Settlement location models, archaeological survey data and social change in Bronze Age Crete

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Abstract (182 words)

This paper builds spatial models of Bronze Age settlement using published survey datasets from the Mirabello region in east Crete. Methodologically, we examine how point process modelling can account for uncertainties in legacy survey datasets, and thereafter can highlight patterns of both cultural change and continuity in Mirabello settlement. Comparison of fitted models over different chronological periods gives an insight, we argue, into the kinds of settlement and subsistence choices that lay behind settlement patterns, holding constant the broadly similar environmental constraints faced by inhabitants throughout the Bronze Age. Overall, the results suggest prehistoric preference for, and exploitation of, agriculturally favourable parts of the landscape, although contrasting emphases in different periods do emerge despite this unsurprising overall preference. Many of the analytical results prove robust to a sensitivity analysis which addresses commonplace uncertainties associated with settlement survey data. The results also dovetail well with previous archaeological interpretations of changing settlement and Bronze Age life in the Mirabello region. Survey datasets are also relatively common in other archaeological settings worldwide and we advocate for more widespread application of similarly formalised methods to them.

Keywords: archaeological surface survey; point-process modelling, legacy data, Bronze Age Crete

1. Introduction

This paper explores the degree to which multiple published survey datasets can be formally synthesised to reconstruct Bronze Age settlement patterns and to discern changing locational priorities through time. As a substantive case study, we consider three published Cretan surveys from the Bay of Mirabello. In what follows, we refer to the results from these and other moderately intensive field surveys from the 1970s to 2000s as ‘legacy data’ to indicate that, although they have involved knowledgeable specialists and careful methods, they have typically been published only as hard copy distribution maps and site-level summaries, rather than as artefact-scale collections and georeferenced digital databases. Without artefact-level distributions, there are limits to how much survey datasets can be interrogated for issues such as sampling bias and relative survey intensity, as well as surveyor judgements of site size, phasing and function, etc., but even so, legacy surveys are still extremely valuable records and constitute the bulk of the better-published evidence worldwide. They have also arguably not received as much assessment and comparative analysis as they should. With these methodological goals in mind, this paper therefore re-purposes three well-published surveys of the Bay of Mirabello, Crete to build contrasting models of Cretan Bronze Age settlement in the Late Prepalatial (EM III-MM IA), Protopalatial (MM IB-II), Neopalatial (MM III-LM IB)[1] and Postpalatial (LM IIIA-IIIB) periods, and thereby to discuss the relative significance of external and internal processes on the Bronze Age occupation history.

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[1] General chronological note. Neopalatial ceramic phases delineated in the survey data include MMIIIA, MMIIIB, LMIA and LM IB. It should be noted while the Neopalatial period generally started at the beginning of the MM IIIB period, there is certainly not enough known about regional coarseware pottery to differentiate between MM IIIA and

An explicitly diachronic study of survey data can highlight fluctuations between centralisation and fragmentation, variations in settlement size and overall demographic levels in different areas of the landscape. In this paper, we discuss the current state of Cretan research and how spatial simulation can address certain lingering challenges in using Cretan survey data. In particular, we examine how computational models can account for uncertainty in survey datasets, and we use this flexibility to highlight both change and continuity in the Mirabello system in relation to wider processes across Crete.

2. Research Context

2.1 Bronze Age state formation

For over a century, Cretan archaeological research has worked with relatively well-established interpretive frameworks to understand Bronze Age social, economic and political organisation, largely based on the traditional convention that the prehistoric territories of Crete were centred around the major palaces of Knossos, Malia and Phaistos (Cherry 1984, 1986; Renfrew 1972; Schoep 2001). Research has variously studied the extent of the palaces' socio-political and economic control through production and consumption patterns of material culture, written evidence from administrative records, and more recently, through the relative distribution of other Bronze Age sites across the island. Challenging these conventions are discoveries over the last few decades of similarly 'palatial' structures that appear and then fall out of use at different times and in a wider set of places across the island (Whitelaw *in press*), highlighting greater variability in the extent of palatial systems than first thought (Adams 2006; Knappett 1999; Schoep 1999), and in the processes structuring regional settlement (Schoep 2001; Whitelaw 2004). Moreover, while the role of palaces within prehistoric society was traditionally thought to have remained relatively constant from their inception in the Protopalatial period onwards (Renfrew 1972; Cherry 1986), recent reassessments questioned the nature of political authority and the social interactions they supplanted prior to the palatial period (e.g. Driessen et al. 2002; Hamiliakis 2002; Whitelaw 2004; Schoep 2006), as well as whether socio-political transformations in the Bronze Age were gradual or rapid (Cherry 1983; Schoep 1999; Driessen 2007; *cf*. Manning 1997; Watrous 2001; Whitelaw 2012). The emphasis on urban centres as central places has not only left interpretive voids about the nature of society in pre- and post-palatial (and dramatically less urbanised) periods, but also in our understanding of the relative position of smaller sites and those more marginal settlement networks seemingly outside of direct palatial manipulation from central Crete, especially during the Middle Bronze Age.

