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Letters to ESEX

An initial evaluation of drone-based monitoring of boulder beaches in Galicia, north-western Spain

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ABSTRACT: Low altitude flights by a micro-drone were made in 2012 and 2013 over two boulder beaches in north-western Spain. Geographical information system software was used to map the data. Boulder outlines from the first flight were recorded on 4796 clasts at Laxe Brava and 2508 clasts at Oia. Changes in location were identified by overlaying these outlines on the 2013 images. About 17.5% of the boulders (mean surface area 0.32 m^2) moved at Laxe Brava and about 53% (mean surface area 0.23 m^2) at Oia. Most movement on both beaches was between the mid-tide to about 2 m above the high tidal level. The location and elevation of the highest points were also recorded on the 2012 images on 4093 boulders at Laxe Brava and 3324 boulders at Oia. These elevations were compared with the elevations at the same locations in 2013. The occurrence and scale of the elevational changes were generally consistent with changes in the boulder outlines. The study confirmed that boulder beaches can be cheaply and effectively monitored using high resolution, micro-drone technology. Copyright © 2014 John Wiley & Sons, Ltd.

KEYWORDS: micro-drone; boulder beach; boulder movement; GIS; Galicia

Introduction

Large boulders are common on rocky, high-energy coasts. They occur as discrete deposits on shore platforms, in ridges and small clusters, in more continuous and largely intertidal boulder beaches which sometimes have shore platform foundations, and at and near the foot of large cliff failures (McKenna, 2005; Paris *et al.*, 2011). Even very large boulders are being moved today by high storm waves, often at considerable elevations above present sea level (Goto *et al.*, 2011; Fichaut and Suanez, 2011; Pérez-Alberti *et al.*, 2012). The evidence has been based largely on field observation, including identification of erosional scars and other indications of boulder sources (Cruslock *et al.*, 2010; Pérez-Alberti *et al.*, 2012), recently abraded and impacted boulder and rock surfaces (Knight *et al.*, 2009; Etienne and Paris, 2010; Pérez-Alberti *et al.*, 2012), and the surface freshness of transported boulders deposited among much older, immobile clasts (Pérez-Alberti *et al.*, 2012). The Schmidt rock test hammer has also been used to measure differences in the hardness and degree of weathering of the rock in boulders and in the sockets, or scars, from which they were derived (Knight *et al.*, 2009; Knight and Burmingham, 2011).

This paper describes the use of a low-flying micro-drone to obtain high resolution images. Flights were made over two boulder beaches in Spain to test the system and to determine whether it could be used, in a more extensive, longer-term study, to monitor changes in the position of thousands of boulders. The terminology used in this paper to describe boulders and other large clasts follows the revised Udden-Wentworth scale devised by Blair and McPherson (1999). All elevations are referenced to the Spanish national datum, the mean tidal level at Alicante in the Mediterranean.

The Study Area

The study was conducted on granitic boulder beaches along the western coast of Galicia, north-western Spain (Figure 1). Deep-water waves of 1.0 to 2.5 m in height account for about 80% of the yearly total, and over 5.0 m in height for 3% of the total (Puertos del Estado, 2011). The largest waves are generated in autumn and winter by low-pressure systems with westerly, north-westerly, and southwesterly storm winds. Significant wave heights of 11.6, 13.5, and 12.6 m were recorded in November 2010, January 2009, and March 2008, respectively. Wave conditions were lower during the study period with a maximum significant wave height of only 7.4 m on 19 January 2013 (Figure 2). Significant wave heights tend to be 0.3 to 0.4 m higher off the more northerly (Laxe Brava) than off the more southerly (Oia) study areas. The tides in this region have a mean range of 2.5 m with a maximum range of about 4.0 m.

Boulder beaches were studied at northwesterly facing Laxe Brava on the Barbanza Peninsula and at westerly facing Oia

