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Understanding extreme-wave hazards on high-energy coasts requires a standardised approach to field data collection: Analysis and recommendations

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Abstract. Coastal boulder deposits provide vital information on extreme wave events. They are crucial for understanding storm and tsunami impacts on rocky coasts, and for understanding long-term hazard histories. But study of these deposits is still a young field, and growth in investigation has been rapid, without much contact between research groups. Therefore, inconsistencies in field data collection among different studies hinder cross-site comparisons and limit the applicability of findings across disciplines. This paper analyses field methodologies for coastal boulder deposit measurement based using an integrated database (ISROC-DB), demonstrating inconsistencies in current approaches We use the analysis as a basis for outlining protocols to improve data comparability and utility for geoscientists, engineers, and coastal planners. Using a standardised and comprehensive set of measurements, with due attention to precision and reproducibility, will help ensure complete data retrieval in the field. Applying these approaches will further ensure that data collected at different times and/or locations, and by different groups, is useful not just for the study being undertaken, but for other researchers to analyse and reuse. This ~~is~~ fosters development of the large, internally consistent datasets that are the basis for fruitful meta-analysis; and is particularly timely given increasing focus on longitudinal monitoring of coastal change. By recommending a common set of measurements, adaptable to available equipment and personnel, this work aims to support accurate and thorough coastal boulder deposit documentation, enabling broader applicability and future-proofed datasets. Field protocols described and recommended here also apply as best practices for coastal geomorphology field work in general.

1 Introduction

Coastal boulder deposits (Fig. 1) occur on rocky or coral reef coasts that are subject to intense ocean forces. Constituent clasts are moved by waves (in many cases against gravity), and stranded in place on rocky coasts (Fig. 1A-E) or reef flats (Fig. 1F). Coastal boulder deposits represent a record of extreme marine inundation, but they are still poorly understood. The transporting agent may be storm waves or tsunami, and in some places both may operate at different times; but we still lack definitive indicators (other than before-and-after imagery) to uniquely identify the transporting mechanism from deposit characteristics. However, coastal boulder deposits are often the only preserved signatures of high energy inundation on rocky coastlines, providing direct links to past emplacement and transport conditions, and decoding this record is therefore important for long-range coastal risk analysis, with applications spanning climate reconstruction, seismology, environmental modelling, coastal engineering, and hazard assessment.

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Figure 1.: Examples of coastal boulder deposits from a variety of locations. Each photo includes a person or persons for scale (indicated with an arrow where they are difficult to see). A: Aran Islands, Ireland. Broad boulder ridge (5m high and 40 m wide) is 20 m above highest tide, and 35m from the cliff edge (photo by Peter Cox). B: Banneg Island, France. Boulder ridge is about 11m above topographic datum IGN69 and 50 m inland (photo by Serge Suanez). C: Aceh, Indonesia. Boulder (6.5t) transported 132m inland by 2004 tsunami (photo by Raphaël Paris). D: Diplomo Petris, Crete. Boulder clusters in the intertidal zone (photo by Michael Whitworth). E: Eleuthera, Bahamas. Base of deposit is 10m above high water and 13 m inland (photo by Rónadh Cox). F: Makemo Atoll, French Polynesia. Scattered reef-top boulders in the intertidal zone (photo by Annie Lau).

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Study of these enigmatic deposits is still in its infancy. There are some historical accounts of large boulder and coral-head emplacement by storm waves (Süssmilch, 1912; Stevenson, 1845; e.g. O'donovan, 1839; Stoddart, 1971) and by tsunami (e.g. Kato and Kimura, 1983; Nakata and Kawana, 1995; Shepard et al., 1949), as well as a recognition that it could be very difficult to determine whether storms or tsunami were the causative mechanism (Bourrouilh-Le Jan and Talandier, 1985; Jones and Hunter, 1992). But there was little systematic study until seminal work in the 1990s and early 2000s (Jones and Hunter, 1992; Nott, 2003b; Bryant and Nott, 2001; Nott, 1997) started people thinking about the importance of coastal boulder deposits for understanding extreme wave hydrodynamics and hazards in the nearshore environment. This drove rapid growth in the number of publications, from less than one per year in the 1990s to an average of almost 20 per year over the past 10 years (Fig. 2). However, this is still a small overall number of studies by comparison with more established areas of inquiry, for example analysis of beaches or coastal dune fields, for which there may be hundreds of papers published per year. There is a lack of generally accepted best practices for coastal boulder deposit data collection and reporting. This is largely because of the rapid and relatively recent growth of this field, with a lack of centralised community and little communication between research groups. This is a problem, because coastal boulder deposits present many challenges in field measurement and documentation (which will be described below). With a large number of new researchers entering the field (including students embarking on early-career work and skilled scientists moving into a new arena), many people measuring coastal boulder deposits are doing it for the first time. Therefore, without a repository of information on standardised methodologies, there is a wide variety in the kinds of measurements collected and (as reported here) substantial inconsistency in data reported in published work. This creates difficulty in comparing datasets from different sites and work groups (Kennedy et al., 2025a), forming a barrier to objective, reliable comparative analysis, and an impediment to growth of synthetic understanding.

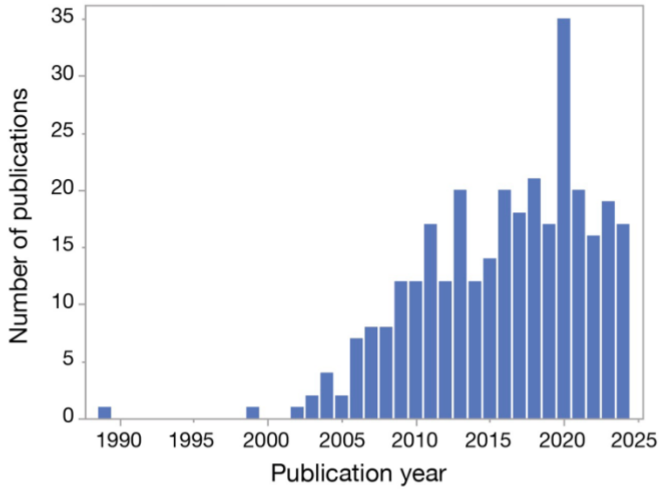

Figure 2. Increase in coastal boulder deposit studies from the 1990s to present. Data are complete through the end of 2024. Compiled from Google Scholar using search string "coastal boulder deposit" OR "coastal boulder deposits" OR "megagravel" OR "megaclast deposit" OR "megaclast deposits" with "include citations" unchecked. Search returns were individually scrutinised and verified. For example, the citations filter was not flawless, so papers on other topics that simply cited coastal boulder work had to be identified and removed. Similarly, papers that mentioned coastal boulder deposits broadly in other contexts but did not study them directly were likewise excluded.

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To demonstrate the lack of central similarity in coastal boulder deposit studies, and to quantify and evaluate the range of approaches taken, we carried out a meta-analysis of published data. We focused on measurements of individual boulders rather than broader mapping of the geometry of boulder accumulations. However, many of the principles and recommendations laid out here apply equally well to documentation of clusters or ridges, and can be adapted as necessary to those applications. Our exploration reveals a lot of variability in what people measure and how they measure it, and we use this analysis to make a case for community-wide consistency in data collection and reporting. We propose a set of core measurements that should accompany any coastal boulder deposit study (Table 1).

In this work, we emphasise the description, measurement, and characterisation of coastal boulder deposits, independent of their origin. Figuring out objective measures for distinguishing the deposits of tsunami from those of extreme storms is perhaps the single most important question in the coastal boulder deposit field (e.g. Costa and Andrade, 2020; Lau and Autret, 2020; Bujan and Cox, 2020; Weiss et al., 2022, and many others; Oetjen et al., 2021; Mottershead et al., 2020), but solving that puzzle requires evidence-based analysis that foregrounds the impartial collection of data. In this paper therefore we will not discuss different processes by which features may have formed, but focus on precise and accurate characterisation of the deposits, for the production of internally consistent datasets that facilitate comparison among sites and over time. Although we focus on coastal boulder deposits, the protocols we outline are applicable to a wide range of coastal geomorphologic situations and may be considered as general best practices.

