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Ecosystem service provision sets the pace for pre-Hispanic societal development in the central Andes

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1 Title: **Ecosystem service provision sets the pace for pre-Hispanic societal development in**
2 **the central Andes**

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10
11 **Abstract:** Human access to natural resources (or provisioning ecosystem services) is
12 controlled by climate conditions and usage. In the central Andean highlands, around Lake
13 Titicaca, water and woodlands have been critical resources for human populations over the
14 last 5000 years. During this time period human society developed of mobile hunter-forager
15 groups into settled agrarian populations (c. 3400 years ago) through to the rise of some of the
16 first ‘civilizations’ in the central Andes (c. 2500 years ago). Records of past environmental
17 and vegetation change reveal that coincident with these societal reorganizations were
18 variations in the availability of water and woodland resource. Prior to Hispanic arrival in the
19 central Andes (before A.D. 1532) changes in availability of natural resources are shown to be
20 concomitant with societal reorganizations; however, changes in societal organisation are
21 shown not to necessarily result in the degradation of ecosystem services (i.e. woodland
22 resource available). Through the last 5000 years three concomitant repeated adaptive cycles of
23 destabilization, reorganisation, growth and maxima are identified in human and ecological
24 systems. This suggests that long-term (>100 year) societal development was paced by both
25 increases and decreases in ecosystem service provision. The approach of past societies to

dealing with changes in baseline resource availability may provide a useful model for policy makers to consider in the light of the predicted scarcity of resource over the coming decades.

Keywords: archaeology, natural resources, palaeoecology, past environmental change, pre-Columbian, shifting baseline

A Introduction

The Lake Titicaca region of the Andes (Bolivia/Peru) has supported human populations for thousands of years and saw the development of one of the first civilizations in the central Andean highlands (c. 2500 years ago). However, the environmental background to the changing organization of Andean societies from mobile hunter forager populations, through small settled village communities onto urban civilizations remains ambiguous (Stanish, 2011). Today rural human population activity in the Titicaca region is limited by access to two key natural resources/provisioning ecosystem services: (1) water, and (2) woodlands. Rains are seasonal with 3-4 ‘dry’ months (<10 mm precipitation) and consequently human populations rely on seasonal snow and glacier melt to maintain agricultural production (Fjeldså and Kessler, 1996). The high Andean vegetation is dominated by grasslands which contain only patches of woodland. Woodlands are restricted to isolated, high elevation areas, and are dominated by the tree genus *Polylepis* (Fjeldså and Kessler, 1996). The patchy spatial distribution within the landscape forces rural populations to travel large distances to access timber resources for building and fuel. It therefore seems probable that variation in the availability of water and woodland resources would have been particularly important to people prior to the Hispanic ‘conquest’ of populations in the Lake Titicaca region (Bennett, 1946a), i.e. before the arrival of Pizarro on the continent in A.D. 1532 (Rowe, 1946). Understanding how pre-Hispanic societies dealt with resource change is particularly pertinent

given the similarities in land use practice with modern populations and projections of changing resource availability for the coming decades (Gosling and Bunting, 2008).

Throughout the last 5000 years the amount of both water and woodland resource in the Andes has varied in response to climate changes as well as human exploitation (Bush and Gosling, 2012). The impact of climate variation on regional human populations (10's kilometres) close to Lake Titicaca has been suggested to be potentially catastrophic on timescales of 10-100's years (Binford *et al.*, 1997). However, establishing causal links between societal change and the environment/climate on the basis of archaeological and past environmental change records is challenging due to the fragmentary nature of the evidence and the difficulty in constructing comparable chronologies (Bennett, 1946b; Calaway, 2005); consequently any suggested links are often subject to vigorous debate, e.g. Binford *et al.* (1997), Erickson (1999) Kolata *et al.* (2000). In addition, it is important to remember that people within landscapes are not passive and have the capacity to innovate when faced with changes to their environment, climate and/or ecosystem service provision. For example, palaeoecological evidence from three sites in the Cuzco region of Peru indicate that agroforestry techniques were deployed in response to landscape degradation in three separate instances during the last c. 1,300 years (Sublette Mosblech *et al.*, 2012). In interpreting past human-environment/climate interaction it is therefore necessary to be careful not to either: (1) assume that environment/climate determines human activity, or (2) disregard the influence of changing baseline environment/climate conditions on human populations. Given the fragmentary nature of the evidence available striking this balance is challenging.

