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Boulder accumulations related to storms on the south coast of the Reykjanes Peninsula (Iceland)

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ABSTRACT

Coastal boulder accumulations are often mentioned in the literature, even though their interpretation remains difficult, especially along rock coasts affected both by storms and tsunamis. Studies on the geomorphic impact of such high-energy events are actually of great interest, since their intensity and frequency are key issues for the future evolution of coasts in the framework of the global change. The southwest coast of Iceland faces the powerful storms of the North Atlantic Ocean, with wave heights of more than 15 m. The probability for past and present tsunamis to hit this coast is very low. In this paper, we describe boulder accumulations along the volcanic rock coast of Reykjanes (southwest Iceland). They consist of cliff-top boulders, clusters and ridges, beaches, and boulder fields. Large boulders, up to 70 t in weight, have been transported and deposited up to 65 m inland (6 masl). The maximum limit of boulder deposition and driftwood was found respectively 210 m and 550 m inland. Storms appear to be a predominant factor in the geomorphic evolution of Reykjanes coasts. Our observations also give new insight for the interpretation of coastal boulder accumulations. Processes of erosion and deposition by tsunamis are a rising topic in the literature, and the effects of recurrent and powerful storms are neglected.

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1. Introduction

Coastal boulder accumulations are often mentioned in the literature, in different tectonic and morphological settings (Oak, 1984; McKenna, 1990; Felton and Crook, 2003). They appear as isolated mega-boulders on coastal platforms (e.g. up to 1500 t in French Polynesia and in the Bahamas: Bourrouilh-Le Jan and Talandier, 1985; Hearty, 1997; Kelletat et al., 2004), fields of scattered boulders up to hundreds of meters inland (e.g., Shi et al., 1995; Nott, 1997; Mastronuzzi and Sansò, 2000; Noormets et al., 2002; Mastronuzzi and Sansò, 2004; Whelan and Kelletat, 2005; Scheffers and Scheffers, 2007; Scicchitano et al., 2007; Paris et al., 2009), cliff-top boulders (e.g. Williams and Hall, 2004; De Lange et al., 2006; Hall et al., 2006), boulder ridges and ramparts (Scheffers, 2004), and conglomerates (e.g. Moore and Moore, 1984; Felton, 2002; Pérez Torrado et al., 2006). Their emplacement is usually attributed to high-energy events (tsunamis, hurricanes or powerful storms), but the interpretation remains difficult along coasts where both storms and tsunamis occurred in the past, especially when high-stand marine deposits are also present (Felton, 2002). Nott (2004) presents the assumption that "storms waves and tsunamis can likely achieve the same results, except storm waves need to be much larger at the shore". Comparisons between storm and tsunami deposits appear as a rising topic in the literature (e.g. Nanayama et al., 2000; Goff et al., 2004; Kortekaas and Dawson, 2007; Morton et al., 2007). Nevertheless, most of these studies focus on fine-grained deposits, and the origin of many coastal boulder accumulations around the world is still under debate. Oak (1984) proposed that boulder beaches are fundamentally distinct sedimentary assemblages. The sedimentation models established for finer sediments (e.g. gravel beaches) seem inapplicable.

Iceland is located in the middle of the North Atlantic Ocean, a high-energy marine environment with frequent storm waves (Davies, 1972). Storm days per year are >50 at exposed coastal areas (Einarsson, 1976). The southwest coast of Iceland faces the powerful storms of the North Atlantic Ocean, with significant wave heights over 15 m (Sigbjarnarson, 1986). A powerful storm destroyed a Danish trading centre at Básendar on January 7th 1799 and flooded large low-lying areas inland in the Reykjanes and Seltjarnarnes peninsulas (Valsson, 2003). The probability for past and present tsunamis to hit this coast is very low. Phreatomagmatic explosions offshore may generate tsunamis, but in southern Iceland, the magnitude of these eruptions is not high enough to generate significant tsunamis. Furthermore, no tsunamis have been reported along the southern coast of Iceland during the last 250 years (NGDC, 2007). This study describes boulder deposits related to storms along the volcanic rock coast of Reykjanes Peninsula (Fig. 1).

2. Geological and geomorphological background

The Reykjanes peninsula forms the southwestern part of Iceland. It corresponds to the emerged part of the mid-Atlantic oceanic rift and,

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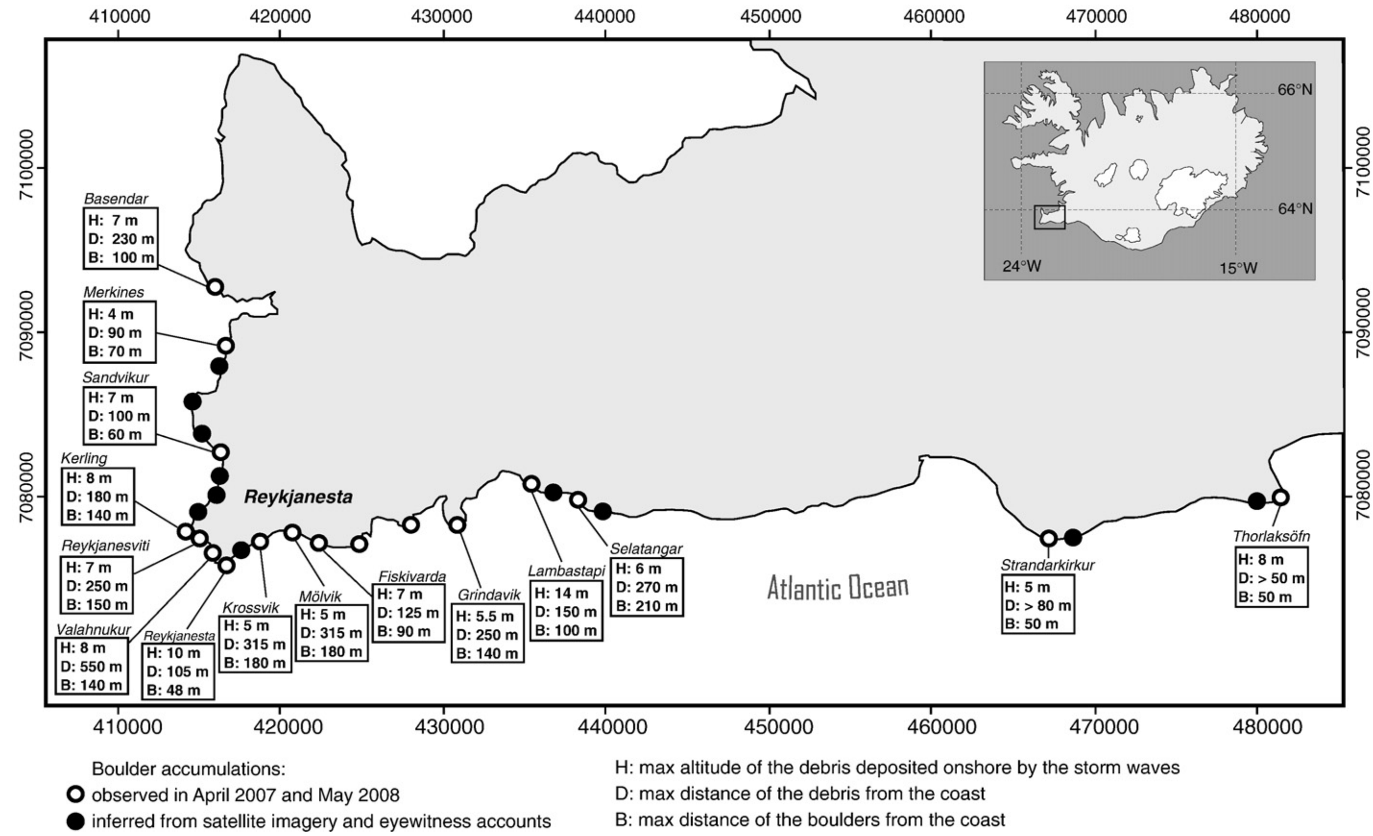

Fig. 1. Location, altitude and distance from the shoreline of the boulder accumulations.

as so, is made of volcanic rocks (Fig. 2). Volcanism is continuous in this area since the Middle Pleistocene, with twelve historic (post-874 AD) eruptions and at least nine prehistoric eruptions (Jónsson, 1983; Jóhannesson and Einarsson, 1988a,b; Jóhannesson, 1989; Einarsson and Jóhannesson, 1989; Einarsson et al., 1991). In Iceland, the nature of volcanic products — notwithstanding the magma nature — is affected by the climatic settings of the land at the time of eruption: during glaciation periods, cooling of the lava occurs under an ice cover (subglacial volcanism) and rocks produced will belong to the hyaloclastite family. Pillow lavas mounds or sheets are from these times (e.g. Vatnsfell). Submarine (surtseyan) eruptions also produced that kind of rock. Basaltic lavas, scorias or tuff are associated with interglacial, interstadial or post-glacial period and subaerial volcanism. In this study, we have selected volcanic lands that were formed after the last glaciation (Weichselian) in a way to assume that boulders encountered on the lava surface near the shoreline could not have a glacial origin (erratic boulders). Indeed, age of the coastal lavas ranges between 11.5 ka (e.g. Eldborg, Elvorp) and 750 years (the so-called "Reykjanes fires": Jónsson, 1983; Sigurgeirsson, 1995). Ice rafting can also be eliminated as a past or modern boulder source, since south coasts of Iceland are not affected by the presence of sea ice due to the advection of warm Atlantic water in the Irminger current (Andrews, 2005). Typical ice-rafted boulder barricades or boulder pavements have not been reported in South Iceland. Jökulhlaups do not affect the Reykjanes peninsula due to the absence of icecaps (Russell et al., 2005). Then, large rounded sediments found on theses lavas are of exclusive marine origin.