Position papers such as this play a crucial role in shaping methodologies used for data collection, providing a foundation for standardised practices across diverse research and applied fields. By outlining best practices, challenges, and guiding principles, this contribution will facilitate a unified approach to data collection that enhances comparability, reliability, and reproducibility. This work will also contribute to the broader scientific community by setting a benchmark for data quality, encouraging transparency, and fostering collaboration. We hope this work will encourage both new and experienced researchers to use a common framework, helping reduce discrepancies and improving the integration of datasets from multiple sources.

2 Coastal boulder deposits: definitions and background

Coastal boulder deposits take a variety of forms, ranging from isolated single blocks (Fig. 1C) to extensive boulder ridges (Fig. 1A, B) (as will be discussed in more detail below). The term highlights the predominance of boulders (i.e. intermediate axis > 0.25 m: Udden, 1914; Wentworth, 1922) but they can include a broad sweep of clast sizes. They often include colossal blocks in the megagravel size class (i.e. intermediate axis greater than 4.1 m, as defined by Blair and Mcpherson, 1999), for example 15 m x 11 m x 9 m in Tonga (Frohlich et al., 2009), 15m x 10m x 5m in Tuamotu (Bourrouilh-Le Jan and Talandier, 1985), and 11 m x 10 m x 3 m on Ireland's Aran Islands (Cox

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et al., 2018b); but many accumulations also incorporate much smaller gravel trapped in spaces between the large framework clasts (e.g. Cox et al., 2012; Scheffers et al., 2009; Paris et al., 2011). Boulders not emplaced by waves (e.g. those that fall from cliffs or are brought to the coast by rivers) are not included in this definition, unless they are subsequently entrained and re-deposited by wave action.

Because of the amount of energy required to displace them, coastal boulder deposits may be dormant for extended periods (multiple years to decades to centuries, depending on the topography, clast size and wave climate). The protracted timescales complicate efforts to interpret their hydrodynamics and to untangle the relative roles of extreme storms versus tsunami. Nevertheless, these long-lived deposits provide what are sometimes the only records of historic and prehistoric coastal inundation, and therefore reconstructions have direct application to understanding past and present conditions, and have predictive value for future inundation regimes.

The first recorded use of the term “coastal boulder deposits” is by Bishop and Hughes (1989). Since then it has gained progressively more traction and recognition as the formal name for wave-emplaced accumulations of large clasts that are out of equilibrium with the local wave climate and require extreme events for their transport. The advantage of this term is that it is general and non-genetic, and can therefore be applied to any coastal boulder accumulation regardless of emplacement mechanism. This is important, as the origin of a majority of coastal boulder deposits remains in question, with relative roles of storm and/or tsunami still under debate. A unifying term that does not presuppose deposit origin provides maximum flexibility in description and analysis.

On that note, the phrase “cliff-top storm deposits” (Autret et al., 2016; Hall et al., 2006; Suanez et al., 2009; Fichaut and Suanez, 2011) has sometimes been applied as a synonym for coastal boulder deposits, but we recommend against its use because it can be misleading. First, the term “cliff” is quite loosely defined in geomorphology in both height and steepness, and thus means different things to different workers, making its use ambiguous. Second, and most importantly, embedding the term “storm” in the deposit name makes suppositions about the depositional mechanism, which creates problems for researchers trying to conduct objective analysis of depositional mechanisms. Whereas this term—and others such as reef-platform coral boulders (e.g. Terry et al., 2013)—have been useful for certain sites and applications, we argue that they should be discontinued in favour of the more general term "coastal boulder deposits".

There are two distinct kinds of coastal boulder deposits—land-derived and reefal—characteristics of which are unpacked below.

2.1 Land-derived (terrigenous) coastal boulder deposits

Occurring along rocky coasts exposed to extreme wave energies, land-derived coastal boulder deposits originate by wave erosion of local igneous, metamorphic or sedimentary bedrock, whether from shore platforms, stepped or uneven exposures, or cliff edges. However, to be classified as coastal boulder deposits they cannot simply have accumulated in place via collapse but must have been transported (usually against gravity) by waves.

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They take several forms, on a spectrum from individual isolated clasts (Fig. 1C) to clusters (Fig. 1D) to highly organised imbricated boulder ridges (Fig. 1A, B, E) (Cox et al., 2018a; Spiske et al., 2008). Isolated clasts may occur as a field of widely-scattered boulders (Fig. 1F), or there may be just one or a few large boulders along a stretch of shoreline (Lau and Autret, 2020; May et al., 2015; Frohlich et al., 2009; Etienne et al., 2011). Clusters are aggregates of several boulders clumped together (Fig. 1D), sometimes showing seaward imbrication and in other cases forming disorganised groups or piles (Biolchi et al., 2019a; Evelpidou et al., 2020; Mhammdi et al., 2008).

Ridges are highly organised coast-parallel features involving large numbers of clasts (hundreds to thousands), with an angle-of-repose face dipping steeply seaward and a more shallowly sloping landward side (Nott, 2003b; Williams and Hall, 2004; Suanez et al., 2009; Cox et al., 2012). Whereas clusters are rarely more than one or two clasts high, boulders in ridges can be stacked several deep, leading to accumulations that may be several metres tall, 10s of metres in cross-shore width, and in some cases can extend for hundreds of metres along the coast (Cox et al., 2012; Hall et al., 2006; Lau and Autret, 2020; Etienne and Paris, 2010). Whereas isolated clasts or clusters might form during a single event, extensive ridge systems—sometimes referred to as ridge complexes (Morton et al., 2006, 2008) or ramparts (Scheffers et al., 2014)—are interpreted as representing the cumulative impacts of multiple extreme-wave events.

Placement is as diverse as the geomorphology of the rocky coasts that host these deposits. Some are found on cliff tops that may be several metres or even several tens of metres high (the highest known coastal boulder deposits occur about 50 m above sea level: Hall et al., 2006). Others occur at the inland edges of low-elevation shore platforms, up to several hundred metres inland (Cox et al., 2018b). On irregularly-stepped coasts, deposits can occur at multiple levels, often nucleating at bedrock steps or other obstacles that provide a backstop (Autret et al., 2023; Lau and Autret, 2020).

Location relative to water level is also varied. For many occurrences, the accumulations occur above the high-water level (not reached by the tide or by fairweather waves). Generally these are bedrock coasts where wave energy is persistently high and the coastline is predominantly erosional, with negative sediment budgets. Therefore, these high-and-dry supratidal boulders are separated from the ocean by a bare bedrock surface that is swept clean of sand and fine gravel (Williams and Hall, 2004; Hansom et al., 2008; Autret et al., 2023; Engel and May, 2012; Biolchi et al., 2019a). At other sites, where high energy inundation is more infrequent, deposits may be found on beaches or in the intertidal zone (Abad et al., 2020; Whelan and Kelletat, 2005; Engel et al., 2016). And in some cases boulders can be cast far inland and may be found among vegetation (e.g. Kennedy et al., 2017; Goto et al., 2012; Dunán-Avila et al., 2025; Jones and Hunter, 1992; Paris et al., 2010; Atwater et al., 2017).

The size and shape of constituent boulders is controlled by lithology and planes of weakness (including joints, fractures, and bedding planes), which control the size and shape of boulders released from bedrock. Once formed, their transport history and locus of deposition are a complex function of wave energy and coastal topography. The

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largest blocks tend to be found at lower elevations near the coastline, with deposits at higher elevation and further inland generally being formed from smaller boulders, and as a general rule of thumb, the higher the elevation and/or the steeper the coast the smaller the maximum clast size; but datasets show that these trends are often noisy (Cox et al., 2018a; Kennedy et al., 2021; Boesl et al., 2020).

