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Coastal Boulder Deposits of the Neogene World: A Synopsis

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Abstract: Modern geoscience research pays significant attention to Quaternary coastal boulder deposits, although the evidence from the earlier geologic periods can be of great importance. The undertaken compilation of the literature permits to indicate 21 articles devoted to such deposits of Neogene age. These are chiefly case studies. Such an insufficiency of investigations may be linked to poor preservation potential of coastal boulder deposits and methodological difficulties. Equal attention has been paid by geoscientists to Miocene and Pliocene deposits. Taking into account the much shorter duration of the Pliocene, an overemphasis of boulders of this age becomes evident. Hypothetically, this can be explained by more favorable conditions for boulder formation, including a larger number of hurricanes due to the Pliocene warming. Geographically, the studies of the Neogene coastal boulder deposits have been undertaken in different parts of the world, but generally in those locations where rocky shores occur nowadays. The relevance of these deposits to storms and tsunamis, rocky shores and deltas, gravity processes, and volcanism has been discussed; however, some other mechanisms of boulder production, transportation, and accumulation (e.g., linked to seismicity and weathering) have been missed.

Keywords: bibliography; large clasts; Miocene; Pliocene; rocky shore; storm; tsunami

1. Introduction

Modern marine sedimentology grows rapidly, and new research directions have strengthened in the past two decades. One of such directions embraces studies of coastal boulders. On the one hand, these studies aim at development of nomenclature of large clasts. Concerning nomenclature, some advances have been made in the works by Blair and McPherson [1], Blott and Pye [2], Bruno and Ruban [3], and Terry and Goff [4]. On the other hand, boulders are regarded as precious evidence of present and ancient rocky shore facies and extreme events (such as storms, tsunamis, hurricanes, typhoons, and cyclones). This evidence has been examined by Autret et al. [5], Bhatt et al. [6], Biolchi et al. [7], Cox et al. [8–10], Dawson [11], Engel et al. [12], Erdmann et al. [13], Hearty and Tormey [14], Herterich et al. [15], Hongo et al. [16], Johnson et al. [17,18], Kennedy et al. [19], Kortekaas and Dawson [20], Lau et al. [21], Olsen et al. [22], Paris et al. [23], Pepe et al. [24], Scheffers et al. [25], Schneider et al. [26], Shah-Hosseini et al. [27], Suanez et al. [28], Terry and Goff [29], Terry et al. [30], Trenhaile [31], Watanabe et al. [32], and Weiss and Sheremet [33]. Most probably, the devastating catastrophes like the 2004 Indian Ocean tsunami [34] and the 2011 Tohoku tsunami [35] have fueled the interest of researchers in coastal sedimentology and, particularly, large clasts [36]. Evidently, investigations of the two noted issues often interconnect.

A significant amount of information about coastal boulders has accumulated, and it appears to be highly important to systematize it for further critical analysis and conceptualization. Such an approach is very common in social sciences [37–39], although geoscientists, unfortunately, often underestimate its potential. Marine sedimentologists need a simple guide permitting orientation in the growing research direction. The objective of the present paper is to offer an overview of the literature on Neogene coastal boulder deposits with some inferences on the current state of research. The importance of such a bibliographical analysis in megaclast research was demonstrated earlier [40]. The peculiarities of this paper are triplicate. First, it presents a synopsis summarizing the already-published data. Second, it focuses on the principal literature sources on the noted subjects, which means articles in international journals accessible via major bibliographical databases and considering large clasts in their title, abstract, and/or keywords. Third, this paper deals with the only Neogene Period, the sedimentary record of which is significantly more representative than that of the earlier periods, but differs from the Quaternary coastal deposits.

2. Conceptual Basis

2.1. Terminology

The focus of the present paper requires clear definition of several terms, from which two principal terms are "boulder" and "coastal boulder deposit". Evidently, the former indicates a sedimentary particle (clast, grain), and the latter indicates a specific sediment type consisting of (dominated by) such particles.

In the "classical" geological literature, the term "boulder" refers to particles larger than 256 mm (e.g., according to the widely used Udden–Wentworth classification scheme) [3]. However, intensification of studies of large clasts occurring in storm- and tsunami-related deposits raised the question of a more detailed nomenclature of such sedimentary particles. In 1999, Blair and McPherson [1] proposed a nomenclature of large clasts and limited the upper size of boulders to ~4 m (larger clasts are blocks). Different approaches were proposed later [2–4]. Of special interest is the distinction between boulders, mesoboulders, and macroboulders attributing to different categories [4]. Boulders are also opposed to megaclasts (Figure 1). Up to now, there is not broad, international agreement of how large clasts should be termed. As a result of this, it is not a mistake to use the very general term "boulder" for all sedimentary particles larger than 256 mm, except for only some specific studies focusing on the nomenclature development or devoted to a very particular size category of large clasts. In the present paper, this term is considered in such a broad way, and its partial substitutes (like megaclasts) are also taken into account.

