Measurements of shoreline wave action to establish possible environmental and ecological effects from wave energy converter arrays.

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***Abstract*— This research has been to establish possible shoreline effects due to the future exploitation of marine renewable wave energy. The distance from shore, operational regime and the variability in the annual downstream shadow effect are key requirements to enable predictions of possible ecological effects on the shoreline. The accepted method of estimating the amount of shoreline wave action or 'exposure' to which the rocky shore is subject has been to use quantitative ecological surveys and indicator species vertical range. Difficulties can occur when natural and anthropogenic disturbances have a significant influence on these particular species, fundamentally altering the community structure and spatial distribution, which can result in different assemblages evident even though subject to comparatively similar levels of wave action.**

To overcome these limitations a new efficient and cost effective device is presented that is able to measure an average quantitative level of wave action over weeks and/or months at the relevant spatial scale of rocky shore biota. This new device will not only enable specific biotopes to be studied in relation to an objective proxy measurement of wave action over biologically meaningful timescales but could also be used, with bathymetry data, for economical evaluations of near-shore wave energy resources in developing nations.

Long term monitoring data from Orkney are presented which shows good correlations of significant wave height and direction from concurrent wave buoy data at the European Marine Energy Centre wave test site. Initial measurements have found that habitat and biotope classifications currently used to underpin European protected areas have an over simplistic classification of wave energy levels needed for both accurate comparisons and impact determination between certain rocky shore biotopes. Equivalent rocky shore biotopes classed within the same level of energy are observed to have similar levels during the summer but are subjected to a difference in the ratio of wave action of up 1:2 in winter.

***Keywords*— Wave action, Ecology, Wave Energy Converter Arrays, Rocky Shore, Marine Renewable Energy.**

I. WEC EFFECTS

The environmental effects from wave energy converter (WEC) arrays are dependent on the type of technology, operational characteristics and their spatial array design with any impact on the shoreline diminishing with increasing separation distance. The reduction in short period wave heights immediately in the lee of offshore arrays have the ability to recover over the fetch distance due to the wind forcing but longer period swell produced over greater distances, and not related to local wind forcing, will have negligible recovery. Results from a number of models have reported that wave height will be reduced by approximately 10 cm at 10 km distance [1], up to 29 cm at 10 km distance [2] and approximately 60% reduction at 2.5 km equating to a reduction of 120 cm with a significant wave height (H_s) of 2 m [3].

The operational regime of WEC arrays are expected to extract energy over a large percentage of time installed, with non-generation only when automatically disconnected from the electricity grid (i.e. the electrical distribution company for network integrity) or during extreme storm events (when the devices may be in a survival mode). With the exception of these intermittencies WEC arrays would form a recurrent to chronic reduction of wave action during most of the year. With winter extreme waves remaining unaffected by WEC arrays, increased seasonal differences of wave energy levels will be introduced.

Both swell and local wind waves along Orkney's west and north coast waters, frequently originate from discrete directions. Therefore wave action at specific points on the shoreline within the shadow zone of a WEC array may also be subject to unnatural modification by differentially attenuated wave periods. Maximal forces at these sites are usually produced both when the wind direction is in line with the swell, transferring energy to the waves, and when the main wave direction is perpendicular to the shoreline due to less energy dissipation in the shorter shoaling distance. The distribution of these altered energy levels on the shoreline will be dependent upon both array location and wave directions so subsequent studies would benefit with the ability to derive shoreline wave directional measurements.

It should be noted of the significant difference between the United Kingdom's wave energy test sites, the European Marine Energy Centre (EMEC) and the WaveHub, with the latter sited approximately 20 km offshore and the former only 2 km. Also, the first round of Crown Estate seabed leases for wave energy developments, off the West Coast of Orkney, are all within 10 km from the shoreline [4]. This would favour Orkney locations, in the optimum situation, for further ecological research studies into quantifiable impacts from the anthropogenic reduction of wave energy.

