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Time scales and modes of reef lagoon infilling in the Maldives and controls on the onset of reef island formation

C.T. Perry[1], P.S. Kench[2], S.G. Smithers[3], H. Yamano[4], M.O'Leary[5], and P. Gulliver[6]
[1]Geography, College of Life and Environmental Sciences, University of Exeter, Exeter EX4 4RJ, UK
[2]School of Environment, The University of Auckland, Private Bag 92019, Auckland, New Zealand
[3]School of Earth and Environmental Sciences, James Cook University, Townsville, QLD 4811, Australia
[4]Center for Environmental Biology and Ecosystem Studies, National Institute for Environmental Studies, 16-2 Onogawa, Tsukuba, Ibaraki 305-8506, Japan
[5]Department of Environment and Agriculture, Curtin University, Bentley, WA 6102, Australia
[6]NERC Radiocarbon Facility (E), SUERC, University of Glasgow, East Kilbride G75 0QF, UK

ABSTRACT

Faro are annular reefs, with reef flats near sea level and lagoons of variable depth, characteristic of both the perimeter and lagoons of Maldivian (Indian Ocean) atolls. Their geomorphic development remains largely unknown, but where faro lagoons (termed *velu* in Maldivian) have infilled and support reef islands, these provide precious habitable land. Understanding the timing and modes of velu infilling is thus directly relevant to questions about reef island development and vulnerability. Here we use a chronostratigraphic data set obtained from a range of atoll-interior faro with partially to fully filled velu (including those with reef islands) from Baa (South Maalhosmadulu) Atoll, Maldives, to determine time scales and modes of velu infilling, and to identify the temporal and spatial thresholds that control reef island formation. Our data suggest a systematic relationship between faro size, velu infilling, and island development. These relationships likely vary between atolls as a function of atoll lagoon depth, but in Baa Atoll, our data set indicates the following faro-size relationships exist: (1) faros <~0.5 km^2 have velu that were completely infilled by ca. 3000 calibrated years B.P. (cal yr B.P.) with islands having established on these deposits by ca. 2.5 cal kyr B.P.; (2) faros >0.5 km^2 but <~1.25 km^2 have velu in late stages of infill, may support unvegetated sand cays and, given sufficient sand supply, may evolve into larger, more permanent islands; and (3) faros >~1.25 km^2 have unfilled (deeper) velu which might only infill over long time scales and which are thus unlikely to support new island initiation. These new observations, when combined with previously published data on Maldivian reef island development, suggest that while the velu of the largest faro are unlikely to fill over the next few centuries (at least), other faro with near-infilled velu may provide important foci for future reef-island building, even under present highstand (and slightly rising) sea levels.

INTRODUCTION

Faro are annular-shaped reefs with reef flats near sea level and lagoons (*velu* in Maldivian) of variable depth that are characteristic of both the perimeter and lagoons of atolls (Woodroffe, 1992). While rare at the global scale, faro are abundant in the Maldives (Indian Ocean), where more than 1000 are known, with their lagoons ranging from near empty to completely infilled. Although the origins of faro and the infill histories of velu are largely unknown, and indeed have been a source of speculation since they were first described by Darwin (1842), the timing of velu infilling has been implicated as critical for the formation of atoll-interior islands in the Maldives (Kench et al., 2005). Thus an improved understanding of faro development and time scales and rates of velu infill will help better resolve key questions about when and where reef islands form, and where they may establish in the future. These questions are relevant because of the perceived vulnerability of reef islands to sea-level rise (Khan et al., 2002; Woodroffe, 2008), and thus have direct application to ongoing attempts to better constrain variations in the timing of reef island formation.

There is increasing evidence that island formation is dependent on a number of factors that include relative accommodation depth (Kench et al., 2012), sediment supply (e.g., Perry et al., 2011), and the foundation types on which islands accumulate. In some studies islands have clearly formed on emergent reef flats (Woodroffe et al., 1999; Kayanne et al., 2011; Kench et al., 2012) and contemporary reef surfaces (Kench et al., in press) in the mid- to late Holocene. In the Maldives, however, evidence suggests that some islands formed directly over sediment-infilled velu rather than over established reef flats (Kench et al., 2005). In this alternate model, island initiation and establishment are critically dependent on the rate and timing of velu infill. Here we test this hypothesis using a chronostratigraphic data set encompassing a spectrum of faro with partially to fully filled velu (including several with islands) from Baa (South Maalhosmadulu) Atoll in the Maldives. We use this data set to determine time scales and modes of velu infilling, and to identify temporal and spatial thresholds that control reef island formation.

