Intertidal boulder transport: a proposed methodology adopting Radio Frequency Identification (RFID) technology to quantify storm induced boulder mobility

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Abstract

Boulder transport is an area of growing interest to coastal scientists as a means of improving our understanding of the complex interactions between extreme wave activity and the evolution of rocky coasts. However, our knowledge of the response of intertidal boulder deposits to contemporary storm events remains limited due to a lack of quantifiable field-based evidence. We address this by presenting a methodology incorporating Radio Frequency Identification (RFID) tagging and Differential Global Positioning Navigation Satellite System (DGNSS) technology to monitor and accurately quantify the displacement of RFID tagged boulders resulting from storm wave activity. Based on preliminary findings we highlight the suitability of the technology and methodology to better understand the spatial and temporal response of intertidal boulders to contemporary storm events. We inserted RFID tags in 104 limestone boulders (intermediate axes from 0.27 to 2.85m) across a range of morphogenic settings at two sites on the intertidal shore platforms at Bembridge, Isle of Wight (UK). Fifteen topographic surveys were conducted between July 2015 and May 2017 to relocate and record tagged boulder locations (tag recovery rate: 91%). The relocated boulder coordinate data from both sites identified 164 individual transport events in 63% of the tagged boulder array amounting to 184.6 m of transport, including the displacement of a boulder weighing more than 10 tonnes. Incidents of boulder quarrying and overturning during transport were also recorded, demonstrating that despite the relatively sheltered location, intertidal boulders are created and regularly transported under moderate storm conditions. This suggests that contemporary storm events have a greater propensity to mobilise boulders in the intertidal range than has previously been realised. Consequently, by documenting our methodology we provide guidance to others and promote further use of RFID technology to enable new hypotheses on boulder transport to be tested in a range of field settings and wave regimes.

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Keywords: RFID tagging, boulder transport, storm events, sediment tracing, coastal change

INTRODUCTION

The anticipated increase in storm activity and intensity resulting from climate change (Easterling et al., 2000; Beniston et al., 2007) is expected to drive geomorphic alteration to shore platforms and increase the vulnerability of coastal zones globally (Paris et al., 2011). Given the irreversible erosional impact of storm waves on rocky coasts (Naylor et al., 2010) understanding the geomorphic response to such events is of growing significance. As a result, storm wave impacts on rocky coasts are of increasing interest in terms of understanding landform evolution and monitoring coastal change.

The presence of large boulders on shore platforms is testament to the dynamic nature of the coastal environment. However, the mechanisms that facilitate detachment, transport and deposition of boulder-sized sediment within the intertidal zone are poorly understood. We defined boulders as clasts with an intermediate (*l*) axis between 0.25 and 4.1m (Blair and McPherson, 1999).

Sediment tracing provides a means of monitoring and quantifying displacement while offering an insight to the hydrodynamic conditions that enable episodes of mobility

(Lee et al., 2000; Sear et al., 2000). The basic principle of sediment tracing is to introduce material to a study site which is distinct from, yet accurately reflects the physical properties (e.g. particle size, shape and density) of the indigenous sediment (Sear et al., 2000; Lee et al., 2007; Black et al., 2007). This can be achieved using artificial tracers such as aluminium cast material (Bray et al., 1996) or by adapting the indigenous material found at the selected study site. Following tracer deployment, successive searches are undertaken to recover the particles and record their precise location allowing distance, direction and frequency of transport to be determined.

In littoral settings sediment tracers are monitored *in-situ* where they are subjected to a series of site specific conditions (e.g. wave climate, tidal regime, topography and bathymetry) which are difficult, if not impossible to accurately replicate within the confines of the laboratory. This paper demonstrates the feasibility of using Radio Frequency Identification (RFID) technology in combination with periodic topographic surveys using Differential Global Positioning Navigation Satellite System (DGNSS) to accurately quantify the mobility of intertidal boulders resulting from contemporary storm activity.

Historically, tracer techniques have included painted sediment (Russell, 1960; Jolliffe, 1964; Nordstrom and Jackson, 1993); radioisotopic tracers (Steers and Smith, 1956; Kidson et al., 1958), magnetic tracers (Osborne, 2005), aluminium tracers (Wright et al., 1978), electronic radio transmitters (Bray et al., 1996) and RFID's (Dickson et al., 2011; Dolphin et al., 2016) as a means of monitoring littoral sediment transport across a range of particle sizes. The development of tracer techniques has been driven by the need to improve tracer recovery rates over broader timescales. Table 1 identifies how different tracer methods and technological

advances have facilitated this. It also highlights the preponderance of research focusing on pebble and cobble-sized particles, and subsequently, the paucity of long term tracer studies relating specifically to the mobility of boulder-sized clasts. Further reviews pertaining to the development of sediment tracing techniques have been published by Sear et al. (2000) and Chapuis et al. (2014).

Insert table 1.

RFID tagging has proven to be effective in transport studies in both fluvial (Bradley & Tucker, 2012; Liébault et al., 2012) and littoral settings (Allan et al., 2006; Dickson et al., 2011; Dolphin et al., 2016). It has facilitated longer term monitoring studies yielding more favourable recovery rates when compared with alternative methods. The success of previous RFID-based studies documenting sediment transport was integral to our decision to adopt this technology for monitoring boulder displacement.

It is well documented that storm waves have the ability to detach, transport and deposit boulders on intertidal shore platforms (Stephenson and Naylor, 2011; Paris et al., 2011; Etienne and Paris, 2010; Barbano et al., 2010; Goto et al., 2011; Biolchi et al., 2016; Shah-hosseini et al., 2011; Cox et al., 2012). Boulder accumulations on shore platforms frequently develop distinctive geomorphic features such as clusters, ridges, fields and cliff top deposits (Nott, 2003a; Paris et al., 2011). These boulder assemblages have been used to infer the mechanisms by which detachment, transport and emplacement occur, including past tsunamigenic wave events (Engel and May, 2012; Nandasena et al., 2013; Mottershead et al., 2014; Etienne et al., 2011; Goto et al., 2012) and contemporary storm activity (Hall, 2011; Fichaut and Suanez, 2011; Autret et al., 2016, Cox et al., 2018). However, despite growing interest in the effects of extreme waves the subsequent modes and rates of boulder

transport over time are poorly understood owing to a lack of accurate, reliable and quantifiable field data (Goto et al., 2011; Paris et al., 2011; Moses, 2014).

Recent studies have sought to address this by documenting boulder transport during, and resulting from, contemporary storm events. Extreme storm activity occurred in the winter of 2013-2014 which had a dramatic impact on the Atlantic coastline of Europe (Masselink et al., 2016a) with reports of significant wave heights exceeding 9m (Castelle et al., 2015). During this period Autret et al. (2016) recorded the morphological and sedimentological alteration of cliff-top boulder deposits. They documented quarrying of 178 clasts, one weighing 86 tonnes, and the transport of 507 blocks some as far as 40m inland at elevations up to 14m above mean sea level. This was achieved using unmanned aerial vehicles (UAV's) and kite-mounted cameras which were deployed to obtain pre/post site imagery for comparative purposes. These techniques were complimented by field observations of boulder mobility and the use of pressure sensors to establish hydrodynamic conditions during the period of storm activity.

Stephenson and Naylor (2011) and Naylor et al. (2016) employed marine paint as a tracer to document evidence of periodic detachment, entrainment, deposition and the breakdown of boulders. The latter study quantified the transport distance of fine and medium-sized boulders and is thought to be the first intra-storm assessment of boulder transport. Using painted tracers an 81% recovery rate ($n=39/48$) was achieved over a four day monitoring period. Despite the valuable insights gained from these studies the paint methodology has limitations, as follows: (1) the reliance on visual detection prevents relocation of buried tracers resulting in reduced rates of recovery; (2) the paint coating may arouse unwanted attention and encourage anthropogenic transport; (3) prolonged exposure leads to paint abrasion limiting the

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3 98 longevity of the study; (4) being visually obtrusive issues may arise with gaining
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5 99 authorisation for the use of painted tracers in sensitive and designated coastal
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7 100 locations. These factors suggest an alternative, more discreet technique is required
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9 101 for effectively tracing boulder displacement over monthly and annual timescales,
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11 102 RFID tagging provides a viable alternative. Furthermore, with a non-visual mode of
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13 103 detection, RFID tags allow for the relocation of buried clasts, resulting in improved
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15 104 rates of recovery (Bray et al., 1996).
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18 105 Despite the potential of RFID tags for quantifying boulder transport (Paris et al.,
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20 106 2011) their use has focused predominantly on mixed gravels and cobbles (Allan et
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22 107 al., 2006; Miller et al., 2011; Dolphin et al., 2016) opposed to boulder-sized clasts
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24 108 (Table 1). The limited use of RFID's to monitor boulder displacement may be due to
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26 109 perceived limitations with the technique, identified by Paris et al. (2011) and Naylor
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28 110 et al. (2016). Specifically, the ability of the tags to remain operational, concerns with
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30 111 clast breakdown and the ability to recover tagged material in a short tidal window. To
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32 112 date, we are aware of only one study that has incorporated the use of RFID's in
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34 113 monitoring clast mobility that extends into the boulder size range (Brayne, 2015);
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36 114 where the maximum size classification used was fine boulders with an intermediate
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38 115 axis up to 0.51m. We broaden the scope of this previous work and allay concerns
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40 116 with the use of RFID's having conducted the first known field investigation applying
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42 117 RFID tagging to boulder-sized clasts only, from fine through to very coarse boulders.
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47 118 We embedded RFID tags in 104 limestone boulders across two sites, Bembridge
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49 119 Ledge (n=50) and Black Rock (n=54) at Bembridge, Isle of Wight, U.K. Boulders
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51 120 were selected from the indigenous sediment to reflect a range of shapes, particle
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53 121 sizes and morphological settings. Between July 2015 and May 2017 fifteen
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55 122 topographic surveys were conducted to relocate tagged boulders. Recovered
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3 123 boulder positions were recorded using DGNS; the collated data providing a spatial
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5 124 and temporal context to boulder displacement. This coordinate data was processed
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7 125 using a tailored python script (included in the supplementary documentation) which
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9 126 calculates the distance and azimuth between successive points.
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12 127 The focus of this paper is the RFID methodology. We describe in detail the
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14 128 procedures undertaken and recommend a series of considerations, highlighting best
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16 129 practice for successful field tag deployment and monitoring. We draw upon incidents
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18 130 of mobility from the field surveys to illustrate the capability and effectiveness of the
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20 131 methodology for use in future boulder transport studies.
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23 132 **RFID METHODOLOGY**

24 133 **RFID operational overview**

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30 134 The term RFID describes the various technologies that utilise radio waves to identify
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32 135 objects (Aluf, 2017). It has been integrated into numerous mainstream applications,
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34 136 primarily as a means of asset tracking. RFID technology comprises four key
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36 137 components, a transponder, more commonly referred to as a tag, an antenna, a
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38 138 reader and a user interface (PDA), Figure 1.
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40 41 139 **Insert figure 1.**

