Chapter 6
Outlook for Boulder Studies Within Tropical Geomorphology and Coastal Hazard Research

Abstract Reef-platform coral boulders are produced, transported and deposited during high-energy marine inundation events such as large storms or tsunamis. Documented for centuries as extraordinary features of the coastal landscape, these enigmatic boulders have recently proven invaluable indicators for characterising and interpreting marine erosion and transport processes on shorelines. As such, the examination of boulder deposits has become increasingly applicable to coastal hazard and risk assessment studies, although a number of challenges remain unresolved. Future prospects are optimistic for improving boulder analysis, within the broader scope of developing multi-proxy approaches for investigating the impacts of high-magnitude inundation events on coasts.

6.1 Brief Summary: Current Understanding, Guiding Questions

On tropical coastlines, under infrequent conditions of exceptional wave height and surge currents, such as are encountered during intense storms or powerful tsunamis, large fragments of adjacent coral reefs are often detached and emplaced on the reef surface. The resulting reef-platform coral boulders (RPCBs) are normally conspicuous features that are easily identified and, crucially for the coastal geomorphologist, often accessible for investigation. Official records of reef boulders can be traced back to at least the early 1800s and examples may be highlighted where local communities have named boulders as singular coastal landmarks. Since earliest accounts by the British navigator Matthew Flinders in 1814 on the Great Barrier Reef of Australia, a variety of terms have been coined for coral boulders throughout history. Even within the burgeoning scientific interest of recent decades, terminology in use has remained colourful but become somewhat inconsistent. Unfortunately this situation causes confusion and raises hurdles against easy comparison of coastal boulder observations from place to place. For the purposes of clarification, our review has identified the plethora of expressions that have been used to refer to coastal boulders at various times, but we reiterate the advice that future research should abide by the

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recognised Blair and McPherson (1999) grain-size scheme for describing the sedimentology of large clastic deposits (see Table 2.2).

A number of applications of coastal boulder research, especially studies of RPCBs, for understanding fundamental aspects of the behaviour of high-energy marine inundation (HEMI) events have been explained. In particular, by measuring the position, distribution and dimensions of RPCBs, information on HEMI wave height and inundation direction at specific coastal locations can be derived. By knowing the volume, shape and weight of boulders, as well as their original environmental setting, the minimum flow velocity required for initialising their movement can be inferred from several hydrodynamic transport equations developed and refined by other workers. Together with age-dating and frequency analysis of past (unrecorded) events, this is helpful in determining the vulnerability of coastal locations, which in turn is necessary for carrying out risk assessments and mitigating against the possible impacts of future catastrophic inundation hazards.

Notwithstanding this enormous potential, however, a number of problems hampering coastal boulder studies have been identified. The following list is not intended to provide an exhaustive coverage, but draws attention to the major difficulties faced. Next, this logically encourages the formulation of relevant research questions, which are summarised here (in brackets) and expanded upon in the next section.

- There is inconsistent presentation of boulder data in the existing scientific literature, resulting in incomparability between available datasets. (How can this situation be rectified?)
- Inaccuracies with both measuring boulder dimensions and calculating volume tends to over-estimate boulder size. (To what extent do emerging photogrammetric techniques reduce boulder measurement errors?)
- Identifying original boulder source locations is problematic, potentially leading to misrepresentation of the strength of HEMI events. (What possibilities exist for improving on boulder source identification?)
- Assumptions of boulder emplacement by a single inundation event are often invalid. Reworking of boulders by backwash or subsequent events leads to erroneous estimations of wave energy. (Boulder reworking mechanisms need to be much better understood; what evidence should be targeted?)
- The size of coastal boulders, especially carbonate clasts, decreases over time through various processes of degradation. Old boulders are probably appreciably smaller now than at the time of their production and deposition. Again, this has implications for interpreting the nature of palaeo-events correctly. (Is it possible to establish rates of boulder attrition, weathering and bioerosion according to environmental setting?)
- Deliberate human interference on coastlines means that some large boulders are removed, and so the opportunity for their analysis is lost.
- Hydrodynamic transport equations for estimating the wave energy needed to initiate boulder movement are of tremendous value. Inevitably though, approximation means that existing equations simplify the processes involved and

essential parameters have been neglected. (How influential is seawater turbidity for sediment transportation? Does mobilisation of smaller sediment-size fractions (cobbles, gravels and sands) contribute to boulder transport through buoyant support and inter-clast collision? To what extent does bed roughness limit incipient boulder movement and overall transport distance?).