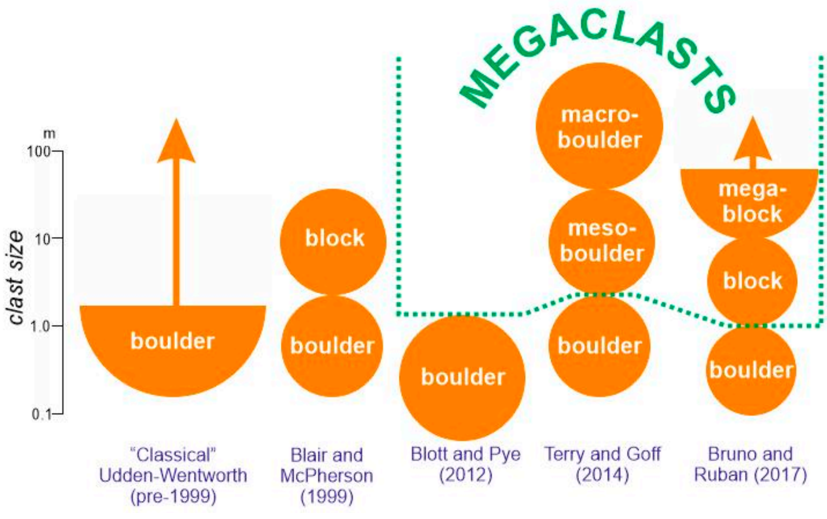

Figure 1. Different definition of boulders (see text for references).

The term "coastal boulder deposit" has been used in the works of several authors, although it still requires proper definition. Consideration of the context of its usage in the journal articles permits outlining some characteristics of such a sedimentary formation. These include, particularly, accumulation of boulders distinguished by their large size and/or huge weight [9,10,17,18,25–27], angularity with certain roundness [8], high-topography and inland occurrence [8,9,25,27], high-energy coastlines [5,8,15,17], and relevance to storm and tsunami activity [9,10,18,26,27]. It is notable that the previous works focused more on boulders individually rather than on entire deposits. Even the superficial analysis of the available literature implies that one should distinguish coastal boulder-dominated deposits, i.e., deposits consisting chiefly of boulders (say with their amount of >50%), from coastal boulder-bearing deposits, i.e., deposits dominated by sedimentary particles of lesser size (sand, gravel, cobble, etc.) and bearing a small number or individual boulders. Interestingly, such individual boulders, if too large in size, may look sediment-dominating. The problem seems to be even more complicated in the case of ancient deposits. Large clasts themselves are subject to erosion in the coastal zone with active hydrodynamics, and, thus, large clasts tend to disappear quickly from the geological record. As a result, an ancient coastal boulder-bearing deposit may be legacy of the really existed boulder-dominated deposit. Until these problems are resolved and the nomenclature of large-clast deposits is fixed, it is possible to apply the general term "coastal boulder deposit" broadly, but preferably in those cases when boulders tend to concentrate.

Dewey and Ryan [41] introduced the term "boulderite". Evidently, this can be applied to boulder-dominated deposits. Importantly, the both modern and ancient deposits of this type are called as boulderites [41]. It is the right of the noted authors to use it so, although one may question whether the term "boulderite" can be used for only ancient boulder-dominated deposits, i.e., sedimentary rocks, not recent sediments.

2.2. Stratigraphical Framework

The Neogene Period lasted ~20.5 Ma, and it is subdivided into the Miocene and Pliocene Epochs. After strong disputes in the 2000s when the Neogene was extended to the Holocene, a "classical" (almost) scheme has been fixed by the International Commission on Stratigraphy (Table 1), although it is not excluded that the formal definition of the Anthropocene would result in reorganization of the Late Cenozoic stratigraphical nomenclature with subsequent changes in the extent of the Neogene.

Table 1. Current version of the Neogene time scale (after International Commission on Stratigraphy [42]).

Eon	Era	Period	Epoch	Stage	Numerical Age (Ma) of Stage Start
Phanerozoic	Cenozoic	Quaternary			2.580
		Neogene	Pliocene	Piacenzian	3.600
				Zanclean	5.333
			Miocene	Messinian	7.246
				Tortonian	11.63
				Serravallian	13.82
				Langhian	15.97
				Burdigalian	20.44
				Aquitanian	23.03
		Paleogene			66.00

What is necessary to note is the significant disproportion of the Neogene subdivision: the Miocene constitutes ~87% of the period length, and, thus, the Pliocene seems to be too short. This fact should be taken into account when the temporal distribution of any class of geological objects like coastal boulder deposits is analyzed by epochs.

3. Bibliographical Synopsis

3.1. Research Foci

Although coastal boulder deposits are mentioned in the modern geoscience literature not so rarely, the majority of works deal with the recent and Quaternary boulders. The knowledge of the Neogene sediments of this type remains very restricted. The number of the principal sources does not exceed two dozen. Most probably, this reflects the both low preservation potential of large clasts that themselves are subject of erosion and destruction starting immediately after their deposition and the absence of well-known and broadly accepted techniques for their investigations in the geological record. Nonetheless, the research in the Neogene coastal boulder deposits intensified in the 2010s when up to a half of these principal works were published (Table 2).

Table 2. General information about the localities considered in the main articles on Neogene coastal boulder deposits (see also Tables 3–5 for terms, ages, and depositional environments).

