Geomorphological signatures of known climatic extreme events and validation of theoretical emplacement approach: Boulders on Cuban low-lying Marine Terraces

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1- Issues and Context

Coastal boulder deposits (CBDs), found along coastlines worldwide, represent the geomorphological evidences of **meteorological events** (Tropical cyclones) or **tsunamis** (local or far away earthquakes, landslides) (Fig. 1). Nevertheless, the analysis of **hydrodynamic parameters** during known **extreme events** that produced the emplacement of **coastal boulders** have been only scarcely studied, specially in Cuba. Decodded correctly these **geomorphic markers** can unlock the understanding of **cuban coastal hazards** (Fig. 2).

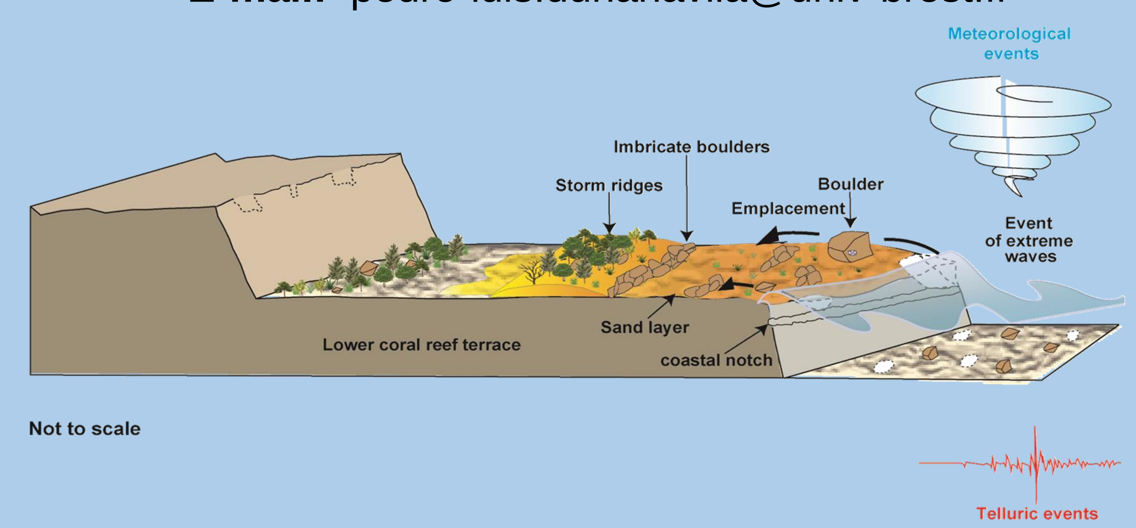

Figure 1. Ideal graph showing the emplacement of boulders on the lower coral reef terrace as consequence of meteorological and telluric events.