Boulders show variable amounts of transport-based breakage and rounding based on jointing and fracture mechanics, but also depending on how frequently they are moved around, which varies with boulder size, elevation, and distance inland (Cox et al., 2018a; Biolchi et al., 2016). Static boulders can also experience physical and chemical weathering in situ over long time periods, which may be mediated or accelerated by biologic agents (e.g. vegetation, cyanobacteria, lichens, intertidal organisms) (e.g. Bahlburg and Spiske, 2015; Kelletat et al., 2020; Oliveira et al., 2020c).

2.2 Reefal coastal boulder deposits

Tropical settings with fringing reefs provide a special category of rocky coastline on which blocks excavated from the reef may be deposited by high-energy waves. This subset of coastal boulder deposits has distinct characteristics that differ from land-derived examples. First, boulders are sourced from modern reefs rather than lithified bedrock, which means that they are generally highly porous and less dense than bedrock-sourced boulders. Second, they often become grounded on reef flats that are submerged at high tide (e.g. Lau et al., 2014; Etienne et al., 2011; Boesl et al., 2020; Goto et al., 2007), so this category of coastal boulder deposits is commonly found within the intertidal zone (although some boulders may be transported onto shores of adjacent islands and elevated substantially above the high water mark (Terry et al., 2013; Nakata et al., 2023; Atwater et al., 2017; Bourrouilh-Le Jan and Talandier, 1985; Dunán-Avila et al., 2025). Third, deposits on reef flats occur only as isolated blocks and/or small clusters. Organised shore-parallel boulder ridges are not found on the fringing reefs themselves, although reef-derived boulders that have been transported ashore may pile up (Lau and Autret, 2020). Finally, reefal boulders often have rounded shapes that are due to growth forms of the coral source material rather than abrasion during transport (Goto et al., 2010a; Lau et al., 2016). For example, some coral species form almost spherical colonies that are transported more easily and farther inland than angular boulders of the same size (Massel and Done, 1993). As with terrestrial coastal boulder deposits, they may be created and/or modified by storm waves or by tsunami (e.g. Goto et al., 2010b; Lau et al., 2018). Reactivation and repositioning are similarly rare because of the intense energy required to move them (Terry et al., 2013).

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3 Coastal boulder deposits as records of extreme marine inundation (storms vs. tsunami): the need for standardised approaches to field data collection

Coastal boulder deposits, because they record forces exerted by extreme waves, serve as enduring indicators of the impacts of marine hazards and the magnitude of inundation events. Each boulder pinpoints a minimum force exerted at some point in time to transport that mass to that location. This in itself is valuable information in terms of tracking coastal hazards; but to fully analyse long-term risk, we need to determine whether the inundation forces are due to storm waves or tsunami.

Early studies used boulder mass as the primary determinant, contending that only tsunami were capable of moving the largest clasts in coastal boulder deposits (e.g. Young et al., 1996; Scheffers et al., 2009). These arguments cited a lack of first-hand records showing storm-wave transport of very large boulders, especially at elevation or far inland (e.g. Scheffers et al., 2009) and also relied on hydrodynamic equations that purported to provide a relationship between boulder mass and the size of the storm wave or tsunami required to move it. This was based on a premise that the sustained force exerted by tsunami permitted them to move enormous masses despite relatively small wave heights, while for storm waves to move comparably large masses would require heights that were dynamically improbable; and they included equations that purported to relate boulder transport to wave height as a determinant of whether storm waves could or could not move a given boulder (Nott, 2003b; Benner et al., 2010; Nott, 1997; Pignatelli et al., 2009; Barbano et al., 2010).

But this rationale fell apart in recent years, when pre- and post-event measurements at several different locations revealed storm-wave movement of blocks weighing hundreds of tonnes close to shorelines, as well as multi-tonne rocks deposited at tens of metres elevation or at inland distances up to a quarter kilometre (Cox et al., 2018b; Kennedy et al., 2017; e.g. May et al., 2015; Medina et al., 2018; Biolchi et al., 2019b). These observations of storm wave coastal boulder deposit transport led to greater scrutiny of widely used hydrodynamic equations relating transported masses to wave heights. The equations were shown to be based on assumptions that the physics of storm wave runup were fundamentally different from those of tsunami, and review of advances in wave dynamics (that had occurred in the decades after the equations were developed) showed that in fact those assumptions were not supported by data (Cox et al., 2020; Oetjen et al., 2021). Additional work on wave flow velocities required to initiate boulder movement (e.g. Nandasena et al., 2022) has further refined our understanding of how wave energy translates to boulder motions, providing tools to calculate realistic incipient motion velocities.

The upshot of work in the past decade has been to grow our understanding that in fact there is substantial overlap in the power of storm waves and tsunami. Storm-wave flows can achieve supercritical flow (Froude number >1) and exert tremendous forces (Ma et al., 2024; Bujan and Cox, 2020; Steer et al., 2021). While this is exciting, and opens new avenues for investigation and understanding of extreme wave behaviour, it is also frustrating because—with the sole exception of certain phenomenally large boulders, and those deposited at kilometre-scale distances from the shoreline (Goto et al., 2011; Terry et al., 2021)—it torpedoes any hope of distinguishing storm from tsunami deposits based on boulder size alone. Aseismic tsunami sources provide an additional complication because whereas earthquake-induced tsunami or large landslides create seismic events that can be detected geophysically, meteotsunami are harder to detect, and could go unnoticed (Gusiakov, 2021; Hansom et al., 2015).

Consequently, it has become increasingly clear that distinguishing storm from tsunami transport is a challenging and unsolved problem (e.g. Marriner et al., 2017; Lorang, 2011; Barbano et al., 2010; Weiss, 2012; Costa and Andrade, 2020; Lau and Autret, 2020; Scardino et al., 2025). An increasing number of studies have produced primary observations that many coastal boulder deposits are generated and activated by storm waves (Cox et al., 2018b; Kennedy et al., 2017; e.g. May et al., 2015; Medina et al., 2018; Biolchi et al., 2019b; Naylor et al., 2016; Goto et al., 2009; Autret et al., 2016; Oliveira et al., 2020a; Scicchitano et al., 2020) and that for others transport and deposition are unequivocally due to tsunami (Bourgeois and Macinnes, 2010; Nandasena et al., 2013; Goto et al., 2007; Etienne et al., 2011; e.g. Goff et al., 2006). There are some characteristics that appear linked to wave type. For example, tsunami are not known to create organised boulder ridges (Etienne et al., 2011), but they can shift megagravel over extreme distances (>1 km) inland (Goto et al., 2010a); and storm-dominated boulder fields often show inland fining (Goto et al., 2009; Lau et al., 2014), compared to more random patterns in tsunami boulders (Goto et al., 2012; Boulton and Whitworth, 2017). However, none yet have been definitively proven to be unique markers.

Currently, the only way to make a fully confident determination is to have a smoking gun, whether from historical records (which are rare) or by capturing proof of the movement (via before-and-after imagery). However, for the majority of coastal boulder deposits these data are not available, which means that researchers must weigh various other kinds of evidence (including local wave climate, regional tsunami histories, and hydrodynamic principles) to attempt to make a determination of the boulder transport mechanism (Goto et al., 2010a; Morton et al., 2008; e.g. Nott, 2003a; Regnauld et al., 2010; Williams and Hall, 2004; Roig-Munar et al., 2023).

Ideally we would hope to develop a general predictive solution or set of criteria that could be applied to any coastal boulder deposit to uniquely determine whether they are of storm or tsunami origin. Efforts are ongoing (Cox et al., 2020; Kennedy et al., 2021; Weiss et al., 2022; Costa and Andrade, 2020; Watanabe et al., 2020), although the solution remains elusive. Of critical importance are field and remote-sensing data from coastal boulder deposits, both to characterise deposits thoroughly and to serve as a baseline against which future changes can be measured. To that end, it is important to maximise the broad comparability of data collected by different groups in different areas. But there is a wide range of approaches to coastal boulder deposit measurement, and a lack of consensus on what parameters should be measured and recorded: and this limits progress.