Work	Locality ID	Location and/or Formation	Context of Study
Aguirre and Jimenez, 1997 [43]	1	Almeria-Nijar Basin	Palaeobiological: hard-bottom coastal communities
Allen et al., 2007 [44]	2	Manukau Subgroup	Sedimentological: submarine volcaniclastic deposition
Cantalamessa and Di Celma, 2005 [45]	3	Mejillones Peninsula	Sedimentological: tsunami backwash deposits
Dewey and Ryan, 2017 [41]	4	Matheson Formation	Sedimentological: deposition under extreme conditions
Edwards et al., 2004 [46]	5	Lady Julia Percy Island	Sedimentological and geomorphological: volcanic environment
Emhoff et al., 2012 [47]	6	Isla Cerralvo, Baja California Sur	Stratigraphical and sedimentological: massive crushed-rhodolith deposit
Gutierrez-Mas and Mas, 2013 [48]	7	Gulf of Cadiz	Sedimentological: deposition under extreme conditions
Hanken et al., 1996 [49]	8	Northeast Rhodes	Sedimentological: deposition in coastal graben
Hartley et al., 2001 [50]	9	Hornitos; La Portada Formation	Sedimentological: tsunamite
Hood and Nelson, 2012 [51]	10	eastern Taranaki Basin	Sedimentological: carbonate debrites and tectonic control
Johnson, 2006 [52]		global	Sedimentological and palaeobiological: rocky shores and their ecosystems
Johnson et al., 2011 [53]	11	Madeira Archipelago	Sedimentological and palaeobiological: rhodolith transport
Johnson et al., 2012 [54]	6	Isla Cerralvo, Baja California Sur	Sedimentological and palaeobiological: rhodolith stranding event
Le Roux et al., 2004 [55]	12	Coquimbo Formation	Sedimentological: scarp-controlled rocky shoreline
Roberts and Brink, 2002 [56]	13	Western Cape; Prospect Hill Formation	Stratigraphical: dating of coastal deposits
Rodriguez-Tovar et al., 2015 [57]	14	Sorbas basin	Palaeobiological: borings in gneiss boulders
Shiki and Yamazaki, 1996 [58]	15	Chita Peninsula; Morozaki Group	Sedimentological: upper bathyal tsunamites
Tachibana and Tsuji, 2011 [59]	15	Chita Peninsula; Morozaki Group	Sedimentological: upper bathyal tsunamites
Watkins, 1992 [60]	16	Salton Trough region; Imperial Formation	Sedimentological and palaeobiological: shallow marine conglomerates and the relevant communities
Wesselingh et al., 2013 [61]	17	Balgoy; Oosterhout Formation	Palaeobiological: brachiopod-dominated sea-floor assemblage from hardened sandstone boulders
Winn and Pousai, 2010 [62]	18	Papuan Peninsula; Orubadi and Era Formations	Sedimentological: alluvial-fan and fan-delta deposition

Interestingly, different researchers use different terminology (Table 3). The majority informs about boulders. In only one case megaclasts are mentioned. Coastal boulder deposits are indicated in five works, although in none of them the term "coastal boulder deposit" is used. These deposits are recognized as boulder beach, boulder conglomerate, or boulderite. Boulder-bearing conglomerate and breccia are also considered, but these should be distinguished from boulder-dominated deposits (see terminological notes above). Finally, a few works employ two or even three terms simultaneously.

Table 3. Coastal boulder-related terminology in the main articles on Neogene coastal boulder deposits.

Work	Basic Terms			
	Boulder	Coastal Boulder Deposit	Megaclast	Other
Aguirre and Jimenez, 1997 [43]	+			
Allen et al., 2007 [44]	+			
Cantalamessa and Di Celma, 2005 [45]	+			boulder-bearing breccia
Dewey and Ryan, 2017 [41]	+	boulderite	+	
Edwards et al., 2004 [46]		boulder beach		
Emhoff et al., 2012 [47]	+			
Gutierrez-Mas and Mas, 2013 [48]	+			
Hanken et al., 1996 [49]		boulder beach		
Hartley et al., 2001 [50]	+			
Hood and Nelson, 2012 [51]	+			
Johnson, 2006 [52]	+			
Johnson et al., 2011 [53]	+			
Johnson et al., 2012 [54]	+			
Le Roux et al., 2004 [55]	+			
Roberts and Brink, 2002 [56]		boulder beach		
Rodriguez-Tovar et al., 2015 [57]	+			
Shiki and Yamazaki, 1996 [58]				boulder-bearing conglomerate
Tachibana and Tsuji, 2011 [59]	+			
Watkins, 1992 [60]	+	boulder conglomerate		
Wesselingh et al., 2013 [61]	+			
Winn and Pousai, 2010 [62]	+			

The majority of the works are case studies focusing on a given location and given stratigraphical intervals. Only two papers of general kind (conceptual) are found (Table 4). The first is the synthetic work of Johnson [52] who overviewed the knowledge of rocky shorelines where boulders often accumulate and the relevant palaeoecosystems. Particularly, he noted that the Neogene deposits of this facies are often linked to ramps, in contrast to the dominance of terrace deposits in the Pleistocene. The second paper of this kind can be judged conceptual only provisionally because this is dealing with the comparison of the examples of the modern and Neogene coastal boulder deposits with a discussion of their storm versus tsunami origin [41]. Importantly, this paper [41] employs the term "boulderite" as equivalent to "boulder-dominated deposit". The other works explore some particular aspects of Neogene coastal boulder deposits, including their relevance to extreme events such as storms and tsunamis, as well as palaeoecological issues.

Table 4. Stratigraphical and geographical foci of the main articles on Neogene coastal boulder deposits.

Work	Conceptual	Miocene	Pliocene	Location
Aguirre and Jimenez, 1997 [43]			+	Spain
Allen et al., 2007 [44]		+		New Zealand
Cantalamessa and Di Celma, 2005 [45]		+		Chile
Dewey and Ryan, 2017 [41]	+	+		New Zealand
Edwards et al., 2004 [46]		+		Australia (south)
Emhoff et al., 2012 [47]			+	Mexico
Gutierrez-Mas and Mas, 2013 [48]			+	Spain
Hanken et al., 1996 [49]			+	Greece (Rhodes)
Hartley et al., 2001 [50]			+	Chile
Hood and Nelson, 2012 [51]		+		New Zealand
Johnson, 2006 [52]	+	+	+	World
Johnson et al., 2011 [53]		+		Portugal (Madeira)
Johnson et al., 2012 [54]			+	Mexico
Le Roux et al., 2004 [55]		+	+	Chile
Roberts and Brink, 2002 [56]		+		South Africa
Rodriguez-Tovar et al., 2015 [57]		+		Spain
Shiki and Yamazaki, 1996 [58]		+		Japan
Tachibana and Tsuji, 2011 [59]		+		Japan
Watkins, 1992 [60]			+	USA (California)
Wesselingh et al., 2013 [61]			+	Netherlands
Winn and Pousai, 2010 [62]			+	Papua New Guinea

It is possible to classify all principal sources on the basis of their stratigraphical, geographical, and genetic foci (Tables 4 and 5). The main observations are as follows. First, Miocene and Pliocene coastal boulder deposits have been generally considered with attention (Table 4). Second, the relevant studies tend to represent different parts of the world (Table 4). Third, the diversity of the discussed mechanisms leading to boulder production, transportation, and accumulation in coastal zone is moderate if not low (Table 5).