The coastline consists mainly of cliffs less than 20 m high cut into post-glacial basaltic lava flows. The summit surface of the cliff always corresponds to the structural surface (i.e. top of the lava flow). It is partially covered with aeolian deposits consisting of material first deposited by the sea along the coast and then transported inland by the wind (Preusser, 1976). Cobbles, pebbles, boulders of marine origin are disseminated over the surface along the cliff edge. These basaltic surfaces might have experienced severe weathering, especially with the combination of frost and salt weathering processes and oldest boulders also show extensive alveolar weathering or flaking (Etienne and André, 2003). The cliff bases can be rock platforms or benches, sometimes occupied by sediments (sand to boulder in size). Cliffs cut into postglacial tuff cones remain rare (e.g. Karl cone, XIIIth century). East of Grindavík, hyaloclastites ridges, cones or sheets from Weichselian times form massive cliffs more than 50 m high. An extensive dunefield with an associated lagoon can also be encountered at the contact of Hafnaheidi and Syrfells lava flows (Stora sandvik). Smaller black dunes can be found around Thorlákshöfn where they are partially covered with *Psamma arenaria* and *Elymus arenarius* (Biays, 1956).

3. Methodology

Over 100 km of coasts, from Sandvíkur (west coast of the peninsula) to Reykjanesta (southwest point) and Thórlakshöfn (eastern end of the peninsula) was ground surveyed in April 2007 and May 2008 (Fig. 1). Geological and geomorphological settings of 17 boulder accumulations were investigated on field. We systematically noted the landward limit (altitude and distance to the shore) of boulder deposits and other debris (driftwood, seaweed beach wracks, buoys), some of them deposited onshore by the 2007 and 2008 winter storms. Other accumulations were only inferred from satellite imagery or eyewitness accounts.

Major accumulations were studied in detail, using a GPS, laser range finders and a high-resolution digital camera. Spatial extension and altitude of deposits, their lithology, size, shape and density of the biggest boulders, granulometric trends, orientation of imbricated clusters of any,

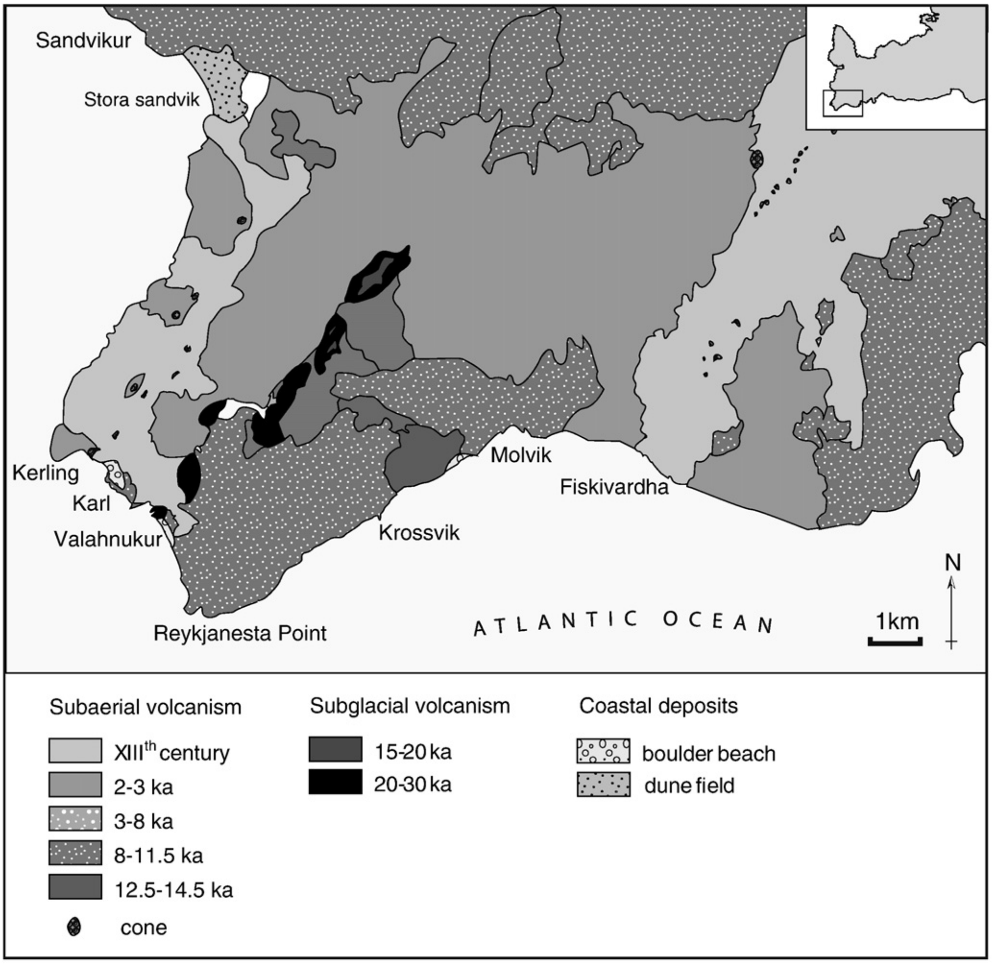

Fig. 2. Geological map of the southwest part of the Reykjanes Peninsula.

and surface morphology were systematically recorded. Boulder size trends have been investigated along topographic profiles for boulder beaches or boulder ridges: *A*, *B*, *C* axes have been measured (5 contiguous boulders per station and 5 stations per profile), and each boulder shape has been systematically assessed following a three-fold division: quadrangular, ovoid or polymorph. As cliff-top storm deposits are usually composed of heterometric material, clast-size measurement have been done in a squared-meter quadrat, thus including pebbles, cobbles and boulders.

The morphometry (shape, roundness) of individual boulders was estimated using photo-interpretation in order to estimate the evolution of the boulder shape landward at Karl and Mölvik boulder beaches. For each station of transects realised, 17 to 58 boulders were analyzed and classified as angular, sub-angular, sub-rounded, or rounded. At Karl, data were collected following a grid of 14 stations, equally distributed between top beach and bottom beach.

We also took rock samples of the biggest boulders in order to calculate their density, and deduce their volume and weight (Table 1). The equations proposed by Nott (2003) were applied in order to estimate the minimum wave height required to initiate the transport of coastal boulders. We also calculated the transport figure of the largest boulders (weight × altitude × distance to coastline, see Scheffers and Kelletat, 2003; Kelletat et al., 2004).

All data were integrated in a GIS database. A Digital Elevation Model (DEM) of the largest boulder ridge was constructed after topographic profiles and its volume was estimated (Valahnukur boulder beach, Reykjanesta).

4. Results

4.1. Typology of boulder accumulations

A typology of storm deposits along the South Reykjanes Peninsula has been established based on relationships between sea-land contact, the presence or absence of cliff, types of sediments and the morphology of the boulder deposit (Table 2; Fig. 3). A distinction between cliffed and uncliffed coast must be done first. In the former category, plunging cliffs are “swash-reluctant” shores where wave energy is mostly reflected against the rock wall (Sunamura, 1992). Shore platforms are absent and a storm beach cannot be present in this particular setting. Storm deposits are represented by cliff-top storm deposits only, the boulder material coming from a submarine source or from the uprooting of the cliff edge during an extreme event.

When the cliff starts to erode near the mean sea level, a small bench appears. Material is more abundant, thus allowing the development of boulder ridges on the summit surface of the cliff. Storm waves wash the surface frequently, and then the boulder ridge will be built several meters inland, a few large boulders being left near the cliff edge or trapped on rock pools (e.g. Kerling headland).

Shore platforms strongly modify the wave conditions at the coast, acting sometimes as a buffer zone in front of the cliff (Etienne, 2007). Clasts cannot stay in the seaward zone where wave swashes are frequent. The biggest material is concentrated at the cliff foot which acts as a sediment trap. In this condition, the boulder beach stabilizes and slightly protects the cliff foot by dissipating storm wave energy.

Table 1
Characteristics of some storm boulders along the Reykjanes Peninsula (Iceland).