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44 140 1 - RFID TAGS (transponder): the tags enclosed circuitry is housed within a
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46 141 hermetically sealed glass casing. Each tag is pre-programmed with a unique 16-digit
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48 142 ID code allowing for the unequivocal identification of an individual object, in this
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50 143 instance a boulder.
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54 144 2 - POLE ANTENNA: connected to the reader via a cable the circuitry housed within
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56 145 the antenna tubing emits and receives electromagnetic signals via the circular loop.
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3 146 The pole is operated in the field in a sweeping movement, similar to that of a
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5 147 conventional metal detector.
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8 148 3 - BACKPACK READER: powered by a 14.8 volt lithium polymer (Li-Po) battery the
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10 149 reader is housed in a backpack. It produces a low frequency (134.2 kHz)
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12 150 electromagnetic signal which is transmitted via the pole antenna.
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15 151 4 - HANDHELD COMPUTER (PDA): featuring specialist software that enables the
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17 152 identification of the unique tag ID number. This is wirelessly connected to the reader
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19 153 via a Bluetooth adapter.
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22 154 Tag detection occurs when the pole antenna comes within range of a deployed tag,
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24 155 detection range details are documented in Table 2. The emitted electromagnetic
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26 156 signal from the loop of the pole antenna provides sufficient power to prompt tag
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28 157 activation. The tag becomes energised and transmits a return signal containing the
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30 158 unique tag ID code which is received by the antenna and relayed to the reader. An
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32 159 audible alarm also alerts the user to the detection of a tag. The return signal is
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34 160 translated by the reader and transmitted via the Bluetooth functionality to the PDA or
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36 161 alternative mobile device, notifying the user of the tag ID code (Figure 2).
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41 162 **Insert figure 2.**
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43 163 RFID tags can be described as active or passive in their operation (Nichols, 2004).
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45 164 Active tags require a power source (e.g. a battery) which renders them impractical
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47 165 for sediment tracking purposes based on size, cost and longevity of operation.
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49 166 Passive tags, also referred to as Passive Integrated Transponder (PIT) tags have no
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51 167 internal power source making them smaller (tag sizes of 12mm, 23mm and 32mm in
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53 168 length are available). Without the need for a battery the tags have a potentially
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3 169 unlimited operational capacity (Want, 2006) although Allan et al. (2006) suggest a
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5 170 more conservative 50 year lifespan.
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8 171 RFID systems are available from a variety of sources. We selected a field ready
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10 172 solution supplied by Oregon RFID as the manufacturer's specification fulfilled our
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12 173 criteria of tag detection ranges approaching 1m.
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15 174 Typically, existing tracer techniques rely on the collection and removal of sediment
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17 175 from a study site for tagging in the comfort of a laboratory with access to a range of
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19 176 specialist equipment (Dickson et al., 2011; Allan et al., 2006). Size constraints
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21 177 dictate boulder tagging must be conducted in the field. This generates a number of
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23 178 novel issues which require consideration prior to, and during tag deployment to
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25 179 ensure a successful monitoring campaign. These will be addressed herein.
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29 180 **Site selection and description**

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32 181 A pre-requisite of any proposed site is the presence of coarse clastic material known
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34 182 to be mobile during periods of increased wave activity. Accessibility is a key
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36 183 consideration as site visits may be required at short notice in response to storm
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38 184 activity. Further consideration is afforded to the locality of wave recording devices to
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40 185 establish hydrodynamic conditions relating to specific storm events which provides
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42 186 insight to the wave thresholds required to initiate transport.
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45 187 Bembridge is located at the most easterly point of the Isle of Wight (50.6883°N, -
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47 188 1.06982°W), Figure 3. It was selected as it fulfils the aforementioned criteria. We
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49 189 selected two field sites, Bembridge Ledge and Black Rock Ledge upon which 104
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51 190 RFID tags were inserted into boulders of varying size and shape ($n=50$ and $n=54$
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53 191 respectively). Each site covers an area of approximately 0.1km². Boulders are
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distributed across both sites either as individual, solitary clasts, or collectively as clusters or as distinct assemblages such as boulder ridges. The nearest wave buoy, operated by the Channel Coast Observatory (CCO) is located approximately 5km to the southwest of the study site at Sandown Bay. The buoy is positioned 1.2km from the coast in a water depth of 10.7m (chart datum). There is also a tidal gauge recording wave and tidal parameters located on Sandown Pier (Figure 3c). Wave, tidal and selected meteorological parameters are recorded every 30 minutes (CCO, 2017a).

The area is classified as meso-tidal with a spring and neap tidal range of 3.7m and 1.8m respectively. Current research relating to boulder transport has focused on site locations with considerable fetches (Scheffers et al., 2009; Switzer and Burston, 2010; Noormets et al., 2004). Comparably, Bembridge has a limited fetch (Figure 3d), its eastern aspect providing shelter from large Atlantic swell waves and the prevailing south westerly wind and wave direction. Bembridge Ledge is east facing opposed to Black Rock with its southern aspect which is more exposed to wave activity.

Average wave direction is dominant in the southern quadrant with a mean of 164° over the 22 month study period (July 2015 - May 2017). Average significant wave height (H_s) was 0.6m and a maximum wave height (H_{max}) of 6.8m was recorded over the same period (CCO, 2017b).

Insert figure 3.

A key feature of the Bembridge coastline is an extensive series of intertidal terraced shore platforms that extend up to 500m seaward at its widest point. The platforms are characterised by an abrupt terminus, akin to the type-B shore platform as

described by Sunamura (1992). The platforms are formed of well jointed, near horizontally bedded Late Eocene Bembridge Limestone (Daley & Edwards, 1990; Armenteros & Daley, 1998). The limestone beds are interspersed by thin layers of Bembridge Marl which are preferentially eroded creating an overburden of the more consolidated limestone. The overburden, coupled with dense bedding and jointing facilitates the liberation of blocks from the shore platform edge (Trenhaile 2002; Knight et al., 2009; Hall, 2011). Block removal, or quarrying, occurs when waves break against fractured rock structures resulting in increased pressure within air-filled joints (Stephenson and Kirk 2000, Knight and Burningham 2011). Increased wave impact pressures promote crack propagation leading to boulder quarrying (Müller et al., 2003). Many of the Bembridge boulders (including RFID tagged clasts) originate from the quarrying process, and are therefore, created, and subsequently transported and deposited by wave activity within the intertidal zone (Figure 4).

Insert figure 4.

Tag selection

RFID tags used in sediment tracing are available in three sizes, 12mm, 22mm and 32mm. The choice of tag size depends on; (1) the size of clast to be tagged: the tag required needs to be smaller than the clast into which it is being inserted; (2) the likelihood of clast burial: the smaller the clast size the greater the likelihood of burial, therefore the vertical tag detection range requires consideration; (3) the required tag detection range: the distance across which a tag can be detected is contingent on a number of factors including tag size, tag orientation, proximity of noise (e.g. electrical appliances), reader battery level and antenna diameter (Oregon RFID, 2017; Allan et al., 2006; Chapuis et al., 2014). To maximise the tag detection range we selected

32mm tags thus increasing the likelihood of tag recovery (Chapuis et al., 2014; Oregon RFID, 2017).

As part of the pre-deployment testing we conducted a series of laboratory trials to establish the significance of tag orientation on the detection range. We placed the 32mm RFID tag horizontally on the floor aligned along the north-south axis with the visible copper wire circuitry (Figure 5) orientated north, 0°, replicating Chapuis et al. (2014). We approached the tag from the north, east, south and west with the antenna elevated 0.1 - 0.2m above the ground. When the audible detection alarm was activated we recorded the distance from the end of loop antenna to the tag. Testing was conducted on 5 different tags with 20 approaches from the aforementioned cardinal directions. The results identified that approaching the tag ‘head on’ from the north towards the copper coil tag end provided a greater read range than from any other direction (Table 2). We recorded a mean detection range of 0.77m, within 15% of the manufacturer’s published detection range of 0.89m (Oregon RFID, 2017). Similar experimental analysis by Chapuis et al. (2014) suggested approaching the tag from the northeast maximises tag detection although this was based on 23mm tags opposed to 32mm.

Insert table 2.

Prior to insertion within the boulder, tags were checked in the laboratory to ensure operational functionality by placing them within range of the antenna. The last four digits of the transmitted tag ID were noted. Tags were placed in a protective silicone sleeve to provide additional protection from impact forces during displacement.

The ends of the sleeved tag were capped with a waterproof sealant and allowed to cure. This created a waterproof seal around the tag providing further protection and

prolonging operational use. The silicon sleeve was numbered with the last 4-digits of the tag ID code and the copper coiled end was marked for identification in the field at the time of insertion (Figure 5).

Insert figure 5.

Boulder selection

Prior to selecting boulders for tagging a number of factors should be considered as they can affect the ability to successfully relocate and record boulders within a single tidal cycle. These include site terrain, tidal regime, spatial distribution of tagged boulders, the number of RFID tag detectors, and the availability of field assistance. Additionally, wave climate requires consideration as this has the ability to disperse tracers across a wider area extending the time required to relocate tagged clasts.

A key factor in tracer studies relates to the effectiveness of the introduced material to accurately reflect the physical properties, namely size and shape of the indigenous sediment (Black et al., 2007). This was achieved by measuring a random selection of 100 indigenous boulders at each of the two Bembridge sites, recording the long (*L*), intermediate (*I*) and short (*S*) axial dimensions. These measurements were also used to establish boulder shape as characterised by Zingg (1935). Comparisons of size and shape between the indigenous and tagged boulders are presented in Table 3. The values express a degree of similarity between the two populations.

Insert table 3.

Samples of the Bembridge Limestone were analysed in the laboratory to determine rock density using the displacement method. Repeated experimentation produced

286 values of 2.4g/cm^3 . All tagged boulders were formed of the local Bembridge
287 Limestone.

288 The number of boulders selected for tagging was based on the ability to recover the
289 entire array within a single tidal window. With time allocated to setting up the survey
290 equipment and based on a working team of two persons we estimated it would be
291 possible to relocate between 50-55 boulders. Further consideration should be
292 reserved for tagging boulders in close proximity to one another. This relates to the
293 detection range of the RFID tags. For example, given an approximate tag detection
294 range of 0.75m, upon detection, any two or more tagged boulders within that range
295 may simultaneous transmit a tag ID code. These multiple transmissions create a
296 shadowing effect whereby both tags are activated yet only one code can be received
297 and displayed on the PDA (Lamarre et al., 2005; Dolphin et al., 2016; Chapuis et al.,
298 2014). Therefore, it is suggested the minimum distance between tagged boulders
299 should exceed the mean detection range of the deployed tags.

300 In selecting boulders for tagging we aimed to represent a range of zones from both
301 sites as Naylor et al. (2016) identify the significance of morphological setting in
302 controlling boulder mobility. These locations also serve to establish a pre-transport
303 setting for each tagged boulder. The significance of the pre-transport setting is well
304 documented when used in conjunction with hydrodynamic equations to calculate the
305 magnitude of retrospective wave conditions responsible for boulder transport (Nott,
306 2003a; Spiske and Bahlburg, 2011; Nandasena et al, 2011b; Switzer and Burston,
307 2010). The boulder zones are summarised in Table 4.