In attempt to mitigate the uncertainty caused by the comparison of fragmentary records of different time resolution we have chosen to examine variation at the larger temporal and

spatial scales, i.e. by examining societal change alongside landscape scale environmental or climatic change (Fig. 1) (Gunderson and Holling, 2002). In this paper we combine archaeological data with records of long-term (100-1000's years) past environmental change to place pre-Hispanic societal reorganization within the context of variations in baseline ecosystem service provision (*sensu* Pauly *et al.*, 1998) across the Lake Titicaca region (100-1000's km²) (Fig. 2). The comparison of the societal development (derived from the archaeological record) and ecosystems service provision (inferred from records of past environmental change) over the last 5000 years reveal three coincident cycles of societal and ecological change.

A Materials and Methods

We selected four types of past environmental change record from the published literature from which we have extracted the pattern of change in water and woodland ecosystem service provision: (1) ice accumulation (Thompson *et al.*, 1998), (2) lake level (Abbott *et al.*, 1997; Abbott *et al.*, 2003), (3) calcium carbonate precipitate (Williams *et al.*, 2011), and iv) percentage abundance of the key woodland taxa *Polylepis* (Ybert and Miranda, 1984; Graf, 1992; Paduano *et al.*, 2003; Williams *et al.*, 2011). We do not attempt to reconstruct exact amounts of resource available in the past due to the great uncertainty in converting proxy records into actual numbers, e.g. it is very difficult to take a given abundance of pollen in the fossil record and quantify the amount of woodland area to which it related. Instead we use the proxy records to identify the trajectory of change in resource availability, i.e. a decrease in the amount of woodland taxa in the fossil pollen record equates to a reduction in the woodland resource available for people to use.

We also use the record of past environmental change to provide an insight into how people

were utilizing the landscape in the past. We present two types of data which give insight into human usage of the landscape: (1) charcoal (>180µm) (Paduano *et al.*, 2003; Williams *et al.*, 2011), and (2) *Sporormiella* or dung fungus (Williams *et al.*, 2011). We have chosen to present charcoal data for particles >180µm found in lake sediments because these data provide information related to fire activity close to the lake, i.e. large particles do not travel very far (Whitlock and Larsen, 2001). The abundance of *Sporormiella* within lake sediments is a function of lake level and the amount of herbivores present within the landscape (Raper and Bush, 2009). In the context of the Lake Challacaba study site presented here the abundance of *Sporormiella* is thought to most strongly relate to the numbers of camelids using the lake as a watering hole (Williams *et al.*, 2011).

A

Results

B

Evidence for change in societal organisation.

Archaeological records reveal three major states of pre-Hispanic societal organisation around Lake Titicaca during the last 5000 years: i) mobile populations engaged in hunting and foraging (before 3750 yr B.P.), ii) at least partially settled populations organised into village groupings with trade links and agricultural activity (c. 3250-2750 yr B.P.), and iii) urban centres containing complex social, political and religious structures often termed ‘civilizations’ (c. 2500 yr B.P. onwards) (Aldenderfer, 1998; Stanish, 2011). The transition from mobile hunter-foragers to more sedentary communities is evident in the archaeological record from the appearance of at least semi-permanent settlement sites at Chiripa, Pucara and Taraco (Fig. 2) from c. 3350 yr B.P. (Fig. 3Bb-d). The settled populations are closely associated with extended human capability to modify the environment at a landscape scale, e.g. widespread implementation of basic irrigation systems, Quinoa cultivation, crude pottery (Fig. 3Ab-e). Regional political organisation is indicated from c. 2500 yr B.P. with the growth