Table 5. Genetic focus of the main articles on Neogene coastal boulder deposits.

Work	Rocky Shore	Storm (S), Tsunami (T)	Delta, Fan	Volcanism	Gravity Movement
Aguirre and Jimenez, 1997 [43]			+		+
Allen et al., 2007 [44]				+	
Cantalamessa and Di Celma, 2005 [45]		T			+
Dewey and Ryan, 2017 [41]		S, T			
Edwards et al., 2004 [46]				+	
Emhoff et al., 2012 [47]			+		
Gutierrez-Mas and Mas, 2013 [48]		S, T			
Hanken et al., 1996 [49]			not specified		
Hartley et al., 2001 [50]		T	+		
Hood and Nelson, 2012 [51]		S			+
Johnson, 2006 [52]	+				
Johnson et al., 2011 [53]	+	S		+	
Johnson et al., 2012 [54]	+	S	+		
Le Roux et al., 2004 [55]	+				+
Roberts and Brink, 2002 [56]			not specified		
Rodriguez-Tovar et al., 2015 [57]			not specified		
Shiki and Yamazaki, 1996 [58]		T			
Tachibana and Tsuji, 2011 [59]		T			
Watkins, 1992 [60]	+				+
Wesselingh et al., 2013 [61]		S			
Winn and Pousai, 2010 [62]			+		+

3.2. Further Inferences

The Miocene coastal boulder deposits are considered in 57% of the analyzed works, and those Pliocene are considered in 52% of the works (two articles deal with the both epochs). Apparently, this means equal attention to the both epochs. However, it is necessary to take into account that the Miocene is by ~6.5 times longer than the Pliocene (Table 1). In regard to this fact, it is possible to conclude about significant overemphasis on the Pliocene coastal boulders. Although it cannot be excluded that such a disproportion results from occasional bias in the international research, it can be also hypothesized that the Pliocene environment was more favorable for production and accumulation of boulders in coastal zones of seas and oceans. The evidence of a potentially greater number of hurricanes under the conditions of the Pliocene warming [63–65] makes this hypothesis meaningful. For coastal zone dynamics, sea-level fluctuations seem to be important control of boulder production. Rising sea level accelerates abrasion (especially of sea cliffs) and also leads to growth of shoreline length. For instance, boulders are reported from some areas that were embraced by the sea in the Neogene, but are located inland nowadays, as in the case of the Sorbas Basin in Spain [57]. The global sea level was rather high in the Miocene, but it experienced significant fluctuations that intensified in the Pliocene [66–71]. On the one hand, the relevant instability of the coastal zones could contribute to more boulder formation. On the other hand, the same instability could trigger boulder motion and destruction by waves.

The geographical distribution of the reported Neogene coastal boulder deposits is broad (Figure 2). Despite the rarity of the described locations, the latter occur in all parts of the world (except for Antarctica). It is notable that these deposits have been described chiefly in the same regions where the modern rocky coasts with boulders exist. This is not surprising because of the absence of too striking differences in the position of continents and oceans between the Neogene and the Recent. However, another, complex explanation can be proposed. Sedimentologists and geomorphologists specialized in the studies of coastal boulder deposits often deal with the modern objects. If so, it is evident that they are able to detect ancient deposits of this kind in the same geographical loci. Nonetheless, it is evident that the knowledge of Quaternary coastal boulders is much wider. For instance, these have been reported from many localities of the Mediterranean, including (but not limited to) Istria [7], Sicily [24], northern Egypt [27], Malta [72], Ibiza [73], Crete [74], Lesvos [75], southern France [76], and Apulia [77]. Better to say, boulders and their accumulations are found on the majority of coasts of the Mediterranean Sea. In contrast, Neogene large clasts are reported from very few localities of the same basin. Most probably, this reflects the both sedimentological research bias and low preservation potential of boulders.

An interesting inference is linked to the origin of the Neogene coastal boulder deposits. Many previous studies focused on their relevance to storms and tsunamis as the leading boulder production, transportation, and accumulation forces, as well as on gravity processes linked to downslope movement with consequent cliff retreat (Figure 3). The main depositional environments analyzed in the course of the coastal boulder research are rocky shores, deltas, and areas of volcanism (Figure 3). On the one hand, it is clear that chiefly extreme events like storms, tsunamis, and volcanic eruptions are able to provide the energy necessary to produce and to move large clasts. On the other hand, it seems to be questionable if some other forces were responsible. For instance, seismicity would cause giant cliff collapse or heterogeneity of exposed substrate would lead to its differential erosion. Finally, what about the possible role of wind erosion in coastal zones? Undoubtedly, identification and correct interpretation of such phenomena even in geological records as young as that of the Neogene is highly challenging and requires very creative analysis. Examples of the latter can be found in the works deciphering the origin of boulders from the Miocene upper bathyal deposits of the Chita Peninsula (Japan) [58,59] ensures the possibility of such state-of-the-art investigations. Anyway, coastal boulders, especially those measured by meters are highly specific and uncommon geological objects, and their analysis should be undertaken in regard to individual peculiarities of each given locality.