308 **Insert table 4.**

Owing to differences in local conditions it was not possible to maintain consistency of selected boulders between sites, therefore some classifications are underrepresented. This is due to the limited availability and accessibility of suitable boulders to tag, e.g. the lower platform elevation at Black Rock restricts access to boulders located seaward of the shore platform to only the lowest spring tides. Finally, boulder selection was limited to those boulders that were deemed too large to be moved by human intervention. All tagged boulders had an intermediate axis $>0.25\text{m}$, this restricted the agent of transport to wave activity alone.

Field tag deployment

The current literature refers to the deployment of RFID tags in gravel and cobbles only. There are no published accounts relating to the specific requirements for boulder tagging. We aim to address this with a detailed review of the tagging procedure demonstrating some key refinements that are required for boulder sized sediments.

Firstly, holes have to be drilled into boulders in the field to enable tag insertion. In preparation, drill tests were conducted within the laboratory on samples of the indigenous boulder rock type (Bembridge Limestone). These tests provided a valuable assessment on the operational capacity of the drill and the longevity of the battery and drill bits. Testing identified the necessity for a quality, industrial cordless drill and drill bits. We found the Makita 8391DWPQ 18v Ni-Cad Cordless Hammer Drill and DeWalt Extreme II 7mm drill bits performed particularly well.

Due to the number of boulders to be tagged in the field and based on the preceding laboratory tests a number of spare drill bits and a second drill battery were required

332 together with a means of recharging drill batteries in the field. We achieved this using
333 a 12V car battery connected to a power inverter which converts DC power to AC
334 enabling continued recharging of the spare drill battery whilst the other is in use. The
335 additional weight may prompt logistical considerations particularly where a study site
336 has restricted access and/or limited field assistance is available. Due to the
337 changeable nature of weather conditions at coastal locations we kept the recharging
338 equipment dry by securing it in a watertight receptacle.

339 The chosen location for tag insertion within the boulder is of great importance. To
340 accurately quantify boulder transport it is necessary to relocate and record the same
341 position on tagged boulders during each survey; we selected the tag insertion point
342 (TIP) for this purpose. Tag insertion in the *L/I* plane should be avoided as in the
343 event of transport the boulder may be overturned on to the *L/I* plane obstructing
344 access to the TIP. To increase the likelihood of accessing the TIP the tag should be
345 inserted in the *S*-axis parallel with the orientation of the *L*-axis (Figure 6). Knowing
346 the location of tag insertion makes identifying the TIP easier should the boulder
347 become colonised with algae and/or barnacles.

348 **Insert figure 6.**

349 Once a suitable TIP was identified a drill hole was made to the required depth with a
350 7mm drill bit (hole depth and width required is dependent on tag size). Excess dust
351 was expelled from the hole prior to tag insertion to create a dust-free surface. A
352 waterproof, silicon-based sealant (Evo-Stik Wet grab) was injected into the hole,
353 filling to approximately 75%. The pre-prepared sleeved tag was inserted with the
354 copper coils orientated towards the drilled exit hole. This was based on the
355 increased read range of the tags positioned in this manner, as identified in Table 2.

Once embedded any excess sealant was removed. A further protective seal was applied using Plastic Padding Marine Epoxy creating an additional barrier to prevent the ingress of seawater (R. Brayne, 8th April 2014, pers. comm.). Prior to application the epoxy should be mixed as per the manufacturer's instruction. Curing time varies between products and depending on ambient temperature meaning incoming tides may not allow for the necessary curing times. Hence, it is important to use an epoxy resin that can, if necessary, be applied and cured underwater. Once embedded it is advisable to ensure the tag is detectable and the unique ID code can be transmitted from within the boulder prior to moving on to the next tag insertion. We suggest undertaking laboratory trials of the adhesive and protective properties of the chosen sealant and epoxy prior to full-scale field deployment.

Existing research has indicated that wave activity is capable of flipping, or overturning a range of boulder sizes (Sousa 1979; Noormets et al., 2004; Imamura et al., 2008). Such events can be inferred by algal growth on a boulders underside (Knight et al., 2009), by the presence of biotic indicators (Mastronuzzi and Sansò 2004) or using comparative photographic evidence (Cox et al., 2018). The ability to identify overturning during entrainment provides a useful insight to the mode of transport. To establish when incidents of overturning occur we suggest drilling a secondary orientation hole, approximately 0.01m deep above the TIP. This identifies the upward orientation of the boulder at the time of tag deployment. Any relocated boulder found with the orientation hole below the TIP can unequivocally be identified as being overturned during transport.

Recording tagged boulder characteristics

On completion of the tagging procedure a series of boulder characteristics were noted, as described in Table 5.

Insert table 5.

Under favourable conditions the tag insertion procedure and collation of characteristics took approximately 5-8 minutes per boulder.

Insert figure 7.

Tag retrieval surveys

The frequency of the retrieval surveys was dictated by a number of factors including favourable tides, the occurrence of storm activity and availability of field assistance.

As part of this study fifteen surveys were undertaken between July 2015 and May 2017 (seven at Bembridge Ledge and eight at Black Rock). Accessibility to tagged boulders limited surveys to periods of low water only.

To date RFID studies relocate tagged sediment by systematically scanning the survey area with the pole antenna in the same manner as a standard metal detector (Nichols, 2004; Dolphin et al., 2016). To ensure a more productive use of time in the field we utilised the ‘stake-out survey’ functionality of the Topcon DGNSS. This allowed us to upload boulder coordinate data as recorded on the preceding survey to the DGNSS handheld interface. By accessing the uploaded data points in the field we were directed to the previously recorded coordinate of the selected boulder as indicated on the interface display screen. If the boulder was not relocated at that location the RFID detection equipment was used to scan the surrounding area until it was found. Once relocated, boulder characteristics 3-8 as described in Table 5 were documented.

At Bembridge Ledge we found that tagged boulders deposited towards the beach toe were subject to burial from the seasonal accretion of sediment. Despite being obscured from view we were able to relocate buried boulders using the RFID equipment to depths of up to 0.4m. Upon relocation, the overlaying sediment was removed and the TIP recorded (Figure 8). Once the boulder location was recorded the excavated sediment was replaced.

Insert figure 8.

Field survey equipment

In order to detect boulder movement in the centimetre range a DGNSS setup was required to provide a high survey resolution. Recreational GPS receivers or mobile phones with GNSS capabilities do not offer this level of precision (Schaefer and Woodyer, 2015). DGNSS uses static base stations with known positions to correct for the biases that cause GNSS errors (van Sickle, 2008; Kaplan and Hegarty, 2005). Boulder relocation surveys were conducted using a Topcon Hiper V in Real-Time Kinematic (RTK) mode. This uses a local base station that sends out a correction signal in real time to a mobile GNSS receiver (rover), providing a relative horizontal accuracy of 5mm, $\pm 0.5\text{ppm}$, (Topcon, 2017).

Defining boulder transport

In coarse sediment transport studies the distinction between entrainment and transport is frequently unclear (Naylor et al., 2016). By establishing a displacement threshold we are able to discriminate between the two, making it possible to establish when boulder transport has, or has not, occurred. Previous studies have monitored block displacement by embedding datalogging tri-axial accelerometers

within clasts (Stephenson and Abazovic, 2016 and Brayne, 2015). The loggers record three-dimensional tilt and acceleration of the clast allowing the user to differentiate between incremental entrainment, such as motion about a fixed point, and major movement in a specific direction, akin to transport (Brayne, 2015).

Alternative methods have been employed that avoid the use of loggers, the cost of which can be prohibitive. Naylor et al. (2016) define transport whereby the distance moved and the combined root mean squared (RMSE) exceeds half the long axis length of a given clast, the RMSE being calculated from GPS, rover pole position and clast re-measurement error. This method was adopted as they were unable to re-record the same point on individual boulders. Unlike the aforementioned study we have a fixed point (the TIP) from which the boulder location can repeatedly be re-recorded. Therefore, in defining transport we combine the error from the relative accuracy of the DGNSS, the setup of the base station and the RMSE of re-surveying the TIP. The RMSE is based on recording four fixed points (two at each site) with the DGNSS as part of the field surveys; 30 measurements were recorded giving a RMSE of +/- 0.03m in the horizontal and vertical axis, although maximum values of 0.08m were recorded. Based on the cumulative error values we conservatively set the horizontal and vertical error at 0.1m. This provides an entrainment/transport threshold whereby any movement calculated via the python script exceeding 0.1m is defined as transported. Conversely, values below 0.1m are deemed to be entrained and are not incorporated into any transport distance values.

The transport distance of the tagged boulders is calculated from the coordinate data from each survey which is input to the python script. The summed values for each boulder across all surveys we term the individual boulder transport distance (IBTD).

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2
3 449 The summed IBTD values for each survey we term the cumulative transport distance
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5 450 (CTD), Table 6.
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7

8 451 **RESULTS**

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10
11 452 We report a range of metrics derived from the RFID boulder coordinate data
12
13 453 obtained during successive field surveys. The data presented herein provides an
14
15 454 insight to the feasibility of the methodology. Additionally, we demonstrate the
16
17 455 capability of the method by presenting examples of mobility that occurred during the
18
19 456 field study which further augment the use of RFID's in boulder transport monitoring.
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22 23 457 **Recovery rates**

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25

26 458 A total of 15 field surveys (Bembridge Ledge, 7 and Black Rock, 8) were conducted
27
28 459 between July 2015 and May 2017 to relocate tagged boulders across the two study
29
30 460 sites. We achieved a mean tag recovery rate of 91%, cumulatively recovering 714 of
31
32 461 a possible 782 tagged boulders across all surveys at the two sites. Minimum /
33
34 462 maximum tag recovery rates were 68% / 100% at Bembridge Ledge, and 81% /
35
36 463 100% at Black Rock (Table 6). Reduced tag recovery was attributed to the seasonal
37
38 464 accretion of sediment leading to boulder burial at Bembridge Ledge and
39
40 465 unfavourable and unsafe tidal conditions at Black Rock.
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44 466 **Boulder transport**

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47 467 Once relocated, RFID tag locations were recorded using DGNSS survey equipment.
48
49 468 Successive surveys created a series of coordinates for each of the 104 tagged
50
51 469 boulders. The python script automatically processed the recorded boulder coordinate
52
53 470 data to produce a series of inter-survey transport statistics, including the IBTD (Table
54
55 471 6). We identified 63% of the 104 tagged boulders were transported at least once
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472 ($n=66/104$), i.e. were mobile over distances exceeding 0.1m. Over the study we
473 recorded 164 individual transport events culminating in a total boulder transport
474 distance of 184.6m across the two sites.