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Table 1: Recommended core data for coastal boulder deposit studies. Each property is described in detail in the text. Abbreviations: GPS = Global Positioning System; GNSS = Global Navigation Satellite System; DGPS or DGNSS = Differential GPS or GNSS; RTK = Real Time Kinematic; UAV = Uncrewed Aerial Vehicle or drone. A printable formatted version of this table, for use as a field-planning checklist, is included as a supplemental file.

Property	What is included	How it is measured/recorded
Site characteristics	Bedrock geology, topography, etc.	Observations, literature, existing maps
General boulder characteristics	Lithology, source, transport history (where possible), as well as overall setting; overall shape and rounding	Field observation comparative analysis over time, and/or literature review for previously studied sites
Location	Latitude and longitude, Universal Transverse Mercator, or other coordinate system (with horizontal geodetic datum)	GPS: hand held or from UAV imagery, or via RTK or DGPS/DGNSS. Precision must be reported
Physical properties	Density (for mass calculation)	Hand sample and Archimedes' principle
Dimensions	Long, intermediate, short axes (XYZ); volume	Tape measurement, photogrammetry, DGPS/DGNSS, LiDAR
Mass	Estimate of boulder weight	Calculated from volume and density
Alignment	Orientation of long axis (azimuth and/or relative to shoreline or mean wave direction)	RTK GPS, compass, aerial photos
Horizontal distance	Distance inland from defined local datum (usually measured perpendicular to the shoreline)	RTK GPS or DGPS/DGNSS, laser rangefinder (with trigonometry if terrain is sloped), maps, imagery
Elevation	Vertical distance above a defined datum	RTK GPS or DGPS/DGNSS, laser rangefinder with trigonometry, digital terrain models
Geodetic reference system	For positional data, the geodetic frame of reference (e.g. WGS84, ETRS89, etc.)	From GPS settings
Local datum for horizontal distance and elevation	Some measure of sea level, high water mark, or other landmark; national geodetic benchmark or survey datum; define in methods.	Depends on datum (see text). Must include documentation for reproducibility. Vague reference to sea level without definition is difficult to validate
Tide information	Local range, local tide corrections (if relevant for boulder elevation computations)	Local tidal predictions, phone apps (will usually only have nearest gauge data, not progressive time-distance correction factors), or numerical tidal models

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4 Toward a standard set of field measurements and reporting protocols

Beyond their application to any given local study, coastal boulder deposit data are valuable to the wider research community for comparative analysis. Therefore it is to everybody's benefit to adopt field techniques and data reporting practices that may be clearly interpreted by readers, both so that individual workers can incorporate data from the work of others into their own analysis and so that their own data will be accessible to the extended network. But the current lack of a central reference framework means that individual groups develop their own approaches, which may or may not be fully documented in subsequent publications. In addition, different studies may use various datums or measurement platforms, which may lead to incompatibilities between studies if the specifics are not clearly defined and reported. Adherence to clear reporting and standard practices facilitates useful comparison of data between different areas and over time.

We used ISROC-DB (V1p0: Kennedy et al., 2025a, 2025b) as our data source to analyse the methods and approaches currently in use. ISROC-DB is a freely accessible standardised database of coastal boulder deposit measurements compiled from pre-existing studies, as a product of the NSF-funded ISROC (Inundation Signatures on Rocky Coastlines) project. In addition to boulder and topographic measurements, ISROC-DB tracks other key information such as geospatial parameters applied and datums used. It has the explicit aim of facilitating meta-analyses and comparisons among coastal boulder deposits. We supplemented analysis of the datasets in ISROC-DB with close reading of the descriptive methodology in the source publications. This allowed us to contextualise the database information.

ISROC-DB (V1p0: Kennedy et al., 2025a; 2025b) can be accessed at https://www.designsafe-ci.org/data/browser/public/designsafe.storage.published/PRJ-5756. To date, it includes data from 36 studies published between 2007 and 2023. Constituent datasets range from fewer than ten boulders to more than a thousand, covering sites in 23 countries worldwide (Fig. 3). In aggregate, ISROC-DB provides a cross-section of approaches by active coastal boulder deposit research groups (including about half the co-authors of this paper). ISROC-DB does not include the entirety of available coastal boulder deposit measurements—although it is expected to grow, as there is an open invitation to workers to submit their data (Kennedy et al., 2025b; 2025a)—but it provides a wide-ranging and representative overview of data collection approaches in coastal boulder deposit studies over the past two decades.

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Figure 3. Locations of coastal boulder deposit datasets recorded in ISROC-DB V1p0 (Kennedy et al., 2025b)

4.1 Site characteristics: setting the scene

Basic information about the site and the boulders under study is an important component of the field information. A description of the location including bedrock geology, topography, surface roughness, and other distinguishing features should be provided, based on site observations, literature analysis, and/or existing maps.

Boulder lithology should be recorded. Especially for newly-created or recently moved boulders, sites of origin are important (if they can be determined). The study should distinguish between the original bedrock source and pre-transport location of an already-existing boulder when possible. For example, a boulder might fall from a cliff originally, but subsequently be moved against gravity along a shore platform (Cox et al., 2018b; May et al., 2015). Boulder transport direction is likewise important: where possible, workers should determine whether transport is uphill (against gravity), horizontal (i.e. lateral movement on a level or near-level surface), or with gravity (sliding seaward on a platform, or falling/rolling down a cliff or slope). The orientation of the long axis is an important characteristic in this context, as (in the case of elongate clasts) this will tend to be oriented perpendicular to the direction of transport (Imamura et al., 2008; Spiske and Bahlburg, 2011) and hence says something about flow direction. And care must be taken in designing the measurement campaign to avoid selection biases in data collection, as these can affect any statistical analysis of the data.

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4.2 Local knowledge is valuable

People living near a study site, especially those who spend a lot of time near the coast (e.g. fishing, maintenance, etc.) may have eye-witness information about boulder movements or changes in boulder configurations. Large blocks attract the climbing community, who take photos of that are often posted to social media, and which may provide documentation of boulder locations at specific times (e.g. pre-storm locations of two very large transported boulders in Cox et al.,2018a were determined from photographs provided by climbers). Reaching out to locals can also be a way to engage them as citizen scientists, making them aware of the importance of coastal boulder deposits, and motivating them to take photos that may be useful for longitudinal comparisons.

4.3 Boulder dimensions: how big?

Clast sizes are at the heart of almost every coastal boulder project, whether measured by hand with a tape or digitally via photogrammetry (whether via drone, phone, or other image capture technology). In most cases, dimensions are used to derive volume (usually as a precursor to determining boulder mass). It is unsurprising therefore that all 36 studies in ISROC-DB measured the three principal axes (longest, intermediate, and shortest, referred to as X, Y, Z or a, b, c) of their target boulders, and all also computed volumes. All but four also tabulated those data (although an additional three reported only a subset of measurements).

4.3.1 Axis measurements: harder than you think

Even in the current era of 3D imaging using drone-based structure-from-motion (SfM), and cell phones with LiDAR capability, simple linear measurements of the three principal axes remain the most customary way of recording boulder dimensions. Hand-held tape measurements in the field are by far the most common (Fig. 4A), although the popularity of photogrammetric measurements is increasing (four of the 36 datasets in the database, all from studies published since 2019). Aerial maps of entire deposits provide a mechanism for collecting dimensions quite rapidly by measurement on either an orthoimage or 3D model, and in some cases people have used a hybrid approach, measuring length and width (usually X and Y) from the aerial imagery and collecting the height measurements (usually Z, but with some exceptions where boulder height is not the shortest axis) on the ground with a tape.

Where boulders have simple orthogonal shapes, measurements may be quite straightforward, using either length, width and thickness for rectilinear objects or for more triangular rocks measuring the base and height of the triangular surface in addition to the thickness. More asymmetrical (but still fairly rectilinear) shapes require a more nuanced approach. In some cases it may be appropriate to mentally subdivide the boulder into smaller components that can be measured separately (although this will not provide simple axis measurements, the subsections can be used for volume and mass calculations).