Area	*X*	*Y*	*Z* (m)	*D* (m)	*A* (m)	*B* (m)	*C* (m)	Volume (m^3)	Weight (t)	Deposits	Transport figure	Wave height (m)		
												Joint-bounded	Submerged	Subaerial
Basendar	415303	7093291	2	20	3.60	3.00	2.60	22.46	53.91	Platform boulder	2157	27.1	4.3	9.2
Fiskivarda	421417	7077635	2	18	3.40	3.20	1.70	14.80	38.47	Platform boulder	1385	29.4	8.0	9.8
Fiskivarda	421365	7077703	3	44	2.40	2.40	0.80	3.69	8.85	Boulder beach	1168	18.1	7.6	5.5
Fiskivarda	421353	7077775	6.5	105	3.00	2.50	0.50	3.00	7.20	Boulder ridge	4914	22.6	12.2	6.6
Fiskivarda	421349	7077730	2	29	1.70	1.70	1.20	1.81	4.35	Boulder beach	252	12.8	2.9	4.0
Fiskivarda	421353	7077775	6.5	105	2.20	1.20	0.70	1.48	3.55	Boulder ridge	2422	16.6	2.5	5.3
Fiskivarda	421289	7077762	2	30	1.60	1.30	1.20	1.30	3.39	Boulder beach	203	13.8	2.0	4.5
Fiskivarda	421011	7077931	7	70	1.05	0.85	0.70	0.33	0.85	Boulder ridge	416	9.1	1.5	2.8
Fiskivarda	421318	7077765	4.5	10	1.10	0.95	0.30	0.16	0.43	Boulder ridge	19	9.5	3.7	2.3
Heimaey	537685	7033116	5	25	1.40	1.20	0.80	1.08	2.80	Boulder ridge	349	12.1	2.5	3.8
Heimaey	537685	7033116	6	28	1.45	1.10	0.25	0.32	0.83	Boulder ridge	139	12.5	5.7	3.1
Karl	415146	7077585	2	35	2.70	1.90	1.65	4.42	12.38	Boulder beach	867	26.3	3.5	8.9
Karl	415146	7077585	2	33	1.70	1.60	1.50	2.13	5.97	Boulder beach	394	16.5	2.7	5.5
Karl	414854	7077890	11.5	35	0.39	0.35	0.10	0.01	0.02	Cliff-top boulder	7	3.4	1.5	0.1
Kerling	414501	7077821	6	65	3.50	3.10	3.00	26.04	70.31	Boulder beach	27,420	32.1	4.8	11.0
Kerling	414497	7077804	2	15	4.50	2.30	1.80	9.73	26.28	Platform boulder	788	41.3	4.5	14.2
Kerling	414447	7077879	2	64	3.2	2.7	1.5	6.77	18.28	Platform boulder	2340	29.4	7.0	9.8
Kerling	414517	7077887	8	105	3.70	1.85	1.10	6.02	16.26	Boulder beach	13,662	34.0	4.7	11.5
Kerling	414489	7077972	4	66	3.00	1.80	0.90	3.89	10.50	Boulder beach	2771	27.5	5.3	9.1
Kerling	414472	7077909	2	48	1.85	1.80	1.10	2.93	7.91	Platform boulder	760	17.0	4.2	5.5
Kerling	414536	7077820	5	51	1.90	1.80	0.90	2.46	6.65	Boulder beach	1695	17.4	5.0	5.5
Kerling	414559	7077842	8	30	2.10	1.70	0.80	2.28	6.17	Cliff-top boulder	1481	19.3	5.1	6.1
Kerling	414548	7077830	7	35	2.30	1.30	0.95	2.27	6.14	Cliff-top boulder	1503	21.1	2.7	7.0
Kerling	414536	7077820	5	51	2.10	1.50	0.90	2.27	6.12	Boulder beach	1562	19.3	3.7	6.2
Kerling	414468	7077845	2	65	1.90	1.50	1.30	1.94	5.23	Platform boulder	679	17.4	2.6	5.8
Kerling	414575	7077849	7	28	1.30	1.30	1.30	1.76	4.75	Cliff-top boulder	930	11.9	2.0	3.9
Kerling	414536	7077820	5	51	1.60	1.50	0.75	1.44	3.89	Boulder beach	991	14.7	4.2	4.5
Kerling	414555	7077865	8	48	1.70	0.90	0.80	0.98	2.64	Cliff-top boulder	1015	15.6	1.6	5.1
Kerling	414556	7077956	8	150	1.45	1.10	0.90	0.75	2.03	Boulder field	2430	13.3	2.0	4.3
Krossvik	419570	7077838	4	6	2.45	1.88	1.70	4.09	11.05	Boulder ridge	265	22.5	3.2	7.6
Krossvik	419570	7077838	4	6	2.75	2.05	1.00	2.95	7.95	Boulder ridge	191	25.2	6.0	8.3
Krossvik	419570	7077838	4	6	1.90	1.70	0.85	1.43	3.87	Boulder ridge	93	17.4	4.8	5.5
Lambastapi	435209	7080956	4	20	2.10	1.90	1.50	4.79	12.45	Boulder beach	996	18.1	3.4	6.0
Reykjanesta	416100	7076091	2	50	3.00	2.00	1.60	5.02	14.04	Boulder beach	1404	29.2	4.0	9.9
Reykjanesta	416493	7075906	12.2	25	2.30	1.90	0.50	1.75	4.54	Cliff-top boulder	1386	19.9	8.7	5.9
Reykjanesta	416118	7076087	5	65	1.50	1.10	0.60	0.52	1.45	Boulder ridge	471	14.6	3.1	4.5
Reykjanesta	416235	7075986	11.6	39	1.20	0.85	0.35	0.19	0.48	Cliff-top boulder	219	10.4	2.8	2.8
Selatangar	439286	7079903	11.3	?	1.45	1.40	1.35	1.43	4.01	Palaeo-deposit		14.1	2.3	4.6
Thorlakshofn	480775	7079541	7	20	1.50	1.30	1.20	1.87	4.87	Cliff-top ridge	681			
Valahnukur	415930	7076589	11	49	1.82	1.16	0.86	1.45	3.78	Cliff-top ridge	2036	Not applicable		
Valahnukur	415944	7076588	11	62	1.45	1.40	0.65	1.06	2.74	Cliff-top ridge	1872			
Valahnukur	415928	7076577	10	4	1.20	1.00	0.80	0.50	1.35	Cliff-top ridge	54	11.0	1.9	3.5
Valahnukur	415953	7076554	11	55	1.20	1.15	0.55	0.40	1.03	Cliff-top ridge	624	10.4	3.1	3.0
Valahnukur	415889	7076672	12	20	0.70	0.70	0.60	0.15	0.40	Cliff-top boulder	96	6.0	1.1	1.7
Valahnukur	415920	7076602	12	43	0.90	0.70	0.40	0.13	0.34	Cliff-top ridge	177	7.8	1.7	2.1
Valahnukur	415947	7076595	12	66	0.65	0.45	0.35	0.05	0.14	Boulder field	110	5.6	0.8	1.5
Valahnukur	415868	7076727	5	30	2.40	1.50	1.15	2.16	5.62	Boulder beach	844	20.7	2.8	6.9

X and *Y* are UTM coordinates measured with a GPS, *Z* is the altitude measured by laser range finders, *D* is the horizontal distance from the shore, *A*–*B*–*C* are the three axis of the boulder, transport figure = weight × altitude × distance from the shore. Wave heights correspond to minimum wave heights required to initiate the transport of coastal boulders, as defined by the equations of Nott (2003).

Along the peninsula, small embayments are associated with soft pyroclastic rocks (i.e. hyaloclastite ridges and tuff cones). There, marine erosion creates cliffs fringed by massive boulder beaches. Cliffs have an inland position and are affected by larger storm waves only. Behind the boulder beach, scattered boulders result from extreme event redistribution of the clasts. Karl and Lambastapi are two examples of this morphotype (Fig. 3).

Some areas are not cliffed. This includes lowlands where lava flows stand at or dip below sea level. There, the lava surface acts as a structural ramp where marine erosion is not able yet to cut the lava flow into a cliff or a horizontal bench/shore platform. Boulder ridges are constructed on the structural surface, several meters inland, mostly fed by material coming from adjacent cliffs (Reykjanesviti) or submarine parts of the lava flows (Sandvíkur).

Table 2
Boulder deposit nomenclature.

Deposit type	Sea-land contact		Influence of the substratum profile on the deposit profile	Sediment			Number of boulder layers	
	Cliff	No cliff	+++: strong +: weak	Boulders	Cobbles	Pebbles	1	>1
Boulder beach		X	++	X	X	X	X	X
Boulder field	X	X	+++	X			X	
Boulder ridge	X	X	+	X	X	X		X
Cliff-top storm deposit	X		+++	X			X	

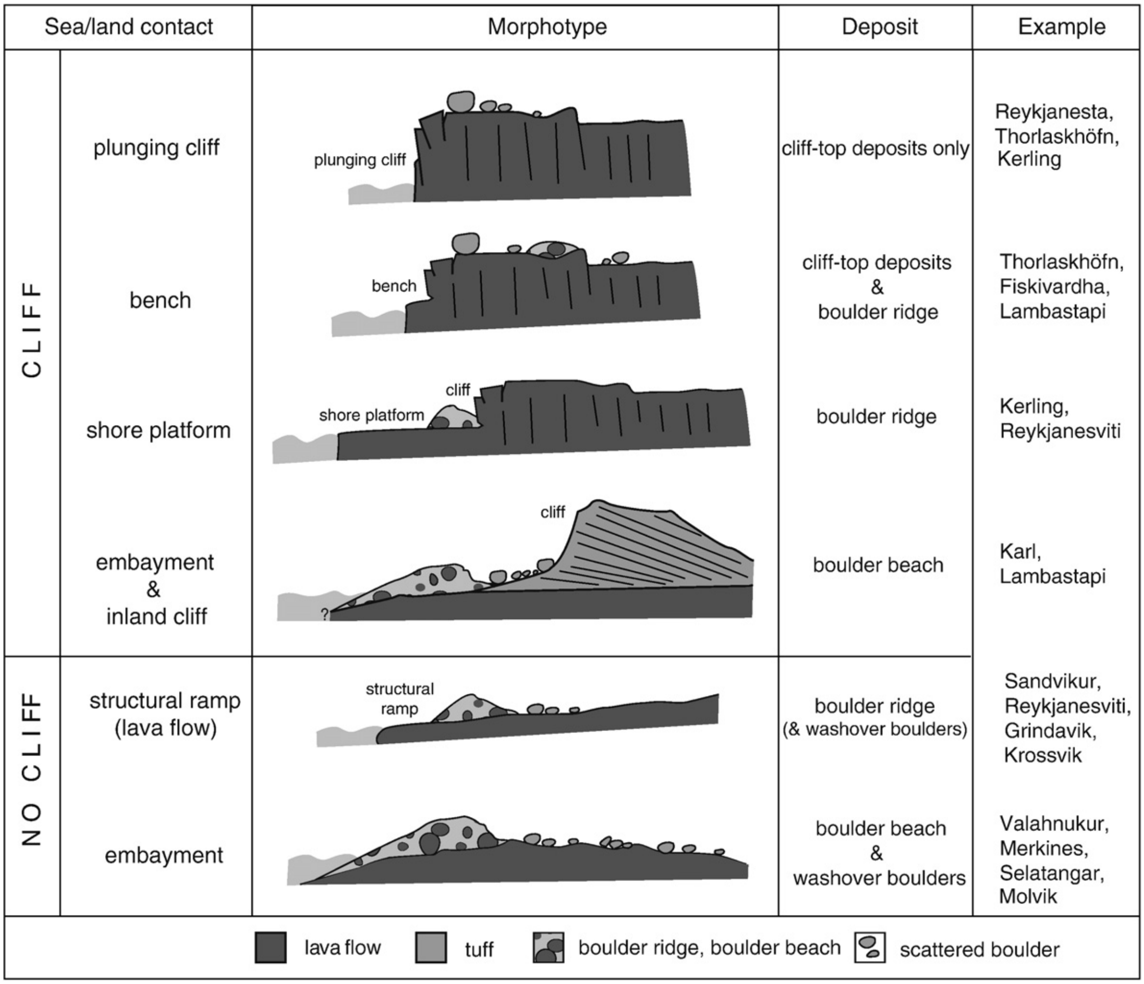

Fig. 3. Conceptual diagram outlining the different morphogenic contexts of storm boulder accumulations along the Reykjanes Peninsula (Iceland). There is no scale. Slopes might vary from place to place.