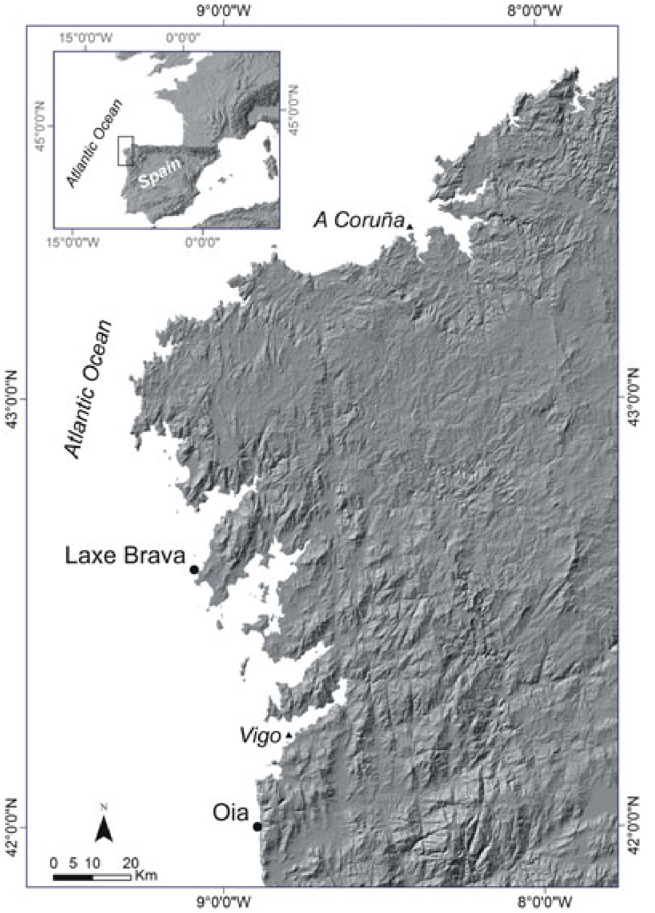

Figure 1. The study areas at Laxe Brava on the Barbanza Peninsula and Oia on the southern coast of Galicia, north-western Spain.This figure is available in colour online at wileyonlinelibrary.com/journal/espl

on the southern coast (Figure 1). The study site at Laxe Brava was described by Pérez-Alberti *et al.* (2012) (Figures 1 and 3). The area behind the coast is low and boulder production must therefore have been largely from wave quarrying on the rocky foreshore, possibly assisted by frost weathering during glacial periods. The beach extends up to several metres above the spring high tidal level and consists of medium to coarse boulders (mean intermediate axis 0.66 m) with a mean mass of 1.0 t. Beach gradient is about 8°, resulting in a maximum slope-induced error in measured boulder dimensions, parallel to the slope, of less than 1%. The beach ranges from about 50 to 65 m in width and it covers all but the seaward-most 20 to 25 m of an underlying shore platform. The second area at Oia was in a shallow embayment where a boulder beach covers the rearmost 19 m of a 74 m wide shore platform (Figures 1 and 4). The gradient of the beach is similar to that at Laxe Brava, but its maximum elevation is generally several metres lower. The beach is backed by an 8 m high cliff composed of coarse periglacial and fluvio-nival sediments (Blanco-Chao *et al.*, 2003, 2007). This beach has a greater variety of boulders than at Laxe Brava, reflecting the diverse nature of the source materials from the cliff and shore platform. Mean clast size ranges from medium boulders (intermediate axes > 60 cm) in the northern part of the embayment to cobbles and pebbles (mean intermediate axis length 7.5 cm) in the southern part.

Materials and Methods

Drones or unmanned aerial vehicles (UAVs) may provide a cost-effective way to study the movement of a large number of individual clasts. They operate at very low altitudes, producing images with a high degree of resolution and accuracy, and data that can be processed with geographical information system (GIS) and applied cartography software (Valavanis *et al.*, 2009; Jones and Reinke, 2009; Green, 2010; Eisenbeiss, 2011; Hugenholtz *et al.*, 2013).

The present study used a multi-rotor micro-drone manufactured by Microdrones GmbH, Siegen, Germany (model md4-200) (Figure 5). The drone had an attached 10 MP digital camera and a ground control station (cockpit) for real-time control of drone altitude and other flight elements and the management of all downlink flight information and recorder data. The mission (flight and data acquisition) was planned in the laboratory with specific software based on the study areas, the required ground sample distance, and the key parameters of the linked digital camera. Flights and data acquisition were made over the two study areas in July 2012 and then in May 2013. The drone flew at 50 m over Laxe Brava acquiring 43 frames with a pixel size of 12.5 mm, and at 30 m over Oia taking 49 frames with a 7.5 mm pixel size. Thirty-two control points at Laxe Brava and 18 at Oia were surveyed using a Stonex S8 GNSS receiver with a static horizontal accuracy of 5 mm and a vertical accuracy of 10 mm. The flights produced: CAD files with the restituted features; digital terrain models (DTMs); contour lines; and orthophotographs (Figures 3 and 4).

