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Emplacement of high-energy mega-boulders along the Atlantic coast of Rabat (Morocco)

Emplazamiento de mega-bloques de alta energía a lo largo de la costa atlántica de Rabat (Marruecos)

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ABSTRACT

Observation of mega-boulders located along the Rabat coast (Morocco) shows that they were emplaced by high-energy waves under different transport modes: incomplete rolling, complete rolling, saltation and sliding. The use of recently proposed equations for the estimation of flow velocity and depth shows that the obtained values are quite different from those for joint-bounded blocks and strongly depend on the values of the coefficient of lift and the Froude number.

Key-words: *Gulf of Cadiz, high-energy waves, sedimentology, coastal hazards..*

RESUMEN

La observación de los mega-bloques ubicados a lo largo de la costa de Rabat (Marruecos) muestra que fueron emplazados por olas de alta energía con diferentes modalidades: rodamiento incompleto, rodamiento completo, saltación y deslizamiento. El uso de las ecuaciones sugeridas recientemente para la estimación de la velocidad y profundidad del flujo muestra que los valores obtenidos son bastante diferentes de los de los bloques separados por diaclasas y dependen fuertemente de los valores del coeficiente de sustentación y del número de Froude.

Palabras clave: *Golfo de Cádiz, olas de alta energía, sedimentología, riesgos costeros.*

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Introduction

Around the Gulf of Cadiz and in western Portugal, large boulders have been described on coastal rocky platforms or cliff tops and thought to have been emplaced by high-energy events such as the first November 1755 tsunami (Scheffers and Kelletat, 2005; Whelan and Kelletat, 2005; Mhammdi *et al.,* 2008; Medina *et al.,* 2011) and/or winter storm waves (Oliveira, 2017; Medina *et al.*, 2018). These observations and many others throughout coastal areas threatened by storms and tsunamis have triggered numerous studies and discussions to understand how these boulders are emplaced and the amount of forces, momentums, flow velocities and depths needed to displace them (Nott, 2003).

In this paper, we present new data on some selected boulders along the coast south of Rabat (Fig. 1), with particular emphasis on the modes of transport of their emplacement. We attempt to quantify their initial motion by using equations for boulder displacement at cliff edges (Nandasena *et al.*, 2013), which are more realistic than the joint-bounded block equation used previously (Medina *et al.*, 2011).

Geological and morphological setting

The recent Quaternary formations south of Rabat consist of superimposed eolianite belts intercalated with marine incursions (Akil, 1980). Chahid (2017) distinguishes a frontal external dune belt (that he named 'first') and a more internal one (called 'second'), separated by a depression (*Oulja*). Optically Stimulated Luminescence (OSL) and Infrared stimulated Luminescence (IRSL) dates obtained by this author assign to the calcarenites ages of 249.78±14.16 to 88.45±7.75 ka (MIS-11 to MIS-5) for the internal dune belt, and 104±8 to 94±7 ka (MIS-5c) to those of the external (frontal) belt. Petrographically, the external dune belt formations consist of sparite-cemented biocalcarenites, very rich in bioclasts, with a 20% rock porosity.

Morphologically, the NE-SW to E-W oriented Rabat coast consists of a succession of rocky cliffs interrupted by river mouths (Bou Regreg, Ykem) and some relatively small beaches. Two main morphologies dominate (Chahid, 2017): a wave platform bounded by Mean Low Water (MLW) and Mean High Water (MHW) cliffs Cité Yacoub El Mansour (CYM), which may be up to 200 m wide, and a more complex system consisting of a 5-15 high cliff which continues inland by a karstic slope that gently dips inland towards a depression (*Oulja*), followed by a small beach and an inactive cliff. Along most segments, the frontal cliff is located offshore and the Oulja depression is inundated by seawater during high tide.