Clasts are absent from the foreshore slope (between the ridge and the sea). Storm waves find a launching ramp which helps sediment removal landward.

The last type includes embayments without cliffs (or inactive ones) where storm deposits build massive boulder beaches with inland extensions (wash-over boulders) due to the more severe events (e.g. Valahnúkur). Sometimes, a shore platform appears at low tide (e.g. Mölvik or Krossvik). Variations in longitudinal profile of the boulder beaches depend on both wave orientation and bottom topography (e.g. ramps, lava tumuli, channels).

Fig. 4. a) Lava block fall on Karl tuff cone (looking north) and b) boulder beach mainly fed by Karl's overlapping lava flow (looking south). Note person for scale on right top corner. Photograph by S. Etienne (April 2007).

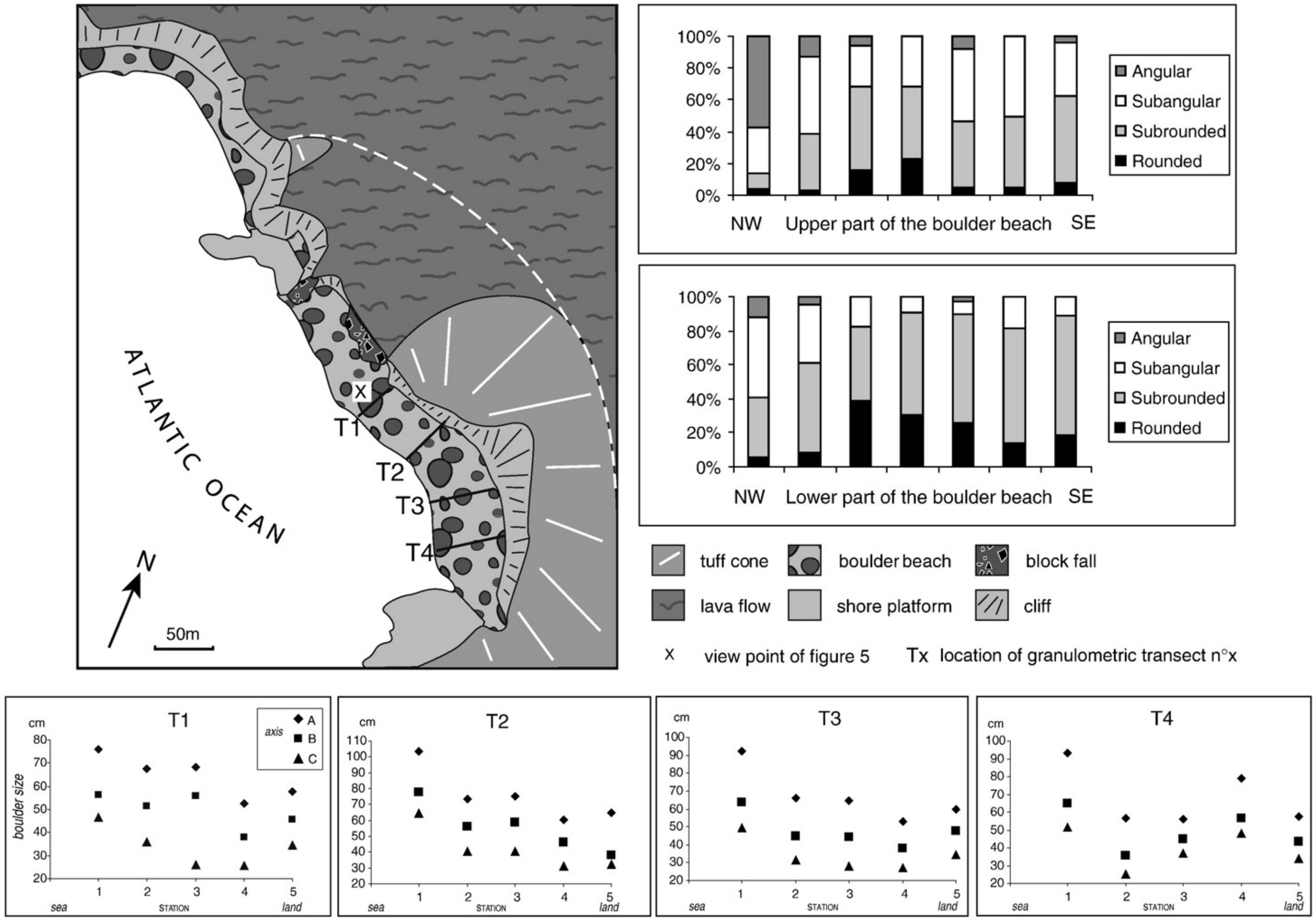

Fig. 5. Morphological setting, clast shape and size trends of Karl boulder beach.

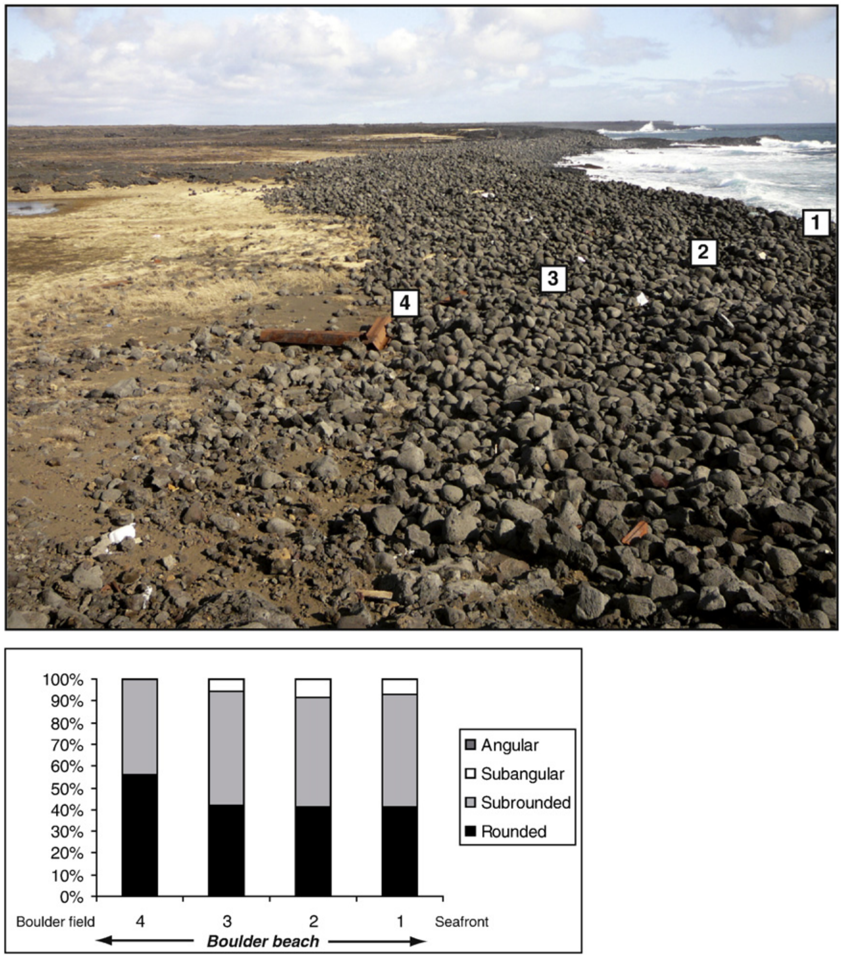

Fig. 6. Clast-angularity longitudinal trend at Mölvik boulder ridge. Photograph by R. Paris (May 2008). Iron bar on the centre is 2 m long.

A boulder field systematically appears where boulder accumulations are not delimited landward by steep slopes. These deposits are scattered and there is only one layer of boulders resting on the substratum which remains largely visible. Boulder fields are usually fed during extreme storms by a boulder beach or a boulder ridge standing closer to the sea (washover boulders).

Fig. 7. Palaeo-storm boulder deposits in Selatangar. Photograph by S. Etienne (April 2007).

4.2. Characteristics of boulder accumulations

4.2.1. Boulder beaches

The term “boulder beach” is used in a general sense to describe coastal depositional features where the sediment is a mixture of boulders and large cobbles (McKenna, 2005). The formal definition of boulder in the term of the Wentworth grade scale correspond to clasts with *B*-axis larger than 256 mm (−8 ϕ) and smaller than 4096 mm (−12 ϕ), larger clasts belong to the block family (Blair and McPherson, 1999). After Oak (1984), boulder beaches have the following characteristics: upbeach fining and abundant breakage of sediment, upbeach decrease in roundness, positively skewed size distributions, no shape zonation, no sphericity grading, and low foreshore slopes. Boulder beaches might be composed of one or more layers of boulders and the substratum can be totally hidden by the deposit.

4.2.1.1. Karl boulder beach. Southeast of the Kerling Point, the cliffs are higher and cut the Karl tuff cone, which was formed during the “Reykjanes Fires” (1211–1240 AD). The phreatomagmatic deposits are locally crossed by the feeding dykes of an overlapping lava flow (Younger Stampahraun, 3–4 m thick). The spatial extension of this boulder beach is limited by cliffs and scarps eroding the tuff cone. Neither cliff-top boulders nor cobbles were found in this area. Undercutting of the tuff base leads to the fall of lava blocks which accumulate at the foot of the cliff (Fig. 4). Rock fragments are then removed towards the south by storm waves and progressively shaped as rounded boulders, as observed in a small bay. In the field, the lava flow seems to feed the boulder beach directly and our data confirm that more angular clasts are found near the cliff (Fig. 5). The proportion of rounded to sub-rounded boulders increases seaward and reaches more than 80% from 50 m from the cliff. Considering