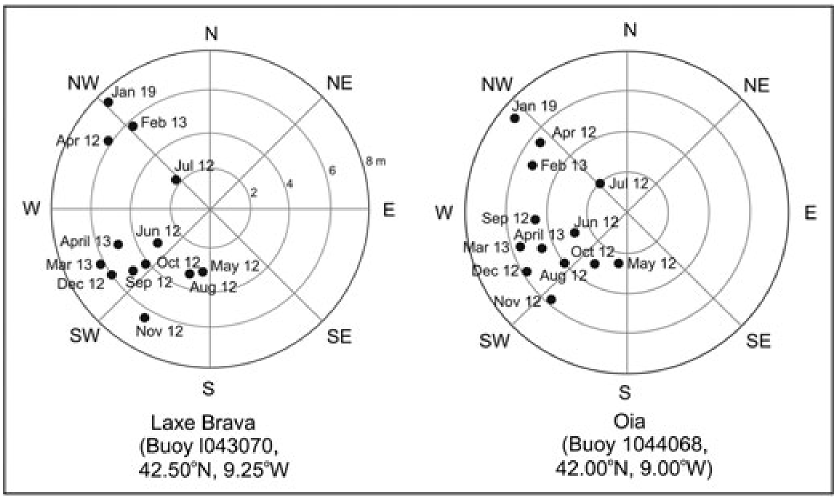

Figure 2. Rose diagrams showing the date (labelled), significant wave height (in metres) (distance from the centre of each diagram), and direction of the highest waves (radial orientation) off the two study areas during the study period (annual data from Puertos del Estado, 2011).