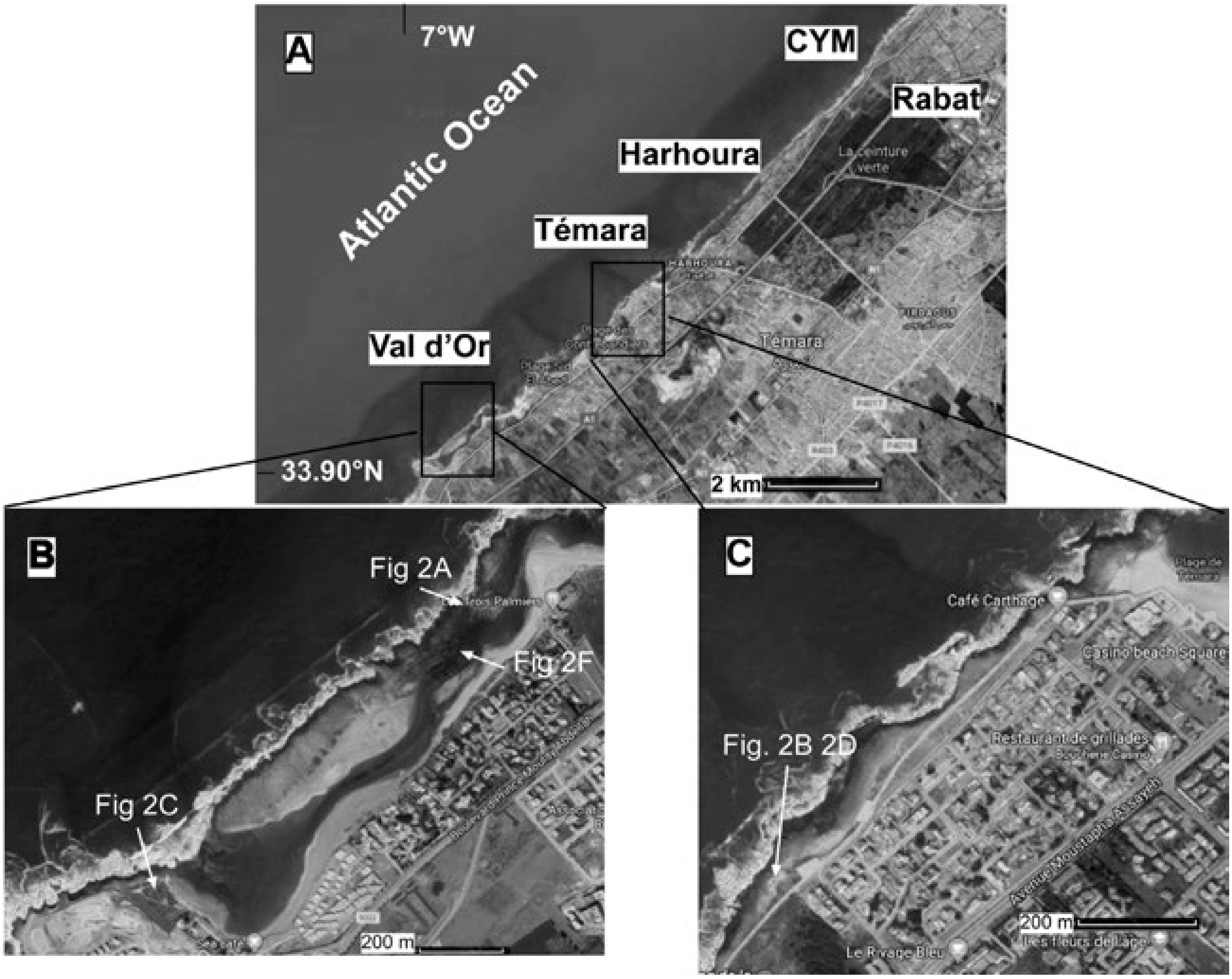

Fig. 1.- A) Location of the studied sites. B) Google Maps image of Val d'Or beach and location of the boulders shown in figure 2A, C and F. C) Google Maps image of Témara promenade and location of the boulders shown in figure 2B and 2D. See color figure in the web.

Fig. 1.- A) Posición de las localidades estudiadas. B) Imagen de Google Maps de la playa Val d'Or la playa y posición de los bloques mostrados en la figura2A, C y F. C) Imagen de Google Maps del paseo de Témara y posición de los bloques mostrados en la figura 2B y 2D. Ver figura en color en la web.