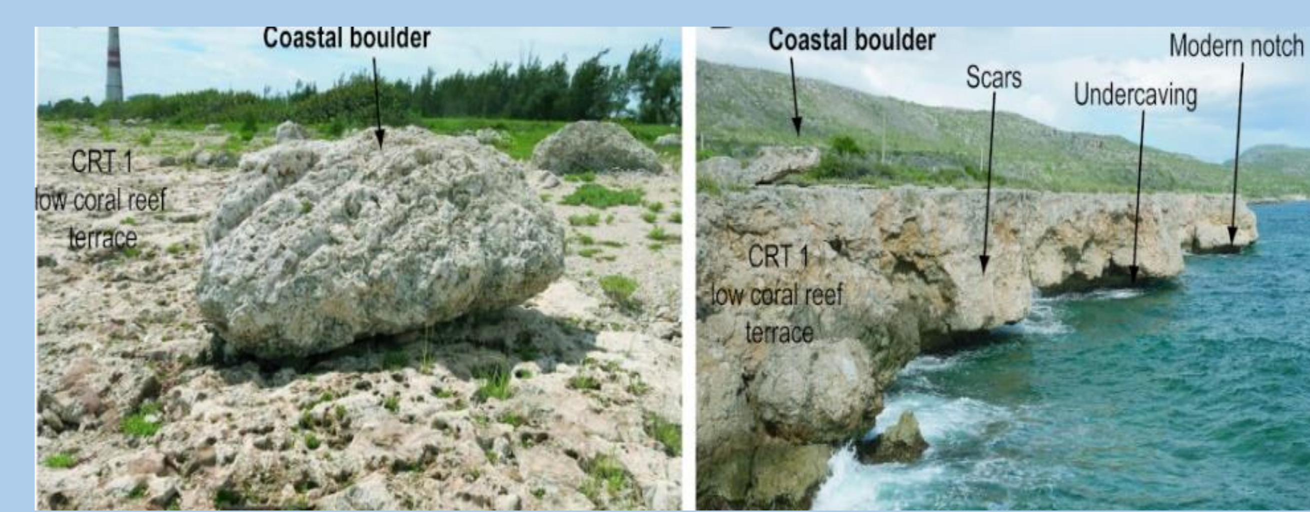

Figure 2. Pictures of boulders and boulder scars along Cuba's South coast.