Figure 2. Geographical focus of the studies of Neogene coastal boulder deposits (based on Table 4). See Table 2 for locality IDs.

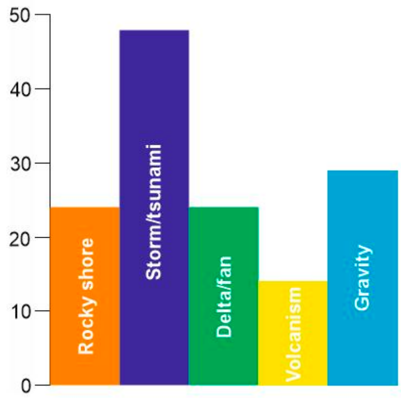

Figure 3. Genetic focus of the studies of Neogene coastal boulder deposits (based on Table 5).

4. Conclusions

The bibliographical synopsis of the knowledge of Neogene coastal boulder deposits implies that the relevant research has been weak. Nonetheless, this research has generated significant evidence of these deposits. The main findings of the present analysis are as follows.

(1) Case studies of the Neogene coastal boulder deposits prevail over conceptual works.

(2) Attention has been paid to the both epochs of the Neogene (although with overemphasis on the Pliocene), to many parts of the world, and to the really principal mechanisms of boulder production, transportation, and accumulation (first of all, to extreme events).

(3) The stratigraphical, geographical, and genetic foci of the research demonstrate certain biases that can be explained, particularly, by peculiarities of the geological record.

Generally, this means that although the Neogene coastal boulder deposits are highly specific and rather uncommon geological objects, the latter have been studied more or less adequately to make further interpretations of their relevance to the dynamics of the Neogene world.

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References

1. Blair, T.C.; McPherson, J.G. Grain-size and textural classification of coarse sedimentary particles. *J. Sediment. Res.* **1999**, *69*, 6–19. [CrossRef]
2. Blott, S.J.; Pye, K. Particle size scales and classification of sediment types based on particle size distributions: Review and recommended procedures. *Sedimentology* **2012**, *59*, 2071–2096. [CrossRef]
3. Bruno, D.E.; Ruban, D.A. Something more than boulders: A geological comment on the nomenclature of megaclasts on extraterrestrial bodies. *Planet. Space Sci.* **2017**, *135*, 37–42. [CrossRef]
4. Terry, J.P.; Goff, J. Megaclasts: Proposed revised nomenclature at the coarse end of the Udden-Wentworth grain-size scale for sedimentary particles. *J. Sediment. Res.* **2014**, *84*, 192–197. [CrossRef]
5. Autret, R.; Dodet, G.; Suanez, S.; Roudaut, G.; Fichaut, B. Long–term variability of supratidal coastal boulder activation in Brittany (France). *Geomorphology* **2018**, *304*, 184–200. [CrossRef]
6. Bhatt, N.; Murari, M.K.; Ukey, V.; Prizomwala, S.P.; Singhvi, A.K. Geological evidences of extreme waves along the Gujarat coast of western India. *Nat. Hazards* **2016**, *84*, 1685–1704. [CrossRef]
7. Biolchi, S.; Furlani, S.; Devoto, S.; Scicchitano, G.; Korbar, T.; Vilibic, I.; Sepic, J. The origin and dynamics of coastal boulders in a semi-enclosed shallow basin: A northern Adriatic case study. *Mar. Geol.* **2019**, *411*, 62–77. [CrossRef]
8. Cox, R.; Lopes, W.A.; Jahn, K.L. Quantitative roundness analysis of coastal boulder deposits. *Mar. Geol.* **2018**, *396*, 114–141. [CrossRef]
9. Cox, R.; Jahn, K.L.; Watkins, O.G.; Cox, P. Extraordinary boulder transport by storm waves (west of Ireland, winter 2013–2014), and criteria for analysing coastal boulder deposits. *Earth Sci. Rev.* **2018**, *177*, 623–636. [CrossRef]
10. Cox, R.; O'Boyle, L.; Cytrynbaum, J. Imbricated Coastal Boulder Deposits are Formed by Storm Waves, and Can Preserve a Long-Term Storminess Record. *Sci. Rep.* **2019**, *9*, 10784. [CrossRef]
11. Dawson, A. The geological significance of tsunamis. *Z. Fur Geomorphol. Suppl.* **1996**, *102*, 199–210.
12. Engel, M.; Oetjen, J.; May, S.M.; Bruckner, H. Tsunami deposits of the Caribbean – Towards an improved coastal hazard assessment. *Earth Sci. Rev.* **2016**, *163*, 260–296. [CrossRef]
13. Erdmann, W.; Scheffers, A.M.; Kelletat, D.H. Holocene Coastal Sedimentation in a Rocky Environment: Geomorphological Evidence from the Aran Islands and Galway Bay (Western Ireland). *J. Coast. Res.* **2018**, *34*, 772–792. [CrossRef]
14. Hearty, P.J.; Tormey, B.R. Sea-level change and superstorms; geologic evidence from the last interglacial (MIS 5e) in the Bahamas and Bermuda offers ominous prospects for a warming Earth. *Mar. Geol.* **2017**, *390*, 347–365. [CrossRef]
15. Herterich, J.G.; Cox, R.; Dias, F. How does wave impact generate large boulders? Modelling hydraulic fracture of cliffs and shore platforms. *Mar. Geol.* **2018**, *399*, 34–46. [CrossRef]
16. Hongo, C.; Kurihara, H.; Golbuu, Y. Coral boulders on Melekeok reef in the Palau Islands: An indicator of wave activity associated with tropical cyclones. *Mar. Geol.* **2018**, *399*, 14–22. [CrossRef]
17. Johnson, M.E.; Ledesma-Vazquez, J.; Guardado-France, R. Coastal Geomorphology of a Holocene Hurricane Deposits on a Pleistocene Marine Terrace from Isla Carmen (Baja California Sur, Mexico). *J. Mar. Sci. Eng.* **2018**, *6*, 108. [CrossRef]
18. Johnson, M.E.; Guardado-France, R.; Johnson, E.M.; Ledesma-Vazquez, J. Geomorphology of a Holocene Hurricane Deposit Eroded from Rhyolite Sea Cliffs on Ensenada Almeja (Baja California Sur, Mexico). *J. Mar. Sci. Eng.* **2019**, *7*, 193. [CrossRef]
19. Kennedy, D.M.; Woods, J.L.D.; Naylor, L.A.; Hansom, J.D.; Rosser, N.J. Intertidal boulder-based wave hindcasting can underestimate wave size: Evidence from Yorkshire, UK. *Mar. Geol.* **2019**, *411*, 98–106. [CrossRef]
20. Kortekaas, S.; Dawson, A.G. Distinguishing tsunami and storm deposits: An example from Martinhal, SW Portugal. *Sediment. Geol.* **2007**, *200*, 208–221. [CrossRef]
21. Lau, A.Y.A.; Terry, J.P.; Ziegler, A.; Pratap, A.; Harris, D. Boulder emplacement and remobilisation by cyclone and submarine landslide tsunami waves near Suva City, Fiji. *Sediment. Geol.* **2018**, *364*, 242–257. [CrossRef]
22. Olsen, M.J.; Johnstone, E.; Driscoll, N.; Kuester, F.; Ashford, S.A. Fate and transport of seacliff failure sediment in southern California. *J. Coast. Res.* **2016**, *76*, 185–199. [CrossRef]