of a settlement at Chiripa and the widespread presence of complex storage, residential and religious structures (Stanish, 2011). The first evidence of the site of Tiwanaku (Fig.2) becoming a regional focal point dates from c. 2200 yr B.P. (Fig. 3e). Within a few centuries of the foundation of Tiwanaku the settlements at Chiripa, Taraco and Pucara declined while Tiwanaku continued to grow and reached a maximum population of 30,000-60,000 people c. 1200-950 years ago (Fig. 3Be). During the period of maximum population at Tiwanaku technological and agricultural practices were developed, including intensification of camelid pastoralism, commencement of silver mining, raised bed agriculture, and integrated flood and irrigation systems (Fig. 3Af-i). The gradual decline of Tiwanaku (c. 950-850 yr B.P.) saw power transfer into four regional polities (Fig. 3Bf-i) which developed new styles of monumental, funereal and defensive structures (Fig. 3Aj-k). Subsequently external rule was imposed by the Inka from c. 580-530 yr B.P. (Fig. 3Bj) and later the Spaniards in A.D. 1532 (Rowe, 1946).

B Evidence for change in ecosystem service provision.

Past environmental change records allow the reconstruction of the pattern of change in ecosystem service provision which have accompanied the last 5000 years of societal change. The availability of water resources in the central Andes is recorded by markers within ice and lake sediment cores which reflect change at different spatial scales. Around 5000 years ago the Andes emerged from a multi-millennial period characterized by increased drought frequency. This mid-Holocene dry event has been recognised across the central Andes (Bush and Gosling, 2012). Following the end of the mid-Holocene dry event the Lake Titicaca region became, on the landscape scale, gradually wetter (Fig. 3Ca-b). However, lake sediments which record changes in water level from in the wider region (Lakes Huiñamarca and Challacaba; Fig. 2) indicate variation in moisture balance was spatially heterogeneous on

100-1000 year timescales (Fig. 3Cc-d). Fossil pollen records obtained from lake sediments indicate that, at a landscape scale, the amount of *Polylepis* woodland within the grassland dominated landscape varied naturally in extent prior to the arrival of humans > 8,000 years ago (Erickson, 2000; Dillehay, 2008; Gosling *et al.*, 2009). Between 5000 and 2000 years ago *Polylepis* pollen constituted c. 8% of the total terrestrial pollen inputting into Lake Titicaca, but after 2000 yr B.P. this figure rarely reaches above 2%. High elevation (>4000 m asl) sites to the north-east (Katantica, Cotapampa, Amarete) and south-east (Chacalataya, Cumbre Unduavi, Rio Kaluyo) of the Titicaca basin do not record *Polylepis* as present during the last 5000 years (Graf, 1992) (Fig. 2); while to the south there is evidence for the persistence of *Polylepis* in the landscape for the entirety of the last 5000 years (Fig. 3Dc-e).

A Discussion

B Abundant resources and settled society.

The end of the mid-Holocene dry event is marked by the rise in Lake Titicaca water level from 5000 years ago (Fig. 3Cb) and the inception of Lake Challacaba at c. 4300 yr B.P. (Fig. 3Cd). The increased moisture availability coincides with the cultural transition from mobile hunter-foragers to more sedentary populations which were organised into coalitions of villages (Fig. 3Bc-d) (Stanish, 2011). The increases in local fire activity within this period of “wetter” climatic conditions (Williams *et al.*, 2011), strongly suggests that populations close to lakes were expanding, i.e. collecting, transporting and burning increasing amounts of wood (Fig. 3Db). However, the transition to more settled populations does not appear to have had a long-term detrimental impact on the woodland resources (Fig. 3Da) despite clear evidence for larger human populations (proliferation of villages) and increased resource use (buildings and charcoal). After 1000 years of relative cultural stability, around 2250 years ago, villages at Chiripa and Taraco began to expand and the settlement at Tiwanaku was founded (Fig. 3Bb,

d-e). The change in societal organisation marked the establishment of the first regional scale political organisation or ‘civilization’ (Stanish, 2011).

B Scarce resources, technological innovation and the centralization of societal organisation.

The reduced availability of water and woodland resources in the Lake Titicaca region from c. 2250-1750 yr B.P. spans a period which saw the gradual emergence of Tiwanaku as a consolidated single regional urban centre for societal organization. As Tiwanaku developed people diversified their economic activity and improved their use of the landscape, e.g. commencement of silver mining and advent of raised bed agriculture (Fig. 3Ag-i). The reduction in water availability from c. 2200 yr B.P. is likely to have been driven by external climate factors (Bush and Gosling, 2012). However, the decrease in woodland resources close to Lake Titicaca (Fig. 3Da), but not in the surrounding region (Fig. 3Dc-e), supports the suggestion that exploitation by the human population close to the lake was the likely cause for locally reduced woodland (Paduano *et al.*, 2003).