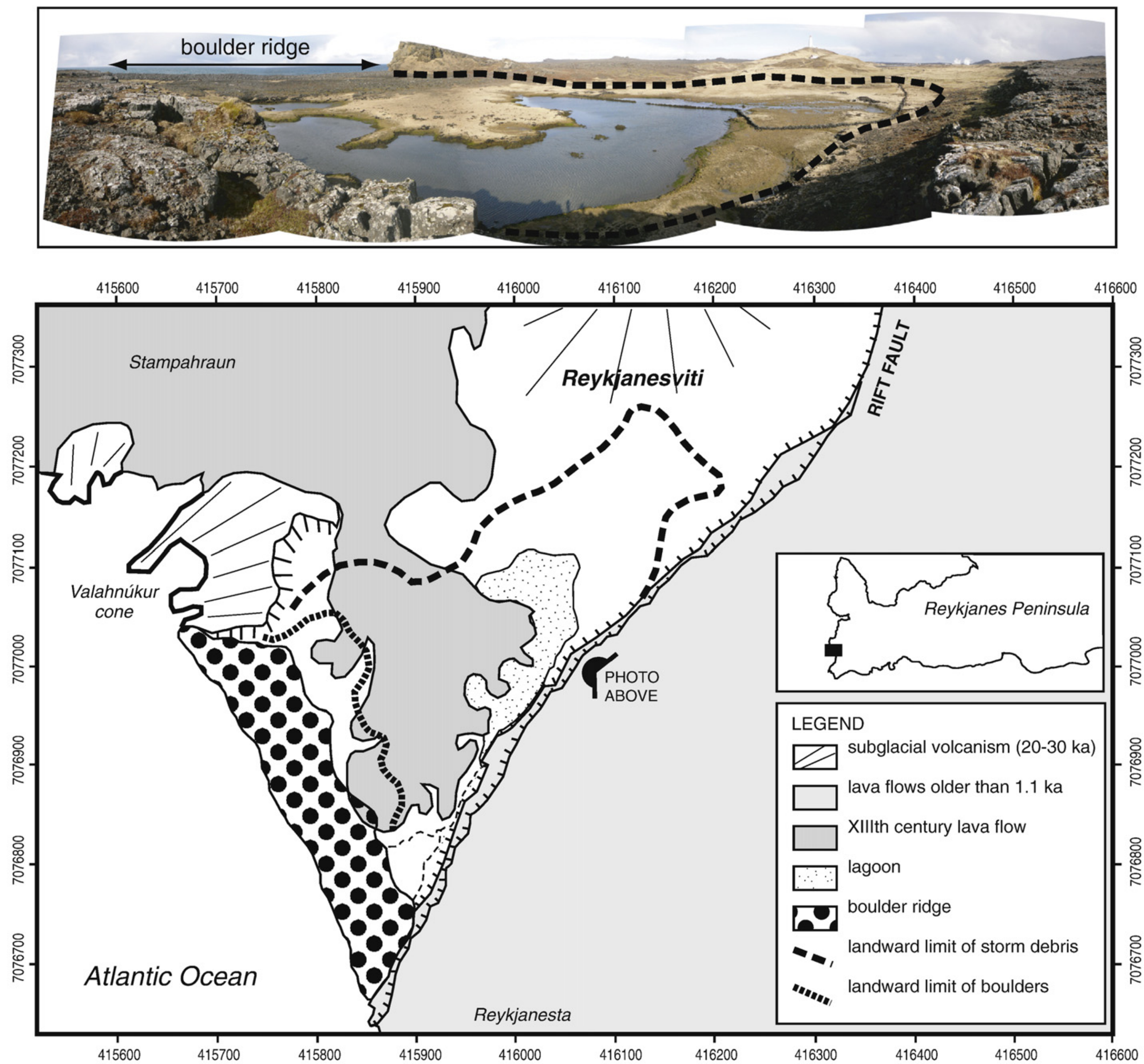

Fig. 8. Morphological setting of the Valahnúkur boulder beach and distribution of the driftwood and debris deposited inland by the winter 2007 storms. Photograph by R. Paris (April 2007).

granulometric data, we observe an upbeach fining of the mean *B*-axis, but no lateral evolution of the boulder size.

4.2.1.2. Lambastapi boulder beach. Five kilometers east of Grindavík, the storm deposits form a 90 m large boulder beach, intercalated between a subglacial lava plug to the west, a postglacial lava flow (Borgarhraun) to the east, and the flanks of a hyaloclastite ridge to the north. The beach has a bimodal distribution: coarse rounded boulders coming from the lava plug, and cobble-to-boulder clasts less rounded, fed by the lava flow. The two clast populations display fining and rounding trend, toward a gully at the contact between the hyaloclastite ridge and the lava flow. Boulders are found up to 11 masl (140 m inland) and debris until 14 masl (150 m). This is the highest altitude we estimated for storm debris along the Reykjanes coast. The flanks of the hyaloclastite ridge concentrate the storm surges in the gully, thus allowing such a runup.

4.2.1.3. Mölvik boulder beach. This area is a lowland (less than 8 masl) where embayments are occupied by thin (1 to 2 m thick) but extensive boulder beaches, 20 to 40 m wide. Structural ramps or small shore platforms are sometimes exposed but boulder accumulations dominate the coastal landscape (Fig. 6). The mean foreshore slope angle ranges between 7 and 15°, the summit of the deposit being flat, or sometimes showing a small upward concavity, as in Valahnúkur. Boulders are subrounded to rounded, with a slight landward rounding trend (Fig. 6). No sediment arrangement according to particle size appears along the profile. Boulders are imbricated with a conspicuous seaward dip. The highest deposit is at 4 masl, with scattered boulder 180 m inland. Other storm debris can be found as far as 315 m inland.

4.2.1.4. Selatangar boulder beach. In Selatangar, the boulder beach is nearly flat and feeds a boulder field up to 210 m inland (5 masl). The material is finer than in Mölvik or Valahnúkur: typically small boulders and cobbles, with a clear bimodal distribution. Like in Sandvikur, the coastal embayment gives place to the deposition of black Aeolian sands and gravels, so that the boulder deposit is not openwork. The boulder beach presents successive crescent-shaped ridges, and is mixed with a pebble beach in the intertidal zone.

Another striking feature in Selatangar is the occurrence of boulder ridges between 250 and 600 m inland (maximum altitude: 11.3 masl). The boulders are rounded, less than 1.5 m large and always covered by lichens (Fig. 7). The deposit is not continuous and typically appears in topographic lows at the contact between the Skollahraun (2–3 ka lavas) and the ögmundarhraun (XIth century). These boulder ridges are very similar to the present-day accumulations described herein, thus we interpret them as palaeo-storm deposits (Fig. 7). Considering the ages of the lava flows, the age of the storm deposits may range between 1 and 3 ka. The orientation of the four main ridges indicates a palaeo-shoreline oriented WSW–ENE. Some clusters of boulders display northward imbrications (landward dip).

4.2.1.5. Valahnúkur boulder beach. The highest relief along the coast of Reykjanesta is the Valahnúkur hyaloclastite cone formed during submarine eruptions at the end of the Weichselian glaciation. A huge boulder accumulation closes the coastal embayment between the Valahnúkur cone and prehistoric lava flows of the Reykjanesta Point (Fig. 8). The embayment is partly filled by the Stampa lava flow (1226 AD in this area). The boulder accumulation covers an area of 27,000 m^2 (length: 425 m, maximum width: 83 m) for an estimating volume of 132,000 m^3 (maximum height: 9.8 masl). The lower part of the deposit extends offshore (Fig. 9), as for a boulder beach, but the high volume of boulders accumulated on the upper part reduces the influence of the underlying topography, as for a boulder ridge (Table 2).

The beach crest is crescent-shaped, thus delineating outsets and insets similar to beach cusps (Fig. 10). Concavity of the beach profile is accentuated in the insets (11–18°), where wave orthogonals tend to converge. We also noted flats or small depressions along the beach crest, typically 1 to 2 m deep and 5 to 10 m across. Locations of these depressions and subsequent berms varied from April 2007 to May 2008. Up-beach fining is clear over 5 profiles with minimal mean *B* values encountered at the ridge crest, i.e. upper part (Fig. 10). The backshore of the ridge shows less systematic trend but downward increasing is noticeable on 4 profiles. No lateral granulometric trends were encountered, neither on the seaward part of the ridge nor on the crest.

Seawater seeps into the embayment through this openwork deposit, thus feeding a small lagoon with salty water. A seaweed belt (*Fucus* sp.) delimits the permanent sea-level. A temporary river drains the lagoon toward the sea. Erosion scars on the banks of the lagoon reveal alternating coarse sand layers rich in marine bioclasts and darker silty layers. We interpret these deposits as the result of storms surges over the boulder accumulation (coarse layers), and decantation phases in the inundated embayment (finer layers). In May 2007, we could identify fresh debris and driftwood up to 550 m inland northeast of the lagoon (8 masl). A boulder field extends the accumulation 140 m inland. The concentration of boulders tends to decrease landward, but this is also controlled by the topography of the Stampa lava flow.

Fig. 9. Valahnúkur boulder beach. Photograph by S. Etienne (April 2007).