Tectonically, the Pleistocene-Holocene formations of Rabat coast are slightly affected by fractures oriented NNE-SSW (Chabli *et al.,* 2014) that may have influenced disjointing of the dune belt at the cliff.

Characteristics of the main mega-boulders

At Temara and Val d'Or, the boulders belong to the lithified frontal dune belt and in a few cases to the Mid-Holocene beachrock of the Oulja depression. At CYM, the lithology of the boulders mainly corresponds to the MIS-5 calcarenite formation mapped by Akil (1980), although some blocks appear to derive from the MHW cliff, which has undergone intense urbanization.

The shape of the Val d'Or boulders is variable, ranging from right triangular, rectangular to hexagonal prisms, to almost-cubic or pyramidal. Boulders near Rabat have a flatness ratio $F=(a+b)/2c$ that ranges from 2.74 to 3.47 (Medina *et al.*, 2011). Most platy boulders deriving from the frontal dune belt always show an eroded pool-bearing surface and an opposite planar one.

The evolution of the boulder size (represented by the A-axis length), in relation to distance to the shoreline, shows a roughly linear decrease depending on the topography and on the morphology of the surface (Medina *et al.*, 2011).

At Val d'Or, the boulders may be arranged in clusters and imbrications involving up to 7 units (Mhammdi *et al.*, 2008, their figure 5A). In Temara, most boulders belonging to the cliff of the frontal dune, are scattered, but a few are imbricated along the promenade. Finally, the boulders in CYM show a dominant single arrangement, although clusters and imbrications were also observed in a few locations. The stereographic plot of the attitudes of 115 inclined boulders shows that the dips range from N30°W to N60°E.

Modes of transport

The shapes of the cliff-edge collapsed blocks are mainly controlled by the almost-vertical fractures (joints and faults) that affect the rock (Chabli *et al.*, 2014). The main directions are N35°E, N77°E and E-W in Temara and N43°E, N85°E and N127°E in Val d'Or. The most conspicuous example of incomplete dislodgement is boulder VO-1, found at Val d'Or (Fig. 2A), consisting of a triangular boulder rotated to vertical in a quite unstable position against the uppermost step of the cliff. Another case of incomplete dislodgement was found at Temara promenade (Fig. 2B; TM-1), where a roughly rectan-