FIELD SETTING AND METHOD

The Maldives Archipelago comprises a double chain of 22 atolls (Fig. 1). These contain ~1200 reef islands and support a population of ~260,000 people. Our study focused on seven atoll-interior faro of varying size (0.08–1.3 km^2) within Baa Atoll (Fig. 1) in different stages of velu infill. In order of increasing velu infill/island development, these sites were: Kambaru Faru (KAM); Boatu Urunu Faru (BUF); Velaa Faru (VEF); Mendhoo (MEN); Dhakandhoo (DK); Thiladhoo (TH); and Hulhudhoo (HUL). Data from TH and HUL are drawn from Kench et al. (2005), as examples of small faro with fully filled velu and with vegetated islands (see Fig. DR1 in the GSA Data Repository[1]). At each site, we collected bathymetric data using a boat-mounted Sonarmite echosounder with connected differential GPS, and measured island morphology using a standard laser level. Multiple percussion cores were retrieved along transects aligned to the long axis of each faro; core sites encompassed the faro reef rim, lagoon, and, where present, the reef island (Fig. 1). Cores were recovered using aluminum piping (internal diameter of 9 cm), with rates and depths of core penetration recorded to ensure accurate vertical stratigraphic reconstructions. Cores were logged and sampled for biosedimentary facies analysis, and 83 ^{14}C dates were used to constrain the chronologies of velu infilling and island development (Table DR1 in the Data Repository).

FARO AND ISLAND STRATIGRAPHY

Bathymetric and topographic surveys show a clear relationship between faro size, degree of velu infill, and, where developed, the areal extent of island accumulation (Fig. 1). The two largest faro, KAM and BUF (1.29 and 1.27 km^2,

[1]GSA Data Repository item 2013308, Table DR1 (dates from cores from the Maldives), Figure DR1 (satellite images of study sites), and Figure DR2 (lagoon benthic habitats), is available online at www.geosociety.org/pubs/ft2013.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