There has been an intense focus on the nature of political organisation in Bronze Age Crete from the very beginnings of Aegean archaeology and arguably a renewed emphasis from the late 1970s onwards (Cherry 1978, 1983, 1984). In his study on Protopalatial state formation, for example, Knappett (1999:616) charts the shift in Minoan archaeology from use of the term 'civilisation' to use of the term 'state', noting nonetheless a continuing obsession with the origins rather than the character of these political units. Others note that as there is no direct evidence for a state in Bronze Age Crete (i.e. declarative ruler iconography or writings, deciphered written records of central administration), we have been forced to build inferences from landscape evidence, architecture and material culture alone. As a consequence perhaps, Cretan research has instead focused on redefining the state to include these caveats (Cunningham and Driessen 2004: 106): rightly or wrongly, we have blurred the idea of how any Minoan state(s) may

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IIIB in the surface material, and indeed even distinctions between MMIII and LMI should be treated with caution given the small proportion of the surface record upon which such distinctions are likely to have been made.

have operated in the past to match the blurriness of our present-day understanding, taking present uncertainty for past ambiguity. Even so, there is clearly some form of centralised organisation and integration of capital, and the overall idea of political life being in some way manifest on the ground, and on the pots, has remained very important, with numerous studies using stylistic similarities in material culture to demarcate territories (Knappett 1999), to suggest diverse exchange networks (Whitelaw et al. 1997; Sbonias 1999; Wilson and Day 2000) and/or settlement patterns (Driessen 2001; Haggis 2002) and to changing administrative practices (Schoep 1999, 2012; Knappett 2012; Relaki 2012; Sbonias 2012) .

More precisely, Cretan studies using survey data have reconstructed the socio-political organisation of different Cretan regions under this assumption that the spatial organisation of sites in some way mirrors the political organisation of society (Driessen 2001: 56). Thus, the explosion of settlements in the Protopalatial period is largely seen as part of the emergence of a palatial system (Nowicki 1999; Sbonias 1999), and an observed decline in overall site numbers in the subsequent Neopalatial period as a process of nucleation, and a further concentration of power at a limited number of palaces, indeed conceivably with overall political authority concentrating at Knossos (Amato et al. 2014: 131; Cunningham and Driessen 2004; Whitelaw *in press*). Although any political hierarchy probably requires "some form of hierarchical [spatial] ordering" (Bevan 2010: 28, see also Cherry 1986; Cadogan 1994; Cunningham and Driessen 2001; *cf*. Manning 1995; Knappett 1999; Adams 2006 who distinguish different kinds of power), this ordering is dependent on the scale and form of the interaction. While discussions of political power have loomed particularly large in studies of Bronze Age Crete, other demographic and/or economic factors, operating at scales independent of or parallel to political systems, could have had influenced the distribution of settlements within a region (Reid 2007; Müller-Celka et al. 2014; Whitelaw *in press*).

Computational simulation has both strengths and weaknesses as a contribution to archaeological understanding, but at its most useful, it allows us to model *our understanding* of how settlement systems are spatially ordered, and how they can reflect certain human prioritisations in the wider environment which might relate to fundamental issues such as day-to-day subsistence. Surprisingly, while interpretative associations between sites and particular landscape features are common in Cretan regional studies, quantitative attempts to address these relationships are rarer (although see Bevan and Wilson 2013; Déderix 2017; Fernandes et al. 2012; Knappett and Ichim, 2017*;* Paliou and Bevan 2016). Arguably, this slow development stems from a patchy set of surveys with different recovery biases and from individual sites' inherent chronological and functional uncertainties. That said, the Mirabello region has been especially favoured by three high quality surveys – Vrokastro, Kavousi and Gournia – that offer one of the best case-study areas anywhere on the island and therefore are the focus of what follows. These surveys were conducted in the late 1980s and early 1990s using similar field methods and immediately adjacent to one another, thereby encouraging their integration into a single dataset (see also Gaignerot-Driessen 2016 for study of later periods). We characterise them nonetheless as 'legacy' surveys not with the intention of diminishing their contribution, but only to stress that sites are the main unit of recording and publication, and there is no easy opportunity to assess artefact-scale issues of site size, function and definition.

Taking these surveys as a yet under-explored opportunity, we apply a point process modelling approach to explore correlations between site locations and key exogenous environmental influences (what statistically would be known as *first-order* trends) while also modelling endogenous forces of attraction/repulsion between sites (aka *second-order* trends e.g. Baddeley et al. 2016). Such correlative models are not meant immediately to imply cause-effect relationships, but they do encourage further speculation about human locational priorities and kinds of social-spatial organisation in the landscape. In this we would argue the approach adopted here is in step with arguments in favour of seeing social processes operating at multiple scales, and change as occurring not only through top-down models of static palatial entities (Cherry 1986; Schoep 2002), but also via local human ecological circumstances (Hamilakis 2002; Haggis 2002; Schoep and Knappett 2004; Whitelaw 2004).