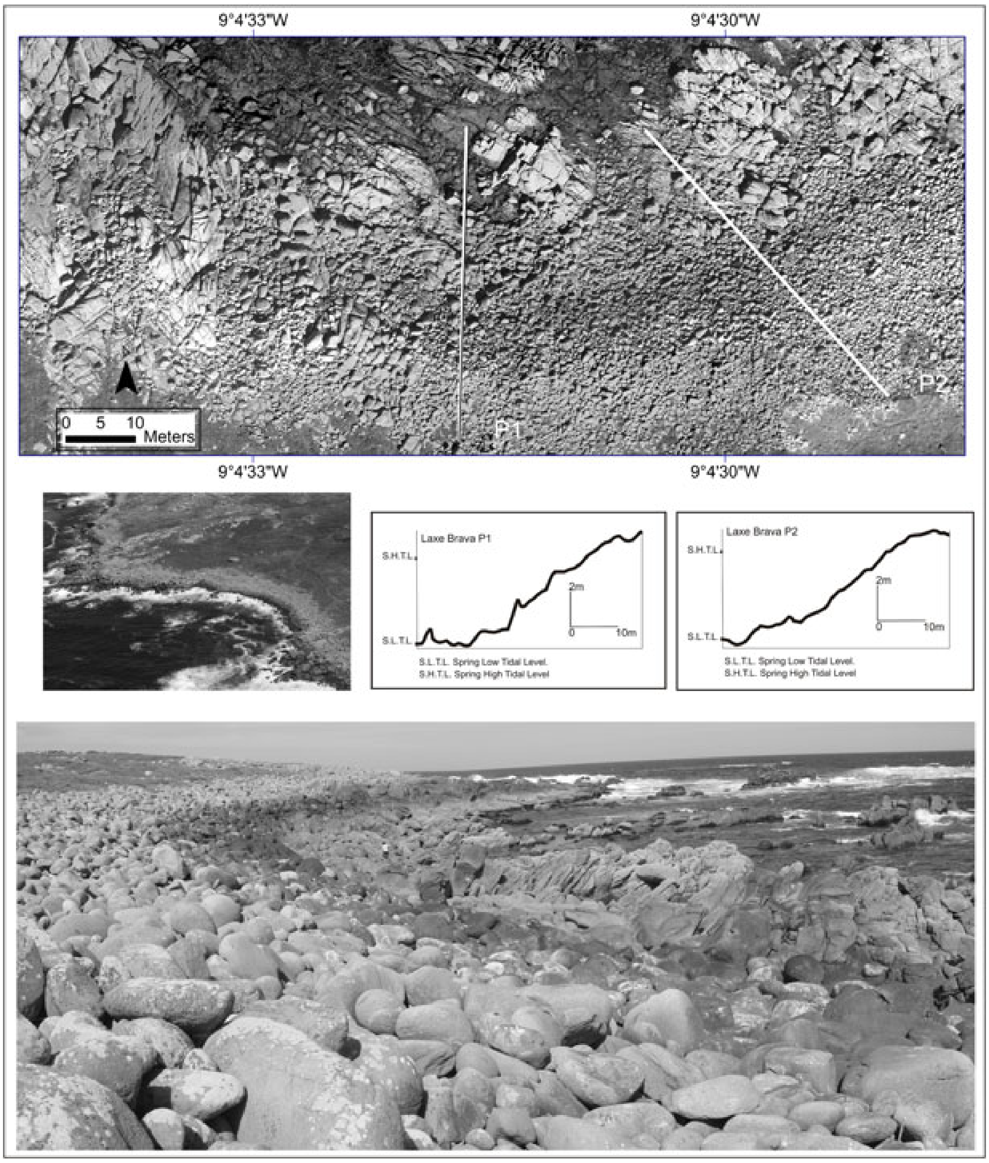

Figure 3. Orthophotograph, oblique aerial photograph, shore normal profiles, and a terrestrial photograph of the boulder beach and granitic shore platform at Laxe Brava (a figure left of centre in the photograph provides scale).This figure is available in colour online at wileyonlinelibrary.com/journal/espl

The images were oriented and georeferenced based on 152 calculated points at Oia and 174 points at Laxe Brava.

The DTMs and contour lines were used to generate a three-dimensional (3D) model of the beach areas. ArcGIS software was used to draw the outlines on the 2012 images of 4582 boulders at Laxe Brava and 2508 boulders at Oia. These outlines were then laid over the 2013 images to identify boulders that had moved (Figure 6). Additionally, the 2012 location and elevation of the highest points were recorded on each of 4093 boulders at Laxe Brava and 3324 boulders at Oia, and then compared with the elevation at the same locations in 2013.

Results

Movement, as shown by a shift in the position of the clast outline, was recorded on 841 boulders at Laxe Brava, about 17.5% of the total monitored. The mean size of the mobile boulders, represented by their surface area as measured from above, was about three-quarters that of the immobile boulders (Table I), although there was a large overlap in the size of the boulders that were mobile and those that were immobile. Almost all the mobile boulders were at altitudes ranging from mid-tide up to 2 m above the highest high tidal level (0 to 4 m), with the majority between mid-tide and 1 m above high tide. There was some movement of boulders in the eastern part of the bay at elevations between 2 and 4 m above the highest high tidal level (4 to 6 m). Most of these mobile clasts were landwards of a broad, shore-normal channel, which was also responsible for a larger cluster of mobile boulders at lower elevation on the exposed shore platform. Another cluster of mobile boulders was along a narrow channel in the eastern part of the beach, although there were other clusters that did not correspond to any topographical channelling (Figure 7). Almost all the boulders at low elevation on the shore platform, other than those in the channels, were immobile.

A much higher proportion of the boulders moved at Oia than at Laxe Brava. Movement was detected in 1333, or about 53%, of the clasts, which can be attributed in part to their fairly small size, the mean surface area being much less than for the mobile boulders at Laxe Brava and almost half that of the immobile boulders at Oia. Nevertheless, although there was a clearer relationship between mobility and size at Oia than at Laxe Brava, the overlap between the size of the boulders in the two categories demonstrated that boulder size offered only a partial explanation for boulder behaviour, there being many cases where large boulders moved whereas much smaller boulders were immobile (Table I). Most of the mobile