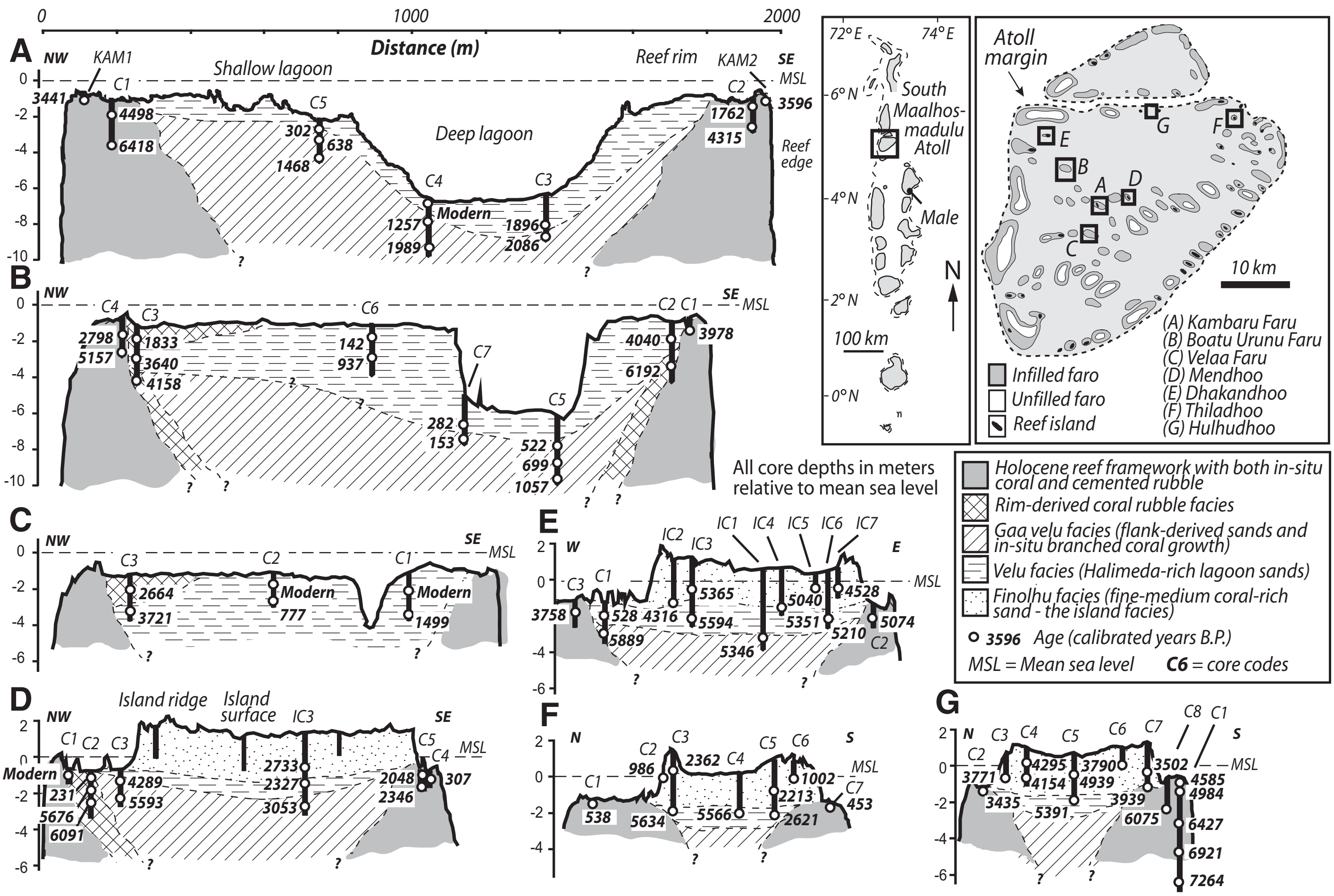

Figure 1. Stratigraphy and age structure of late stages of faro development across the seven study platforms in South Maalhosmadulu (Baa) Atoll (Maldives, Indian Ocean). A: Kambaru Faru. B: Boatu Urunu Faru. C: Velaa Faru. D: Mendhoo. E: Dhakandhoo. F: Thiladhoo. G: Hulhudhoo.

respectively; Figs. 1A and 1B), have only partially filled velu, while on the smaller faro (MEN, 0.34 km^2; DK, 0.22 km^2; TH 0.20 km^2; and HUL, 0.08 km^2; Figs. 1D–1G), the velu are completely filled and have well-established islands that occupy 20%–45% of their surfaces. These data imply an important relationship between faro size and evolutionary state.

Core data also reveal consistent late-stage velu infill facies based on differences in sediment texture and composition, and the presence and taphonomic condition of coral (*gaa*) framework. In cores from the velu of larger faro, and in the basal sections of some deeper cores through smaller faro, we identify a *gaa-velu* facies. This comprises a fine- to medium-grained coral and coralline algal sand, with abundant well-preserved branched *Acropora* sp. Branch orientations and coral preservation suggest these corals are largely in situ and equivalent to the coral thickets commonly observed across the contemporary velu seafloor (Fig. DR2). In the absence of a local sediment source, we interpret the sand matrix to be derived from shallower lagoon environments and/or the reef rim. The geometries of this facies are not well constrained but it clearly forms an important basal unit within the velu.

Consistently overlying the gaa-velu facies is the velu facies (described by Kench et al., 2005): a medium sand dominated by well-preserved (autochthonous) *Halimeda*. We make two observations about its occurrence. First, it represents the final phase of velu filling within central areas of faro, and secondly it can be a potentially thick (up to 5–6 m) late infill unit. Along the lateral margins of faro, and sometimes forming a sheet-like layer overlying the velu facies, is a unit of coarse-grained coralgal sands, with abraded and coralline-encrusted coral clasts derived from the reef rim (Fig. 1). Where islands are present they are composed of an island *finolhu* facies of fine- to medium-grained abraded coralgal sands (Kench et al., 2005).