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Fig. 4. Some field method techniques. A.: tape measurement of boulder axes; the irregularity of this boulder means that volume or mass estimates from tape dimensions are approximation only. B: Siting a photogrammetric ground control point using RTK GPS. C: Site surveying for elevation measurements using a transit compass (Brunton), which in combination with tape or laser rangefinder distance measurements can be used to derive vertical and/or horizontal distance using trigonometry. D: measuring boulder distance from a shoreline marker using a laser rangefinder.. (Photo A by Annie Lau, B-D by Rónadh Cox,)

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For rounded or tapered boulders, care should be taken to ensure that tapes are not draped across the boulder surface, resulting in measurement of a partial circumference rather than the desired axis. This can be prevented by projecting the boulder end points outward (using a clipboard or other straight rigid object), providing a measurement target for the tape. In almost all cases this is a two-person operation.

Where boulders are not orthogonal, reporting the maximum axis lengths will result in misleading dimensions, and so some more representative intermediate or average value should be determined. It's even more complicated for highly irregular shapes such are common in reef environments or young carbonate rocks, where boulders may have pits, pinnacles, and multi-axial shapes. In these cases, axis measurements should be treated (and reported) as rough approximations only. If the boulders in question are large and will be used to constrain transport hydrodynamics, photogrammetric models are strongly recommended.

4.3.2 Volume computations and their complexities

Axis dimensions are generally the basis for volume (and hence mass) determinations, which are the primary way of comparing among sites and evets in terms of transport and depositional forces. Every study in ISROC-DB included volume calculations.

The approach (and the reliability of the result) will vary depending on boulder shape. In the case of user-friendly rectilinear boulders, volumes can be calculated from field measurements as the product of the three measured axes. More irregular (but still fairly rectilinear) shapes require a more nuanced approach, and in some cases it may be appropriate to mentally subdivide the boulder into smaller components for which volumes are calculated separately and then summed. The volume of rounded boulders should be computed based on ellipsoidal geometry, where the product of the axes is multiplied by 4/3 π. For highly irregular boulders it is impossible to determine volume from triaxial measurements alone.

Some workers use the field measurements without modification, and for very regular boulders (e.g. from bedded sequences with orthogonal joint systems) those can provide reasonable first-order volume estimates (Cox et al., 2012). However, this is rarely the case, as most boulders have some degree of irregularity,. The inaccuracy (overestimation) of volume based on triaxial measurements of non-geometric boulders is well documented, with errors exceeding 50% or greater than 100% in some cases (Engel and May, 2012; Yao et al., 2023; Hoffmeister et al., 2020; Boesl et al., 2020; Lario et al., 2023; Dunán-Avila et al., 2025).

Photogrammetric analysis can cut through all these difficulties. Reliable volumes can be obtained from high-resolution 3D models (see for example Canavesio et al., 2023; Dunán-Avila et al., 2025; Scardino et al., 2025), as long as the boulder is fully and carefully imaged. Coverage should include not only of top and sides, but also the base (particularly for irregular boulders with rough and karsted surfaces) to ensure that the final enclosed shape is fully representative. Properly scaling of the model is also critical. Relying on built-in camera GPS positioning may

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result in decimetre or even metre-scale errors in model dimensions, and so the image collection should include an object of known proportions that can be used to check and adjust the model (e.g. Causon Deguara and Gauci, 2017; Froideval et al., 2019; Pedoja et al., 2023; Gienko and Terry, 2014).

Only a few of the studies in ISROC-DB used 3D models to obtain boulder volumes; and of those most used it only for a few boulders, providing simple axis data for the bulk of the clast population. This is not too surprising, because although photogrammetry is a reliable (and increasingly accessible) way to determine dimensions and derived properties of complex three-dimensional objects (Raoult et al., 2017; Pedoja et al., 2023; Yao et al., 2023), there are snags that often make it impractical for surveying large numbers of boulders. For example, it is generally difficult or impossible to image the lower surfaces of boulders or the sides of boulders in multi-boulder accumulations, which limits model accuracy. In addition, volume computations require a closed ("watertight") 3D model, necessitating interpolation across unimaged portions. This can be onerous, particularly in the case of very irregularly shaped boulders, or those with vegetation cover (Difrancesco et al., 2021; Spero et al., 2025; Schneider et al., 2019; Nakata et al., 2023).

For example, if the software fails to properly interpolate across the open surface, some edges or mesh vertices may not connect properly, and the resulting mathematical inconsistencies may make the model difficult to process accurately: residual holes or gaps prevent creation of a watertight surface, leading to problems. Other pitfalls include inverted normals, where some surface elements face inward rather than outward and misrepresent the boulder's shape; or self-intersections, where parts of the model fold over themselves, generating unrealistic overlaps or non-manifold geometries which, if internal to the model's outer surface, may go undetected and inflate volume estimates (Sulzer et al., 2025; Münster et al., 2024).

All of these problems with 3D modelling are very solvable, but they do require hands-on manipulation of the model and can be time intensive. In contrast to axis measurements which, once collected in the field, can be loaded into a spreadsheet and put through batch calculations that rapidly process many hundreds of measurements, each digital boulder scan must be processed and/or checked individually. And although phone-based scanning software means that field collection of model data is quite rapid and straightforward, it still takes several times longer for image acquisition, model generation and on-site checking (to ensure that the boulder was adequately covered) than simply measuring boulder dimensions with a tape. Practitioners of digital volume calculations recommend integration alongside traditional field data collection techniques, not—at least at this stage—as a replacement (e.g. Spero et al., 2025; Nakata et al., 2023; Boesl et al., 2020).

Collecting a number of 3D boulder models will always enrich a coastal boulder deposit dataset. A suite of 3D models can provide validation and/or conversion factors for a larger set of field measurements of boulder dimensions, as well as a high-resolution data subset for the largest or otherwise most significant boulders in a dataset.

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4.3.3 Estimating mass

Volume calculations are the basis for estimating boulder mass, which also requires rock density. Fourteen of the 36 studies in ISROC-DB reported a measured density; two used generalised values for the lithologies of interest, several gave a value but did not say where it had come from, and others provided mass estimates without indicating what density had been used.

To optimise the mass estimates, we recommend that density measurements of the study boulders be included as part of the reporting. These are simple to acquire, needing only a small sample of the rock (or a few small samples so that the range of variability can be established). Using Archimedes' principle, these are simply weighed, and volume measured by displacement in water (Hoffmann et al., 2013; Hoffmeister et al., 2020; Corradino et al., 2025). This is particularly important in the case of reef corals or young carbonate rock, which have high and non-uniform porosity, leading to variable bulk rock density values (Spiske et al., 2008).

4.4 Boulder locations

For coastal boulder studies, in which the long-term evolution of deposits will be key to an ultimate understanding of these dynamic environments, locations of individual boulders are key data points. We found a range of practices relating to collection and reporting of positional data. Some studies provide general information (e.g. site name and/or coordinates), and in most cases a map or diagram showing boulder positions at the site. Others provide GPS coordinates for individual boulders. Whereas the former approach allows people to find the site, the latter method means that individual boulder information can be imported into GIS and other geospatial analytical systems, facilitating data compilation and meta-analysis. This is particularly important for longitudinal analysis, allowing repeat visits and the ability to track boulder movements (or stasis) over time. We therefore urge researchers to collect and report positional data for individual measured boulders.

Only two-thirds of the datasets in ISROC-DB (22 of 36) stated that they recorded GPS positions for individual measured boulders, and of those, just over half (12 of 22) tabulated those locations. There is a time component to these trends—only eight of 19 studies between 2007 and 2017 used GPS, compared with 14 of the 17 studies 2018-2023— but of the 14 GPS-enabled studies in the more recent group, six (almost half) did not provide those data in the publication (either within the main text or in supplementary data). And although most of the non-reporting studies did show boulder positions on maps or orthoimages, in most cases those figures were too small to provide a useful source from which precise locations could be extracted, and boulder location markers were often overlapping at the scale of the diagrams. Nor could mapped locations be connected to specific boulder measurements. In sum: a large proportion of coastal boulder deposit studies either fail to collect or decline to report the positions of the rocks they measure. This limits the usability of published data for detailed longitudinal analysis of coastal boulder deposits.