475 At Bembridge Ledge 94 transport events were documented amounting to a total CTD
476 of 117.0m. Of that figure, the highest percentage of mobility (42% / 49.3m) occurred
477 between July 2015 and 3rd February 2016. Between these survey dates increased
478 wave activity recorded by the CCO wave buoy occurred between 30th December
479 2015 and 7th January 2016. Peak storm activity occurred on 3rd January 2016, when
480 maximum significant wave heights (H_s) of 3.3m and maximum wave height (H_{max}) of
481 5.4m with a peak wave period of 7.7 seconds were recorded (CCO, 2017b). Surveys
482 at Black Rock on 3rd December 2015 and 6th January 2016 identify boulder transport
483 amounting to 6.9m during this period which coincides with the increased wave
484 activity recorded on the 3rd January 2016. Interestingly, peak storm waves occurred
485 between low water and 2 hours thereafter. The most significant transport distances
486 were recorded in boulders located around low water on the exposed shore platform.
487 This suggests boulder transport is influenced not only by storm wave activity but by
488 tidal state at the time of peak storm intensity which determines where on the profile
489 storm energy is focused. This corresponds with comparable work on the role of tidal
490 state in beach morphodynamics (Kroon and Masselink, 2002; Castelle et al., 2015;
491 Masselink et al., 2016b).

492 At Black Rock, 70 transport events were recorded during the study amounting to a
493 total CTD of 67.6m. Of that figure the highest percentage (41% / 27.7m) occurred
494 between surveys conducted on 19th February and 31st May 2016 coinciding with
495 increased wave energy associated with Storm Katie (28th March 2016). For a period
496 of 6.5 hours H_s values exceeded 2.0m, with a maximum H_s value of 4.2m and H_{max}
of

6.6m being recorded; wave periods ranged between 6.3 - 10 seconds (CCO, 2017b). Conversely, surveys at Bembridge Ledge encompassing this period (17th February - 1st April 2016) identified 13 incidents of mobility covering a distance of 6.2m, only 5% of the total CTD at the site. This disparity is thought to be the result of the southerly wind and wave direction during the storm event (mean: 170°). The southerly aspect of Black Rock being more exposed to the storm opposed to the north-easterly orientation of Bembridge Ledge which was afforded a degree of protection.

Incidents of mobility - Bembridge Ledge

At Bembridge Ledge 76% ($n=38/50$) of the tagged boulders were mobile at least once. IBTD values ranged between 0.1m and 21.5m, mobile boulder mass ranged between an estimated 0.1t - 1.3t (Table 6).

Transport was documented in a boulder weighing approximately 1.2t that had become detached from the platform edge yet remained *in-situ* (Figure 9, inset). It was surveyed on 3rd February 2016 however, the subsequent survey on 17th February 2016 identified transport of 7.2m landward of its previous location (Figure 9). Whilst mobile the boulder was overturned prior to deposition at the foot of the shingle beach where the slope angle increases. Overturning was identified by algal growth on the underside of the boulder and the orientation hole being located below the TIP, as opposed to above, as at the time of tag deployment. The transport event described coincided with increased wave activity associated with Storm Imogen (8th February 2016) when H_s of 2.5m were recorded, with a wave period of 7 seconds. Further storm induced transport totalling 2.9m was recorded for this clast amounting to an IBTD of 10.1m over the 22 month monitoring period.

Insert figure 9.

1
2
3 521 The coordinate data attributed to the aforementioned boulder was used to create a
4
5 522 visual interpretation in ArcGIS which documents spatial and temporal boulder
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7 523 mobility. This was generated from the python script (Figure 10).
8
9

10 524 **Insert figure 10.**
11
12

13 525 **Incidents of mobility - Black Rock** 14 15

16 526 At Black Rock 52% ($n=28/54$) of the tagged boulders were mobile at least once.
17
18 527 IBTD values ranged between 0.1m and 10.1m. Mobile boulder mass ranged
19
20 528 between an estimated 0.1t - 11.9t (Table 6).
21
22

23 529 A boulder located 20m from the platform edge weighing an estimated 5t was tagged
24
25 530 at the commencement of the field campaign. Notably, the clast was not visible on the
26
27 531 CCO aerial imagery captured in August 2013 and is thought to have been displaced
28
29 532 and deposited during the winter storms of 2013 - 2014. The boulder location was
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31 533 recorded on 19th February 2016 identified by the circle in Figure 11a. It was
32
33 534 relocated on 31st May 2016 having been transported 6.4m landward and overturned
34
35 535 prior to deposition, imbricate against an extensive boulder ridge. The transport event
36
37 536 described is thought to be attributed to Storm Katie (27th March 2016) when
38
39 537 maximum H_s was recorded as 4.2m, with a maximum wave period of 12.5 seconds.
40
41 538 Further transport, post Storm Katie, was attributed to wave activity associated with
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43 539 Storm Angus on 20th November 2016, maximum H_s of 4.0m and wave period of 6.8
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45 540 seconds (CCO, 2017b) whereby the boulder was overturned 180° and deposited
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47 541 2.5m seawards from its previously recorded location, circle in Figure 11b.
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52 542 **Insert figure 11.**
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3 543 In both instances boulder transport was impeded by topographic (raised shingle
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5 544 beach at Bembridge Ledge) and morphological (boulder ridge at Black Rock)
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7 545 features. This emphasises the significance of localised morphology in restricting and
8
9 546 controlling boulder transport potential affirming the findings of Pérez-Alberti &
10
11 547 Trenhaile (2015b) and Naylor et al. (2016) who suggest such landforms exert a
12
13 548 degree of control over boulder transport potential.
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16
17 549 **Insert table 6.**
18

19 550 **DISCUSSION**

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22 551 Our proposed methodology, employing RFID tags embedded in an array of boulder-
23
24 552 sized clasts has enabled us to identify and accurately quantify boulder mobility as a
25
26 553 result of contemporary storm activity. Upon completion of the study we achieved a
27
28 554 mean tracer recovery rate of 86% at Bembridge Ledge and 95% Black Rock. Field
29
30 555 data identified periodic boulder mobility resulting from contemporary storm activity
31
32 556 despite the locations relatively low to moderate wave exposure in comparison to
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34 557 previously studied boulder transport sites.
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38 558 **Boulder transport**

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41 559 By establishing an entrainment/transport threshold we can reliably identify transport
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43 560 events and differentiate them from entrainment. Using the TIP we are able to
44
45 561 relocate and record a specific point on each tagged boulder. This allows us to apply
46
47 562 a universal displacement threshold that is applicable to each tagged boulder
48
49 563 regardless of size. This is advantageous over alternative methods applied by Naylor
50
51 564 et al. (2016) as it provides greater precision, particularly for coarser sized clasts,
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54 565 when defining the distance over which a boulder has been transported.
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3 566 The calculated transport data identified Bembridge Ledge exceeded Black Rock in
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5 567 terms of the number of transport events (94 / 70) and the distance over which those
6
7 568 mobile boulders were displaced (117.0m / 67.6m). This is, in part, due to the different
8
9 569 lithologies between the sites. The boulder producing limestone outcrops differ in
10
11 570 terms of the extent of jointing and bed thickness. Owing to the thinner, more
12
13 571 discontinuous lithology at Bembridge Ledge smaller, tabular boulders are produced
14
15 572 which have a lower transport threshold than the larger boulders produced at Black
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17 573 Rock, corroborating the significance of localised geology on boulder production
18
19 574 (Stephenson and Naylor, 2011). In addition, obstructions including a greater number
20
21 575 of detached clasts, irregular substrate and an extensive boulder ridge impede
22
23 576 landward transport, particularly at Black Rock, resulting in a higher number of
24
25 577 topographically constrained deposits (Trenhaile, 2016). The substrate varies
26
27 578 between, and within sites. Bembridge Ledge is generally characterised by a
28
29 579 smoother platform surface which promotes clast mobility. Comparatively, Black Rock
30
31 580 has a larger area of pitted terrain which traps boulders impeding landward transport.
32
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35
36 581 The close proximity of the recorded wave data to the study sites allows us to infer
37
38 582 the likely agent of transport and identify the wave conditions under which boulder
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40 583 mobility occurred. Furthermore, by incorporating a boulder orientation indicator we
41
42 584 were able to identify 22 incidents of boulders being overturned during transport, 11 at
43
44 585 each site; 68% of these occurring between July 2015 and 19th February 2016. This
45
46 586 constitutes overturning in 13% of the recorded movements suggesting it is significant
47
48 587 but relatively infrequent. Understanding how boulders respond to hydrodynamic
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50 588 conditions under which they have been transported is of considerable significance
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52 589 when applying numerical models to hindcast wave characteristics such as height
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590 and/or velocity (Goto et al., 2009; Nandasena et al., 2011a; Nandasena et al.,
591 2011b).

592 **Addressing limitations and uncertainties**

593 Prior to the commencement of the study we had reservations regarding the suitability
594 of the RFID tagging technology to monitor boulder transport. Paris et al. (2011) and
595 Naylor et al. (2016) describe a number of potential issues with the technique which
596 we are now able to allay.

597 *(1) Would RFID tags withstand the harsh coastal conditions and remain operational*
598 *throughout the study?*

599 Despite the successful use of RFID tags in long term coastal sediment monitoring
600 (Allan et al., 2006; Dolphin et al., 2016), and our pre-deployment sealant checks,
601 concerns remained regarding how the unfavourable conditions and prolonged
602 exposure may affect tag operation and/or retention within the boulder. However, we
603 experienced no issues with tag functionality during the survey period. With the
604 exception of 5 lost tags, which we were able to replace, the remaining 99 tags
605 remained fully operational and traceable throughout the study. Tag loss was
606 attributed to poor sealant adhesion, perhaps as a result of insufficient curing times.
607 We have since trialled a vinylester chemical anchor resin (ProVenture PRO V200)
608 opposed to the widely available silicone sealant. The resin has performed well in
609 laboratory tests involving wetting and drying in saltwater solutions and has since
610 been deployed in the field to replace the lost tags and to date has functioned well.

611 *(2) How effective would the RFID equipment be in relocating tagged boulders,*
612 *particularly buried clasts?*

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3 613 The RFID equipment performed well in the field. Throughout the survey period it was
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5 614 apparent that concerns over relocating tagged boulders related to environmental
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7 615 factors beyond our control rather than limitations with the equipment and/or
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9 616 methodology. At Bembridge Ledge we frequently encountered incidents of burial
10
11 617 following the accretion of sand and shingle. However, we were able to detect buried
12
13 618 clasts up to a depth of 0.4m. Owing to the extent of burial and time constraints it was
14
15 619 not always possible to excavate the overlying sediment; additional manpower may
16
17 620 have offered increased opportunity to excavate buried clasts. Black Rock recovery
18
19 621 rates were reduced as a result of unfavourable tidal states due to the low elevation of
20
21 622 an area of the field site in proximity to mean low water. On occasion this created
22
23 623 hazardous surveying conditions rendering a number of boulders inaccessible.
24
25 624 Greater consideration of tagged boulder location relative to mean low water may
26
27 625 have reduced the likelihood of such an occurrence and improved rates of tag
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29 626 recovery.
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33
34 627 *(3) Would clast breakdown impact on recovery rates?*
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36

37 628 We documented clast breakage in one of the 104 tagged boulders. The limited
38
39 629 mobility of the clast (IBTD - 0.7m) suggests breakdown was not attributed to impact
40
41 630 during transport but due to the inherent weaknesses within the boulder; breakdown
42
43 631 occurred along a number of structural joints.
44
45

46 632 There was no evidence to suggest drilling for tag insertion initiated boulder
47
48 633 breakdown, as encountered by Cassel et al. (2017) as we took care to avoid drilling
49
50 634 through any discontinuity planes. This suggests clasts exhibiting structural joints
51
52 635 should be avoided when selecting boulders to tag.
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636 *(4) Would it be possible to relocate and document the tagged boulders within a*
637 *single tidal window?*

638 The 'stake-out survey' functionality on the DGNSS hastened the boulder recovery
639 process allowing us to maximising the time available in the field. It enabled us to
640 recover tagged boulders within our 0.1km² survey area with greater ease than
641 adopting a random search approach. Had we not incorporated this feature into the
642 methodology our ability to relocate tagged boulders would have been compromised.