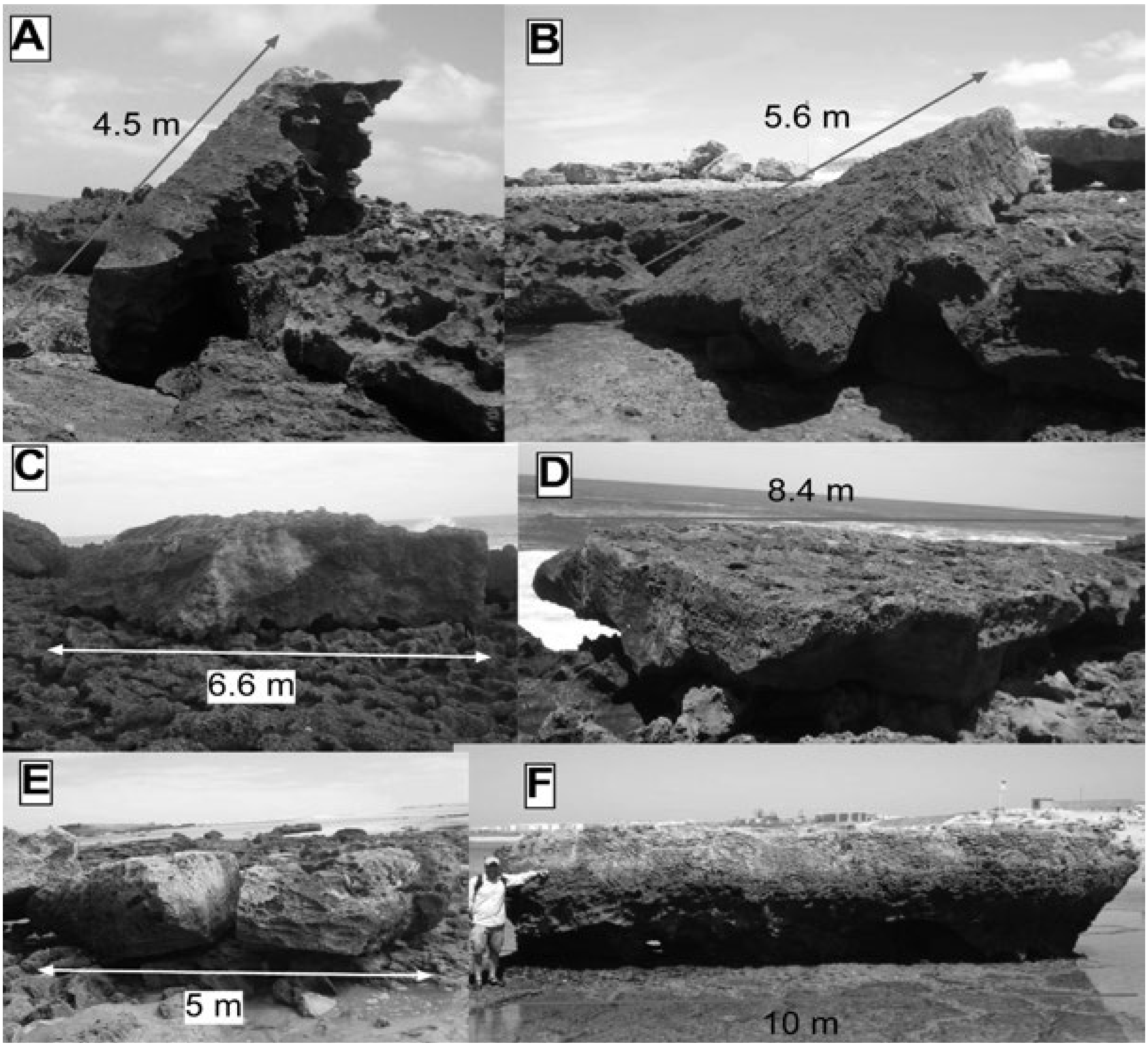

Fig. 2.- Modes of transport of the largest boulders south of Rabat. A) and B) Incomplete rolling of boulders VO-1 and TM-1 at Val d'Or and Temara, respectively. C) and D) Complete overturning of boulders VO-2 and TM-2 at Val d'Or and Temara, respectively. E) Broken boulder (VO-3) by saltation at Val d'Or. F) Large boulder (VO-4) transported for about 80 m by sliding at Val d'Or. See color figure in the web.

Fig. 2- Modalidades de transporte de los bloques más grandes el sur de Rabat. A) y B) Rodamiento incompleto de los bloques VO-1 y TM 1 en Val d'Or y Temara, respectivamente. C) y D) Vuelco completo de los bloques VO-2 y TM 2 en Val d'Or y Temara, respectivamente. E) Bloque fracturado (VO-3) por saltación en Val d'Or. F) Bloque (VO-4) transportado mediante deslizamiento a lo largo de unos 80 m en Val d'Or. Ver figura en color en la web.