CHRONOSTRATIGRAPHY

Dating of coral samples from cores and islands reveals variations in the timing at which faro reefs reached sea level, their velu infilled, and island accumulation began, with variations controlled by faro size. Reefs of the smallest faro (HUL, TH, and DK) were close to sea level ca. 5.5 cal kyr B.P., while on the two large faro (KF and BUF), earliest sea-level attainment is dated at ca. 4.0–4.5 cal kyr B.P. (Figs. 1 and 2A). We observe similar variability in the degree and timing of velu infill. The velu of the smallest faro (<0.25 km^2, HUL, TH, and DK) were completely filled by ~4.5 cal kyr B.P. (Fig. 2A), suggesting near-contemporaneous rates of infill as the platform margin reefs accreted. On MEN, which is slightly larger (0.35 km^2), complete infill occurred by ca. 2.5 cal kyr B.P. (Fig. 2A) and is also near contemporaneous with later reef attainment of sea level at this site. In contrast, the velu of the two largest faro, KAM and BUF, remain unfilled, with deeper lagoon areas to 7.0 m below mean sea level (msl) (Figs. 1 and 2A). Chronostratigraphic data from these deeper velu confirm infilling is ongoing and has shifted from gaa-velu to velu facies as expected during the latter stages of infill (Fig. 1). Velaa Faru, which is intermediate in size in our sample (0.74 km^2), is near full with only a shallow lagoon (~4 m below msl), and radiocarbon ages confirm that velu filling has been recent and is ongoing. A number of the (smaller) faro in our sample