23. Paris, R.; Naylor, L.A.; Stephenson, W.J. Boulders as a signature of storms on rock coasts. *Mar. Geol.* **2011**, *283*, 1–11. [CrossRef]
24. Pepe, F.; Corradino, M.; Parrino, N.; Besio, G.; Presti, V.L.; Renda, P.; Calcagnile, L.; Quarta, G.; Sulli, A.; Antonioli, F. Boulder coastal deposits at Favignana Island rocky coast (Sicily, Italy): Litho-structural and hydrodynamic control. *Geomorphology* **2018**, *303*, 191–209. [CrossRef]
25. Scheffers, A.; Kelletat, D.; Haslett, S.; Scheffers, S.; Browne, T. Coastal boulder deposits in Galway Bay and the Aran Islands, western Ireland. *Z. Fur Geomorphol.* **2010**, *54*, 247–279. [CrossRef]
26. Schneider, B.; Hoffmann, G.; Falkenroth, M.; Grade, J. Tsunami and storm sediments in Oman: Characterizing extreme wave deposits using terrestrial laser scanning. *J. Coast. Conserv.* **2019**, *23*, 801–815. [CrossRef]
27. Shah-Hosseini, M.; Saleem, A.; Mahmoud, A.-M.A.; Morhange, C. Coastal boulder deposits attesting to large wave impacts on the Mediterranean coast of Egypt. *Nat. Hazards* **2016**, *83*, 849–865. [CrossRef]
28. Suanez, S.; Fichaut, B.; Magne, R. Cliff-top storm deposits on Banneg Island, Brittany, France: Effects of giant waves in the Eastern Atlantic Ocean. *Sediment. Geol.* **2009**, *220*, 12–28. [CrossRef]
29. Terry, J.P.; Goff, J. Strongly aligned coastal boulders on Ko Larn island (Thailand): A proxy for past typhoon-driven high-energy wave events in the Bay of Bangkok. *Geogr. Res.* **2019**, *57*, 344–358. [CrossRef]
30. Terry, J.P.; Goff, J.; Jankaew, K. Major typhoon phases in the upper Gulf of Thailand over the last 1.5 millennia, determined from coastal deposits on rock islands. *Quat. Int.*.
31. Trenhaile, A. Rocky coasts–Their role as depositional environments. *Earth Sci. Rev.* **2016**, *159*, 1–13. [CrossRef]
32. Watanabe, M.; Goto, K.; Imamura, F.; Hongo, C. Numerical identification of tsunami boulders and estimation of local tsunami size at Ibaruma reef of Ishigaki Island, Japan. *Isl. Arc* **2016**, *25*, 316–332. [CrossRef]
33. Weiss, R.; Sheremet, A. Toward a new paradigm for boulder dislodgement during storms. *Geochem. Geophys. Geosyst.* **2017**, *18*, 2717–2726. [CrossRef]
34. Lay, T.; Kanamori, H.; Ammon, C.J.; Nettles, M.; Ward, S.N.; Aster, R.C.; Beck, S.L.; Bilek, S.L.; Brudzinski, M.R.; Butler, R.; et al. The great Sumatra-Andaman earthquake of 26 December 2004. *Science* **2005**, *308*, 1127–1133. [CrossRef] [PubMed]
35. Simons, M.; Minson, S.E.; Sladen, A.; Ortega, F.; Jiang, J.; Owen, S.E.; Meng, L.; Ampuero, J.-P.; Wei, S.; Chu, R.; et al. The 2011 magnitude 9.0 Tohoku-Oki earthquake: Mosaicking the megathrust from seconds to centuries. *Science* **2011**, *332*, 1421–1425. [CrossRef] [PubMed]
36. Ruban, D.A. Research in tsunami-related sedimentology during 2001–2010: Can a single natural disaster re-shape the science? *GeoActa* **2011**, *10*, 79–85.
37. Fernandez, K.V. Critically reviewing literature: A tutorial for new researchers. *Australas. Mark. J.* **2019**, *27*, 187–196. [CrossRef]
38. Kumar, P.; Sharma, A.; Salo, J. A bibliometric analysis of extended key account management literature. *Ind. Mark. Manag.* **2019**, *82*, 276–292. [CrossRef]
39. Snyder, H. Literature review as a research methodology: An overview and guidelines. *J. Bus. Res.* **2019**, *104*, 333–339. [CrossRef]
40. Ruban, D.A.; Ponedelnik, A.A.; Yashalova, N.N. Megaclasts: Term Use and Relevant Biases. *Geosciences* **2019**, *9*, 14. [CrossRef]
41. Dewey, J.F.; Ryan, P.D. Storm, rogue wave, or tsunami origin for megaclast deposits in Western Ireland and North Island, New Zealand? *Proc. Natl. Acad. Sci. USA* **2017**, *114*, E10639–E10647. [CrossRef]
42. International Commission on Stratigraphy. International Chronostratigraphic Chart 2019. Available online: Stratigraphy.org (accessed on 18 October 2019).
43. Aguirre, J.; Jimenez, A.P. Census assemblages in hard-bottom coastal communities: A case study from the Plio-Pleistocene Mediterranean. *Palaios* **1997**, *12*, 598–608. [CrossRef]
44. Allen, S.R.; Hayward, B.W.; Mathews, E. A facies model for a submarine volcaniclastic apron: The Miocene Manukau Subgroup, New Zealand. *Bull. Geol. Soc. Am.* **2007**, *119*, 725–742. [CrossRef]
45. Cantalamessa, G.; Di Celma, C. Sedimentary features of tsunami backwash deposits in a shallow marine Miocene setting, Mejillones Peninsula, northern Chile. *Sediment. Geol.* **2005**, *178*, 259–273. [CrossRef]
46. Edwards, J.; Cayley, R.A.; Joyce, E.B. Geology and geomorphology of the Lady Julia Percy Island volcano, a Late Miocene submarine and subaerial volcano off the coast of Victoria, Australia. *Proc. R. Soc. Vic.* **2004**, *116*, 15–35.