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How precise does location information need to be? Positions can be determined with centimetre-scale accuracy using Differential GPS (DGPS) or Real-Time Kinematic (RTK) GPS (Fig. 4B), and if available this is the most accurate way to map boulder placements (Hoffmeister, 2020; Andresen and Schultz-Fellenz, 2023). However, research groups may not have access to the necessary equipment and/or students may not be trained in its use; and it is important to bear in mind that such high precision is not always necessary. Data collected with hand-held GPS units can be perfectly adequate for purpose, especially those that support satellite-based signal augmentation systems such as WAAS (in the Americas), EGNOS (Europe), MSAS (Japan) (and similar systems for other regions). The 1-3 m positional accuracy such devices can achieve serve very well in mapping boulder locations, especially if combined with field photos that record boulder features and locational context. These can be sufficient for re-finding locations and determining whether or not individual boulders have been transported over time. Some researchers also use electronic tagging devices in highly dynamic locations to help locate transported boulders (Naylor et al., 2016; Spero et al., submitted; Hastewell et al., 2019).

Drone photogrammetry of entire locations produces high-precision mapping of deposits, as well as the possibility of quantitative reanalysis year-on-year (Yao et al., 2023; Nagle-Mcnaughton and Cox, 2020; Vaccher et al., 2024; e.g. Autret et al., 2018; Suanez et al., submitted), and is excellent for overall site characterisation. However, aerial imaging alone may not produce accurate 3D rendition of individual clasts, in particular if they are obscured or partially buried in ridges or clusters. Work that involves the characteristics of individual clasts therefore should include clast-specific positional data and measurements, which are best collected on the ground (or for very large boulders, with very low-altitude drone flights that target the individual boulder).

4.5 Horizontal distance

Most studies incorporate some distance measure, documenting how far individual boulders are from some marker, whether that is a shoreline, a cliff edge, or a reef front. In cases where the boulder is known to have moved, this may include a transportation distance. These measurements provide context on the separation between boulder location and the source of transportation energy, with longer distances generally representing more extreme wave events. Horizontal distance was included in 31 of the 36 datasets in ISROC-DB.

However, of those 31, twelve (more than a third) did not tabulate the data. Although some represented boulder locations on maps or orthophotos from which approximate positions could be extracted, this makes the data less accessible (requires manual extraction from the figure). Furthermore, the link between specific boulder measurements (axes, mass) and their distance inland is lost.

We recommend that workers tabulate the distance values they collect along with the boulder data, for maximum long-term relevance and usability of the data. This can be done in GIS (horizontal distance between two points established using GPS, or measurement from aerial imagery), or it can be measured in the field using tapes or a laser rangefinder (Fig. 4D). These measurements are often not very precise, both because the baseline or datum

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may be hard to fix accurately (which will be discussed further below) or there may be variation in what part of the boulder (edge, centre of mass, etc.) is represented. The latter can introduce significant imprecision for large boulders and megagravel. However, high levels of precision are (in many cases) not necessary in the overall context of mapping boulder distributions: It would be valuable to know whether a boulder was 10 or 50 m form a baseline marker, but the difference between 10 and 12 m might not be significant (particularly when taking into account variations in water level due to tides, storm surge, infragravity waves, etc.). Therefore, recording those values (being careful to also report specifics of the methodology and associated precision) adds substantial value to coastal boulder datasets.

4.6 Elevation

Coastal boulder deposit datasets benefit greatly from including deposit elevation, largely because recording work done against gravity is fundamental for understanding hydrodynamics of dislodgement, transport and emplacement. However, it can be a difficult measurement to make, and often represents the greatest source of uncertainty and ambiguity in coastal boulder deposit studies. Of the 36 datasets in ISROC-DB, 15 (more than 40%) provided no record of elevation for their measured boulders (although some of these reported having made the measurement, but it did not appear in the tabulated data). Nine studies provided average elevations for suites of boulders, or had figures with surveyed topographic profiles on which approximate boulder locations were shown; but only 11 (less than a third) tabulated elevation data along with boulder measurements. However, more recent papers were more likely than older ones to include elevation in their study design and reporting: almost half the studies published since 2018 included elevation data, compared with only a quarter of those published 2007-2017.
We recommend the routine collection of elevation in association with boulder measurements, to maximise their usefulness in terms of broad understanding of coastal boulder deposits. We recognize that in some cases where elevation range may be very small (e.g. reef-flat boulders, or accumulations on very shallowly-sloping platforms or flat cliff tops) that a single surveyed value may appropriately represent the entire deposit.
Elevation can be a time-consuming measurement to make. Hand-held GPS is effectively useless, as the vertical accuracy is typically 2-3 times worse than horizontal accuracy, producing elevation errors up to several tens of metres. DGPS or RTK GPS can solve the problem if available. Elevations can also be obtained from a Digital Surface Model (DSM) or topographic map, but it may be tedious and difficult to relate those elevations to field measurements from individual boulders. However, it is possible to measure elevation above some given marker using classical tape-and-compass or laser-rangefinder approaches (Łabuz, 2016; Coe, 2010) (Fig. 4 C,D): if you can measure distance, and the angle from the horizontal, you can calculate the height difference using trigonometry (Cox et al., 2018b; Richmond et al., 2011); and if the marker is of known elevation, or is surveyed in, this can be translated to absolute elevation.

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Accurate elevation data relative to a well-defined datum are essential for inter-site comparisons. We recommend using established local or national datum references where possible. Some countries publish the locations of geodetic reference points on open-access websites, which can be helpful for ensuring proper GPS calibration when available. However, these may be hard to find, or may be located distant from the field site. In such cases, local landmarks or ecological zonation may be surveyed in to provide a benchmark. Consistency in elevation measurement, including specifying datum and tidal conditions (as will be discussed further below), is necessary to avoid discrepancies.

5 The Importance of geospatial context

Our analysis revealed that many studies neglect to report key geospatial information such as which geodetic system was used for positional information, the specifics of local sea-level for elevation and inland distance, and/or information about the local tide regime (as discussed below). Among the 36 ISROC-DB datasets, only three provided complete and clear descriptions of how baselines were established, which datums were used, and how those were locally determined and documented. We expect that other studies used careful procedures for setting the geospatial parameters of their measurements, but did not include the specifics in the published work. However, these details are not trivial in the context of broader data usability and longevity. Clear documentation of the frames of reference is a key aspect of geospatial data reporting to ensure usability, and minimising errors in both longitudinal analysis and inter-site comparison. We recommend that all studies carefully document the geodetic framework of their analysis, either in methods or as a supplementary document.

5.1 For positional data, the geodetic reference system must be specified

GPS surveys provide positions calculated by the GPS receiver using a geodetic reference ellipsoid, which is a mathematically smoothed model of the Earth's shape that allows XY coordinates to be precisely located on the Earth's curved surface. However, there are a number of different ellipsoid models, and therefore it is important to know and report the underlying reference system being used during data collection. There may be considerable error if location coordinates collected in one geodetic system are projected using another, without the requisite transformation. As one illustration of this, the US Global Positioning System satellites use WGS 84 as their underlying reference system for positional determinations, while the European Galileo satellite constellation uses ETRS89. Both were aligned in 1989, but ETRS89 is fixed to the stable Eurasian plate whereas WGS84 is referenced to the Earth's centre of mass. As a result, they have drifted due to plate tectonic motions at an average rate of 2.5 cm/year, meaning that there may almost a metre difference between to be reconciled in converting one to the other (Twigg, 2000; Baselga and Olsen, 2021). Discrepancies with respect to other commonly used systems, such as NAD883 or local state planes, can be up to several meters.