II. ECOLOGICAL IMPACTS

Wave energy levels are linked to littoral species evident on rocky shores especially those within the intertidal zone [5] and are even important in community structuring in subtidal systems [6;7]. Those species that have evolved to successfully exploit this environment are mainly specialised in their ability to endure the hydrodynamic forces involved. Natural variation will consist mainly of seasonal changes in wave action and temperature with several linked variables such as sediment or ice scour and desiccation stresses. With a reduction of wave action it would be expected that the vertical range of suitable habitat will be reduced for intertidal organisms due to decreased water spray and in turn lower hydrodynamic forces may allow 'lower energy' species to remain attached to the substrate. This will most notably occur where local variable populations, in closely distributed diverse range of habitats typically found on rocky shores, disperse propagules into the surrounding water column. The normal (unaffected) high energy events during the winter months may subsequently remove any of these newly settled recruits that are not sufficiently robust enough to remain attached or have grown to a size that will promote detachment from induced drag. Buoyant WEC array installations are substantially different from large scale civil works which permanently reduce wave action, such as within harbour breakwaters, allowing the biased growth of lower energy species and the subsequent permanent alteration of the prior biotopes. Yet depending upon the seaward side design of breakwaters these can provide a degree of mitigation through similar habitat, although not ideal as a surrogate, but in terms of WEC development apart from possible growth on the devices themselves, there will be no alternative habitat provision.

The determination of average wave energy levels associated with individual species and the associated biotic assemblages involved, within the key energy levels associated with rocky shores, would fulfil the need [8] of future predictions of wave action and of the possible resultant scenarios from the anthropogenic reduction of shoreline wave action helping in the formulation of mitigative measures.

III. CURRENT MEASUREMENTS

Current simple methods in estimating 'exposure' use charts to simply establish a sites openness or aspect to the sea, the slope of the nearshore seabed and the prevailing wind direction. This methodology can be useful for sheltered locations but it does not take into account ocean derived swell waves which dominate the wave regime and the fundamental requirement for large scale WEC development sites. It could be argued that most rocky shore biotopes are currently classed in a broader grouping of energy levels than are required for establishing any ecological impacts due to being primarily based upon prevailing wind directions that can be subject to high variability. Habitat and biotope classifications such as European Nature Information System (EUNIS), currently used to underpin European protected areas, features four classifications of the energy levels that could be associated with WEC development on the west coast of Orkney. These are high and moderate energy littoral rock (Levels A1.1 & A1.2) and high and moderate Atlantic and Mediterranean infralittoral rock (Levels A3.1 & A3.2). These energy levels are based upon swell and prevailing wind directions and nearshore bathymetry [9]. All biotopes contained within each classification are estimated to occupy habitats of comparable energy levels but no actual wave action data has been used in its production. This is a major limitation for current environmental impact assessment for WEC developments and would benefit from more specific energy classifications for rocky shore biotopes. As noted above the seasonal change in energy levels are of prime importance for ecological research as many organisms are reported to use changes in wave energy levels as cues for specific life cycle stages such as in the limpet Patella vulgata, abundant on the west coast of Orkney, where spawning and subsequent propagule dispersal occurs during autumn gales [10]. Seasonal change is also not currently taken into account in classification systems yet it is possible that it could form the basis for a specific biotopes continued existence and dominance over other biotic assemblages. Many ecological studies have been constrained by the difficulties involved with long term monitoring and site replication in this extreme environment and have also prevented comparisons to be made between widely distributed sites [11]. Whilst there are many accurate and fine scale electronic devices that can provide detailed measurements of hydrodynamic properties they remain expensive; the decisive reason that no widespread and long-term monitoring has ever been attempted and will remain rarely attempted until costs fall or more economical ideas become available. This outcome of this research could provide the tool for overcoming these problems in particular fields of environmental and ecological research in the future.

IV. METHODOLOGY

Two sites were chosen (Fig. 1) by their aspect to the Atlantic, topographical similarity and ease of access from land. Both sites are classified as 'very exposed' [8] in the energy level hierarchy. Although these sites are equivalent in abiotic classification they have notably different biotopes, the Billia Croo site features dwarf fucoid forms as opposed to foliose coralline algae at the Marwick site.