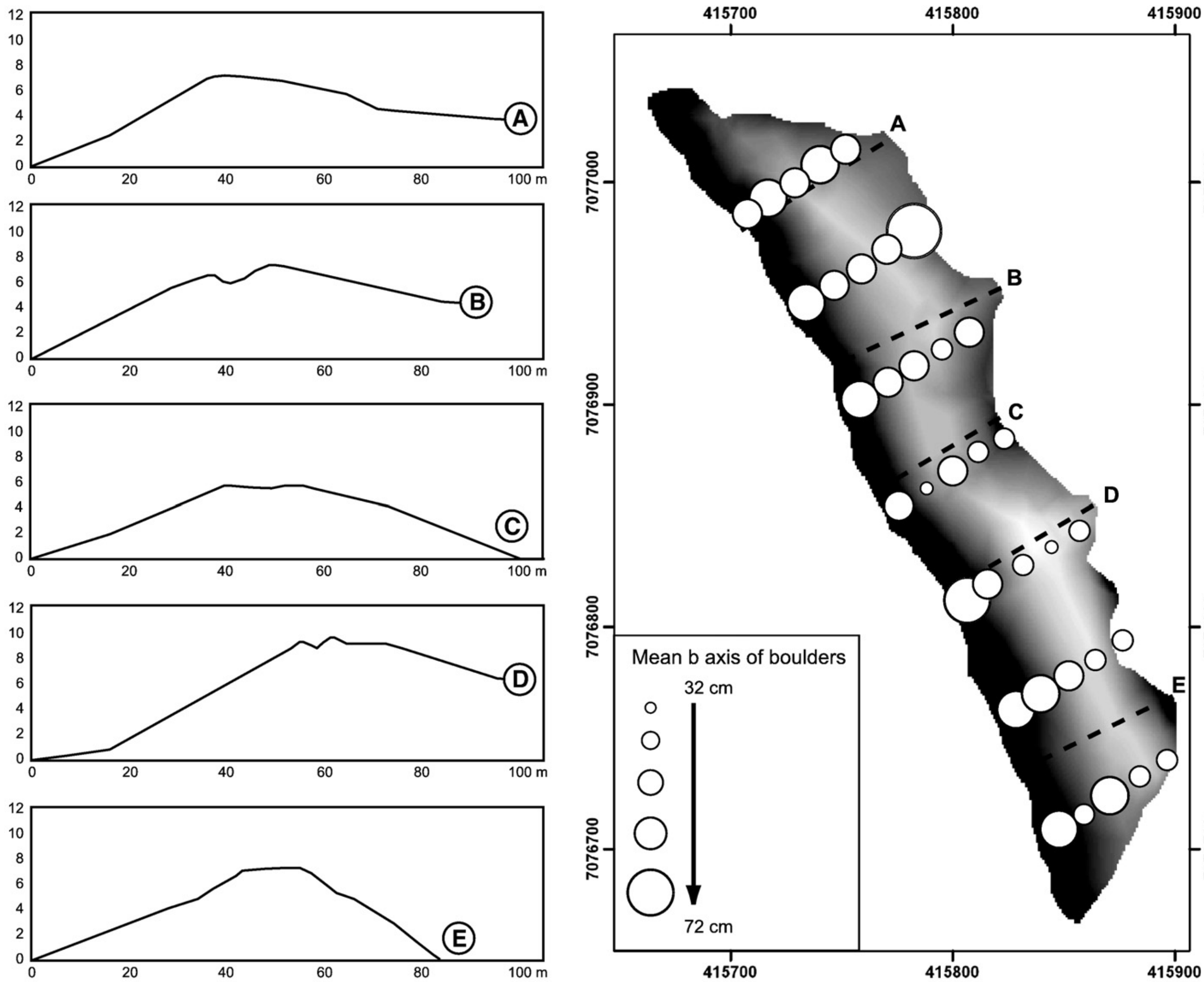

Fig. 10. Longitudinal profiles, clast-size trends (*B*-axis) and Digital Elevation Model of the Valahnúkur boulder beach.

4.2.2. Boulder ridges

Boulder ridges are deposits similar to boulder beaches but their position is higher on the coastal slope in a way that the lower seaward part of the ridge is higher than MHWL. Actually, boulder ridges are boulder beaches "pushed" inland by storm waves and no part of the deposit is in contact with the sea during normal weather conditions.

4.2.2.1. Reykjanesviti boulder ridge. Five hundred meters southwest of the Reykjanesviti lighthouse, the coast displays a 400 m long boulder accumulation (Fig. 11). The northern part of the deposit is a boulder ridge associated with a boulder field until 150 m inland. The boulder ridge is 4 m high and approximately 50 m wide. The foreshore slope is always steeper (3–15°) than the backshore one (1–8°), especially in the southern part of the ridge. Some boulders less than 1 m in diameter display fresh impacts such as striae, percussive marks, or crushing (Fig. 12). Debris and driftwood are deposited until 250 m inland at the front of the Stampa lava flow (XIIIth century). The southern part of the boulder deposit rests on a platform between 2 and 4 masl at the front of the Stampa lava flow, which breaks the development of a ridge and boulder field. We did not observe cliff-top deposits in this area. As in Karl, the erosion of tephra underlying the lava front enhances the production of megaclasts, which are progressively rounded towards the northwest and the boulder ridge.

4.2.2.2. Boulder ridges east of Grindavík. The coast of the Reykjanes Peninsula around and east of Grindavík displays numerous cobble-to-boulder ridges all smaller than the ridges described above (typically 4–5 m high and 25–80 m large, e.g. Strandarkirkur, 37 km east of Grindavík). The southern point of Grindavík, east of the harbour, corresponds to the front of a postglacial lava flow (11.5–8 ka), where wrecks, boulders and debris were deposited by successive storms. The whole point is edged with a 5.5 m high boulder ridge overlying a wide (100–300 m) shore platform. The clasts are mainly sub-rounded. The profile across the ridge is relatively gentle, especially for the foreshore slope, unlike Valahnúkur, Mölvik and Reykjanesviti where the shore platform is less extensive.

4.2.2.3. Sandvikur boulder ridge and beach. In Sandvikur, we could observe numerous debris (e.g. buoys, tanks) and driftwood deposited by recent storms invading the dune field. The rocky coast located north of the dunes (Lendinngamelur) also shows evidence of powerful storms. The lava flow acts as a launching ramp for storm waves (Fig. 3), thus leaving small boulder ridges and boulder fields up to 60 m inland, and driftwoods up to 100 m (altitude: 7 masl). The boulder accumulation is continuous, but appears alternately as a boulder ridge on headlands and a boulder beach on insets (Fig. 13). We could note a

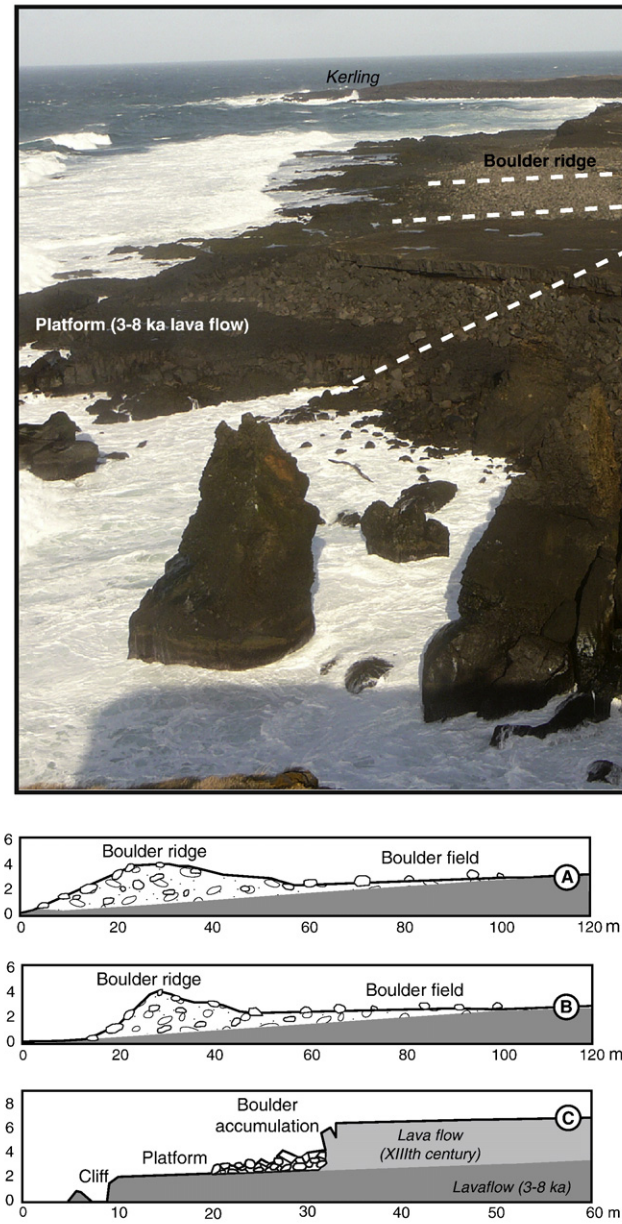

Fig. 11. Boulder accumulations in Reykjanesviti. Photograph by R. Paris (April 2007).

Fig. 12. Fresh impacts on boulders, suggested by striae, percussive marks or crushing. Photograph by S. Etienne (April 2007).

landward fining trend, from boulders up to 1.8 m near the coast to decimetric boulders and cobbles inland.

4.2.3. Cliff-top storm deposits (CTSD)

4.2.3.1. Kerling cliff top boulders. Cliff-top storm deposits are visible at Kerling, a basaltic headland forming the western point of the Reykjanes Peninsula (Fig. 14). The shore platforms and cliffs are cut into post-glacial pahoehoe flows (2–3 ka). The surface of the lava is covered by a thin crust of surge deposits related to the Karl eruption (XIIIth century). Cliff-top boulders are found above the surge deposits at 7 masl, preferentially where the shore platform is narrow (less than 15–20 m). The largest cliff-top clasts (>1 m, up to 5.4 t) are not rounded, thus suggesting that they were uprooted by the storm waves from the upper part of the cliff.

4.2.3.2. Fiskivardha. In Fiskivardha, coastal morphology, together with spatial distribution and size of the boulders, is clearly controlled by the fracturation and internal structure of lava flows (younger than 8 ka in this area). Thus, the storm deposits display a wide variety of clast size and depositional morphologies: cliff-top fields of subangular cobbles

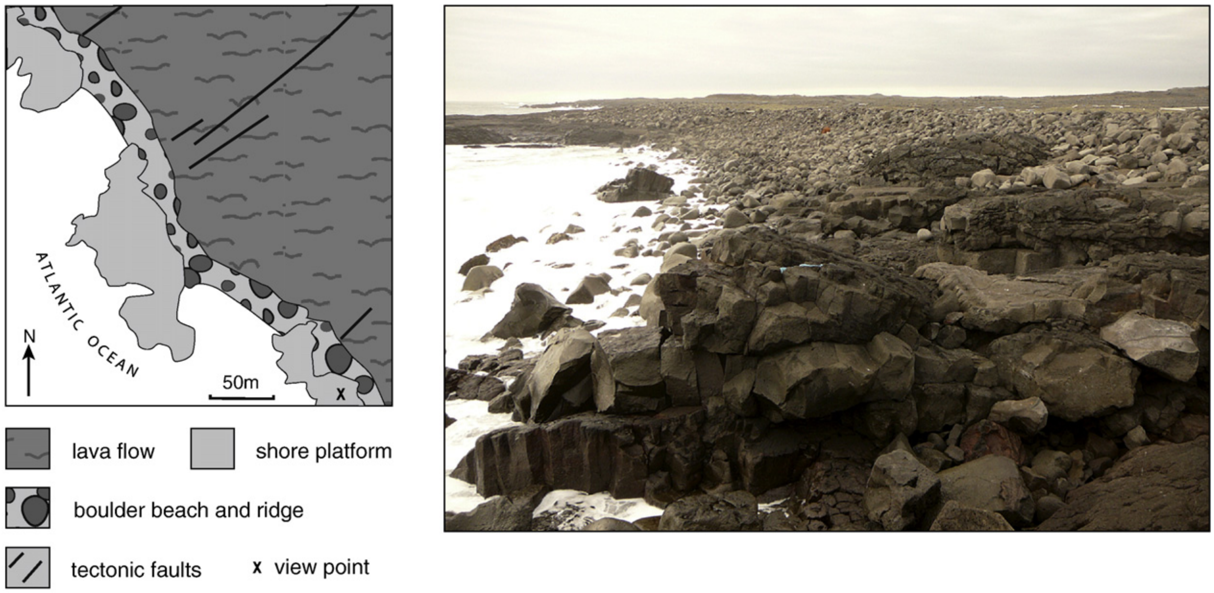

Fig. 13. Morphological setting of Sandvikur boulder accumulations. Photograph: R. Paris, May 2008.