Boulder	Dimensions (m) (A×B×C)	Weight (tons) for density 2200 kg/m ^{3}	Distance to cliff (m)	Minimum flow velocity (ms $^{-1}$) and flow depth (m) (parentheses)			
				C_l=0.178 δ=1	C_l=2 δ=1	C_l=0.178 δ=1	C_l=2 δ=1
Incomplete rolling						*Joint bounded block*	
VO-1 (Val d'Or)	9.0×4.5×1.0	89	0	16.66 (28.31)	3.45 (1.21)	13.5 (18.5)	4 (1.64)
TM-1 (Témara)	5.6×4.2×1.0	51	0	18.34 (34.3)	3.46 (1.22)	13.5 (18.5)	4 (1.64)
B.9.1. (Rabat))	6.6×4.2×2.5	152	100	No solution	6.58 (4.41)	21.3 (46)	6.35 (4.11)
Complete rolling						*Joint bounded block*	
VO-2 (Val d'Or)	6.0×5.5×1.3	94	1	20.67 (43.55)	3.95 (1.6)	15.3 (24)	4.6 (2.14)
TM-2 (Témara)	8.4×5.1×1.0	94	7	14.84 (22.45)	3.43 (1.2)	13.47 (18.5)	4 (1.64)
VO-4 (Val d'Or)	10.0×2.2×1.8	87	?	No solution	7.67 (6)	18.07 (33.3)	5.4 (3)
Sliding							
VO-4	10.0×2.2×1.8	87	82	4.07 (1.7)	3.09 (0.97)	-	-

Table I.- Modes of transport and characteristics of the largest boulders of the Rabat area (dimensions and distance to cliff) and flow velocities obtained from the equations proposed by Nandasena *et al.* (2013) for a flat surface. Cl is the coefficient of lift and δ is the Froude number.

Tabla I.- Modalidades de transporte y características de los bloques desplazados más grandes del área de Rabat (dimensiones y distancia al acantilado) y velocidades de flujo obtenidas a partir de las ecuaciones propuestas por Nandasena et al. *(2013) para una superficie plana. Cl es el coeficiente de sustentación y δ el número de Froude.*

gular boulder was overturned for about 150° but was blocked by the uppermost step of the cliff.

Rolling/overturning is the common mode of transport in Temara and Val d'Or for large boulders observed on cliff top. At Val d'Or, one of the largest overturned blocks found is VO-2 (Fig. 2C). Another large boulder whose karstic pools have been rotated upside down (TM-2) was found in Temara along the walkway (Fig. 2D).

Saltation can be inferred from boulders affected by vertical fractures which may have developed by violent slamming against the floor.

The most conspicuous example appears at Val d'Or where the largest transported block (12 m^3; 4.4×3.4×0.8 m), located at 160 m from the cliff, was broken in two pieces along a N30°E, 40 cm-wide fracture (Fig. 2E). Another broken block (26.7 m^3; 7×2.9×1.3 m) appears southwards on the top of the cliff, at 13 m from the edge.

Cases of evident simple sliding of already emplaced subaerial or submerged boulders can be mainly found in the CYM wave platform, where these boulders attain the largest size and weight along the Rabat coast. The largest block (~107 m^3; 11.4×3.5×2.7 m) is located at some 10 m from the cliff.

Most examples of this combined transport can be found in CYM where the blocks dislodged from the cliff by lifting or rolling were transported along the smooth platform for tens of meters. In the northern inlet of the Val d'Or, a boat-shaped boulder at a distance of 82 m from the platform edge attains 10×2.2×1.8 m (~40 m^3). It has been overturned as witnessed by the downward oriented pools, and transported along the smooth platform (Fig. 2E).

Wave flow velocity and depth

The setting of the boulders of the rocky Rabat coast is best expressed by the cliff-edge scenario where dislodgement, rolling and overturning of the boulder occurs when the lift and drag moments exceed the restrained weight of the boulder moment. The general equation for rolling was proposed by Nandasena *et al.* (2013). Taking u as the flow velocity, ρ_S as the rock density (2200 kg m^{-3}), ρ_w as the water density, C_l as the coefficient of lift (boundary values: 0.178 and 2); C_d as the coefficient of drag (fixed as 1.95), g as the acceleration of gravity (9.81 m s^{-2}); b and c as the lengths of the *B* and *C*-axes of the boulders respectively:

$$u^2 \geq \frac{2\left\{(\rho_b/\rho)-1\right\}cg}{C_l - C_d(c/b)^2} \qquad (1)$$

The sliding scenario can be applied to the CYM and Val d'Or areas for the stage of boulder displacement following lifting with overturning (Fig. 2F), but not to Témara and Val d'Or because their morphology corresponds to a karstified dune belt, which hampers the free displacement of the boulders. The corresponding equation is (Nandasena *et al.*, 2011):

$$u^2 \geq \frac{2\left\{(\rho_b/\rho)-1\right\}cg\,(\mu_s\cos\theta+\sin\theta)}{C_l - C_d(c/b)+\mu_s C_l}$$

Where μ_s is the friction coefficient (0.7) and θ the angle of the platform slope (taken as 0° here).