47. Emhoff, K.F.; Johnson, M.E.; Backus, D.H.; Ledesma-Vazquez, J. Pliocene stratigraphy at paredones blancos: Significance of a massive crushed-rhodolith deposit on Isla Cerralvo, baja California sur (Mexico). *J. Coast. Res.* **2012**, *28*, 234–243. [CrossRef]
48. Gutierrez-Mas, J.M.; Mas, R. Record of very high energy events in Plio-Pleistocene marine deposits of the Gulf of Cadiz (SW Spain): Facies and processes. *Facies* **2013**, *59*, 679–701. [CrossRef]
49. Hanken, N.-M.; Bromley, R.G.; Miller, J. Plio-Pleistocene sedimentation in coastal grabens, north-east Rhodes, Greece. *Geol. J.* **1996**, *31*, 393–418. [CrossRef]
50. Hartley, A.; Howell, J.; Mather, A.E.; Chong, G. A possible Plio-Pleistocene tsunami deposit, Hornitos, Northern Chile. *Rev. Geol. Chile* **2001**, *28*, 117–125. [CrossRef]
51. Hood, S.D.; Nelson, C.S. Temperate carbonate debrites and short-lived earliest Miocene yo-yo tectonics, eastern Taranaki Basin margin, New Zealand. *Sediment. Geol.* **2012**, *247–248*, 58–70. [CrossRef]
52. Johnson, M.E. Uniformitarianism as a guide to rocky-shore ecosystems in the geological record. *Can. J. Earth Sci.* **2006**, *43*, 1119–1147. [CrossRef]
53. Johnson, M.E.; da Silva, C.M.; Santos, A.; Baarli, B.G.; Cachao, M.; Mayoral, E.J.; Rebelo, A.C.; Ledesma-Vazquez, J. Rhodolith transport and immobilization on a volcanically active rocky shore: Middle Miocene at Cabeco das Laranjas on Ilheu de Cima (Madeira Archipelago, Portugal). *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **2011**, *300*, 113–127. [CrossRef]
54. Johnson, M.E.; Perez, D.M.; Baarli, B.G. Rhodolith stranding event on a Pliocene rocky shore from Isla Cerralvo in the lower Gulf of California (Mexico). *J. Coast. Res.* **2012**, *28*, 225–233. [CrossRef]
55. Le Roux, J.P.; Gomez, C.; Fenner, J.; Middleton, H. Sedimentological processes in a scarp-controlled rocky shoreline to upper continental slope environment, as revealed by unusual sedimentary features in the Neogene Coquimbo Formation, north-central Chile. *Sediment. Geol.* **2004**, *165*, 67–92. [CrossRef]
56. Roberts, D.L.; Brink, J.S. Dating and correlation of Neogene coastal deposits in the Western Cape (South Africa): Implications for neotectonism. *S. Afr. J. Geol.* **2002**, *105*, 337–352. [CrossRef]
57. Rodriguez-Tovar, F.J.; Uchman, A.; Puga-Bernabeu, A. Borings in gneiss boulders in the Miocene (Upper Tortonian) of the Sorbas basin, SE Spain. *Geol. Mag.* **2015**, *152*, 287–297. [CrossRef]
58. Shiki, T.; Yamazaki, T. Tsunami-induced conglomerates in Miocene upper bathyal deposits, Chita Peninsula, central Japan. *Sediment. Geol.* **1996**, *104*, 175–188. [CrossRef]
59. Tachibana, T.; Tsuji, Y. Geological and hydrodynamical examination of the bathyal tsunamigenic origin of miocene conglomerates in Chita peninsula, Central Japan. *Pure Appl. Geophys.* **2011**, *168*, 997–1014. [CrossRef]
60. Watkins, R. Sedimentology and paleoecology of Pliocene shallow marine conglomerates, Salton Trough region, California. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **1992**, *95*, 319–333. [CrossRef]
61. Wesselingh, F.P.; Peters, W.J.M.; Munsterman, D.K. A brachiopod-dominated sea-floor assemblage from the Late Pliocene of the eastern Netherlands. *Neth. J. Geosci.* **2013**, *92*, 171–176. [CrossRef]
62. Winn, R.D., Jr.; Pousai, P. Synorogenic alluvial-fan—Fan-delta deposition in the Papuan foreland basin: Plio-Pleistocene Era Formation, Papua New Guinea. *Aust. J. Earth Sci.* **2010**, *57*, 507–523. [CrossRef]
63. Fedorov, A.V.; Brierley, C.M.; Emanuel, K. Tropical cyclones and permanent El Niño in the early Pliocene epoch. *Nature* **2010**, *463*, 1066–1070. [CrossRef] [PubMed]
64. Johnson, M.E.; Uchman, A.; Costa, P.J.M.; Ramalho, R.S.; Ávila, S.P. Intense hurricane transports sand onshore: Example from the Pliocene Malbusca section on Santa Maria Island (Azores, Portugal). *Mar. Geol.* **2017**, *385*, 244–249. [CrossRef]
65. Yan, Q.; Wei, T.; Korty, R.L.; Kossin, J.P.; Zhang, Z.; Wang, H. Enhanced intensity of global tropical cyclones during the mid-Pliocene warm period. *Proc. Natl. Acad. Sci. USA* **2016**, *113*, 12963–12967. [CrossRef] [PubMed]
66. Betzler, C.; Eberli, G.P.; Lüdmann, T.; Reolid, J.; Kroon, D.; Reijmer, J.J.G.; Swart, P.K.; Wright, J.; Young, J.R.; Alvarez-Zarikian, C.; et al. Refinement of Miocene sea level and monsoon events from the sedimentary archive of the Maldives (Indian Ocean). *Prog. Earth Planet. Sci.* **2018**, *5*, 5. [CrossRef]
67. Dumitru, O.A.; Austermann, J.; Polyak, V.J.; Fornós, J.J.; Asmerom, Y.; Ginés, J.; Ginés, A.; Onac, B.P. Constraints on global mean sea level during Pliocene warmth. *Nature* **2019**, *574*, 233–236. [CrossRef]
68. Grant, G.R.; Naish, T.R.; Dunbar, G.B.; Stocchi, P.; Kominz, M.A.; Kamp, P.J.J.; Tapia, C.A.; McKay, R.M.; Levy, R.H.; Patterson, M.O. The amplitude and origin of sea-level variability during the Pliocene epoch. *Nature* **2019**, *574*, 237–241. [CrossRef]