Whereas GPS receivers and GIS programs can make those transformations easily, they require that users input the ellipsoid information; but this is commonly not provided in positional datasets. Many users do not interrogate the details that underpin the GPS data and therefore also do not report them, rendering their data ambiguous within the range of possible values for different models applied at that study site. Users should be aware that the information is given in the settings of GPS receivers, and included in metadata of downloaded readings, so it is simply a matter of adding that information into data tables and/or methods in manuscripts for publication.

5.2 Vertical and horizontal distance relative to what? The dastardly datum

Data collected with RTK or DGPS systems incorporate a geodetic datum that—as long as the reference system is known and incorporated into mapping transformations, as discussed above—provides reliable positional information. These can be international systems such as WGS84 or ETRS89 discussed above, or a national vertical datum can be applied (examples include the Australian Height Datum AHD, New Zealand Vertical Datum NZVD, Nivellement Général de la France IGN69, and many others).

However, many studies use direct measurement to record elevation or inland distance. And at the coast—when we are interested in how positions relate to the shoreline, which is not a fixed marker—this becomes a thorny problem, and the most poorly standardised in published work. Among the 36 studies in ISROC-DB, there was tremendous inconsistency in handling the reference datum for elevation and/or distance.

Some workers tie measurements to a recognisable physical reference. The local high-water mark is one such indicator, used by several papers in our reference group. Of these, one used the high-water datum of the study area's national hydrographic service; others used visual determinations (e.g. height of barnacle encrustations, or rock discolouration due to splash-zone cyanobacteria). Another study used locally developed wave cut notches as the pinning point. These approaches provide a straightforward and repeatable pinning point for repeat studies in the same location (with due attention to potential changes due to rising sea level).

But the problem is that the bulk of studies provide only vague indications of what datum was used. Some, for example, say simply shoreline, or water's edge, with no reference to tidal variation (an important variable in its own right, which we will discuss more specifically below). Others mention mean sea level, without indication of how that was determined on site in the context of field measurements. And whereas microtidal environments might see only several cm vertical water change (which would have minimal influence on elevation measurements), that same tide range might cause a few metres horizontal change on a flat shore platform—which would have a substantial impact on measurements of inland distance.

Reporting clearly and in detail how the measurement datum was established in a study is important for comparisons: in trying to understand, for example, whether local coastal configuration affects the elevations at which different wave heights can act, it is important to be able to compare apples with apples, and know that boulders reported as e.g. 10 m elevation are all in fact at the same elevation. A boulder 10 m above water level at

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low tide may be only 5 m above high tide, or 7 m above mean sea level, and these differences matter, not only for site-to-site comparisons, but also for comparisons between different times at the same site.

5.3 Sea level: it's hard to measure

Important as it is to establish a local measurement datum, it can be very tricky to do. The most commonly invoked reference point is sea level, sometimes referred to as mean sea level, or given simply as "above sea level". However, many studies neglect to specify what specific version of sea level was used, and/or how it was measured or recognized at the study location. This reflects the fundamental problem that "sea level" does not have a unique definition (Huang et al., 2020). And although centuries of water level measurements have produced precise definitions of tidal variations and mean sea levels(Gill and Schultz, 2001), on site these can be difficult to relate to boulder positions.

As examples of how this plays out in practice, seven studies in ISROC-DB referred simply to "sea level" and an additional two referred to the "shoreline", with no details provided as to how those terms were defined for the study, and/or whether local tide variation had been factored in. In some cases terminology changed throughout the paper, with references to distance from shoreline in one part, and sea level in another. Another six referred to "mean sea level" or "MSL", suggesting implementation of a global datum, but without providing the basis. In our set of 36 studies, only a handful provided clear information or related their datum to verifiable hydrographic surveys or markers.

However, as pointed out by Woodroffe and Barlow (2015), mean sea level provides no accumulations or proxies that would be evident on a map, which means that measurements need to be locally referenced to some local datum or indicator. But in very few cases did the writers indicate how they identified a fixed physical reference point in the field and/or in aerial imagery when making their measurements. The bottom line is that because the position of sea level is (literally) a moving target —not only because of tides, but because sea level itself varies across the geoid— it requires thought and proper documentation in field studies (Liu et al., 2014; Pajak and Leatherman, 2002; Parker, 2003; Woodroffe and Barlow, 2015).

5.4 The high-water mark: a useful workaround

Ecological markers provide a physical expression of the highest tide line, so it is feasible to make measurements relative to the barnacle line (for example), or the upper limit of the black cyanobacteria splash zone. Some places may have a distinct erosional feature such as a tidal notch that may function as a reference point (Evelpidou and Pirazzoli, 2015; Antonioli et al., 2015). However, these features all vary with bedrock locality, type and recent wave activity (Whittal and Mackie, 2023). On steeper coasts they commonly form a sharp line that is easy to identify; but on very shallowly-sloping platforms are likely to be much more diffuse and unlikely to provide a repeatable marker (Boak and Turner, 2005; Manno et al., 2017).

Although these physical reference frames can be very useful for repeatable local measurements, they lack generality, which means that comparisons with other areas may require assumptions about tide levels. And although they have the benefit of being reproducible in the short to medium term, they become less reliable on longer timescales in the context of sea level rise (or other shoreline-altering phenomena, including subsidence, tectonic processes and erosion).

5.5 Tides: an additional wrinkle

Tides are a further complication in trying to constrain sea level as a reference during field measurements. The relationship to tide level may be central for understanding coastal boulder deposits, as the additional water surface elevation due to high tide may be critical for boulder movement during storms (Spero et al., subnitted). Although some environments with small tides may see only slight changes (cm to 10s of cm), tide range at many places is measured in metres, on both daily and neap-spring cycles. In such cases it is important to establish whether elevation and distance are given with respect to water level at the time of measurement (in which case the time and date should be given as part of the data), or whether it has been corrected for tide (in which case the correction calculation should be outlined, and the reference datum provided). This should include information about the tide gauge or tide tables that were used to establish tide information.

However, getting reliable local tide data is often difficult. Tide gauges are thinly spread in general; and because timing and magnitude are not uniform along coastlines, it is necessary to apply progressive extrapolations to peripheral sites. These are not always available in published tide tables, and in any event their reliability drops off with distance from the gauge (Egbert and Ray, 2017; Ray et al., 2011; Geyman and Maloof, 2020). As many coastal boulder deposits are remote from population centres and therefore may not have nearby gauges, this can be a substantial problem, undermining our ability to accurately know either the timing or magnitude of local tides.

Ocean tide models derived from satellite altimetry data may be applied, although their precision and accuracy vary based on location and model choice. Satellite data typically provides coarser spatial resolution than tide gauge data, which can make predictions less accurate at localised scales, and shallow-water effects can reduce the accuracy of models in representing the interaction of tides with local bathymetry and shoreline features (Madsen et al., 2015; Salameh et al., 2018; Nehama et al., 2022; Hart-Davis et al., 2024). Furthermore, these products are not yet at the “plug-and-play” development stage, and require considerable expertise to implement at site-specific scale.

A more tractable approach can be to purchase off-the-shelf equipment to deploy on site (Knight et al., 2021; Bresnahan et al., 2023). This can be a useful strategy, particularly in areas targeted for repeat monitoring over multiple seasons or years. The locally-collected data can also be used longer term to calibrate or correct records from the closest permanent reference tide gauge (e.g. Dodet et al., 2018; Hatcher et al., 2022; Earlie et al., 2018).