2- Results

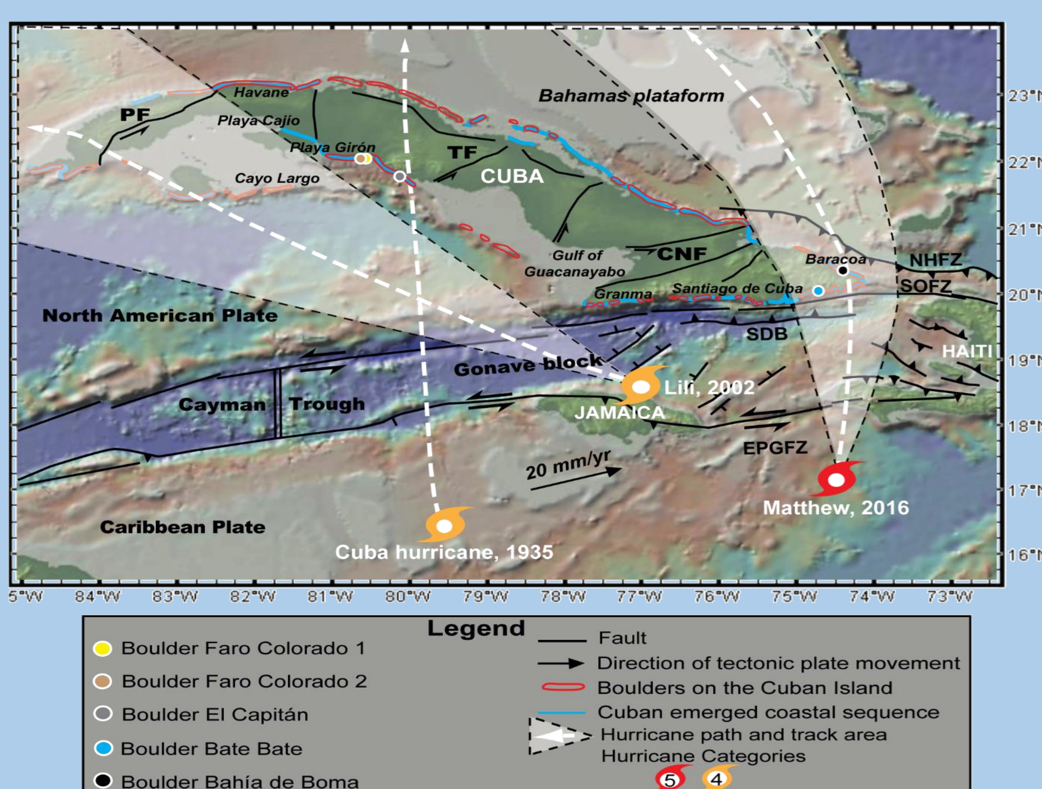

Figure 3. Geodynamics of Cuba Island and locations of the studied coastal boulders. The paths and categories of the hurricanes that produced the studied boulders emplacement are indicated. Spatial distribution of boulders on the Cuban Island is from Matos-Pupo et al., (2023). Marine terrace sequences have been drawn according to Peñalver et al., (2021). Faults of Cuba island are indicated according to Iturralde-Vinent et al., (2016). PF: Pinar fault, TF: la Trocha Fault, CNF: Caute Nipe Fault, NHFZ: North Hispaniola Fault Zone, SOFZ: Septentrional Oriente Fault Zone; EPGFZ: Enriquillo Plantain-Garden Fault Zone; SDB: Santiago Deformed Belt.

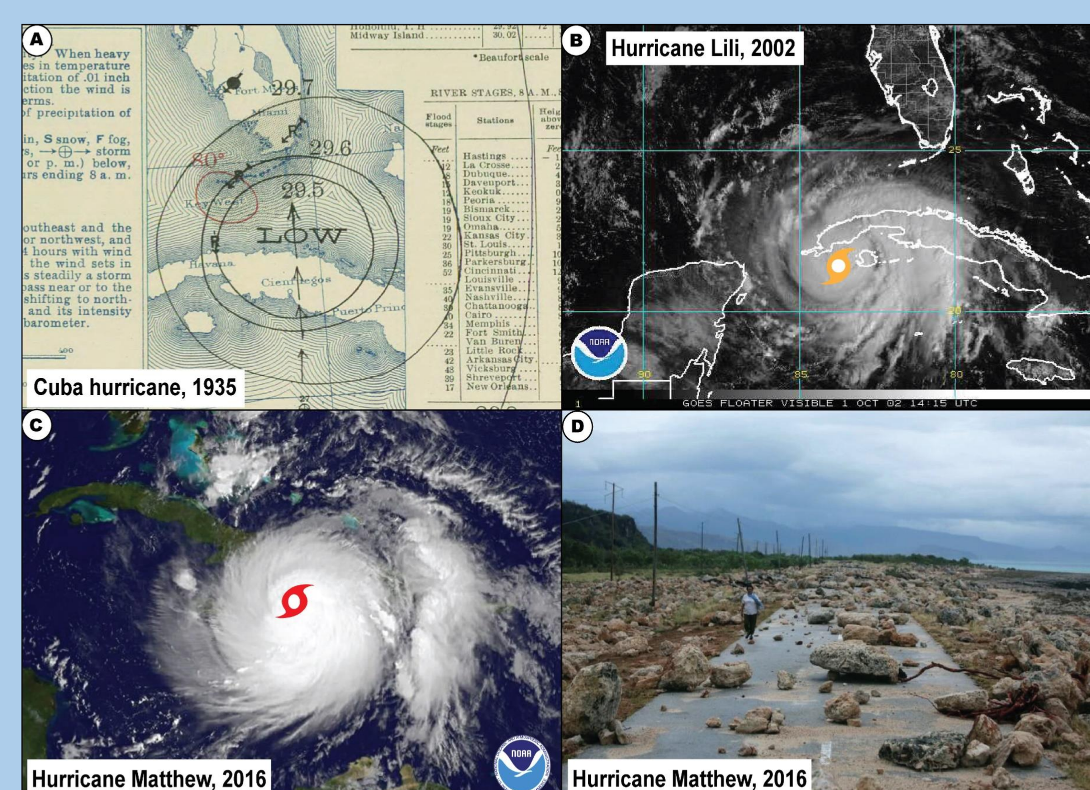

Figure 4. Pictures of hurricanes affecting the study areas (location areas on Figure 3). A) Surface weather analysis of the 1935 Cuba hurricane in the Florida Straits on September 28, 1935; Credits from NOAA Digital Central Library, **B)** Hurricane Lili (2002) satellite image over Cuba on October 1, 2002; Credits from NOAA Digital Central Library, **C)** Hurricane Matthew image from NOAA's GOES-East satellite at 7:45 a.m. EDT on October 4, 2016, within the hour of landfall in western Haiti; Credits from NASA/NOAA GOES Project, **D)** Coastal boulder deposits blocked the San Antonio del Sur road after Hurricane Matthew passage on the Cuban province of Guantanamo on October 5, 2016; Pictures from REUTERS/Alexandre Meneghini.