643 The overall performance of RFID tagged boulders has been encouraging. Coupled
644 with our proposed methodology they have provided new data on the extent to which
645 boulders are transported in the intertidal zone by contemporary storm events.
646 Additionally, they have provided an insight to the mode of transport when displaced
647 through the addition of an orientation indicator. The success of this deployment has
648 enabled the study to continue into a third year. It is anticipated that with regular
649 monitoring and maintenance of the tagged boulder array the study can continue
650 indefinitely ensuring this will be the first known long-term study using RFID tagging to
651 quantify boulder transport resulting from storm activity.

652 **CONCLUSION**

653 Drawing upon previous RFID transport studies and the findings presented here we
654 assert that RFID technology and our methodology are an efficient and effective
655 means of monitoring and quantifying the response of intertidal boulders to
656 contemporary storm events. Using RFID tagged boulders we have been able to
657 identify transport episodes resulting from periods of increased wave activity. The
658 collated data has enabled the production of vector diagrams via a python script
659 which detail the distance and direction of boulder transport.

660 The existing literature relating to boulder transport focuses on coastlines subjected to
 661 considerable storm induced wave energy (Cox et al., 2012; Etienne and Paris, 2010;
 662 Goto et al., 2011; Knight and Burningham, 2011). Significantly, the RFID
 663 methodology has enabled us to identify boulder detachment, transport and
 664 overturning at a relatively sheltered, fetch limited intertidal site subjected to moderate
 665 wave conditions. This demonstrates that contemporary storm events have a far
 666 greater ability to mobilise boulders than had previously been realised.

667 To further augment the methodology we recommend additional deployments in more
 668 exposed settings with larger boulders subjected to higher wave energy regimes.

669 Furthermore, the methodology could be extended to use in the supratidal zone for
 670 the long-term monitoring of cliff-top boulder deposits such as those identified by
 671 Autret et al. (2018) and Cox et al. (2018). This would provide greater understanding
 672 on the impact, ability and associated risk of extreme wave events to mobilise
 673 boulders which may require a reassessment of our current understanding of storm
 674 wave hydrodynamics.

675 The methodology can also be utilised with emerging technologies, such as UAV
 676 monitoring (Pérez-Alberti & Trenhaile, 2015a, 2015b; Biolchi et al., 2016) to provide
 677 greater spatial resolution on the mechanisms that facilitate the transport of intertidal
 678 boulders. Furthermore, deployment in coastal revetment blocks could help mitigate
 679 against damage or loss to coastal defence engineering works.

680 This study has highlighted the feasibility of both the RFID technology and our
 681 methodology to provide coastal researchers with a new field technique to accurately
 682 assess boulder mobility. By adopting the methodology the opportunity exists for
 683 researchers to clearly define and quantify boulder transport pathways and provide

684 clarity on the impacts and responses of contemporary storm events in shaping rocky
685 coastal landforms.

686 **Footnote - Permissions**

687 Under the Marine Licensing (Exempted Activities) Order 2011 the deployment of
688 scientific equipment, including sediment tracers such as RFID's is deemed a
689 Category 2 exemption and may not require a marine license (Marine Licensing
690 Order, 2011). However, owing to the sensitive nature of the study site we obtained
691 an exemption from the Marine Management Organisation (MMO) and sort approval
692 from Natural England prior to tag deployment.

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702

703 **References**

704 Allan JC, Hart R, Tranquili JV. 2006. The use of Passive Integrated Transponder
705 (PIT) tags to trace cobble transport in a mixed sand-and-gravel beach on the high-

- energy Oregon coast, USA. *Marine Geology* 232: 63-86. DOI:
10.1016/j.margeo.2006.07.005
- Aluf O. 2017. RFID Antennas Systems Descriptions and Analysis. In *Microwave RF Antennas and Circuits 2017*: 1-15. Springer International Publishing. DOI:
10.1007/978-3-319-45427-6_1
- Armenteros I, Daley B. 1998. Pedogenic modification and structure evolution in palustrine facies as exemplified by the Bembridge Limestone (Late Eocene) of the Isle of Wight, southern England. *Sedimentary Geology* 119(3): 275-95. DOI:
10.1016/S0037-0738(98)00067-0
- Autret R, Dodet G, Fichaut B, Suanez S, David L, Leckler F, Ardhuin F, Ammann J, Grandjean P, Allemand P, Filipot JF. 2016. A comprehensive hydro-geomorphic study of cliff-top storm deposits on Banneg Island during winter 2013–2014. *Marine Geology* 382: 37-55. DOI: 10.1016/j.margeo.2016.09.014
- Autret R, Dodet G, Suanez S, Roudaut G and Fichaut B. 2018. Long-term variability of supratidal coastal boulder activation in Brittany (France). *Geomorphology* 304: 184-200. DOI:org/10.1016/j.geomorph.2017.12.028
- Barbano, M. S., Pirrotta, C., & Gerardi, F. (2010). Large boulders along the south-eastern Ionian coast of Sicily: storm or tsunami deposits? *Marine Geology*, 275(1), 140-154.
- Barbano MS, Pirrotta C, Gerardi F. 2010. Large boulders along the south-eastern Ionian coast of Sicily: storm or tsunami deposits? *Marine Geology* 275(1) :140-54. DOI: 10.1016/j.margeo.2010.05.005

- Beniston M, Stephenson DB, Christensen OB, Ferro CA, Frei C, Goyette S, Halsnaes K, Holt T, Jylhä K, Koffi B, Palutikof J. 2007. Future extreme events in European climate: an exploration of regional climate model projections. *Climatic Change* 81(1):71-95. DOI: 10.1007/s10584-006-9226-z
- Biolchi S, Furlani S, Antonioli F, Baldassini N, Deguara JC, Devoto S, Di Stefano A, Evans J, Gambin T, Gauci R, Mastronuzzi G. 2016. Boulder accumulations related to extreme wave events on the eastern coast of Malta. *Natural Hazards and Earth System Sciences* 16: 737-56.
- Black KS, Athey S, Wilson P, Evans D. 2007. The use of particle tracking in sediment transport studies: a review. Geological Society, London, Special Publications 274(1): 73-91. DOI: 10.1144/GSL.SP.2007.274.01.09
- Blair TC, McPherson JG. 1999. Grain-size and textural classification of coarse sedimentary particles. *Journal of Sedimentary Research* 69(1): 6-19.
- Bray MJ, Workman M, Smith J, Pope D. 1996. Field measurements of shingle transport using electronic tracers. In Proc. 31st MAFF Conf. River and Coastal Engineers 1996 (pp. 10-4).
- Brayne RP. 2015. The Relationship between Nearshore Wave Conditions and Coarse Clastic Beach Dynamics. Unpublished PhD Thesis, Exeter University.
- Cassel M, Piégay H, Lavé J. 2017. Effects of transport and insertion of radio frequency identification (RFID) transponders on resistance and shape of natural and synthetic pebbles: applications for riverine and coastal bedload tracking. *Earth Surface Processes and Landforms* 42(3): 399-413. DOI: 10.1002/esp.3989

- Castelle B, Marieu V, Bujan S, Splinter KD, Robinet A, Sénéchal N, Ferreira S. 2015. Impact of the winter 2013–2014 series of severe Western Europe storms on a double-barred sandy coast: Beach and dune erosion and megacusp embayments. *Geomorphology*, 238, 135-148. DOI: 10.1016/j.geomorph.2015.03.006
- Channel Coast Observatory, CCO. 2017a. Regional Coastal Monitoring Programmes Sandown Bay. [Online]. Available at: https://www.channelcoast.org/data_management/real_time_data/charts/?chart=80&tab=info&disp_option= [Accessed: 20 May 2017].
- Channel Coast Observatory, CCO. 2017b. Data management catalogue. [Online]. Available at: http://www.channelcoast.org/data_management/online_data_catalogue/metadata/search/index2.php [Accessed: 28 July 2017].
- Chapuis M, Bright CJ, Hufnagel J, MacVicar B. 2014. Detection ranges and uncertainty of passive Radio Frequency Identification (RFID) transponders for sediment tracking in gravel rivers and coastal environments. *Earth Surface Processes and Landforms* 39(15): 2109-20. DOI: 10.1002/esp.3620
- Ciavola P, Castiglione E. 2009. Sediment dynamics of mixed sand and gravel beaches at short time-scales. *Journal of Coastal Research*. Special Issue No. 56. Proceedings of the 10th International Coastal Symposium 2009, Vol. II: 1751-1755.
- Cox R, Zentner DB, Kirchner BJ, Cook MS. 2012. Boulder ridges on the Aran Islands (Ireland): recent movements caused by storm waves, not tsunamis. *The Journal of Geology* 120(3): 249-272. DOI: <https://doi.org/10.1086/664787>

- 792 Cox R, Jahn KL, Watkins OG, Cox P. 2018. Extraordinary boulder transport by storm
793 waves (West of Ireland, winter 2013–2014), and criteria for analysing coastal boulder
794 deposits. *Earth-Science Reviews* 177: 623–636. DOI: 0.1016/j.earscirev.2017.12.014
- 795 Curtiss GM, Osborne PD, Horner-Devine AR. 2009. Seasonal patterns of coarse
796 sediment transport on a mixed sand and gravel beach due to vessel wakes, wind
797 waves, and tidal currents. *Marine Geology* 259(1): 73–85. DOI:
798 10.1016/j.margeo.2008.12.009
- 799 Daley B, Edwards N. 1990. The Bembridge Limestone (Late Eocene), Isle of Wight,
800 southern England: a stratigraphical revision. *Tertiary Research* 12(2): 51–64.
- 801 Dickson ME, Kench PS, Kantor MS. 2011. Longshore transport of cobbles on a
802 mixed sand and gravel beach, southern Hawke Bay, New Zealand. *Marine Geology*
803 287(1): 31–42. DOI: 10.1016/j.margeo.2011.06.009
- 804 Dolphin T, Lee J, Phillips R, Taylor CJ, Dyer KR. 2016. Velocity of RFID Tagged
805 Gravel in a Non-uniform Longshore Transport System. *Journal of Coastal Research*
806 75(sp1): 363–7. DOI: 10.2112/SI75-073.1
- 807 Engel M, May SM. 2012. Bonaire's boulder fields revisited: evidence for Holocene
808 tsunami impact on the Leeward Antilles. *Quaternary Science Reviews* 54:126–141.
809 DOI: 10.1016/j.quascirev.2011.12.011
- 810 Easterling DR, Meehl GA, Parmesan C, Changnon SA, Karl TR, Mearns LO. 2000.
811 Climate extremes: observations, modeling, and impacts. *Science*, 289 (5487), 2068–
812 2074. DOI: 10.1126/science.289.5487.2068