The quantification of wave action in the intertidal zone, primarily designed for ecological research, can for the first time, be carried out with the use of a simple and robust device known as the Terobuoy (Fig. 2). This is achieved by accurately measuring the mass loss (to 0.001 g) of a sacrificial polymer block before and after installation. The interaction of the float with the hydrodynamic regime, both in the surf zone and when submerged, will lead to a controlled removal of material from this block; and is directly related to the forces exerted on the float over an accurately measurable time. All test blocks were manufactured from the same batch of polymer to eliminate possible differences in material properties. The polymer used (high density polyethylene) is highly impact resistant and is not significantly affected by changes in temperature, UV radiation, sediment movement, water absorption, oxidisation or water chemistry. To maintain unit access during the study period the units were installed at heights (detailed in figure 3) that allowed block changes above water level throughout the year even during moderate swell. Measurement blocks were changed on each unit every two weeks during spring tides although on a couple of occasions, high wave action did prevented block change and so this operation was delayed until the next spring tides.

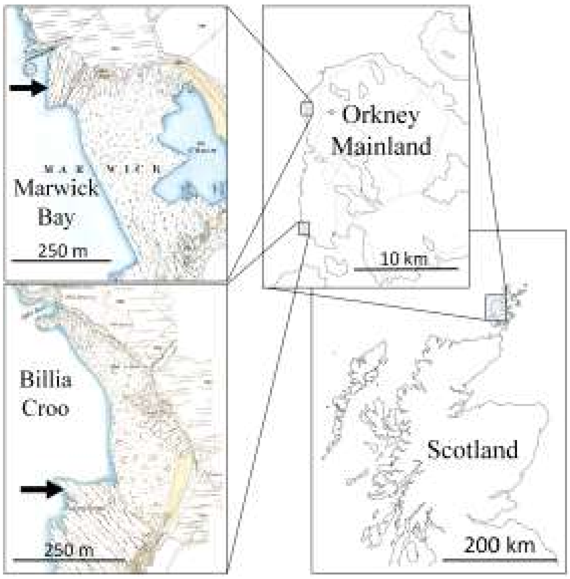

Figure 1. Site areas on Orkney west coast.

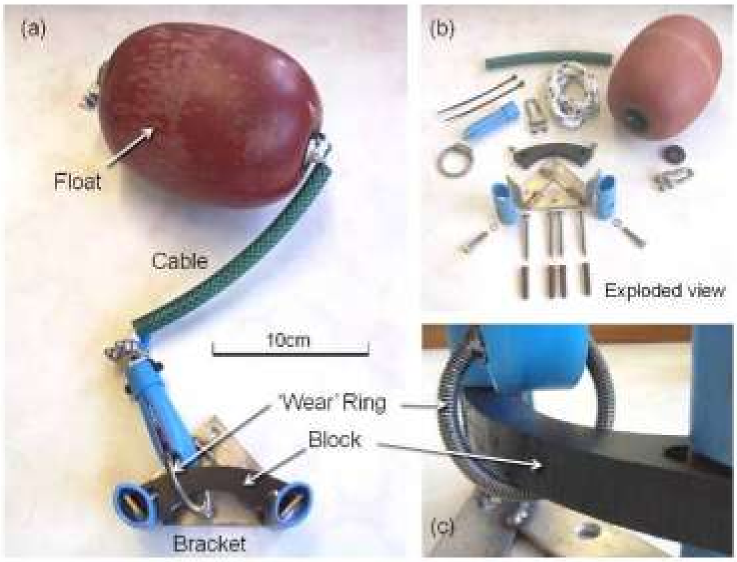

Figure 2. (a)Apparatus details showing assembled unit, (b)Exploded diagram of all parts and (c) detail of wear-ring and block attitude when float buoyant.