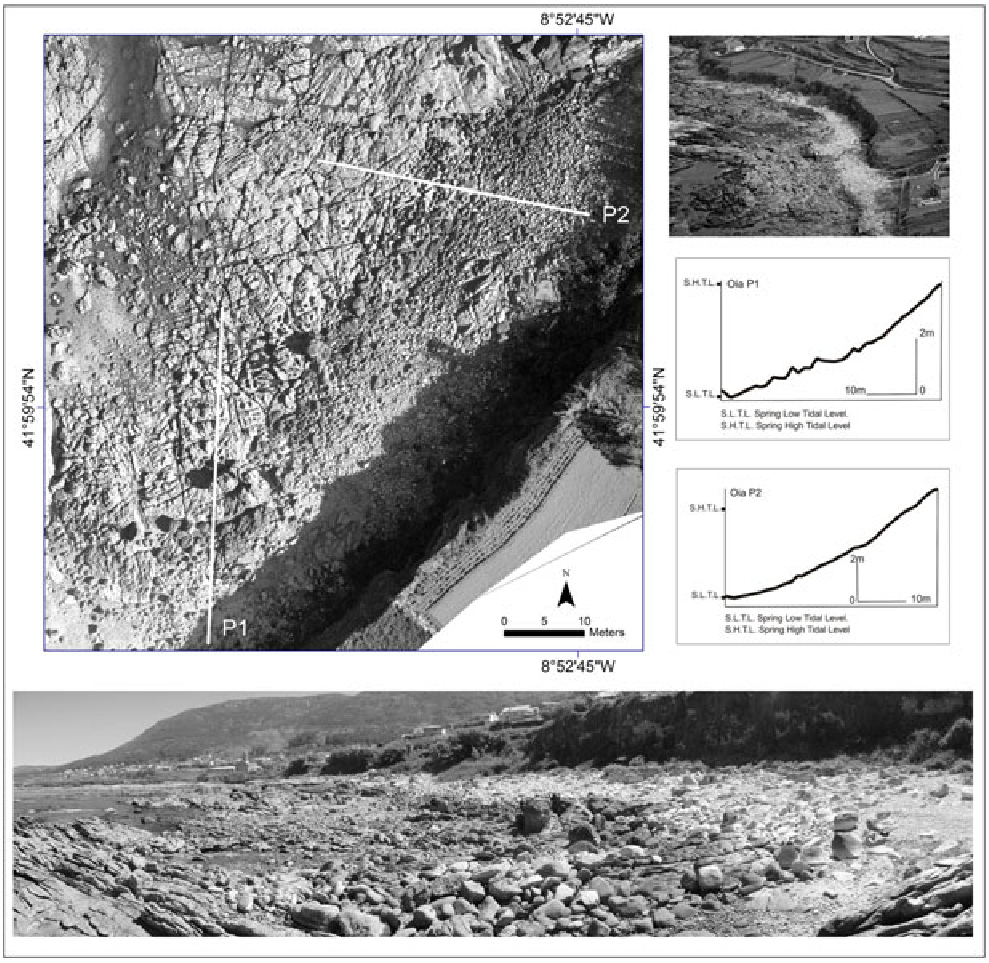

Figure 4. Orthophotograph, oblique aerial photograph, shore normal profiles, and a terrestrial photograph of the boulder beach and granitic shore platform at Oia.This figure is available in colour online at wileyonlinelibrary.com/journal/espl

boulders were in the lower portion of the boulder beach, especially in the area extending from the central to the northern part of the bay, and the boulders in the upper part of the beach, especially in the south, were largely immobile (Figure 7). Less than 1% of the mobile boulders at Oia was more than 2 m above the highest high tidal level (about 4 m above the mid-tidal datum) and the mean surface area (0.12 m^2) of these boulders was about two-thirds of the area of the mobile boulders at lower elevations. Most boulders on the intertidal shore platforms were immobile, either because

Figure 5. The md4-200 micro-drone flying over Oia on 24 April 2013. The camera is slung beneath the vehicle. The micro-drone measures 0.54 m from rotor shaft to rotor shaft, has a mass of about 0.8 kg and a maximum payload of 0.3 kg.

