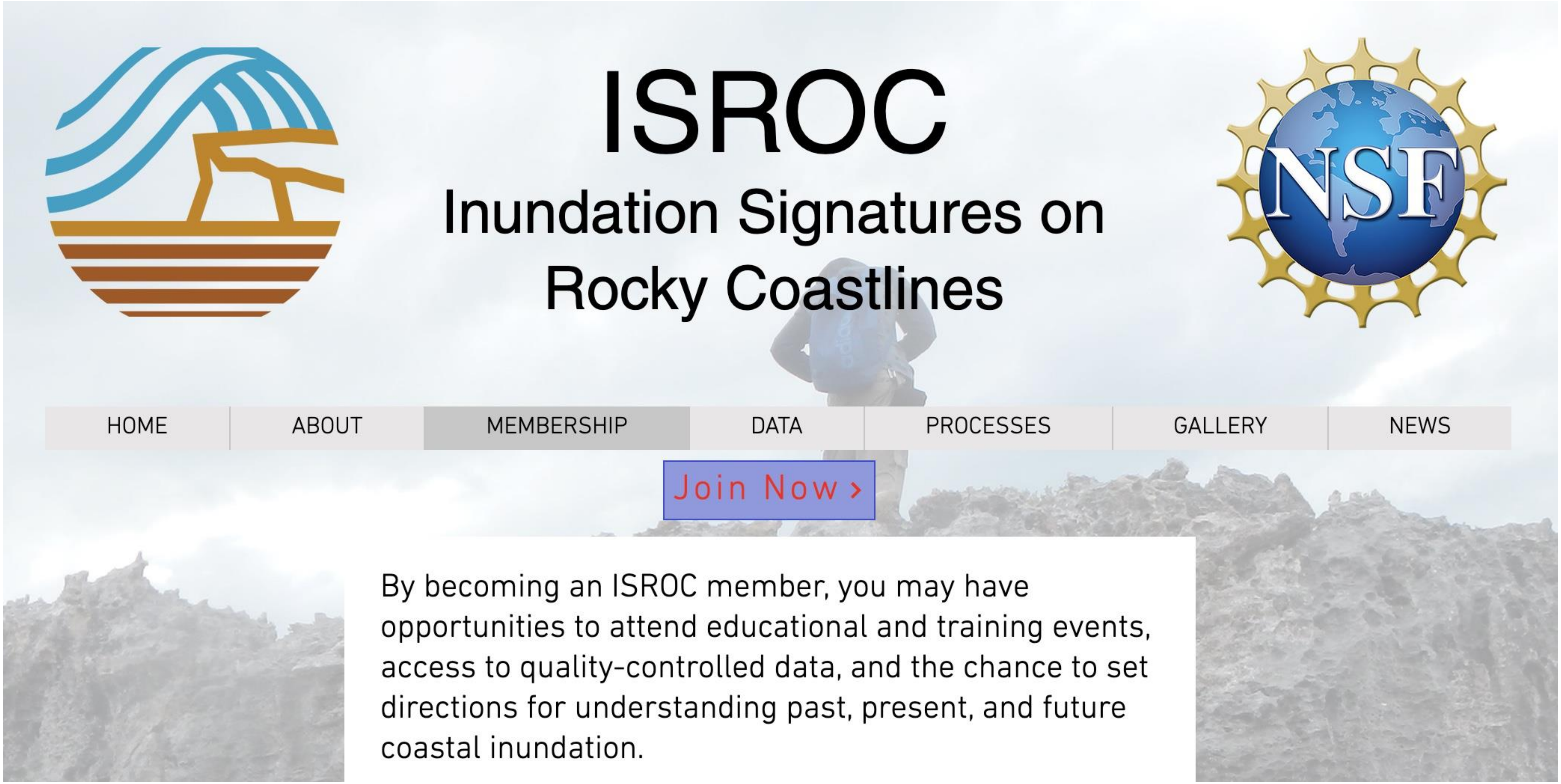
That’s where this new NSF-funded Research Coordination Network comes in

ISROC

Inundation Signatures on Rocky Coastlines

ISROC needs Wave Modelers!!!

Our website is live at www.isroc.network



Joining ISROC is simple: click the “Join now” link

Opportunities for Wave Modelers!

- Archiving/Reanalysis/Reuse of existing model runs
- Set model and data standards for CBD wave modeling
- Publications
- Meetings
- New Research Collaboration Opportunities
- Student training opportunities
- Contact: isroc.network@gmail.com
  or Andrew Kennedy (me)

Reference using Hindcast Wave Data and Boulder Deposits

Kennedy, A.B., Cox, R., and Dias, F. (2021). “Storm Waves may be the Source of Some ‘Tsunami’ Coastal Boulder Deposits”. *Geophysical Research Letters*, 48(11), e2020GL090775

Opportunities for Wave Modelers!

- Archiving/Reanalysis/Reuse of existing model runs
- Set model and data standards for CBD wave modeling
- Publications
- Meetings
- New Research Collaboration
- Student training opportunities
- Contact: isroc.network@gmail.com
  or Andrew Kennedy (me)

DESIGNSAFE

Reference using Hindcast Wave Data and Boulder Deposits

Kennedy, A.B., Cox, R., and Dias, F. (2021). “Storm Waves may be the Source of Some ‘Tsunami’ Coastal Boulder Deposits”. *Geophysical Research Letters*, 48(11), e2020GL090775

Opportunities for Wave Modelers!

- Archiving/Reanalysis/Reuse of existing model runs
- Set model and data standards for CBD wave modeling
- Publications
- Meetings
- New Research Collaboration Opportunities
- Student training opportunities
- Contact: isroc.network@gmail.com
  or Andrew Kennedy (me)

Reference using Hindcast Wave Data and Boulder Deposits

Kennedy, A.B., Cox, R., and Dias, F. (2021). “Storm Waves may be the Source of Some ‘Tsunami’ Coastal Boulder Deposits”. *Geophysical Research Letters*, 48(11), e2020GL090775