Cuba is located on the **North American plate** at its southern boundary with the **Caribbean plate** (Cotilla Rodríguez, 2011) (Fig. 3). **Tropical cyclones** affect the Cuban archipelago annually during **Cuba's cyclonic season.** The studied **CBDs** were **deposited by known hurricanes: The hurricane of 1935** (Figs. 3 and 4) (**El Capitan coastal boulder** Fig. 5), **Lili Hurricane 2002** (Figs. 3 and 4) (**Faro Colorado 1 and 2 coastal boulders** Fig. 6) and **Matthew Hurricane 2016** (Figs. 3 and 4) (**Bate Bate coastal boulder** Fig. 7 and **Bahia de Boma coastal boulder** Fig. 8). Theses **coastal boulders** are located on a **low-lying coral reef terrace** on the Cuban shore. The table shows the results (**geomorphologic and hydrodynamics parameters**) of the **boulders studied**.

ID Boulders	Axis length (m)			Volume SfM (m^3)	Mass based on SfM (t)	Minimum flow velocity (m/s)		Maximum orbital velocity (m/s)
	A	B	C			Nandasena et al., (2013)	Nandasena et al., (2022)	
El Capitán	6.10	3.90	2.85	29.2 ± 3.1	74.75	6.23 ± 0.62	4.69 ± 0.40	9.2
Faro Colorado 1	3.90	2.65	1.69	8.7 ± 1.6	20.88	5.60 ± 0.75	4.66 ± 0.74	4.1
Faro Colorado 2	2.39	2.33	1.39	1.99 ± 0.3	4.77	4.80 ± 0.67	2.84 ± 0.34	4.1
Bate Bate	7.46	3.85	1.95	25.9 ± 2.6	67.08	5.84 ± 0.65	4.74 ± 0.53	6.8
Bahia de Boma	9.66	4.41	2.36	31.5 ± 2.5	74.65	6.00 ± 0.79	3.93 ± 0.45	8.6