813 Etienne S, Buckley M, Paris R, Nandasena AK, Clark K, Strotz L, Chagué-Goff C,
 814 Goff J, Richmond B. 2011. The use of boulders for characterising past tsunamis:
 815 lessons from the 2004 Indian Ocean and 2009 South Pacific tsunamis. *Earth-*
 816 *Science Reviews* 107(1): 76-90. DOI: 10.1016/j.earscirev.2010.12.006
 817 Etienne S, Paris R. 2010. Boulder accumulations related to storms on the south
 818 coast of the Reykjanes Peninsula (Iceland). *Geomorphology* 114(1): 55-70. DOI:
 819 10.1016/j.geomorph.2009.02.008
 820 Fichaut B, Suanez S. 2011. Quarrying, transport and deposition of cliff-top storm
 821 deposits during extreme events: Banneg Island, Brittany. *Marine Geology* 283(1): 36-
 822 55. DOI: 10.1016/j.margeo.2010.11.003
 823 Goto K, Okada K, Imamura F. 2009. Characteristics and hydrodynamics of boulders
 824 transported by storm waves at Kudaka Island, Japan. *Marine Geology* 262(1): 14-24.
 825 DOI: 10.1016/j.margeo.2009.03.001
 826 Goto K, Miyagi K, Kawana T, Takahashi J, Imamura F. 2011. Emplacement and
 827 movement of boulders by known storm waves—field evidence from the Okinawa
 828 Islands, Japan. *Marine Geology* 283(1): 66-78. DOI: 10.1016/j.margeo.2010.09.007
 829 Goto K, Sugawara D, Ikema S, Miyagi T. 2012. Sedimentary processes associated
 830 with sand and boulder deposits formed by the 2011 Tohoku-oki tsunami at
 831 Sabusawa Island, Japan. *Sedimentary Geology* 282: 188-98. DOI:
 832 10.1016/j.sedgeo.2012.03.017

- 833 Hall AM. 2011. Storm wave currents, boulder movement and shore platform
834 development: a case study from East Lothian, Scotland. *Marine Geology* 283(1): 98-
835 105. DOI: 10.1016/j.margeo.2010.10.024
- 836 Han M, Yang DY, Yu J, Kim JW. 2017. Typhoon Impact on a Pure Gravel Beach as
837 Assessed through Gravel Movement and Topographic Change at Yeocha Beach,
838 South Coast of Korea. *Journal of Coastal Research* 33(4): 889 – 906. DOI:
839 10.2112/JCOASTRES-D-16-00104.1
- 840 Imamura F, Goto K, Ohkubo S. 2008. A numerical model for the transport of a
841 boulder by tsunami. *Journal of Geophysical Research: Oceans*, 113(C1). DOI:
842 10.1029/2007JC004170
- 843 Jolliffe IP. 1964. An experiment designed to compare the relative rates of movement
844 of different sizes of beach pebble. *Proceedings of the Geologists' Association* 75(1):
845 77-86. DOI: 10.1016/S0016-7878(64)80012-2
- 846 Kaplan E, Hegarty C. 2005. *Understanding GPS: principles and applications*. Artech
847 House.
- 848 Kidson C, Carr AP, Smith DB. 1958. Further experiments using radioactive methods
849 to detect the movement of shingle over the sea bed and alongshore. *The*
850 *Geographical Journal* 124(2):210-8. DOI: 10.2307/1790248
- 851 Knight J, Burningham H. 2011. Boulder dynamics on an Atlantic-facing rock
852 coastline, northwest Ireland. *Marine Geology*, 283 (1-4). 56-65.

- 853 Knight J, Burningham H, Barrett-Mold C. 2009. The geomorphology and controls on
854 development of a boulder-strewn rock platform, NW Ireland. *Journal of Coastal*
855 *Research* 1:1646-1650.
- 856 Kroon A, Masselink G. 2002. Morphodynamics of intertidal bar morphology on a
857 macrotidal beach under low-energy wave conditions, North Lincolnshire,
858 England. *Marine Geology*, 190(3-4), 591-608. DOI: 10.1016/S0025-3227(02)00475-9
- 859 Lamarre H, MacVicar B, Roy AG. 2005. Using passive integrated transponder (PIT)
860 tags to investigate sediment transport in gravel-bed rivers. *Journal of Sedimentary*
861 *Research* 75(4): 736-741. DOI: 10.2110/jsr.2005.059
- 862 Lee MW, Bray M, Workman M, Collins MB, Pope D. 2000. Coastal shingle tracing: a
863 case study using the Electronic Tracer System (ETS). *Tracers in Geomorphology*:
864 413-35.
- 865 Lee MW, Sear DA, Atkinson PM, Collins MB, Oakey RJ. 2007. Number of tracers
866 required for the measurement of longshore transport distance on a shingle beach.
867 *Marine Geology* 240(1): 57-63. DOI: 10.1016/j.margeo.2007.02.010
- 868 Liébault F, Bellot H, Chapuis M, Klotz S, Deschâtres M. 2012. Bedload tracing in a
869 high-sediment-load mountain stream. *Earth Surface Processes and Landforms*
870 37(4): 385-99. DOI: 10.1002/esp.2245
- 871 Marine Licensing (Exempted Activities) Order 2011 (SI 2011/No. 409). Available at:
872 <http://www.legislation.gov.uk/uksi/2011/409/part/3/made> [Accessed 2nd November,
873 2017].

- 874 Masselink G, Castelle B, Scott T, Dodet G, Suanez S, Jackson D, Floc'h F. 2016a.
875 Extreme wave activity during 2013/2014 winter and morphological impacts along the
876 Atlantic coast of Europe. *Geophysical Research Letters* 43(5): 2135-43. DOI:
877 10.1002/2015GL067492
- 878 Masselink G, Scott T, Poate T, Russell P, Davidson M, Conley D. 2016b. The
879 extreme 2013/2014 winter storms: hydrodynamic forcing and coastal response along
880 the southwest coast of England. *Earth Surface Processes and Landforms*, 41(3),
881 378-391. DOI: 10.1002/esp.3836
- 882 Mastronuzzi G, Sansò P. 2004. Large boulder accumulations by extreme waves
883 along the Adriatic coast of southern Apulia (Italy). *Quaternary International*, 120(1).
884 173-184.
- 885 Miller IM, Warrick JA. 2012. Measuring sediment transport and bed disturbance with
886 tracers on a mixed beach. *Marine Geology* 299: 1-7. DOI:
887 10.1016/j.margeo.2012.01.002
- 888 Miller IM, Warrick JA, Morgan C. 2011. Observations of coarse sediment movements
889 on the mixed beach of the Elwha Delta, Washington. *Marine Geology* 282(3): 201-
890 14. DOI: 10.1016/j.margeo.2011.02.012
- 891 Moses CA. 2014. The rock coast of the British Isles: shore platforms. *Geological*
892 *Society, London, Memoirs*. 40(1): 39-56. DOI: 10.1144/M40.4
- 893 Mottershead D, Bray M, Soar P, Farres PJ. 2014. Extreme wave events in the
894 central Mediterranean: Geomorphic evidence of tsunamis on the Maltese Islands.
895 *Zeitschrift für Geomorphologie* 58(3): 385-411. DOI: 10.1127/0372-8854/2014/0129

- 896 Müller G, Wolters G, Cooker MJ. 2003. Characteristics of pressure pulses
897 propagating through water-filled cracks. *Coastal Engineering*. 1;49 (1-2): 83-98. DOI:
898 10.1016/S0378-3839(03)00048-6
- 899 Nandasena NA, Paris R, Tanaka N. 2011a. Numerical assessment of boulder
900 transport by the 2004 Indian ocean tsunami in Lhok Nga, West Banda Aceh
901 (Sumatra, Indonesia). *Computers & Geosciences* 37(9): 1391-1399. DOI:
902 10.1016/j.cageo.2011.02.001
- 903 Nandasena NA, Paris R, Tanaka N. 2011b. Reassessment of hydrodynamic
904 equations: minimum flow velocity to initiate boulder transport by high energy events
905 (storms, tsunamis). *Marine Geology* 281(1): 70-84. DOI:
906 10.1016/j.margeo.2011.02.005
- 907 Nandasena NA, Tanaka N, Sasaki Y, Osada M. 2013. Boulder transport by the 2011
908 Great East Japan tsunami: Comprehensive field observations and whether model
909 predictions? *Marine Geology* 346: 292-309. DOI: 10.1016/j.margeo.2013.09.015
- 910 Nathan Bradley D, Tucker GE. 2012. Measuring gravel transport and dispersion in a
911 mountain river using passive radio tracers. *Earth Surface Processes and Landforms*
912 37(10): 1034-1045. DOI: 10.1002/esp.3223
- 913 Naylor LA, Stephenson WJ, Smith H, Way O, Mendelssohn J, Cowley A. 2016.
914 Geomorphological control on boulder transport and coastal erosion before, during
915 and after an extreme extra-tropical cyclone. *Earth Surface Processes and Landforms*
916 41(5): 685-700. DOI: 10.1002/esp.3900

- 1
2
3 917 Naylor LA, Stephenson WJ, Trenhaile AS. 2010. Rock coast geomorphology: recent
4
5 918 advances and future research directions. *Geomorphology* 114(1):3-11. DOI:
6
7 919 10.1016/j.geomorph.2009.02.004
8
9
10 920 Nichols MH. 2004. A radio frequency identification system for monitoring coarse
11
12 921 sediment particle displacement. *Applied Engineering in Agriculture* 20(6): 783-787.
13
14 922 DOI: 10.13031/2013.17727
15
16
17
18 923 Nordstrom KF, Jackson NL. 1993. Distribution of surface pebbles with changes in
19
20 924 wave energy on a sandy estuarine beach. *Journal of Sedimentary Research* 63(6):
21
22 925 1152-1159.
23
24
25 926 Noormets R, Crook KA and Felton EA. 2004. Sedimentology of rocky shorelines: 3.:
26
27 927 hydrodynamics of megaclast emplacement and transport on a shore platform, Oahu,
28
29 928 Hawaii. *Sedimentary Geology*, 172(1-2). 41-65.
30
31
32
33 929 Nott J. 2003a. Waves, coastal boulder deposits and the importance of the pre-
34
35 930 transport setting. *Earth and Planetary Science Letters*, 210(1-2). 269-276. DOI:
36
37 931 10.1016/S0012-821X(03)00104-3
38
39
40 932 Nott J. 2003b. Tsunami or storm waves?: Determining the origin of a spectacular
41
42 933 field of wave emplaced boulders using numerical storm surge and wave models and
43
44 934 hydrodynamic transport equations. *Journal of Coastal Research*: 348-356.
45
46
47
48 935 Ordnance Survey. 2017a. Accuracy [Online]. Available at:
49
50 936 [https://www.ordnancesurvey.co.uk/business-and-government/help-and-](https://www.ordnancesurvey.co.uk/business-and-government/help-and-support/navigation-technology/os-net/accuracy.html)
51
52 937 [support/navigation-technology/os-net/accuracy.html](https://www.ordnancesurvey.co.uk/business-and-government/help-and-support/navigation-technology/os-net/accuracy.html) [Accessed: 16 May 2017a].
53
54
55
56
57
58
59
60