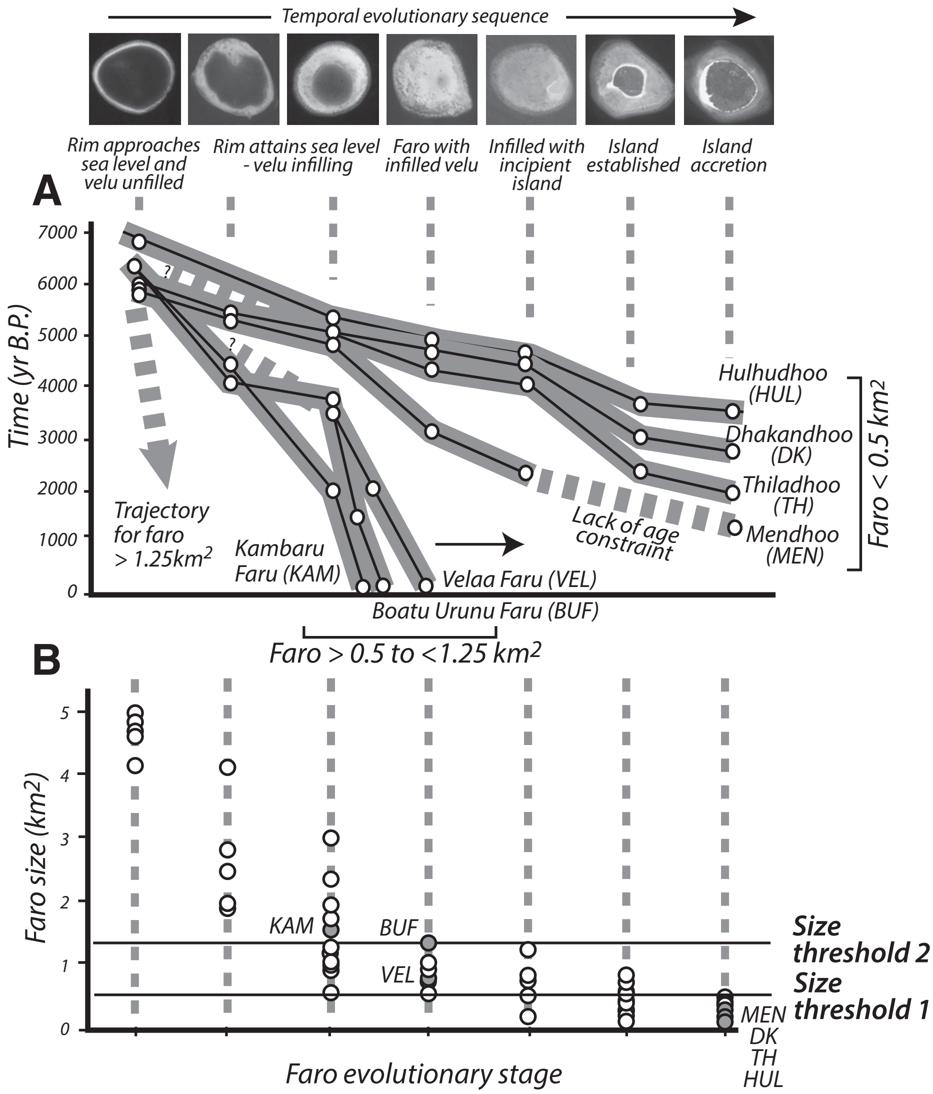

Figure 2. A: Faro evolutionary trajectories and time scale of change based on chronostratigraphic data from the seven sites examined in this study in Baa Atoll, Maldives. B: Plot of faro size against faro evolutionary state for all atoll-interior platforms in Baa Atoll. Remotely sensed images at top are indicative of different stages of velu infilling and are not to scale.

set have established vegetated islands that occupy varying proportions of their surface, from 21.4% (TH) to 54% (MEN). Although island area does not scale linearly to faro size, islands on the smallest faro are generally older and accumulated in a narrow temporal window from ca. 5.5 to 4.0 cal kyr B.P. (Figs. 1 and 2A). Mendhoo island, located on a slightly larger faro, appears to have initiated later, ca. 2.5 cal kyr B.P. However, in each case initiation of the island-building phase appears to have occurred soon after velu infill was complete. The two large faro, BUF and VEL, are devoid of vegetated islands, but both have small unvegetated and mobile sand cays on their southeastern margins that may represent incipient stages of island formation. If correct, this would imply that islands can start to form on near full, but not completely filled, velu.

MODEL OF FARO VELU INFILL AND ISLAND ACCUMULATION

Our chronostratigraphic and morphological results allow a model of velu infill and faro evolution to be constructed that provides new insights into modes and time scales of faro development, and how these relate to the timing of island initiation. These extend the “empty bucket” filling concepts developed for larger atolls by Purdy and Gischler (2005) and recently discussed by Schlager and Purkis (2013). We observe that faro evolution and island formation occur through a multi-phase sedimentary infilling sequence comprising both allochthonous and autochthonous deposition. Earlier and central velu infilling by a gaa-velu facies is followed by deposition of a *Halimeda*-rich velu facies that underlies island sediments. These deposits are augmented by localized sediment wedges comprising rim-derived coral rubble and coarse-grained sands. Of significance, we identify several size thresholds that have controlled velu infilling and the potential for island formation in Baa Atoll. Using island data (Fig. 2A) and size/area data for the other atoll-interior faro (with filled and unfilled velu) in Baa (Fig. 2B) we make the following observations. A first size threshold exists where faro area is less than ~0.5 km^2. Complete sediment filling of these velu occurred by 5.5–3.0 cal kyr B.P., and islands had established on the sediment infill by ca. 2.5 cal kyr B.P. (Figs. 1 and 2A). These faro are in late evolutionary stages (Fig. 2). Second, the velu of faro >0.5 km^2 but <~1.25 km^2 are either infilled or in late infill stages and may have sand cays (Fig. 2B). These may evolve rapidly in the future to form larger islands under appropriate sediment supply regimes. Third, the velu of faro >~1.25 km^2 have not completely filled and do not support islands (Fig. 2B).

These observations suggest a systematic relationship between faro size, velu infilling, and island development, and imply that there are two distinct size-related trajectories for faro systems in the Maldives, one of island formation and one under which the velu of faro are unlikely to fill sufficiently to support islands at any point in the near future. This is because as faro size increases the ratio of productive reef rim to lagoon area diminishes, thus increasing the reliance on autochthonous lagoonal sedimentation and, consequently, the time taken for faro to transit different infilling stages (Fig. 3). On smaller faro (<0.5 km^2), velu fill fast, and islands establish early and build rapidly. These islands are well established, have relatively stable cores, and are subject to seasonal and episodic peripheral reworking (Kench et al., 2005). On faro >0.5 km^2 (and <1.25 km^2) velu infilling occurs over longer time scales, and in most cases has only recently been sufficient to allow incipient island building. On these faro, continued island development is possible but dependent on sufficient sediment supply. As faro size increases further (>1.25 km^2) velu remain unfilled, and given the depth of the velu it is difficult to envisage sufficient sediment supply to fill these structures (and thus to allow island building) over any meaningful future time scale.