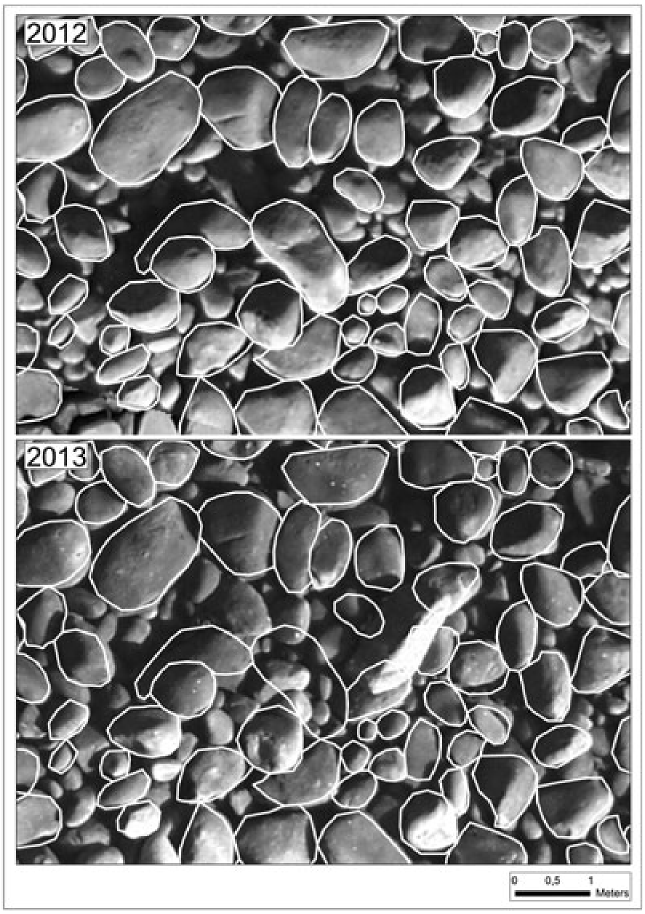

Figure 6. An example of the technique used to track boulder movement by superimposing their outlines from the 2012 image on the 2013 image. In some instances there was only a slight change in the position of a boulder, so that it still occupied much of the original outline polygon. More substantial movement in other cases resulted in the original boulder being replaced by another or by an inter-clast space. In such cases, it was generally impossible to identify where the original boulder had moved to, and therefore to determine the distance or direction of movement.

of their large size or because they were trapped within narrow troughs cut along joints or within broader, topographical depressions.

Boulder movement was also recorded using the elevational data from several thousand points on the highest parts of the boulders at Laxe Brava and Oia in 2012 (Figure 8). There was a mean difference, however, of 0.16 m, with a standard deviation of 0.18 m, in the elevation of 3956 boulders at Laxe Brava that did not move, and a mean difference of 0.13 m, with a standard deviation of 0.20 m, in the elevation of 1175 boulders at Oia that did not move. As it can be reasonably assumed that boulders that did not move in the horizontal plane were also stable in the vertical plane, these differences in elevation must represent errors in the elevational measurements. Because of these errors, only the larger changes in elevation (≥0.20 m) were mapped (Figure 8). The distribution of these changes was similar to the distribution of changes in boulder outlines, being greatest in the lower part of the beaches at Laxe Brava and Oia. Large changes in elevation generally imply that there has been considerable movement of a boulder or its complete removal from a location, whereas smaller changes could result from slight shifts in a boulder's position or rotation about its axes. Large changes in elevation (>80 cm) again corresponded very closely to the areas of highest boulder mobility, as indicated by changes in boulder outlines. These large changes in elevation only occurred at Laxa Brava, however, reflecting the greater size of the boulders on this beach than at Oia.

An attempt was made to determine whether the two-dimensional area of the exposed, upper surface of the boulders, as shown on the orthophotographs, provided reasonable proxies for 3D boulder volume and consequently for boulder mass and mobility. The 3D data used in this analysis were from field measurements made in a previous study (Pérez-Alberti *et al.*, 2012) at Laxe Brava and, lacking specific data from the bay at Oia, at geologically similar sites along the southern coast of Galicia. Correlations were made between the long, intermediate, and short axes of the boulders to determine the relationships between them. There were fairly good correlations between all three axes on the boulders along the southern coast and moderately good correlations on those at Laxe Brava (Table II). The field measured data were then used to correlate boulder surface area derived from combinations of the product of two axes (since two axes can be measured from the air) with boulder volume based on the product of three axes. These calculations were made for boulders resembling a 3D rectangle (a right-angled parallelepiped) and for more spherical forms (volume = $4/3\pi r^3$, where r is half the mean length of the three axes). The correlations, between boulder volume and the upper surface area calculated from any two of the three axes, were high for both basic boulder shapes at Oia and for the more rectangular-shaped boulders at Laxa Brava. The relationships were not as strong for spherical boulders at Laxa Brava apart from that between volume and surface area estimated from the two longest axes (Table II). This latter relationship between volume and the longest and intermediate axes is significant, however, because quasi-spherical boulders that are transported by strong storm waves would tend to assume the most stable positions as they settle, with the two longest axes in the horizontal and the shortest axis in the vertical planes.