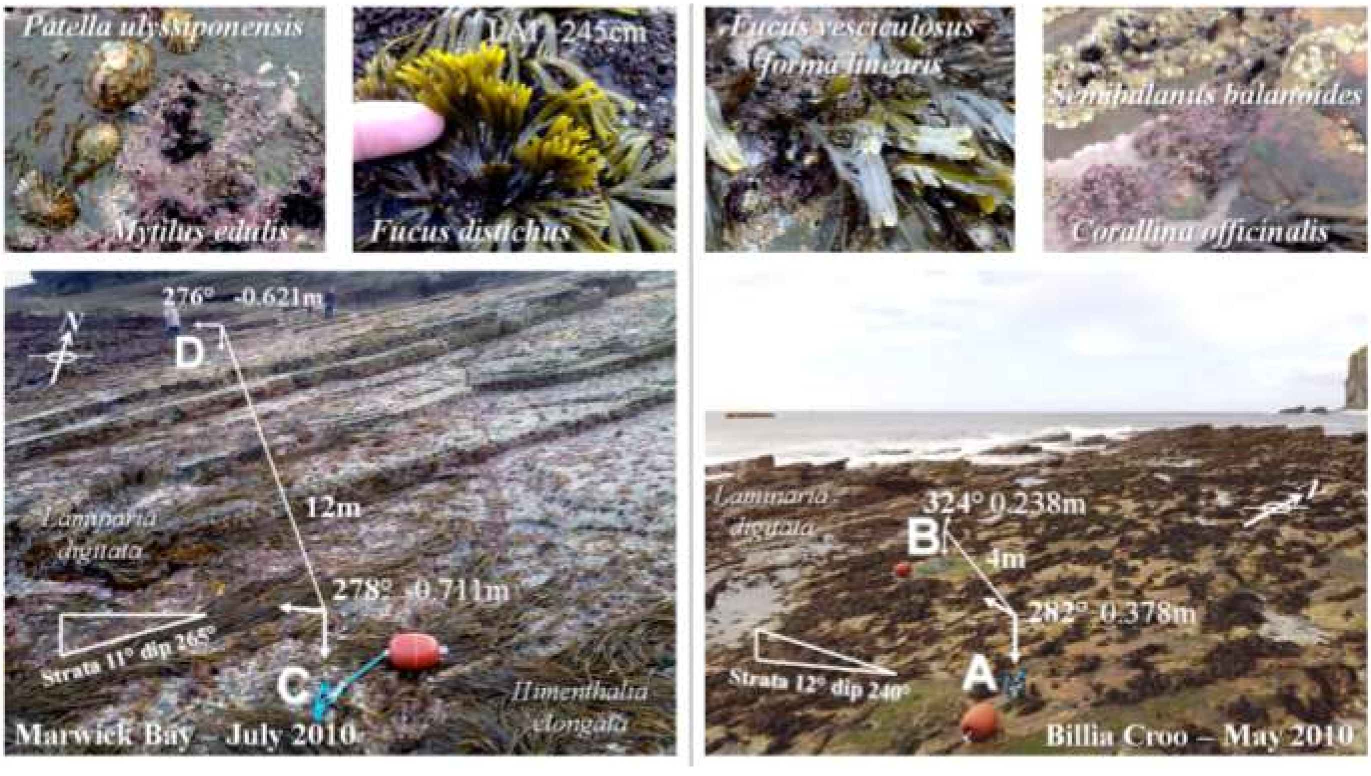

Figure 3 Site details and showing key species evident. Left - Marwick Bay. Right - Billia Croo (with Aquamarine 'Oyster' in background).

To achieve a comparable measurement of wave action between widely dispersed locations requires tidal height and atmospheric pressure data to calculate total immersion times of each device. For this research the Oregon State University Tidal Data Inversion Software (OTIS) for the European Shelf 2008 tidal model used was together with the TMD MATLAB toolbox. Local meteorological data from Kirkwall airport [12] provided the adjustment of tidal height due to the inverse barometer effect (IBE).

The total mass loss per installed hour was then calculated to allow the direct comparison between the two sites spaced 14 km apart. Variables that are related to wave action such as tidal height due to wind set up are not taken into consideration as the prime function of the device is the quantification of these changes in wind and wave interactions. Results given in units of mg per immersed hour (mgh_i) allow direct comparisons of wave action that can now be determined within in the intertidal zone. It can be seen in, figure 4, that there is a particular difference in values at the high energy occurring in the springtime but less difference during calmer weather. Allowing for small scale site differences these summer levels could be seen to be experiencing similar levels of wave action.

In addition to energy levels, the direction of the wave field impacting the shore can also be established by examining the material loss on the curved block. The determination of wave direction over a given installation period is carried out using a digital calliper to measure the thickness of the material at specific points along the block. For this study 8 points at 10 degree increments were used although finer detail could be used if needed. The peak direction was then plotted over time.