The gradual loss of both water and woodland ecosystem service provision is broadly coincident with the consolidation of disparate village based populations into the more substantial urban centre at Tiwanaku (Fig. 3Be). Due to uncertainties inherent with chronologies of the archaeological and past environmental change data, it is not possible to directly attribute specific decreases in resource availability as a ‘trigger’ which instigated societal change. However, it seems likely that the landscape scale (10-100 km) changes to baseline resources, as indicated from the past environmental change record, would have impacted the trajectory of societal change (100-1000 years), as suggested by the archaeological record, because of the populations’ reliance on environmental resources. In

addition, it seems plausible that the underlying environmental pressure could also, in part, have influenced the need, or desire, for people to diversify resource use (i.e. silver mining) and develop new agricultural practice (i.e. raised bed agriculture).

B Increased water resource and regionalization of societal power.

The positive accumulation balance for the Sajama ice core and deepening of Lake Challacaba indicate that regionally the water balance started to increase again around 1000 yr B.P. (Fig. 3Ca, d). Almost immediately there was an increase in regional camelid herding (Fig. 3Dg) as the site of Tiwanaku and its distal influence expanded to its maximum (Fig. 3Be). The rapid expansion of Tiwanaku suggests that the ephemeral societal structures that had developed during the preceding arid period meant that people were well placed to take advantage of increased water availability despite there being no recovery in woodland resources close to the lake (Fig. 3Da). After almost 1000 years as a significant centre of civilization in the central Andean highlands Tiwanaku began to gradually decline around 900 years ago and was replaced by numerous regional polities (Fig. 3Bf-i). The decline of Tiwanaku has been previously linked to both climatic (Ortloff and Kolata, 1993; Binford *et al.*, 1997) and societal pressures (Kolata, 1986). The information collated here is not at a sufficient temporal resolution to comment on the nature of any specific trigger for the decline of Tiwanaku; however, the environmental data suggest that the transition occurred within the context of a general increase in regional water resource availability.

B Abundant resource attracts inward migration.

Societies in the Lake Titicaca region were altered c. 580-530 years ago with the arrival of the Inka (Fig. 3Bj) who imposed an external control over the populations (Rowe, 1946; Hastorf, 2003). The desire for extra-regional Andean peoples' to control the Lake Titicaca region

indicates the presence of valuable resources. During the Inka period the Titicaca region remained an important regional centre within the empire, became part of an increasingly complex inter-connected Andean society (Stanish, 2011), and the more peripheral Cochabamba region (Lake Challacaba) became one of the centres for maize production (La Lone and La Lone, 1987). The brief period between the arrival of the Inka and Europeans in A.D. 1532 means that it is difficult to assess the relationship between Inka led society and ecosystem service provision. However, the continued population expansion (La Lone and La Lone, 1987) and extensive trade linkages (Knudson *et al.*, 2012) suggest that the peoples of the Lake Titicaca region continued to successfully manage the natural resources available.

B Long-term (>100 year) patterns of change in societal organization and ecosystem services.

The spatial and temporal disparity between the archaeological and past environmental change records considered places a fundamental limit on the inferences that can be drawn; for example we acknowledge that there is uncertainty on the dating control on many of the archaeological data (Fig. 3A and 3B). In an attempt to negate these concerns we focus on larger spatial and longer time scales (i.e. upper right portion of Fig. 1) and discuss the larger/longer term patterns of change rather than referring to specific events. To assess if the sequence of change observed in the archaeological and past environmental change record follows any regular pattern we will now consider the evidence presented within the context of “adaptive cycles” (Gunderson and Holling, 2002). Adaptive cycles are an element within the wider concept of “resilience theory” designed to aid understanding of ecosystems, agencies and people, based upon potential, connectivity, and resilience within a landscape (Holling and Gunderson, 2002). The ‘potential’ of a landscape relates to the opportunities for change that are present, i.e. are there resources present which can be better utilised or unlocked by a