CONCLUSIONS

The data presented here illustrate important relationships between atoll-interior faro size in the Maldives, and the time scales and rates over which their lagoons (velu) infill to the extent where they can support island development. Furthermore, when combined with previous island geomorphic data sets (e.g., Kench et al., 2005), these findings suggest that faro with near-infilled velu may provide important foci for future reef-island building, and that this process will continue even under present highstand (or

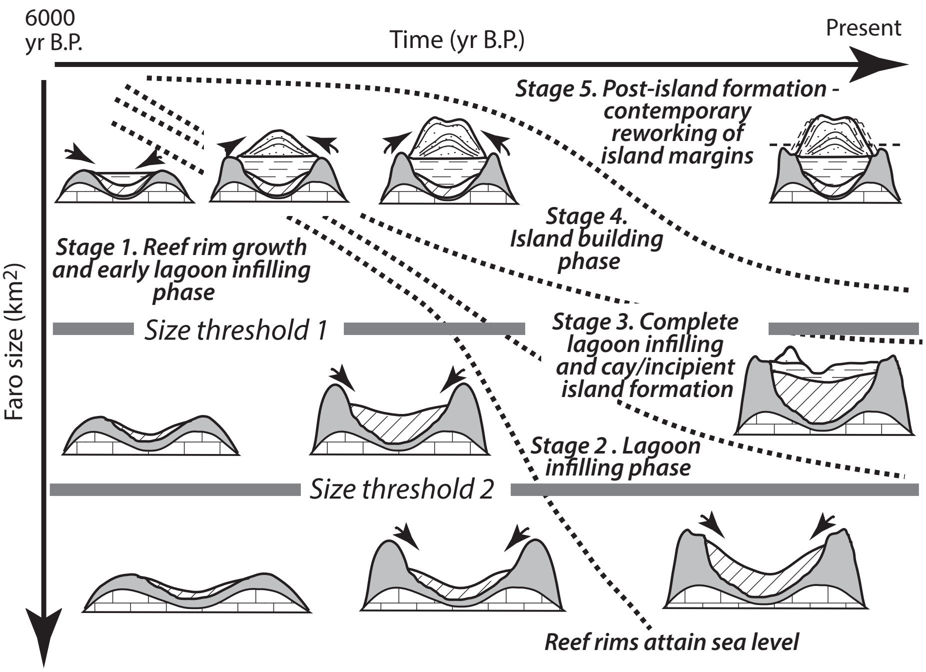

Figure 3. Schematic model showing relationship between faro size and age, and relationship to different stages of velu infilling and island building. Size and age are left unitless as these likely vary between atolls.

projected increased) sea-level states. The concepts and threshold models we present clearly require testing across atolls of differing depths, but we hypothesize that these will vary between atolls as a function of differences in depth to the atoll lagoon seafloor, Holocene reef growth history, and reef productivity. Thus, it is likely that atolls with a shallower lagoon bathymetry (Baa has an average lagoon depth of 48 m; Vescei, 2000) would have a greater proportion of faro with infilled velu and established islands as opposed to deeper atolls. Such differences are evident in the Maldives at the coarse scale where, in the shallowest atolls such as North Maalhosmadulu (mean lagoon depth 26 m; Vescei, 2000) and Thiladhunmathee (mean lagoon depth 29 m), most faro are at sea level, velu are fully filled, and large vegetated islands exist. In contrast, on the deepest atolls such as Kolhumadulu (mean lagoon depth 68 m) most faro either have not fully reached sea level and/or have poorly developed reef rims, and velu are unfilled and are devoid of islands. This would suggest marked spatial (inter-atoll) variability in faro evolutionary histories, in island ages between atolls, and thus clear variability in future island-building potential.

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