- 1
2
3 938 Ordnance Survey. 2017b. OS-Net - Ordnance Survey [Online]. Available at:
4
5 939 <https://www.ordnancesurvey.co.uk/gps/os-net-rinex-data/> [Accessed: 16 May 2017c].
6
7
8 940 Oregon RFID. 2017. HDX Long Range Readers [Online]. Available at:
9
10 941 [https://www.oregonrfid.com/index.php?main_page=product_info&cPath=1&products](https://www.oregonrfid.com/index.php?main_page=product_info&cPath=1&products_id=6&zenid=osn1jjl3mico7k8l9j0q5n3ho5)
11
12 942 [_id=6&zenid=osn1jjl3mico7k8l9j0q5n3ho5](https://www.oregonrfid.com/index.php?main_page=product_info&cPath=1&products_id=6&zenid=osn1jjl3mico7k8l9j0q5n3ho5) [Accessed: 12 September 2017].
13
14
15
16 943 Osborne PD. 2005. Transport of gravel and cobble on a mixed-sediment inner bank
17
18 944 shoreline of a large inlet, Grays Harbor, Washington. *Marine Geology* 224(1): 145-
19
20 945 56. DOI: 10.1016/j.margeo.2005.08.004
21
22
23 946 Osborne PD, Macdonald N, Curtiss G. 2011. Measurements and Modeling of Gravel
24
25 947 Transport under Wind Waves, Vessel-Generated Waves, and Tidal Currents. *Journal*
26
27 948 *of Coastal Research*. Special Issue 59: 165-172. DOI: 10.2112/SI59-017.1
28
29
30
31 949 Paris R, Naylor LA, Stephenson WJ. 2011. Boulders as a signature of storms on
32
33 950 rock coasts. *Marine Geology* 283 (1-4): 1–11. DOI: 10.1016/j.margeo.2011.03.016
34
35
36 951 Pérez-Alberti A, Trenhaile AS. 2015a. An initial evaluation of drone-based monitoring
37
38 952 of boulder beaches in Galicia, north-western Spain. *Earth Surface Processes and*
39
40 953 *Landforms* 40(1): 105-111. DOI: 10.1002/esp.3654
41
42
43
44 954 Pérez-Alberti A, Trenhaile AS. 2015b. Clast mobility within boulder beaches over two
45
46 955 winters in Galicia, northwestern Spain. *Geomorphology* 248: 411-426. DOI:
47
48 956 10.1016/j.geomorph.2015.08.001
49
50
51
52 957 Russell RC. 1960. The use of fluorescent tracers for the measurement of littoral drift.
53
54 958 *Coastal Engineering Proceedings* 1(7): 24. DOI: 10.9753/icce.v7.24
55
56
57
58
59
60

- 959 Schaefer M, Woodyer T. 2015. Assessing absolute and relative accuracy of
960 recreation-grade and mobile phone GNSS devices: a method for informing device
961 choice. *Area* 47(2): 185-196. DOI: 10.1111/area.12172
- 962 Scheffers, A., Scheffers, S., Kelletat, D., & Browne, T. (2009). Wave-emplaced
963 coarse debris and megaclasts in Ireland and Scotland: boulder transport in a high-
964 energy littoral environment. *The Journal of Geology*, 117(5), 553-573. DOI:
965 10.1086/600865
- 966 Sear DA, Lee MW, Oakley RJ, Carling PA, Collins MB. 2000. Coarse sediment
967 tracing technology in littoral and fluvial environments a review. *Tracers in*
968 *Geomorphology*, 21-55.
- 969 Shah-hosseini M, Morhange C, Beni AN, Marriner N, Lahijani H, Hamzeh M,
970 Sabatier F. 2011. Coastal boulders as evidence for high-energy waves on the Iranian
971 coast of Makran. *Marine Geology* 290(1): 17-28. DOI: 10.1016/j.margeo.2011.10.003
- 972 Sousa WP. 1979. Disturbance in marine intertidal boulder fields: the nonequilibrium
973 maintenance of species diversity. *Ecology*, 60(6), 1225-1239.
974 DOI:org/10.2307/1936969
- 975 Spiske M, Bahlburg H. 2011. A quasi-experimental setting of coarse clast transport
976 by the 2010 Chile tsunami (Bucalemu, Central Chile). *Marine Geology*, 289(1-4), 72-
977 85. DOI: 10.1016/j.margeo.2011.09.007
- 978 Steers JA, Smith DB. 1956. Detection of movement of pebbles on the sea floor by
979 radioactive methods. *The Geographical Journal* 122(3): 343-345.

- 1
2
3 980 Stephenson WJ, Abazović A. 2016. Measuring Coastal Boulder Movement Under
4
5 981 Waves Using Tri-Axial Accelerometers. *Journal of Coastal Research*, 75(sp1), 607-
6
7 982 611. DOI: 10.2112/SI75-122.1
8
9
10 983 Stephenson WJ, Kirk RM. 2000. Development of shore platforms on Kaikoura
11
12 984 Peninsula, South Island, New Zealand: Part one: the role of waves. *Geomorphology*
13
14 985 32 (1-2): 21-41. DOI: 10.1016/S0169-555X(99)00061-6
15
16
17
18 986 Stephenson WJ, Naylor LA. 2011. Geological controls on boulder production in a
19
20 987 rock coast setting: insights from South Wales, UK. *Marine Geology* 283(1): 12-24.
21
22 988 DOI: 10.1016/j.margeo.2010.07.001
23
24
25
26 989 Sunamura, T. 1992. *Geomorphology of rocky coasts* (Vol. 3). John Wiley & Son Ltd.
27
28
29 990 Switzer AD, Burston JM. 2010. Competing mechanisms for boulder deposition on the
30
31 991 southeast Australian coast. *Geomorphology*, 114(1-2), 42-54. DOI:
32
33 992 10.1016/j.geomorph.2009.02.009
34
35
36 993 Topcon. 2017. HiPer V - Topcon Positioning Systems, Inc. [Online]. Available at:
37
38 994 <https://www.topconpositioning.com/gnss/integrated-gnss-receivers/hiper-v>
39
40 995 [Accessed: 16 May 2017b].
41
42
43 996 Trenhaile A. 2002. Rock coasts, with particular emphasis on shore platforms.
44
45 997 *Geomorphology*, 48(1-3), 7-22. DOI: 10.1016/S0169-555X(02)00173-3
46
47
48
49 998 Trenhaile A. 2016. Rocky coasts - their role as depositional environments. *Earth-*
50
51 999 *Science Reviews* 159:1-13. DOI: 10.1016/j.earscirev.2016.05.001
52
53
54 1000 Van Sickle J. 2008. *GPS for land surveyors*. CRC Press.
55
56
57
58
59
60

- 1
2
3 1001 Want R. 2006. An introduction to RFID technology. IEEE Pervasive Computing, 5(1),
4
5 1002 25-33. DOI: 10.1109/MPRV.2006.2
6
7
8 1003 Wright P, Cross JS, Webber NB. 1978. Aluminium pebbles: A new type of tracer for
9
10 1004 flint and chert pebble beaches. Marine Geology 27(1-2): 9-17. DOI: 10.1016/0025-
11
12 1005 3227(78)90069-5
13
14
15 1006 Zingg T. 1935. Beitrag zur Schotteranalyse. Schweizerische Mineralogische und
16
17 1007 Petrographische Mitteilungen 15, 39–140. DOI: 10.3929/ethz-a-000103455
18
19
20
21 1008
22
23
24 1009
25
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42 1015 **TABLES**
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Table 1. Littoral tracer studies of coarse sediment reporting the selected tracer technique, duration of study and rate of recovery.

Authors & date	Tracer method/technique	Particle size (after Blair & McPherson, 1999)	No. of deployed tracers	Study duration	Reported recovery rate
Kidson et al., 1958	Radioactive	Size not specified - pebbles	2000	6 weeks	~5%
Jolliffe, 1964	Artificial (concrete) & painted	Coarse pebbles / fine cobbles	2500	4.5 days	58%
Nordstrom & Jackson, 1993	Painted	Fine / coarse pebbles	8.9 kg	29 days	6% (0.53 kg)
Ciavola & Castiglione, 2009	Painted	Cobbles (>64mm)	35.1 kg	4 days	30% (10.5 kg)
Naylor et al., 2016	Painted and numbered	Coarse cobbles - fine / medium boulders	48	4 days	81%
Wright et al, 1978	Aluminium	Very coarse pebbles	75	17 days	61%
Bray et al., 1996	Aluminium & Electronic	34 - 65mm: very coarse pebbles	246 & 139 respectively	6 weeks	47-96% & 80-100% respectively
Osborne, 2005	Magnetic	Intermediate axis between 19-108mm: coarse pebbles / fine cobbles	90	2 months	93%
Allan et al., 2006	RFID	Mode value 90.5mm: fine cobbles	400	17 months	90% after 8 months 18% after 17 months
Curtiss et al., 2009	RFID	23mm: coarse pebbles	96	14 months	>80% throughout survey
Dickson et al., 2011	RFID	Minimum long and short axes of 60 mm and 30 mm respectively	180	8 months	0-30%
Miller & Warwick., 2012	RFID	64-128mm: fine cobbles	54	24 hours	93-100%
Dolphin et al., 2016	RFID	Size not specified: gravel	940	3 years	78% on completion
Han et al., 2017	RFID	64mm: very coarse pebbles / fine cobbles	200	2 days	33%

Table 2. The effect of tag approach direction on detection range; all values expressed in metres.

Tag approach	Mean detection range (m)					Mean	Min. range	Max. range	Std deviation
	Tag 1	Tag 2	Tag 3	Tag 4	Tag 5				
North	0.78	0.78	0.78	0.78	0.76	0.77	0.72	0.84	0.03
East	0.42	0.44	0.43	0.43	0.42	0.43	0.36	0.5	0.03
South	0.61	0.62	0.62	0.63	0.62	0.62	0.56	0.69	0.03
West	0.35	0.34	0.35	0.34	0.34	0.34	0.29	0.41	0.03

Table 3. Particle size and shape of indigenous and tagged boulders, mean boulder size classifications are based on the length of the intermediate axis.

		Bembridge Ledge	Black Rock
Size	Mean indigenous boulder size (m)	0.76	0.84
	Mean tagged boulder size (m)	0.78	0.82
Shape (Zingg, 1935)	Disc (% indigenous / tagged)	(65 / 66)	(49 / 46)
	Blade (% indigenous / tagged)	(32 / 30)	(19 / 15)
	Rod (% indigenous / tagged)	(1 / 2)	(13 / 11)
	Sphere (% indigenous / tagged)	(2 / 2)	(19 / 28)

1025 Table 4. RFID tagged morphological boulder zones, pre-transport setting and
 1026 description; Bembridge Ledge (BL) and Black Rock (BR).