technological advance, the ‘connectivity’ relates to the degree of linkages within the systems, and ‘resilience’ relates to the robustness of that system. As the amount of these various factors fluctuates within a system, a pattern of change occurs which can be summarized into four key states: i) release or destabilization of a system allowing previously ‘locked up’ resources to be released (Ω), ii) renewal or reorganization when system undergoes change (α), iii) growth and exploitation as resources are easily accessed (r), and iv) conservation or maximum connectivity as systems peak and resources are locked up (K) (Gunderson and Holling, 2002; The Resilience Alliance, 2002). The use of the adaptive cycle’s framework provides a concise way of describing the long-term (>100 year) complex interactions between humans and the environment (Fig. 4). In addition, the application of adaptive cycles to the record of past human and environmental change allows discussion to be placed in a language relevant to international policy development (Dearing, 2012).

The overall pattern of societal (Fig. 3A-B) and ecosystem service (Fig. 3C-D) development observed in the Lake Titicaca region during the last c. 5000 years show three repeated adaptive cycles (Fig. 3E). Increased water resources c. 3400 yr B.P. saw the destabilisation (Ω) of hunter-forager societies and reorganisation (α) into more sedentary village coalitions. The subsequent period of resource stability (water and woodland) resulted in growth (r) until a period of ‘maximum connectivity’ was achieved (K) and the first regional scale political and societal organisation in the central Andes was established (c. 2500 yr B.P.). The decline in woodland and water resources near Lake Titicaca c. 2200 yr B.P. resulted in another gradual destabilisation (Ω) and reorganisation (α) of societies. Societal organisation was consolidated into one regional urban centre (Tiwanaku), activity within the landscape diversified and new methods for maximising natural resource use were developed (r); despite low water and woodland resource availability. Technological advances and increasing water availability

culminated in the growth of Tiwanaku to its maxima by c. 1000 yr B.P. (K). Increase in access to water resource regionally from c. 1000 yr B.P. destabilised the region again (Ω), facilitated a regionalization of power and attracted the Inka into the region (α).

A Conclusions

The central Andean highland landscape has been modified by humans since their arrival over 8000 years ago (Erickson, 2000; Dillehay, 2008). Our synthesis of archaeological data and records of past environmental change reveals the pattern of background environmental/climate change to the human activity in the Lake Titicaca region over the last 5000 years. In terms of access to provisioning ecosystem services though the last 5000 years Andean people have had: (1) constant access to water resource (no evidence of extended regional drought) but have had to deal with major change in water availability at a landscape scale, e.g. arid event in the agriculturally important Cochabamba (Lake Challacaba) area (c. 2250-1750 years B.P.), and (2) relatively constant, albeit low level, access to woodland resource at the landscape scale; however, a decline in woodland resource is evident close to Lake Titicaca c. 2000 years B.P. co-incident with regional drying and the establishment of the urban centre at Tiwanaku.

Three coincident repeated cycles of adaptive response are evident within both the societal and environmental systems in the Lake Titicaca region. Increases and decreases in the availability of water and woodland resources are concomitant with repeated destabilization, reorganization, growth and maxima within pre-Hispanic societies. We suggest that the coincident long-term (100-1000 year) cycles demonstrate a sensitivity of the human populations to the shifts in the baseline availability of ecosystem service provision. Long-term change in baseline resource, either as a consequence of human or environmental change, on

100-1000 year timescale is likely to be unrecognised by individual populations (*sensu* Pauly *et al.*, 1998); however, long-term environmental change can still set the pace for societal change, i.e. ecosystem service provision underpins societal function. This environmental pacing of societal change does not imply environmental determination of the nature of that change. The diversity of societal responses to both increases and decreases in resource availability shown for the Lake Titicaca region demonstrates the complexity of competing interactions which are responsible for the societal changes. The ability of pre-Hispanic societies to respond to changing resource provision by reorganising political structures and diversifying/change landscape scale activity to release previously ‘locked up’ resources may provide a useful model for policy makers in the future. In particular adaptation to past reductions in water availability may be particularly pertinent in the light of predicted increases in the scarcity of water resource in the Titicaca region over the coming decades (Gosling and Bunting, 2008).