V. RESULTS

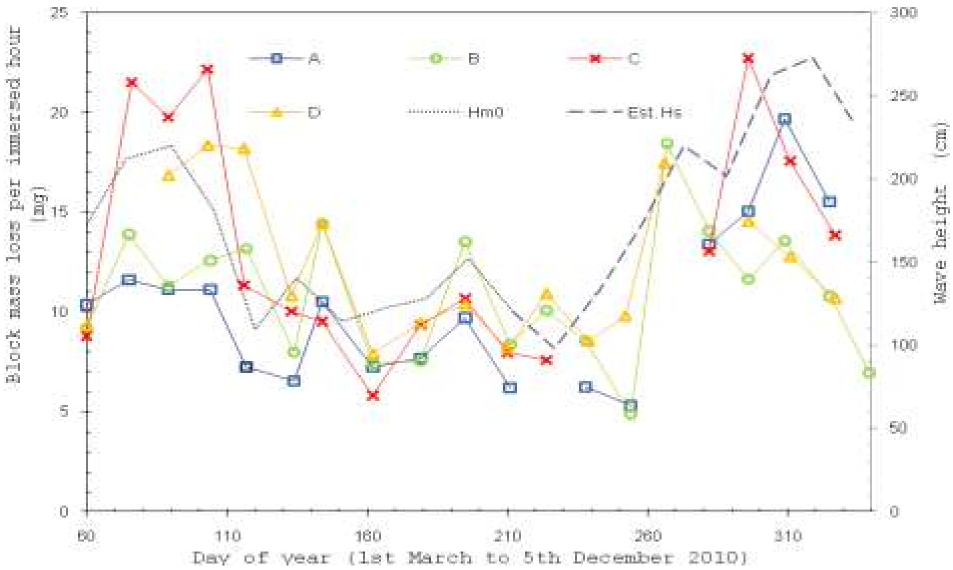

Figure 4. Terobuoy block mass loss per immersed hour (mgh_i) 1st Mar - 5th Dec 2010 with concurrent 2 week mean wave data: *Hm0* (EMEC) and estimated *Hs* (from day 210).

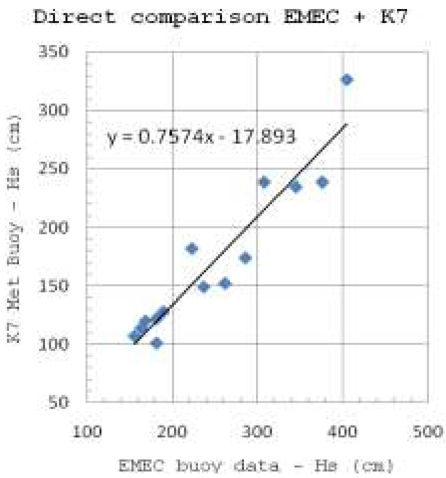

Figure 5. Direct comparison of 2 week mean average of both EMEC wave buoy and K7 MET buoy data (214 days of data over the May to November period).

Energy determination

Results from the West coast of Orkney shows good correlation (See figure 4) with significant wave height (H_s) and direction of concurrent and accurate 'Waverider' buoy data located at the EMEC wave energy test site located adjacent (just 2.3 km) to the Billia Croo study site [13] and Met Office data from the K7 buoy located 195 km NNE of the study sites [14] also initial modelled data for the EMEC site [15]. It can be seen that shoreline wave action is closely related to significant wave height with greater levels experienced during the winter months. Units A & B located at Billia Croo experience a relatively consistent level of wave action throughout the year at a level of 10 mgh_i. Whereas units C & D (Marwick) also undergo comparable levels during the summer months but are significantly higher during the winter months with unit C providing a measurement of 20 to 23 mgh_i. This occurs when average 2 week H_s, measured at the wave rider buoy location, is greater than approximately 1.5 m.

Total immersion times of bracket can be seen in figure 6, showing the bracket of units A & B (Billia Croo) being immersed between 35 – 50 % of installed time, whereas, units C and D (Marwick) were immersed for 70 – 80% of total time due to the lower installation height. This data has been calculated with the assumption of a still water level and does not take into account the wave run up from impacting wave so it would not give a good account of 'wetting' time as in reality in winter these levels will rarely be dry.