- Storms and tsunamis are two types of HEMI events with very different wave return periods and behaviour. Yet, until now agreement has not been reached on how to distinguish with certainty between boulders delivered by these contrasting types of coastal hazards. (Which new approaches show most promise for differentiating tsunami from storm boulders? How far does the study of constructional landforms on coasts (e.g. boulder ridges) assist in understanding the respective dynamics of storm or tsunami waves?).

6.2 Future Prospects and Recommendations

Recognising existing shortcomings is not a criticism of earlier work, but is the cornerstone of sound deductive reasoning. Only through the identification of gaps in current knowledge can scientific methodology then be applied to tackle the issues that need to be addressed. In this way real progress can be made. Thus, grasping the nettle of the difficulties mentioned above is necessary within the broader context of uncertainties in coastal boulder studies. A sensible starting point is to prioritise a set of tasks that can provide avenues for future research. The special emphasis here is on RPCBs observed on tropical (coral reef) coastlines, but the majority of recommendations also have direct relevance for coarse clastic deposits seen on coastlines beyond tropical regimes.

Improving hydrodynamic transport modelling is a priority concern. This may be accomplished in a variety of ways. One suggestion is for greater flexibility in existing transport equations through the substitution of a range of values for the water density parameter to represent turbidity. Turbid waters, i.e. marine water mixed with variable sediment loads, are a common characteristic of tsunami waves. The sediment load modifies the water viscosity, the fluid behaviour and the buoyancy afforded to boulders by the water column. Accordingly, the assumption that a tsunami acts as a Newtonian fluid is not entirely valid. Indeed, Kain et al. (2012) recently hypothesised that certain tsunamis act more as a Bingham fluid, especially where depositional evidence indicates *en masse* (or debris flow) type transport of sediments. Boulder movement is also affected by inter-clast collision. For example, where boulders form part of wider accumulations (boulder fields), constructional features (gravel ramparts or ridges) or man-made sea defences (rock armour), numerous clasts may be reworked simultaneously during an energetic marine inundation event. When an individual mobile boulder collides with another static boulder lying on the reef flat, sufficient momentum may be transferred to initialise movement of the static clast, which might otherwise not occur by fluid pressure alone. So far, however, such influences have largely been ignored. In addition, the topographic rugosity of the surface over which the boulders are mobilised (e.g. coral reef, inter-tidal flat, wave-cut shore platform, emerged terrace) undoubtedly influences boulder transport. It is therefore advisable that a rugosity coefficient be developed, ranging from 0 (flat rock surface) to 1 (highly irregular surface with boulder-sized traps) (Fig. 6.1).

In light of these considerations, it is apparent that available hydrodynamic transport equations would benefit from further refinement, to incorporate both the function of suspended and bedload sediments, and the factor of surface roughness. Yet tackling these complex issues will not be a trivial undertaking. Consequently, it is likely that a combination of theoretical approaches, modelling simulations and physical experiments carried out in wave laboratories (Fig. 6.2) will all be required. Although perhaps daunting, therein lie an exciting set of new endeavours for modern coastal geomorphology.

It is similarly anticipated that future research will address and eventually overcome the other questions posed in the preceding section. In this regard, it would be advantageous for boulder studies to leverage on the recent advancements made in relevant arenas such as computer-aided interpretation of satellite images (especially new spectral bands), high-precision dating techniques and close-range photogrammetry. Clearly there are inherent advantages and limitations with studying both coarse and fine textured extreme-wave deposits. While coastal boulders are normally better preserved than sandsheets in high-energy coastal settings, their absence need not necessarily imply an absence of hazard risk entirely (Kelletat et al. 2007). Moreover, new methods for the analysis of well-preserved sand and mud deposits are continually achieving greater degrees of precision, particularly as applied to modelling wave dynamics and sediment transport capacity. Innovative methods include anisotropy of magnetic susceptibility (AMS) (Wassmer and Gomez 2011), inverse sediment-transport modelling (Jaffe et al. 2011) and analysis of nannoliths (heterogeneous suites of biogenic carbonate particles with silt–clay size dimensions; Paris et al. 2010). Overall it is understood that a multi-proxy approach is deemed preferable for obtaining a more robust and comprehensive record of past HEMI events (Yu et al. 2009; Etienne et al. 2011). Multi-proxy approaches rely not only on the geological proxies of fine-grained sediment layers and coastal boulders, but also encompass geomorphological, geochemical, ecological, historical and archaeological evidence, as elaborated adeptly by Goff et al. (2010).