Table I. Descriptive statistics for the exposed, upper surface area (m^2) of mobile and immobile boulders at Laxe Brava and Oia

	Laxe Brava		Oia	
	Boulders that moved	Boulders that did not move	Boulders that moved	Boulders that did not move
Number of boulders	841	3956	1333	1175
Maximum	1.936	5.81	0.917	4.490
Minimum	0.021	0.003	0.008	0.015
Mean	0.323	0.486	0.230	0.368
Median	0.245	0.358	0.1430	0.241
Standard deviation	0.264	0.474	0.1320	0.404
Skewness	2.125	3.869	1.754	3.667
Kurtosis	8.952	26.145	7.182	23.65

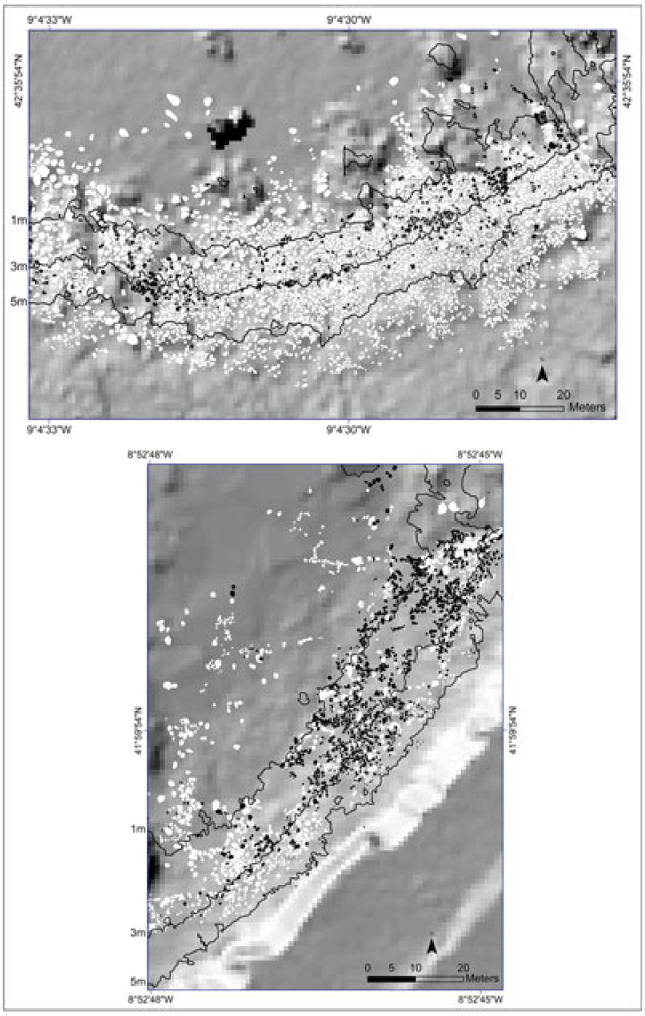

Figure 7. Boulder mobility, shown by changes in boulder outlines, plotted on contoured DTMs at Laxe Brava (top) and Oia (bottom). The boulders that moved over the study period are shown in black and those that did not move in white.This figure is available in colour online at wileyonlinelibrary.com/journal/espl