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Figure legends

Figure 1. Time and space scales of the high Andes related to environmental systems (white boxes), climate systems (black ovals) and humans (text in capital letters). Adapted from (Gunderson and Holling, 2002).

Figure 2. Topographic map of the Lake Titicaca region showing sites discussed in the text. Archaeological sites (circle, black): 1) Chiripa, 2) Pucara, 3) Taraco, 4) Tiwanaku, 5) Lupacas, 6) Pacajes, 7) Collas and 8) Omasuyus. Past environmental change sites (squares) from which data is presented (black): 1) Sajama, 2) Lake Titicaca (main basin), 3) Lake Titicaca (Huiñiamarca sub-basin), 4) Lake Challacaba, and 5) Monte Blanco; and other sites mentioned (white): 1) Amarete, 2) Chacalataya, 3) Cotapampa, 4) Cumbre Unduavi, 5) Katantica, and 6) Rio Kaluyo (Graf, 1992).

Figure 3. Societal development and natural resource provision in the Lake Titicaca region over the last 5000 years.

(A) Age of first evidence in archaeological record for: (a) camelid domestication (solid right triangle) (Lynch, 1983; Aldenderfer, 1998), (b) basic irrigation (solid square) (Zimmerer, 1995), (c) cultivation of Quinoa (*Chenopodium quinoa*) (solid left triangle) (Bruno and Whitehead, 2003), (d) crude pots widespread (solid circle) (Stanish, 2011), (e) wide-spread villages around lake (open circle) (Stanish, 2011), (f) camelid herding (open right triangle) (Pollard and Drew, 1975), (g) silver mining (cross) (Schultze *et al.*, 2009), (h) raised bed agriculture (Kolata, 1991; Erickson, 2000) (open left triangle), (i) integrated flood and irrigation canal system (open square) (Zimmerer, 1995), (j) Chulpa funeral towers (solid half circle) (Janusek, 2008a), and (k) Pucara fortified hilltops

(open half circle) (Stanish, 2011).

(B) Duration of archaeological periods and sites discussed in text: (a) terminal archaic, (b) Chiripa, (c) Pucara, (d) Taraco, (e) Tiwanaku, (f) Lupacas, (g) Pacajes, (h) Collas, (i) Omasuyus, and (j) Inka (Hyslop, 1977; Hastorf, 2003; Janusek, 2008b; Janusek, 2008a; Stanish, 2011). Duration of period/site indicated by lines with societal peak indicated by a thick line. Catastrophic fire events within archaeological sites indicated by (*) below line.

(C) Palaeoenvironmental records of water resource availability: (a) ice accumulation at Sajama (Thompson *et al.*, 1998), (b) Lake Titicaca (main basin) level (Abbott *et al.*, 2003), (c) Lake Titicaca (Huiñiamarca sub-basin) lake level (Abbott *et al.*, 1997), and (d) Lake Challacaba calcium carbonate (Williams *et al.*, 2011).

(D) Palaeoenvironmental records of woodland resource and fuel usage in the Lake Titicaca region over the last 5000 years: (a) Lake Titicaca *Polylepis* (Paduano *et al.*, 2003), (b) Lake Titicaca charcoal (Paduano *et al.*, 2003), (c) Sajama *Polylepis* (Ybert and Miranda, 1984), (d) Monte Blanco *Polylepis* (Graf, 1992), (e) Challacaba *Polylepis* (Williams *et al.*, 2011), (f) Lake Challacaba charcoal (Williams *et al.*, 2011), (g) Lake Challacaba *Sporormiella* (Williams *et al.*, 2011). Feint lines are x5 exaggeration.

(E) Application of adaptive cycles to explain the transformations observed in the societal and natural systems: destabilization (Ω), reorganization (α), rapid growth (r) and maximum conservation/connectedness (K) (Gunderson and Holling, 2002). Vertical bars highlight correlation across archaeological and palaeoenvironmental records.

Figure 4. Adaptive cycle loop showing connections between system states identified in the Lake Titicaca region (solid white arrows), and other potential conceptual connections (dashed white arrows). Adapted from (The Resilience Alliance, 2002).

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488 **Figure 1**

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495 **Figure 3**

Figure 4

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