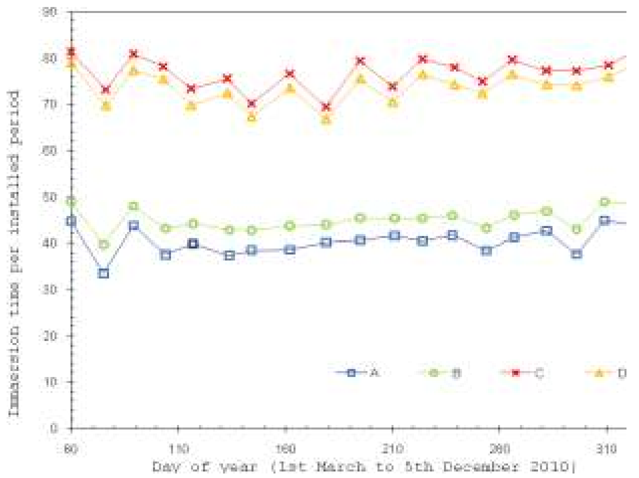

Figure 6. Immersion (underwater) time as percentage of overall installation time for each Terobuoy unit.

Directional determination

Figure 7 shows that wave direction between replicate units at each site are within 20 degrees. Particular events such as at day 150 with the wave buoy data indicated a westerly wave direction change to 285 degrees only impacted certain units.

This would indicate that at that the Marwick site significant refraction occurs to the propagating waves to change their onshore impact direction by 40 degrees. Only when offshore wave direction becomes more perpendicular to the shoreline does it produce measurable change. Higher H_s levels may be an additional directional forcing mechanism but does not seem to have provided any significant readings in the results.

Looking back at figure 4, average wave height was reducing before day 150 then slowly increased, which would indicate that unit D was susceptible to wave direction change even though there is no obvious reason for this difference from unit C only separated by 12 m. Again if we examine the results for unit A, this seems to register a difference in wave direction in line with the wave data yet unit B remains unaffected. It could be assumed that due to the topographical difference in roughness seaward of these intertidal rock surfaces it remains difficult to estimate with high accuracy, at least within 20 degree difference shown in figure 7, the mean wave direction for unmeasured adjacent sites.

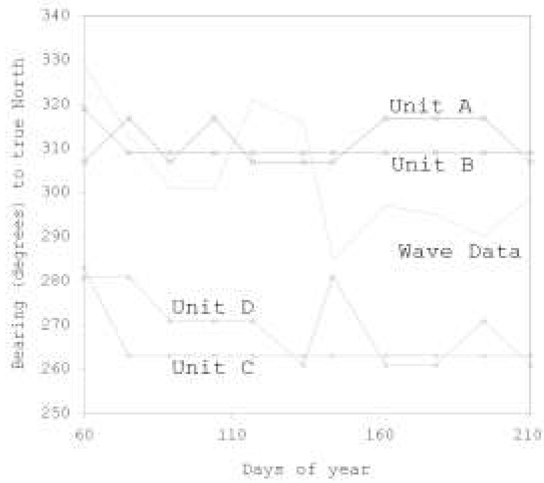

Figure 7. Peak directional determination over installation periods showing concurrent EMEC wave data.

VI. Conclusions

There are significant measured differences in received seasonal energy levels between two sites that are currently classified as equivalent. These levels are to some extent affected by changes in mean wave direction. Difference in installed shoreline height has been corrected for by calculating the results in mass loss, in grammes, per immersed hour.

Using the Terobuoy device can not only provide, for the first time, an economical monitoring strategy for the environmental impact assessment of the littoral zone due to the anthropogenic reduction of wave energy but can aid marine ecological research and the direct comparisons of internationally diverse studies into the distribution of species and global impacts from climate change.

The size of the device can also establish levels at an appropriate biological scale. Rocky shores have assemblages that form a patchwork of algal cover and in particular vertical flora and fauna zonation patterns. To assess the energy levels associated within these assemblages then measurements need to be taken within their spatial extents.

The current methodology allows the installation of units at spring low tides to enable safe working in an otherwise dangerous environment. This restricts the measurement interval to every two weeks (within the Orkney tidal regime) but there is the opportunity, where wave energy is reduced, to double the frequency by accessing the devices at mean low water allowing weekly measurements although, longer term installations are more suited to the average levels associated with biologically meaningful timescales.

Further research need to be carried out with Terobuoy installations positioned within all relevant stable biotopes that occur on the rocky shore, within the medium to higher energy levels, and listed in the EUNIS classification. This will enable the direct comparison of wave action between them and the possible biotic change that may occur when energy levels are reduced by WEC arrays.

VII. ACKNOWLEDGEMENTS

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