Table I shows the example of megaboulder VO-4 transported for about 80 m inland after overturning (Fig. 2F).

The relationship between flow depth and flow velocity of fluid flow is described by the Froude number:

$$\delta = u/\sqrt{gh} \qquad (3)$$

$$h = u^2/g\delta^2 \qquad (4)$$

The obtained flow velocities and depths obtained from each boulder are shown in table I.

Discussion and conclusion

In this study, we presented selected observations on the setting of the largest boulders that appear along cliff edges and platforms south of Rabat, and we have shown that the modes of their emplacement are incomplete rolling (<180°), rolling and saltation on cliff tops and sliding on platforms. We have also attempted to calculate the flow velocities and depth from recently proposed equations. The values of flow velocity and depth appear to be strongly related to those of the coefficient of lift, in turn related to ratio *c/b*, and the Froude number, as discussed by Nandasena *et al.* (2013) and Rovere *et al.* (2017). However, measuring flow depth and velocity from imagery during the 2004 and 2011 tsunamis, and new numerical modelling have improved determination of the values of the Froude number and the coefficient of lift showing that they may vary during inundation, thereby setting additional uncertainties to the calculations.

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References

Akil, M. (1980). *Contribution à l'étude sédimentologique des formations littorales quaternaires de la région de Rabat*. Memoir Diplôme Etudes Supérieures, Univ. Mohammed V, Faculty of Sciences, Rabat.

Chabli, A., Chalouan, A., Akil, M., Galindo-Zaldívar, J., Ruano, P., Sanz de Galdeano, C., López-Garrido, A.C., Matin-Lechado, C. and Pedrera, A. (2014). *Journal of Geodynamics* 77, 123-134.

Chahid, D. (2017). *Paléo-environnements littoraux atlantiques (Pléistocène moyen - supérieur, Holocène) de Rabat-Témara (Maroc): lithostratigraphie, pétrographie et géochronologie*. PhD Thesis, Univ. Moulay Ismail, Faculty of Sciences Meknès and National Museum of Natural History, Paris, 249 p.

Medina, F., Mhammdi, N., Chiguer, A., Akil, M. and Jaaidi, E.B. (2011). *Natural Hazards* 59, 725-747.

Medina, F., Mhammdi, N. Emran, A. and Hakdaoui, S., (2018). *IX Symposium MIA*, Coimbra, 4-7 September 2018, book of proceedings 215-216.

Mhammdi, N., Medina, F., Kelletat, D., Ahmamou, M. and Aloussi L. (2008). *Science of Tsunami Hazards* 27, 1, 17-30.

Nandasena, N.A.K., Paris,. R. and Tanaka N. (2011). *Marine Geology* 281, 70-84.

Nandasena, N.A.K., Tanaka, N., Sasaki, Y. and Osada, M. (2013). *Marine Geology* 346, 292-309.

Nott, J. (2003). *Earth and Planetary Science Letters* 210, 269-276.

Oliveira, M. (2017). *Boulder deposits related to extreme marine events in the western coast of Portugal*. PhD Thesis, Faculty of Sciences, Lisbon, 369 pp.

Rovere, A., Casella, E., Harris, D.L., Lorscheid, T., Nandasena, N.A., Dyer, B., Sandström, M.R., Stocchi, P., D'Andrea, W.J. and Raymo, M.E. (2017). *Proceedings of the National Academy of Sciences* 114, 46, 12144-12149.

Scheffers, A. and Kelletat, D. (2005). *Science of Tsunami Hazards* 23, 1, 3-15.

Whelan, F. and Kelletat, D (2005). *Science of Tsunami Hazards* 23, 25-38.