Site Trinidad

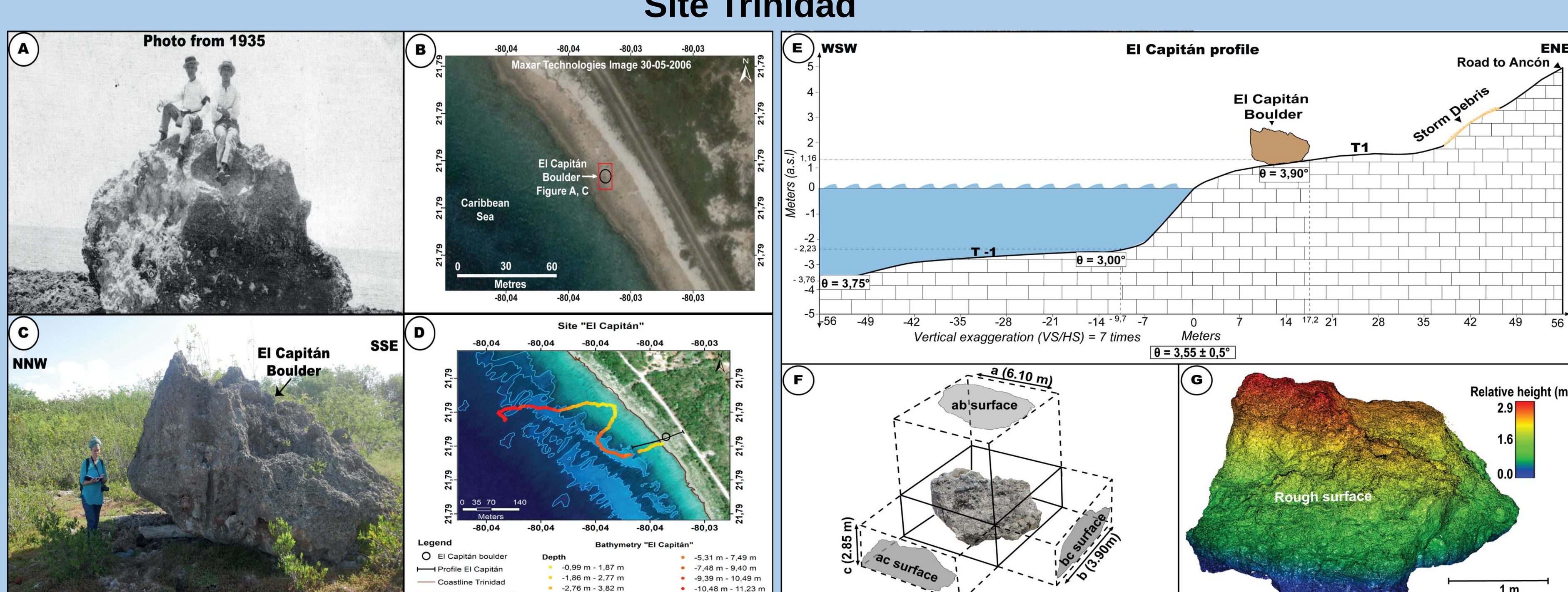

Figure 5. Site Trinidad and El Capitán coastal boulder. A) Field photo after the 1935 hurricane showing the El Capitan boulder, Source: Trinidad Municipal Historical Archive, Sancti Spíritus, Cuba. **B)** Maxar satellite image obtained in 2006 showing the coastal boulder in place. **C)** Morphology of the El Capitan boulder. **D)** Map of the bathymetric profile of Trinidad, Sancti Spíritus site. **E)** Plan of the elevation, profile of the submerged platform (T-1) and emerged (T1) marine terrace with inclination angle and General view of El Capitán Site (DGPS profile). **F)** Polygonal model of the El Capitan CBD; dimensional features are shown: a - b - c axis lengths and ab-ac-bc projected surfaces, **G)** Perspective view of the El Capitán CBD highlighting and relative elevation.