69. Kominz, M.A.; Browning, J.W.; Miller, K.G.; Sugarman, P.J.; Mizintseva, S.; Scotese, C.R. Late Cretaceous to Miocene sea-level estimates from the New Jersey and Delaware coastal plain coreholes: An error analysis. *Basin Res.* **2008**, *20*, 211–226. [CrossRef]
70. Raymo, M.E.; Mitrovica, J.X.; O'Leary, M.J.; Deconto, R.M.; Hearty, P.J. Departures from eustasy in Pliocene sea-level records. *Nat. Geosci.* **2011**, *4*, 328–332. [CrossRef]
71. Raymo, M.E.; Kozdon, R.; Evans, D.; Lisiecki, L.; Ford, H.L. The accuracy of mid-Pliocene d18O-based ice volume and sea level reconstructions. *Earth Sci. Rev.* **2018**, *177*, 291–302. [CrossRef]
72. Causon Deguara, J.; Scerri, S. Ras il-Gebel: An extreme wave-generated bouldered coast at Xghajra (Malta). *World Geomorphol. Landsc.* **2019**, 229–243.
73. Roig-Munar, F.X.; Rodríguez-Perea, A.; Martín-Prieto, J.A.; Gelabert, B.; Vilaplana, J.M. Tsunami boulders on the rocky coasts of Ibiza and Formentera (Balearic Islands). *J. Mar. Sci. Eng.* **2019**, *7*, 327. [CrossRef]
74. Scheffers, A.; Scheffers, S. Tsunami deposits on the coastline of west Crete (Greece). *Earth Planet. Sci. Lett.* **2007**, *259*, 613–624. [CrossRef]
75. Vacchi, M.; Rovere, A.; Zouros, N.; Firpo, M. Assessing enigmatic boulder deposits in NE Aegean Sea: Importance of historical sources as tool to support hydrodynamic equations. *Nat. Hazards Earth Syst. Sci.* **2012**, *12*, 1109–1118. [CrossRef]
76. Piscitelli, A.; Milella, M.; Hippolyte, J.-C.; Shah-Hosseini, M.; Morhange, C.; Mastronuzzi, G. Numerical approach to the study of coastal boulders: The case of Martigues, Marseille, France. *Quat. Int.* **2017**, *439*, 52–64. [CrossRef]
77. Mastronuzzi, G.; Sansò, P. Boulders transport by catastrophic waves along the Ionian coast of Apulia (southern Italy). *Mar. Geol.* **2000**, *70*, 93–103. [CrossRef]