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5.6 And of course: sea level changes over time

Although this discussion is framed largely in the context of coastal boulder deposits in equilibrium with modern sea level, this is not always the case. Some accumulations were deposited thousands or even hundreds of thousands of years in the past (e.g. Carballeira et al., 2022; Kennedy et al., 2007). Failing to account for sea level difference could lead to misinterpretation of depositional elevation and transport forces. This can be true even for relatively young deposits (a few thousand years old), for which sea level may have been lower or higher than present: post-glacial sea level patters are complex, and include mid-Holocene highstands in some areas (Chua et al., 2021; Leonard et al., 2018; Creel et al., 2024; Khan et al., 2015). For deposits dating to the last inter-glacial there is even greater uncertainty linking boulder elevation to sea level (Rovere et al., 2025). Tectonics also can alter the relative position of sea level and coasts over Holocene or longer timescales and so must also be considered where relevant (e.g. Carballeira et al., 2022).

In sum: the difficulties attending the definition and measurement of "sea level" should be acknowledged, and not glossed over in study design or reporting The reference frame for measurements should be clearly described, whether that relies on a local physical indicator or the geoid model underpinning a GPS survey. Clear statements should also be made about local tide regime, and in cases where tidal range is sufficient to impact the repeatability of distance or elevation measurements, tidal stage and height should be reported (as closely as possible).

6 Dating coastal boulder deposits

Determining the emplacement age(s) of coastal boulder deposits is very desirable, but it is difficult at best and in many cases (at the present time) impossible. Some boulders with preserved calcareous marine epifauna or infauna may yield radiocarbon ages recording the death time of the organism (hence presumably the time at which the boulder was removed from a subtidal or intertidal location, depending on the organism). This has provided valuable insights into multi-centennial history of deposits in some locations (Cox et al., 2012; e.g. Scheffers et al., 2010; Shah-Hosseini et al., 2011; Boulton and Whitworth, 2017; Scicchitano et al., 2007), but can be used only in suitable lithologies (primarily carbonates), requires a sub- or intertidal origin for the boulders (whereas many coastal boulder deposits consist of clasts torn from supratidal platforms or cliff edges), and can be complicated if the local marine ^{14}C reservoir age is not well constrained (Heaton et al., 2023; Atwater et al., 2017) or due to diagenetic effects and the incorporation of old carbon from the parent rock (Rixhon et al., 2018).

Other radioisotopes (particularly Uranium series $^{230}Th/U$) have been applied to reef-derived coral boulders with some success (Araoka et al., 2010; Rixhon et al., 2018; Terry et al., 2016; Lau et al., 2016; Yu et al., 2012; Zhao et al., 2009), although the uncertainties can be substantial (Rixhon et al., 2018), and again there are lithologic limitations. Innovative application of viscous remanent magnetism (Sato et al., 2022) at present is beset with uncertainties. Lichenometry has been attempted in some locations (Oliveira et al., 2020b; Hall et al., 2006).

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Whereas it may produce useful results in areas that are well characterised (Mccarthy, 2021), the range of variability in growth rates (seasonally, annually, and in different locations), as well as uncertainty in colonization rates on fresh surfaces, mean that this is an imprecise technique that is primarily useful for relative dating (Winchester, 2023). The application of surface exposure dating using cosmogenic nuclides (Rixhon et al., 2018) or optically stimulated luminescence (Brill et al., 2021) is in its infancy and still associated with large uncertainties. Whereas it may not be possible to date deposits, we encourage workers to investigate possible geochronology options, and where possible to use more than one, to provide internal validation and error checking.

7 Data reporting

Many studies generate 100s or even 1000s of measurements and cannot be reported as simple tables within manuscripts. They can be provided in supplemental tables, or may be uploaded to a repository that can be cited and linked in the paper. Tabulated data are simplest for ingesting into larger databases, but GIS shapefiles or KML files work too. There are several general-purpose data repositories (e.g. FigShare, or OpenAIRE's Zenodo) that are both free and open-access, as well as numerous options that may be either discipline or country specific (too numerous to list here). However, the ISROC-DB database used for this analysis network is a DesignSafe data archive specific to coastal boulder deposits (Kennedy et al., 2025a, 2025b). Researchers wishing to submit data for future updates to ISROC-DB can send an email to isroc.network@gmail.com. Making full datasets available online helps ensure long-term usability and relevance of the study. Whichever is chosen, the location and access information should be included with the published paper.

8 Discussion and conclusions

Individual studies of coastal boulder deposits may have a range of objectives, whether characterising deposit geomorphology and sedimentology (Bishop and Hughes, 1989; Cox et al., 2018a; Lau and Autret, 2020; Lau et al., 2014; Goto et al., 2012); documenting changes in response to events (Nagle-Mcnaughton and Cox, 2020; Autret et al., 2018; Naylor et al., 2016; Goto et al., 2011; Kennedy et al., 2016); using boulder characteristics to deduce hydrodynamics (e.g. initiation of motion criteria and bore velocity) (Nott, 2003b; Shah-Hosseini et al., 2016; Pepe et al., 2018), and attempting to determine whether the emplacing forces were from storm waves or tsunami (Switzer and Burston, 2010; Biolchi et al., 2019a; Causon Deguara and Gauci, 2017). The cited studies are examples, and of course most studies have multiple aims. All however share the fundamental goal of trying to better understand coastal boulder deposits overall, whether in the local context or more broadly. Therefore, data collected by one set of researchers may also be valuable to others making comparative analyses—or to the same research group coming back to sites later in time.

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Coastal geomorphology research may inform critical decisions on climate change, natural resource management and hazard mitigation. Thus, standardised methodologies are essential for consistent, high-quality datasets that can be confidently interpreted and applied across regions and disciplines. Reliable comparisonss allow researchers to generalize findings on wave energy, boulder transport mechanisms, and deposit persistence. This knowledge informs models predicting future storm impacts and supports coastal defence planning, which may integrate coastal boulder deposits insights into structural design (Cox and Pakrashi, 2023).

Although our discussion is specific to coastal boulder deposits, many of the methods and approaches that we describe would be best practices for studies of other kinds of coastal sites, including shore platforms, cliffs, and other energetic and geomorphologically dynamic environments.

8.1 Good data collection does not necessarily require expensive equipment.

Whereas tools such as drone photogrammetry and laser rangefinders are increasingly common and can certainly simplify field work, we are keenly aware that such equipment is not available to all researchers. We want to ensure that the recommended best practices do not erect barriers to participation in the coastal boulder deposit community. Classical, low-tech field methods are very valuable, offering high precision, and for many applications are just as good as modern digital options.

By the same token, workers should bear in mind that whereas ultra-high-precision measurements may be necessary for some applications (e.g. measuring fine-scale platform erosion: Cullen and Bourke, 2018), in other instances they may exceed the requirements of the questions being asked, as discussed above. The stochastic nature of coastal systems makes many measurements inherently approximate, and high precision data readouts may give a false sense of accuracy in the context of the messy real world. For example, given the non-linearity of wave behaviour, and the numerous factors that influence bore velocity or initiation of boulder motion, it is usually sufficient to know boulder masses to within ~10%, and topographic dimensions to the nearest half-metre or so.

8.2 "Future-proofing" the data is important.

The coastal research community is diverse, including geologists, geomorphologists, engineers, applied mathematicians, and wave physicists (among others), with a wide range of different backgrounds. Storm inundation and wave modelers need and want the kind of data that field geoscientists can provide. Civil engineers may be interested in coastal boulders as riprap or seawall analogues, and a kind of natural experiment in wave-infrastructure interactions as they simulate real-world wave-structure interactions, informing designs for riprap and seawalls (Cox and Pakrashi, 2023). Communities and schools may want to incorporate data into projects, or to use them in environmental planning. So in collecting data, we urge coastal boulder deposit researchers to remember the range of ways in which it is likely to be used, and make the information as usable as possible.

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Author contributions

Sections of this paper were drafted by participants in an ISROC-sponsored workshop on Field Methods and Standards (May 9th 2022), and those participants are the co-authors of this submission. RC compiled the draft sections and produced the complete draft manuscript. Significant edits and revisions were provided by MCB, ME, ABK, AL, SS, with supporting critical review from SJB, MAO, RP, SR, DS, MS, WS, AS.

Competing interests

The authors declare that they have no conflict of interest.

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