(5.5 masl) coming from the erosion of the lava crust; deposits with a bimodal distribution (5–20 cm and >40 cm) at the base of the cliffs; coarse rounded boulders trapped in lava tumuli, trenches, tilted large boulders (Fig. 15); cliff-top boulder-to-cobble ridges between 5 and 6.5 masl. The coarser boulders are composed of the same rock types as those of the shore platform, which is 40–70 m wide. The most spectacular deposits of this area are imbricated boulders up to 8.4 t (3 × 2.5 × 0.5 m) deposited 105 m inland at 6.5 masl. The debris and driftwood reach 125 m inland (7 masl).

As in Selatangar, a boulder accumulation partly covered by subsequent lava flows indicates the palaeo-shoreline at 150 m from the present-day shoreline.

4.2.3.3. Thórlakshöfn. The rocky coast south of the Thórlakshöfn harbour displays a 5–7 m high cliff cut in a postglacial lava flow. The main section of the cliff is made of massive prismatic lavas, whereas its upper part presents well-preserved pahoehoe structures showing slight marine erosion on the top (Bodéré, 1971). The highest storm waves tend to destroy the lava lobes and crusts, thus building a cliff-top boulder ridge located between 20 and 50 m inland (7–8.3 masl). The clasts are mainly subangular, due to a short transit between their lifting and their deposition (≤50 m).

4.2.3.4. Southeast Valahnúkur. Cliff-top deposits also appear at 45–55 m from the shore (11–12 masl), south of the Valahnúkur boulder

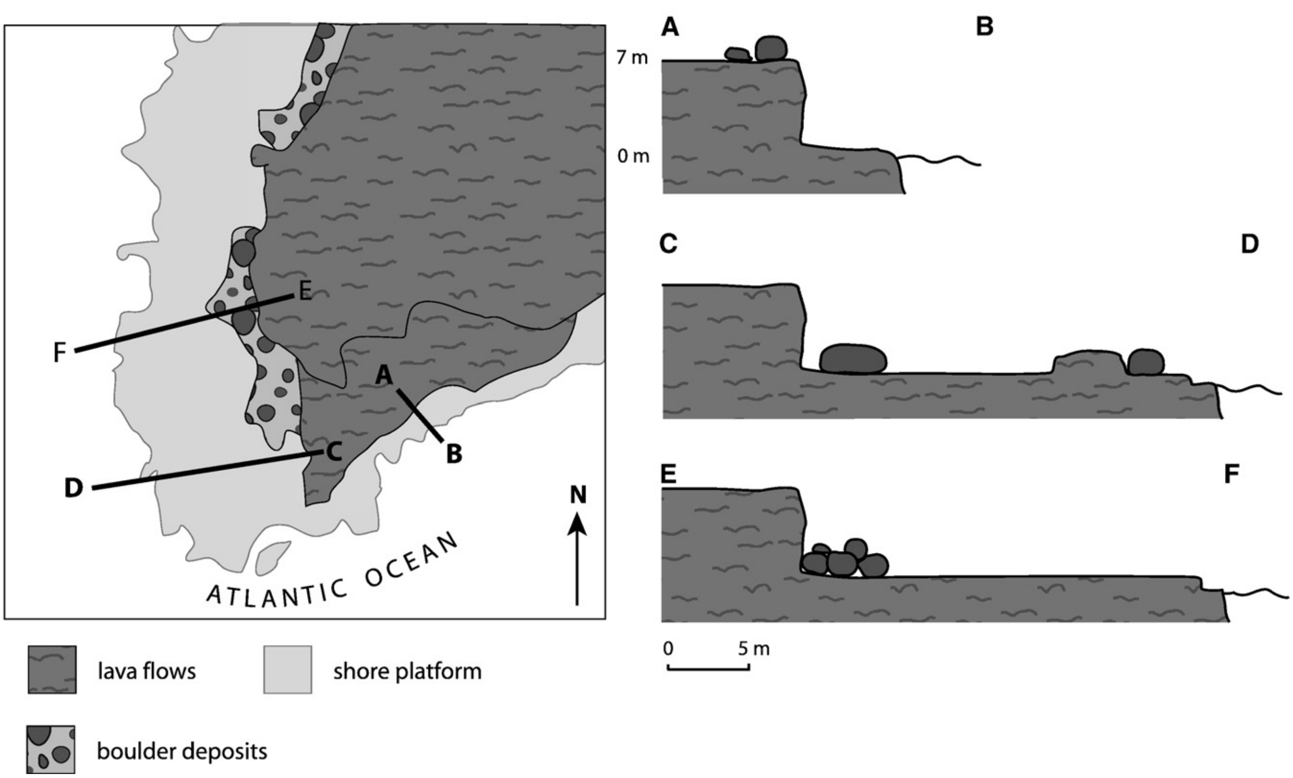

Fig. 14. Morphological setting of the boulder accumulations in Kerling.

Fig. 15. Imbricated boulders in Fiskivardha (elevation is 6–7 m and distance from shoreline 90–110 m). Photograph by R. Paris (April 2007).

beach. The deposit is a discontinuous ridge mainly composed of pebble-to-medium boulder clasts (Fig. 16). Largest ones are restricted to the foreshore of the accumulation. Sorting increases landward. The deposit is mainly fed by the upper crust of the lava flow, which typically releases large cobble-size fragments (>40% of the clasts).

4.3. Wave heights to initiate transport

We have applied Nott's equations (Nott, 2003, Appendix A) to the largest boulders of each site and for distinct morphological settings, thus allowing estimations of the minimum wave height required to initiate their transport. These equations do not provide any information about the transport and depositional processes, since the distance, altitude and weight of the clast are not integrated in the equations. We have applied the three equations (for subaerial boulders, submerged boulders and joint bounded blocks) and present height ranges (Table 1). As demonstrated by Nott (2003), the boulders derived from joint bounded blocks on shore platforms predominantly experience lift force and require a wave of greater height to be transported. The majority of the largest boulders described herein are derived from joint bounded blocks, but the rounding of some clasts may indicate successive phases of deposition and reworking offshore. Nott's equations do not apply to angular clasts directly derived from the cliff edges and deposited inland (e.g. cliff-top deposits in Thórlakshöfn and south of Valahnúkur).

The decennial and centennial waves recorded in Reykjanes are typically 14–15 m and 17–18 m high (Sigbjarnarson, 1986). Mean wave height estimated after the equation for joint bounded blocks is 17.8 m, but most of the values appear overestimated when considering field

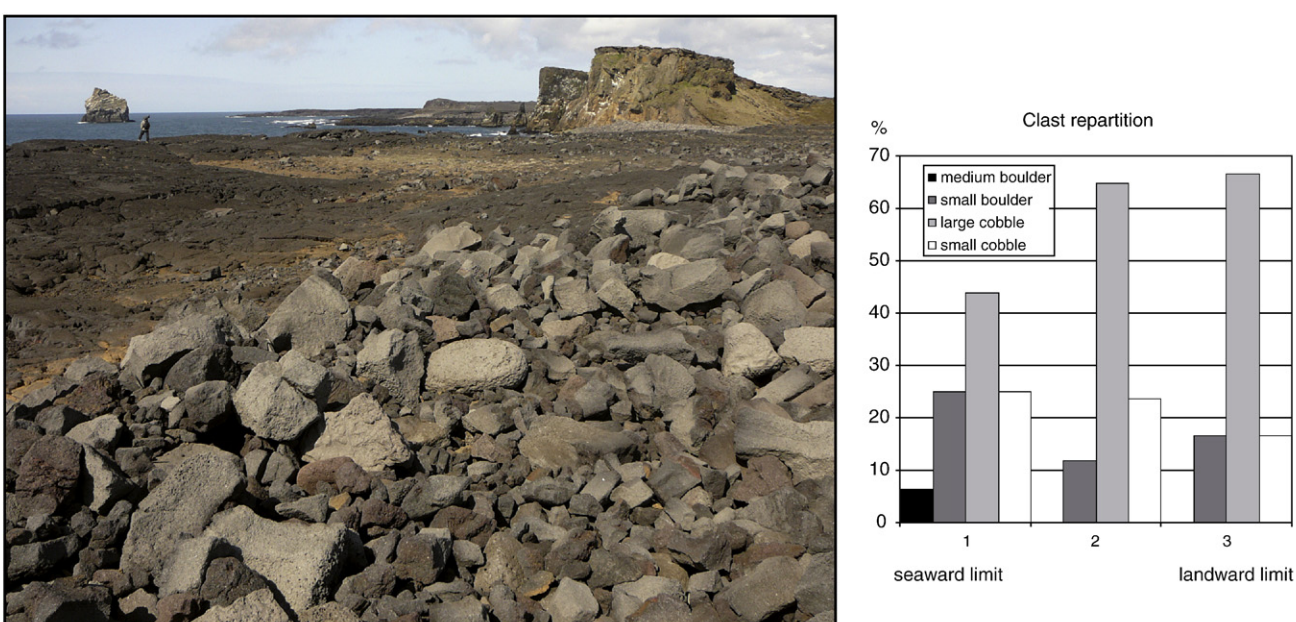

Fig. 16. Cliff-top ridge of storm deposits, located at 11–12 masl (south of Valahnúkur). Photograph by R. Paris (May 2008).

arguments. For instance, >30 m wave heights should be required to initiate the transport of the largest boulders found on the Kerling platform (e.g. 26 m^3, 70 t at 65 m from the shore). The structure of lava flows (e.g. prismation, cooling fronts) offers numerous joints, which are progressively enlarged by successive wave impacts, thus preparing the detachment of large clasts during storms. Wave heights calculated for submerged boulders range between 1.1 m and 12.2 m, with a mean value of 3.8 m. These values seem more reasonable and suggest that decennial storm waves (and even smaller) are able to move submerged boulders weighting up to 70 t. After being deposited onshore, boulders are reworked and eventually removed by subsequent storms. The Nott's equation for subaerial boulders can then be applied, but values calculated for cliff-top deposits may not be relevant (the critical height being estimated from the surface submerged and not from the mean sea level). Results suggest that waves higher than 9 m are required to move subaerial boulders more than 10 t. Full dataset does not show any geographical trend along the Reykjanes coastline (i.e. sectors where wave energy release would be more important than the other). It reminds again the importance of the cliff or the shore platform structure on the size of the released clasts, especially in volcanic settings (Etienne, 2007).