Site Punta Los Colorados Lighthouse

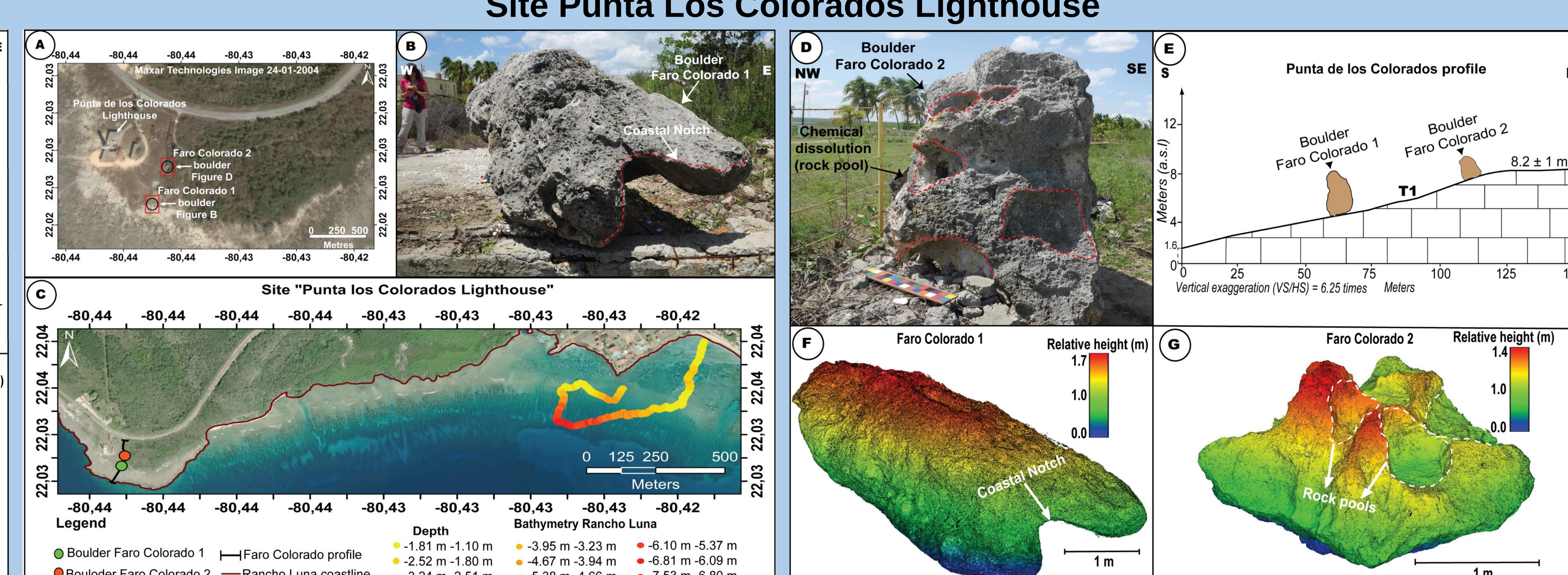

Figure 6. Site Punta Los Colorados Lighthouse and Faro Colorado 1 and 2 boulders. A) Maxar satellite imagery obtained in 2004 showing the coastal boulders in place. **B)** boulder morphology and dissolution marks. **C)** Map of the bathymetric profile of Faro Colorado, Cienfuegos. **D)** boulder morphology and dissolution marks. **E)** General plan of the marine terrace of Faro Punta los Colorados with the boulder emplacements (DGPS profile). **F)** and **G)** Perspectives view of the Faro Colorado 1 and 2 CBDs highlighting and relative elevations.