In conclusion, it is hoped that this treatise has laid out a convincing argument: studies of reef-platform coral boulders (and other carbonate/non-carbonate boulders) form an integral component of scientific research that aims to better comprehend the nature of high-energy marine inundation events on tropical coastlines. Although much research in the past decade has focused on boulders deposited by known HEMI events, such as the 2004 Indian Ocean tsunami in Indonesia and Thailand and the 2009 South Pacific tsunami in Samoa and Tonga, a positive outcome in the aftermath of these disasters has been the identification of a range of key features of boulder distribution and transportation. The opportunity now exists to broaden investigations to further locations where coastal boulder deposits have been generated by hitherto unknown ancient events, or by recognised

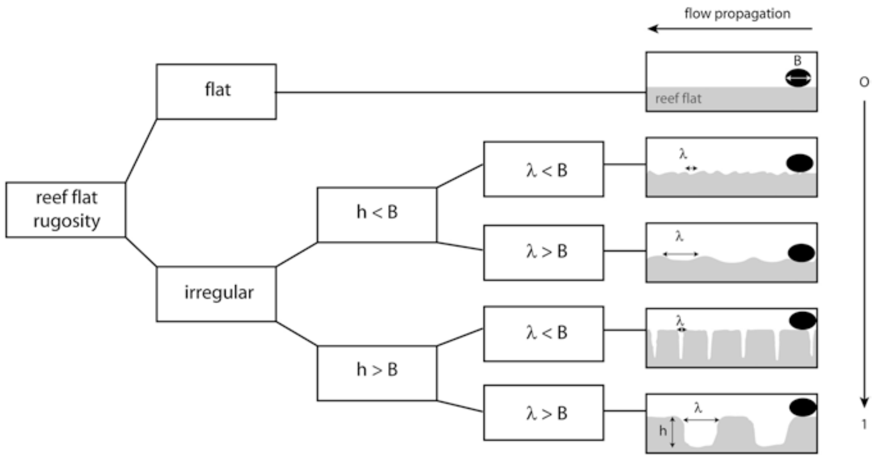

Fig. 6.1 Conceptual model of a rugosity coefficient for a coral reef platform, with increasing rugosity affecting the transport distance of a coastal boulder. Zero (0) implies that topographic rugosity is nill and does not interfere with boulder propagation over the reef flat. One (1) would be the case of a very irregular surface where depressions (grooves, potholes) might entirely trap the boulder. In this situation, varying levels of energy are necessary to displace a boulder from the reef crest to the beach. For example, sliding is possible across the spurs, but lifting would be necessary if a boulder were initially trapped in a depression. The idea can be extended to include other kinds of coastal platforms, such as raised or karstified marine terraces, wave-cut rock shorelines or intertidal mud flats

Fig. 6.2 The 36 m-long wave tank at Nanyang Technological University (NTU) in Singapore. The facility is designed for laboratory studies of wave behaviour and wave interaction with coastlines of various configurations (Photo courtesy of Mr. Shawn Sim, NTU Department of Civil Engineering and the Earth Observatory of Singapore)

historical events that have so far escaped close attention. Across the vast expanse of the Asia–Pacific region in particular, innumerable islands offer prized sites for exploration. Many are fringed by coral reefs where carbonate boulders are common, but the character of their coastal deposits is still underrepresented in the geomorphic literature. At the same time, an increasing awareness for people living on low-lying coastlines is necessary to fully appreciate the potential for future marine inundations. Continuing work on coastal boulders will undoubtedly enrich the information available and thereby assist in the long-term ambition of adapting vulnerable coastal societies to the natural hazards they face.

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