5. Discussion

5.1. Sedimentological trends of boulder accumulations

Mean clast size is cited as the most significant parameter determining the sedimentary character and behavior of a boulder beach (Oak, 1984; McKenna, 2005). Generally, the boulder size decreases landward (e.g. Karl beach: Fig. 5). On major boulder beaches and ridges (e.g. Valahnúkur), upslope fining can also be found on the seaward slope, but a coarsening is observed beyond the ridge crest where, in general, smallest *B*-axis values are encountered. This might be explained by the conditions of formation: whereas the seaward slope of the ridge is built by annual storm waves with a progressive dissipation of the energy upward (Oak's explanation), the backshore is shaped by extreme storm waves which are able to push and roll larger boulders over the crest. Downslope coarsening is then locally observed on the backshore of the major boulder accumulation.

The shape-controlled sorting processes observed on pebble beaches seem inoperative on boulder beaches (Oak, 1984). The shape of the clasts described here is controlled by breakage, sediment source and internal structure of the lava flows (i.e. from large columnar jointing to small anisotropic jointing). Oak (1984) points out that boulder roundness tends to decrease landward, but it is not systematic and not pronounced along the Reykjanes coast. When observed, the seaward rounding seems limited to the foreshore slope of the boulder beaches (e.g. Mölvik: Fig. 6). In fact, roundness is rapidly achieved on Icelandic shores (1 to 5 years) and tends to stay constant over time (Moign and Moign 1970). This could be a particularity of basaltic boulders as rounding in basaltic material is achieved faster when the mass increases (Bigelow, 1982).

Slope is usually considered one of the main indexes of morphological response to wave action (e.g. Carter, 1988). We observed beach cusps on all boulder beaches of the studied area. The slope-reducing backwash is reduced by percolation (Oak, 1984). The absence of seaward dipping clasts confirms that the influence of the imprint of the backwash is negligible. Thus, the boulder beaches are more likely to be concave upwards than finer beaches. Oak (1984) and McKenna (2005) noted that the boulder beaches tend to have low foreshore slopes (approximately 6–14°), because they are formed by, and adjusted only to storm waves. We found comparable or slightly higher values for the foreshore slopes of the Valahnúkur, Reykjanesviti and Mölvik deposits (3–18°, typically 7–15°). The evolution of the profile reflects the competence and frequency of successive storms. The profile is persistent when competent storms are infrequent, but it is not the case in southwest Iceland. More investigations are needed to follow the evolution of these boulder accumulations with time.

The shape and size-controlling processes describe above for boulder beaches are different for cliff-top deposits. For instance, the size of the clasts is clearly controlled by the internal structure of the lava flow, the pahoehoe surface giving finer material (large cobbles) but easier to transport than the prismatic lower part (boulders). CTSD are generated by highest storm waves (>14 m), which are higher than the cliffs and rework the deposits of less intensity storms.

5.2. The geomorphic impact of storms compared to tsunamis

Hall et al. (2006) note that “the significant progress made in recent years modeling the forces involved in fracture, lift and transport of large clasts indicates that rapidly-moving bores are capable of quarrying and moving large blocks can be generated by breaking waves not only close to sea level but also on cliff-top platform”. Nevertheless, the effects of storms, as described in Iceland (this study), Scotland and Ireland (Williams and Hall, 2004; Hall et al., 2006), appear well in excess of those generally reported in the literature. The tsunami origin is actually preferred. Historical accounts, tide-gauge data, transport figures and wave heights given by Nott's equations are commonly used to discount the storm origin for coastal boulder accumulations.

Yet the maximum transport figures of the largest boulders in Reykjanes (Table 1: 2700–32,000) are in the range of values estimated for past-tsunamis on the coasts of Italy (1456 Ionian tsunami: Mastronuzzi and Sansò, 2000), Spain (1755 Lisbon tsunami: Whelan and Kelletat, 2005) and Hawaii (1946 Aleutian tsunami: Noormets et al., 2002). Paris et al. (2009) reported transport figures respectively less than 13,000 and 45,000 for shore platform mega-clasts and coral boulders transported by the 2004 tsunami in Sumatra. The 20–30 m high tsunami front was able to detach and transport coral boulders with weights more than 10 t over 500–700 m landward, and mega-clasts of the platform with weights in excess of 85 t over a few metres. Paris et al. (2009) suggest that greater mega-clasts transport could have been expected for the 2004 tsunami in Sumatra. Transport figures exceeding 70,000 and 100,000 were calculated for coastal boulders in the Netherlands Antilles and in Australia (Scheffers and Kelletat, 2003), but their actual elevation and distance from the coastline could have been different at the time of deposition.

The elongated boulders found in tsunami deposits also tend to dispose their imbrication or long axis tangent to the direction of the tsunami wave train (Mastronuzzi and Sansò, 2000; Scheffers, 2004; Whelan and Kelletat, 2005; Paris et al., 2009). The long axis and imbrication axis distribution can thus help to reconstitute the direction of both storm surges and tsunami wave trains period (Fig. 15). Powerful storms are able to modify the position of boulders deposited by tsunamis (Noormets et al., 2002; Felton and Crook, 2003).

A fundamental distinction between storms and tsunamis could be their capability of forming ridges. Indeed, the organisation of coarse clasts into ridges requires repeated reworking by waves rather than the single impact of a tsunami front wave (Williams and Hall, 2004). As far as we know, observed tsunamis did not leave boulder ridges. Pleistocene tsunami conglomerates described in the Canary Islands by Pérez Torrado et al. (2006) are lenticular patches attached to the valley walls, rather than well-formed ridges. The extensive cobble-to-boulder ridges and ramparts described by Scheffers (2004) in the Leeward Netherlands Antilles are the only ridge-like features attributed to tsunamis so far studied. Nevertheless, Spiske et al. (2008) calculated accurately the porosity of these boulders and found that a hurricane origin was more likely than a tsunami origin.

5.3. The geomorphic impact of storms — a global change perspective

Storm intensity trend is then a key issue in the future evolution of coasts. After Kushnir et al. (1997), northeast Atlantic wave heights during the cold season have increased at a rate of up to 0.3 m per decade since 1962. Wang and Swail (2001) found highly significant increases of wave heights in the North Atlantic, especially in winter (10%–35%, i.e. 40–204 cm over the last 40 years), a trend found to be associated with an intensified Azores high and a deepened Icelandic low. Alexander et al. (2005) found a global decrease in average intensity of each severe storm event in whole Iceland since 1983. In detail, northeastern Iceland shows a large decrease, and northwestern to southwestern parts show an increase in 'storminess', although the statistical significance of the trend is not strong (Alexander, pers. comm., 2007). Nevertheless, even if storminess shows a general decrease in Iceland, the mean number of severe events recorded at the coast is increasing: 4.7 storms per year during the 1959–1982 ($n = 107$) period and 5.3 storms per year during the period 1983–2003 ($n = 111$). Facing the future global climate evolution and the reinforcement of atmospheric gradient between high and low latitudes, storm-induced geomorphic processes might have greater impacts on the coasts.

6. Conclusions

Storms appear as a predominant factor in the geomorphic evolution of Reykjanes coasts. Considering individual clasts, boulder deposits might be totally reworked during winter storm season. During winter 2008, boulders up to 16 t have been mobilized. But, notwithstanding these drastic seasonal individual changes, at a higher scale, boulders deposits (beaches or ridges) are landforms with a strong remanence in the landscape over years. Depending of the topographic situation and landward configuration they might stay active deposits for several years before final deposition (i.e. washover deposit). This study provides new insight for the interpretation of coastal boulder accumulations. It also highlights that the geomorphic effects of recurrent and powerful storms are probably underestimated, although processes of erosion and deposition by tsunamis are a growing topic in the literature.

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Appendix A. Nott's (2003) equations for estimating the minimum wave heights required to initiate the transport of:

— subaerial boulders:

$$H_s \geq \frac{(\rho_s - \rho_w / \rho_w)\left[\left(2a - 4C_m(a/b)\left(\ddot{u}/g\right)\right]}{C_d(ac/b^2) + C_1}$$

— submerged boulders:

$$H_s \geq \frac{(\rho_s - \rho_w / \rho_w)2a}{C_d(ac/b^2) + C_1}$$

— and joint bounded blocks:

$$H_s = \frac{(\rho_s - \rho_w / \rho_w)a}{C_1}$$

where

H_s height of storm wave at breaking point
a, b and c main axis of the boulder
ρ_s density of the boulder (km/m^3 or g/cm^3)
ρ_w water density (typically 1.025 g/ml for sea water)
C_d drag coefficient ($C_d = 2$ for submerged boulders)
C_1 lift coefficient ($C_1 = 0.178$).

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