Site Bate Bate

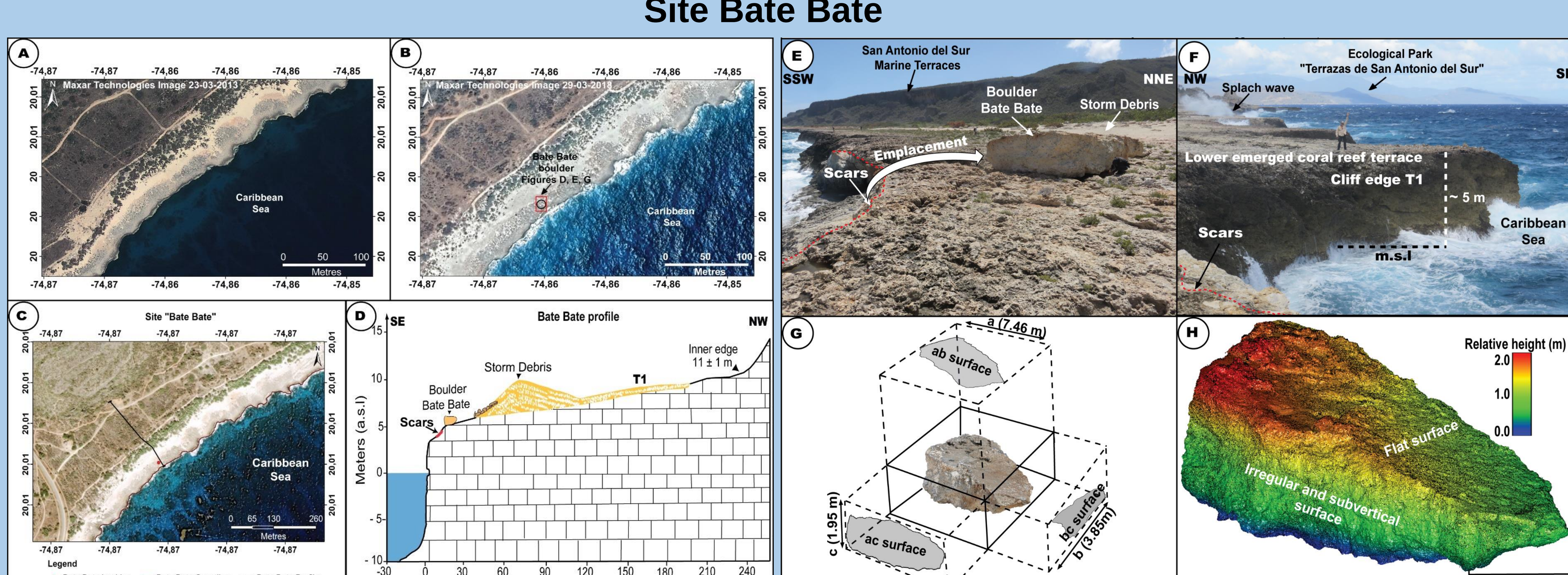

Figure 7. Site Bate Bate and coastal boulder. A) and **B)** Temporal set of Landsat images from 2013 to 2018 before and after the passage of the Matthew hurricane. **C)** Map of the topographic profile location in the Bate Bate Site. **D)** Bathymetry and DGPS topographic profile of the marine terrace (T1) and the Bate Bate boulder location. **E)** and **F)** Interpreted field pictures. **G)** Polygonal model of the Bate Bate CBD; dimensional features are shown: a - b - c axis lengths and ab-ac-bc projected surfaces **H)** Perspective view of the Bate Bate CBD highlighting and relative elevation.