Morphological boulder zones	Pre-transport setting	Description	Number (BL / BR)	Figure
Located on the seaward side of the shore platform.	Platform edge (detached)	Boulders located at the edge of the shore platform which are fully detached and awaiting transport. The tagged clasts located here are impeded in their transport potential by the raised shore platform edge.	13 / 3	4 (1)
Located at the shore platform edge.	Platform edge (joint bound)	Described by Nott (2003a) as joint bound blocks. The geologically discontinuous lithology at Bembridge creates angular blocks at the platform edge. These blocks may, or may not, be fully detached from the platform edge being constrained on one or more sides by the surrounding strata.	4 / 2	6 & 9 (inset)
Located on the shore platform (limited transport potential owing to local topography and/or morphology).	Platform top (constrained)	Boulders deposited on the platform, the transport of which is considered to be restricted by local topography and/or morphological features, i.e., positioned in a depression or imbricate against a rock feature (scarp) or other boulder/s (Trenhaile 2016).	18 / 25	11a
Located on the shore platform (greater transport potential owing to local topography and/or morphology).	Platform top (unconstrained)	Boulders deposited on the platform, further transport is unhindered by local topography and/or morphological features (Trenhaile 2016).	15 / 24	7

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Table 5. Details the suggested boulder characteristics that should be recorded at the time of tag insertion.

Item	Noted characteristics	Description	Use	Figure
1	Boulder axial dimensions	The long (<i>L</i>), intermediate (<i>I</i>) and short (<i>S</i>) axis dimensions are measured.	To establish boulder shape and approximate mass.	6
2	Rock type	Noted to determine rock density by conducting laboratory testing on rock samples using the displacement method.	Values used to calculate boulder mass.	N/A
3	Long (<i>L</i>) axis orientation	Recording the boulder orientation offers insight to the transport direction as mobilised boulders often have the <i>L</i> -axis aligned perpendicular or parallel to the direction of travel (Nott, 2003b).	Subsequent measurement of the <i>L</i> -axis orientation during relocation surveys can help establish where small rotational movements (entrainment) may have occurred between surveys.	N/A
4	Distinguishing features	Distinctive boulder shape, impact scars, abrasion markings or biological indicators such as algal growth, evidence of boring and/or the presence of organisms (e.g. limpets, barnacles).	This may suggest the direction or mode of transport and provide insight to the pre-transport setting and direction and/or mode of transport.	7 & 9
5	Morphological context	Is the boulder topographically constrained in its ability to be transported, e.g. buried, imbricate against other clasts, located within a depression or against a raised scarp? Accumulated sediment may result in boulder burial during subsequent surveys restricting mobility.	Provides detail on the morphological setting which is known to influence boulder mobility (Naylor et al., 2016).	8, 9 & 11a
6	Boulder photograph	Individual boulder images capture a broader visual account of the boulder setting.	Used to compile a boulder identification inventory for each survey. This proved useful for tag relocation and comparative purposes throughout the study.	1, 6, 7, 8, 9 & 11
7	Record the boulder location using the TIP	The DGNSS rover pole is placed next to the TIP and the coordinate recorded (Figure 7). The last 4-digits of the unique tag ID code are entered to the DGNSS interface for processing following survey completion.	Provides a spatial and temporal account of the boulder location.	7 & 8
8	Noting the position of the orientation hole	Noting the location of the orientation hole relative to the TIP (above the TIP at time of tag deployment). This is of relevance when conducting relocation surveys.	Identifies incidents of boulder overturning during transport if orientated differently to previous survey.	7

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3 1037 Table 6. Summary of boulder transport data from Bembridge Ledge and Black Rock
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BEMBRIDGE LEDGE
(50 RFID tagged boulders)

Survey Period		Boulders transported (% of total)	CTD (m): (Max IBTD ^a)	CTD (% of total)	Mean transport dist. (m)	Mean transport dist. between surveys (m/day)	Mean mass of transported boulders (t): (Max. mass)	Mean direction of transport (°)	Overturning events	Max. Hs between survey period (m) ^a	Hmax between survey period (m) ^b	Date of storm activity (named where applicable).	Mean tag recovery rate
From	To												
25th July '15	3rd Feb '16	21 (42)	49.2 (16.1)	42	2.3	0.25	0.5 (1.1)	229	6	3.3	5.4	3rd Jan '16	94%
3rd Feb '16	17th Feb '16	12 (24)	12.1 (7.5)	10	1.0	0.86	0.6 (1.2)	226	1	2.5	4.0	8th Mar '16 (Imogen)	74%
17th Feb '16	1st Apr '16	13 (26)	6.3 (1.2)	5	0.5	0.14	0.6 (1.2)	177	0	4.2	6.6	28th Mar '16 (Katie)	78%
1st Apr '16	23rd Sept '16	11 (22)	5.5 (1.6)	5	0.5	0.03	0.5 (1.3)	192	0	1.8	3.0	10th Apr '16	68%
23rd Sept '16	25th Nov '16	13 (26)	12.7 (4.6)	11	1.0	0.20	0.5 (1.2)	233	3	4.0	6.8	20th Nov '16 (Angus)	90%
25th Nov '16	8th Feb '17	15 (30)	27.2 (8.9)	23	1.8	0.36	0.5 (1.2)	246	1	2.4	4.0	3rd Feb '17	100%
8th Feb '17	5th May '17	9 (18)	4.0 (2.3)	4	0.5	0.05	0.5 (1.3)	260	0	2.5	4.3	22nd Mar '17	100%
TOTAL		94	117.0		1.1 (st. dev 0.7)				11				86%

BLACK ROCK
(54 RFID tagged boulders)

Survey Period		Boulders transported (% of total)	CTD (m): (Max IBTD ^a)	CTD (% of total)	Mean transport dist. (m)	Mean transport dist. between surveys (m/day)	Mean mass of transported boulders (t): (Max. mass)	Mean direction of transport (°)	Overturning events	Max. Hs between survey period (m) ^a	Hmax between survey period (m) ^b	Date of storm activity (named where applicable).	Mean tag recovery rate
From	To												
10th July '15	3rd Dec '15	15 (28)	9.3 (2.9)	14	0.3	0.06	0.4 (1.8)	189	3	2.2	3.9	26th Jul '15	81%
3rd Dec '15	6th Jan '16	12 (22)	6.9 (2.8)	10	0.6	0.20	0.6 (1.8)	192	3	3.3	5.4	3rd Jan '16	93%
6th Jan '16	19th Feb '16	12 (22)	10.5 (4.0)	15	0.9	0.24	1.0 (5.0)	181	2	2.6	4.8	7th Jan '16	100%
19th Feb '16	31st May '16	12 (22)	27.7 (7.8)	41	2.3	0.27	2.0 (11.9)	240	2	4.2	6.6	28th Mar '16 (Katie)	100%
31st May '16	1st Sept '16	4 (7)	1.3 (0.8)	2	0.3	0.01	0.4 (0.7)	97	0	1.5	2.4	20th Aug '16	100%
1st Sept '16	9th Dec '16	6 (11)	9.6 (3.1)	14	1.6	0.10	3.4 (11.9)	194	1	4.0	6.8	20th Nov '16 (Angus)	98%
9th Dec '16	22nd Feb '17	7 (13)	1.2 (0.4)	2	0.2	0.02	0.7 (1.5)	143	0	2.4	4.0	3rd Feb '17	91%
22nd Feb '17	24th May '17	2 (4)	1.1 (0.8)	2	0.6	0.01	0.3 (0.4)	26	0	2.5	4.3	22nd Mar '17	100%
TOTAL		70	67.6		0.9 (st. dev 0.7)				11				95%
TOTALS		164	184.6		1.0 (st. dev. 0.7)				22				91%

^a - Maximum significant wave height (m) – as recorded by the Channel Coast Observatory wave buoy.

^b - Maximum wave height (m) – as recorded by the Channel Coast Observatory wave buoy.

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1041 * - NOTE: Additional detail on IBTD values is provided in the supplementary material.

Figure 1. RFID detection equipment. (Photo, M. Schaefer).

73x54mm (300 x 300 DPI)

Figure 2. Schematic diagram of RFID operation illustrating signal transmittance to/from a boulder embedded RFID tag.

67x34mm (300 x 300 DPI)

Figure 3. Bembridge study sites. (a) Black Rock and Bembridge Ledge - tagged boulders are located within the survey areas; (b) Isle of Wight's geographic location within the U.K.; (c) proximity of wave and tidal recording locations relative to the study site; (d) fetch distances to the study site.

120x79mm (300 x 300 DPI)

Figure 4. Boulder detachment, transport and deposition at Bembridge Ledge. The clearly defined bedding and jointing at the platform terminus facilitates the production of boulders via quarrying and undermining. (1) detached boulders deposited seaward of the platform edge awaiting transport; (2) transported boulders deposited upon the gravel beach. Boulder transport pathways are highlighted.

84x52mm (300 x 300 DPI)

Figure 5. RFID tag; (1) 32mm RFID tag, the copper coils are located in the transparent end of the tag, circled; (2) RFID tag within a numbered protective silicone sleeve.

89x117mm (300 x 300 DPI)

Figure 6. Recommended tag insertion point (TIP) within the S-axis indicated by the circle with the recorded boulder axial dimensions.

75x54mm (300 x 300 DPI)

Figure 7. Recording the boulder location, the DGNSS pole is positioned against the TIP. The orientation hole is located above the TIP, (circled), indicating the boulders upward orientation at the time of relocation.

100x133mm (300 x 300 DPI)

Figure 8. RFID tagged boulder relocated and excavated following the seasonal accretion of sand during the summer months. The TIP is being recorded with the DGNSS rover, the dashed line represents the remaining buried boulder.

84x113mm (300 x 300 DPI)

Figure 9. Evidence of transport at Bembridge Ledge (RFID tag ID: 1127). Boulder location recorded on 3rd February 2016, (circle), relocated 7.2m from its previously recorded position on 17th February 2016. The arrow indicates the direction of transport. Algal growth present on the underside of the boulder indicates overturning during transport. Inset: pre-transport setting, in-situ boulder prior to displacement. Note the extensive algal growth on the exposed upper plane (pad for scale: 0.25 x 0.3m).

77x57mm (300 x 300 DPI)

Caption : Figure 10. ArcGIS visual output documenting the direction of incremental step lengths and the Individual Boulder Transport Distance (IBTD) for the boulder pictured in figure 9 (RFID tag ID: 1127). The absence of colour markers associated with specific survey dates indicates that no transport was recorded on that date.

90x96mm (300 x 300 DPI)

Figure 11. Evidence of transport at Black Rock (RFID tag ID: 1187). (a) boulder location recorded on 19th February 2016, (circle), relocated 6.4m from its previously recorded position on 31st May 2016. Further landward progression was hindered following deposition against a boulder ridge; (b) the same boulder recorded on 1st September 2016, (circle), relocated 2.5m seaward from its previously recorded position on 9th December 2016. The arrows indicate the direction of transport.

113x173mm (300 x 300 DPI)

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