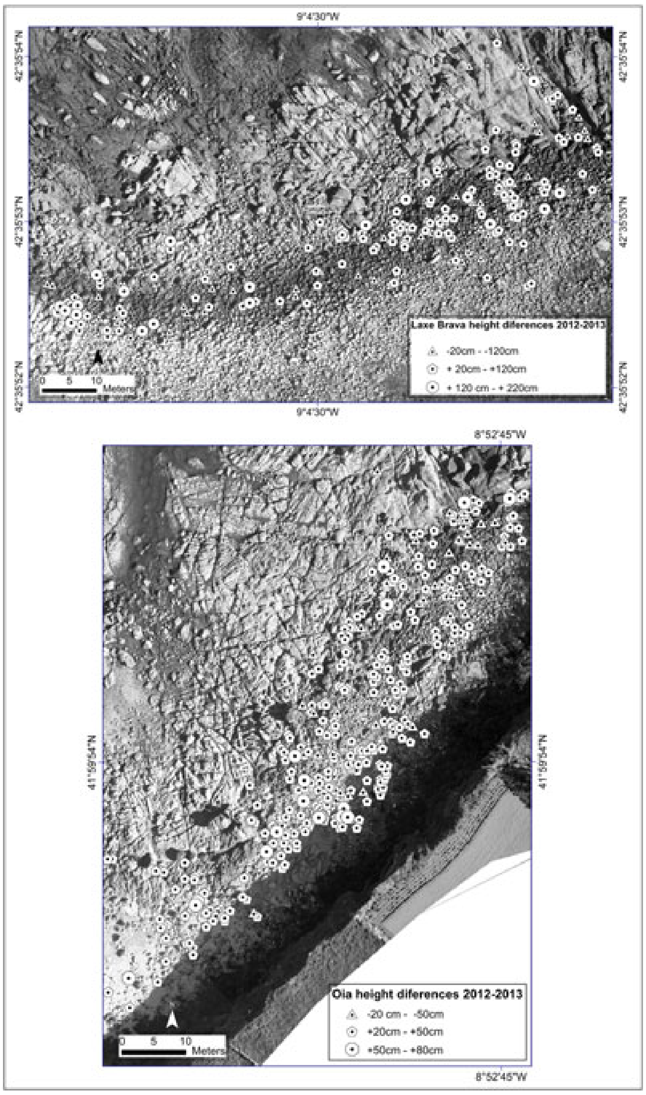

Figure 8. Positive (higher) and negative (lower) changes in elevation on DTMs at Laxe Brava (top) and Oia (bottom).This figure is available in colour online at wileyonlinelibrary.com/journal/espl

Table II. The R^2 values for correlations between individual boulder axes and for the relationship between two axis (as measured aerially) and the product of the three axes (which determines mass)

	Laxa Brava ($n = 178$)			South coast ($n = 101$)		
	IA	SA		IA	SA	
LA	0.65	0.43		0.80	0.66	
IA		0.51			0.73	
	LA × IA	LA × SA	IA × SA	LA × IA	LA × SA	IA × SA
LA × IA × SA	0.90	0.87	0.92	0.88	0.91	0.95
4/3 πr^3	0.87	0.74	0.76	0.88	0.86	0.88

Note: LA, IA, and SA are the long, intermediate, and short axis lengths, respectively; n is the number of measured boulders.

Discussion

This preliminary study showed that drones can be used to determine the mobility of large clasts on rocky coasts. Among the advantages of using drones in such studies are the fairly low cost, the high resolution of the images, the size of the area that can be covered, and the quantity of data that can be produced in a single day.

The study has, however, identified several problems with aerial surveys. Once a boulder had moved, and possibly turned on its axis, it was generally impossible to distinguish it from other blocks and to determine to where it had moved. Although this makes it difficult to measure transport rates and directions from drone data, tracking boulder movement is also a problem in the field. The fairly strong relationships between boulder area and volume (Table II) suggest that reasonable estimates of clast size and corresponding mass in the study areas can be based on measurements of two boulder axes; similar relationships may not exist under more geologically heterogeneous conditions. Another problem is that relating boulder movement to specific storms or to a series of storm events would require flights to be made very frequently, escalating the cost of the research. Furthermore, as the type of drone used in this study could be deployed only when wind speeds were less than 40 k hr^{-1} (all data presented here were collected with velocities around 15 k hr^{-1}), this precluded data collection during winter storms, when most boulder movement takes place.

This investigation provided further confirmation that boulder beaches in exposed areas are dynamic deposits (Oak, 1984; Etienne and Paris, 2010; Chen *et al*., 2011; Pérez-Alberti *et al*., 2012). Nevertheless, despite some boulders in Galicia having been moved at elevations up to 2 m above the highest high tidal level, the winter of 2012 to 2013 was only moderately stormy. Only a fairly small proportion of the boulders at

Laxe Brava moved in that year. Most movement was within the intertidal zone and many of the mobile boulders were located landwards of shore-normal channels that funnel strong storm waves landwards. Some boulders above the high tidal level moved on both beaches but not to the degree that has previously been observed following stormier winters in this area (Pérez-Alberti *et al.*, 2012).

Conclusions

The main conclusions of this paper are as follows:

a. Micro-drones provide a fairly low cost, high resolution means of monitoring the movement of a very large number of boulders on rocky coasts.
b. The application of drone technology to boulder research needs to be complemented with work in the field to trace boulder movement.
c. Further work needs to be undertaken on the relationship between two-dimensional boulder dimensions as recorded by aerial surveys and boulder volume and mass, particularly where the boulders are of variable provenance.

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