Site Bahia de Boma

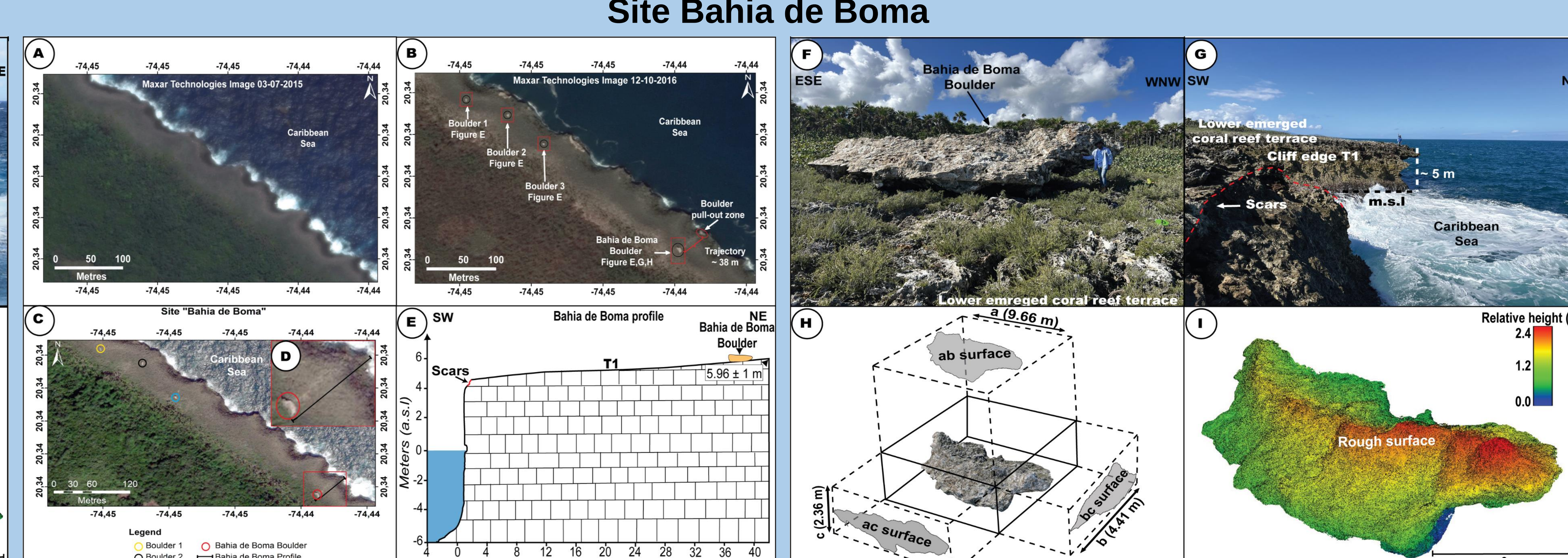

Figure 8. Site Bahia de Boma and boulder. A) and **B)** Temporal set of Landsat images from 2015 to 2016 before and after the passage of the Matthew hurricane. **C)** and **D)** (inset) Topographic profile in the Bahia de Boma Site. **E)** Bathymetry, general view of Bahia de Boma boulders (DGPS profile). **F)** and **G)** Interpreted field pictures. **H)** Polygonal model of the Bahia de Boma CBD; dimensional features are shown: a - b - c axis lengths and ab-ac-bc projected surfaces, **I)** Perspective view of the Bahia de Boma CBD highlighting and relative elevation.

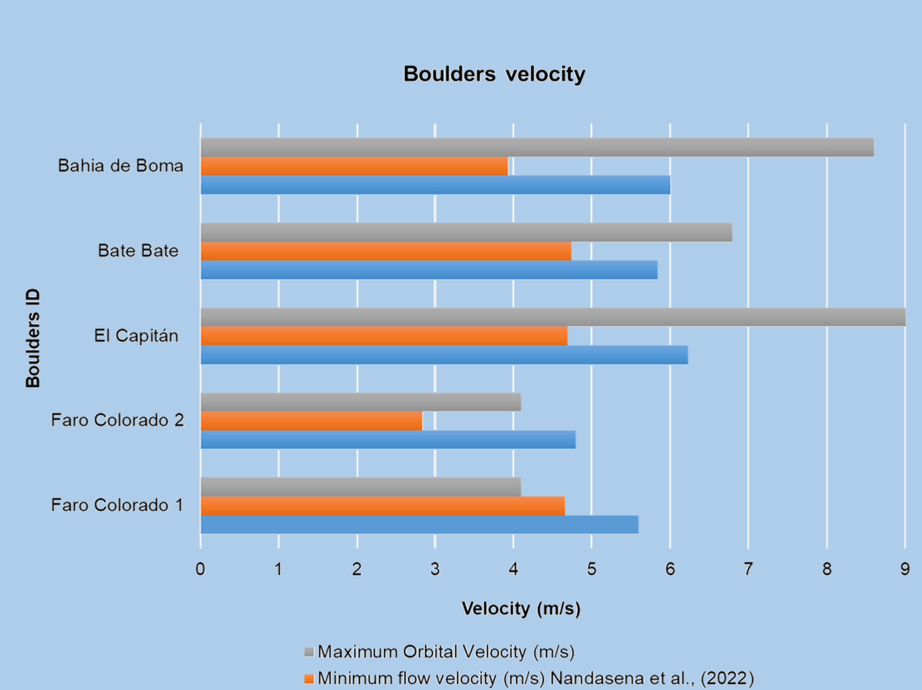

Figure 9. Calculated velocities for the boulders studied

Comparison of **minimum flow velocities** with **maximum orbital velocities** shows a **good agreement** for **all the sites** studied, with the **exception of the Faro Colorado site** (Figure 9). However, despite the potential uncertainties related to site effects, we observe in general a **good correlation** between the **minimum flow velocity** and the **maximum orbital velocity** for past **hurricane events**.

3- Conclusions

We studied **5 coastal boulders** on the island of Cuba emplaced by **3 known hurricanes**. We estimated their **volume**, **density** and **weight** and based on **geomorphological observations** we elucidate their mode of emplacement. Using this data, we calculated the **minimum flow velocity** needed for their emplacement. The values obtained were compared with the **maximum orbital velocity** estimated different **hurricane events**. This method opens the door for extending this method to determine the **magnitude** and the **origin** of past **extreme wave events**. Our new proposed approach has the potential of improving our understanding of **coastal hazards** considering the increase of extreme climatic events driven by **climate change** and their **impact** in **population and ecosystems**.

4- Bibiography

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