2.2 Setting and Survey in the Mirabello

The Mirabello region is defined by a large embayment on the eastern end of Crete, beyond the Lasithi mountains, and is positioned on the northern side of the island's narrowest north-south point (the isthmus of Ierapetra). As such, it has arguably always exhibited elements of both affiliation with and autonomy from politically 'core' areas of central Crete, and has acted as both bridge and barrier to wider Cretan island interaction. Viewed in terms of off-island contacts through time, it arguably has had some of its strongest links with the Cyclades to the north, but not necessarily the wider Mediterranean contacts boasted by north-central coastal sites or those in the far east. Of the three survey areas considered below, Kavousi is the easternmost (**Figure 1**; Haggis 1996, 2005) and consists mostly of a large fertile alluvial plain protected from the sea by a small coastal ridge, and the archaeologically surveyed region is bounded on the eastern side by the bare eroded slopes of the Sitia massif. The Gournia survey area west of this (**Figure 1**; Watrous et al. 2012) includes the coastal area around the palatial town site of Gournia, and follows the extension of the Ierapetra-Vasiliki-Kavousi plain towards the south coast. Despite detailed work on the Neopalatial settlement history of the town and hinterland, there are no definitive theories on the nature and character of its political, economic or ideological influence on the outlying areas in its region during this period (*cf.* Soles 1992; Haggis 2002). The Vrokastro survey area (**Figure 1**; Hayden 2003, 2004, 2005) makes up most of the southwestern portion of the bay, and extends beyond the coastal area into the rural uplands to the south. Together they form an area that covers the northern half of the Ierapetra isthmus, and the coastal plains and low uplands of the Lasithi region overlooking the Bay of Mirabello.

Figure 1.

For the purposes of this paper, we have combined published data from some 263 single- and multi-phase occupation sites across all three survey regions. These sites were published in their respective survey catalogues as belonging to one or more of the ceramic phases dated between approximately 2200-1200 cal BC (**Table 1**). We have extracted the stated period of occupation, site size and site type[2] from the published reports and added these as vector polygons and attributes to a spatial database. Each phase of a multi-period site was given a phase-specific polygon following the mapped site area where available or an arbitrary buffer where only a site centre and size were published. This produced a total of 488 single-phase polygons that could be variously grouped by survey, period or size.

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[2] Site type was used to exclude clear non-habitation sites (e.g. tombs, caves) from the dataset so as to reduce noise in the spatial analyses of *settlement* patterns. Otherwise, due to difficulties in the field defining types of sites on the basis of surface material (e.g. farm or field house), all habitation sites were treated equally in this analysis.

Period	*Ceramic Phase*	*Approx. Duration*	*Estimated Absolute Dates*
Final Neolithic		1500 years	4500-3000 cal BC
Prepalatial	EM I – II	800 years	3000-2200 cal BC
Late Prepalatial	EM III – MM IA	250 years	2200-1950 cal BC
Protopalatial	MMIB – MM II	150 years	1950-1800 cal BC
Neopalatial	MM III – LM IB	310 years**	1800/1700-1490/1430 cal BC
Third Palace/Postpalatial	LM II *	60 years**	1490/1430-1430/1390 cal BC
	LM IIIA – LM IIIB	230 years**	1430/1390-1200/1190 cal BC
	LM IIIC	120 years**	1220/1190-1100 cal BC
Sub-Minoan		100 years	1100-1000 cal BC
Proto-Geometric		200 years	1000-800 cal BC
Geometric		100 years	800-700 cal BC
Orientalising – Archaic		200 years	700-500 cal BC
Classical		175 years	500-323 cal BC
Hellenistic		250 years	323-66 cal BC
Early Roman		500 years	66 BC – 400 cal CE
Late Roman		300 years	400-700 cal CE

** Late Minoan II is not recognised in the survey material; only LM IIIA-IIIB material provides the evidence for the Postpalatial period in the Mirabello.*

*** Approximate duration of phase for these phases are taken from the high chronology for the Late Bronze Age (see Momigliano 2007: 7 for more detail).*

Table 1. Table depicting the different time scales used as chronological attributions in the survey, periods discussed in this paper are shaded grey. The Mirabello surveys attributed sites to ceramic phases. The duration of each phase follows conventions from Manning 1999, the estimated absolute dates (calibrated ^{14}C) follow those used in Momigliano 2007 and Watrous et al. 2012.

As this analysis uses data published at site-level, similarity in on-site sampling methods (running cross transects through notional site centres, samples collected at specified intervals) justifies their amalgamation into a single dataset. While any spatial uncertainty from variation in site size definition could be not explored with the published information, **figure 2** illustrates the similarity in site-size estimations across the Mirabello surveys, further validating a regional dataset.

Figure 2.

One major interest of this paper is in the relationship between the spatial density (hereafter we will prefer the more common statistical term ‘spatial intensity’) of sites in a given period as correlated with various environmental variables and how this environmental relationship changes *between* periods over the Bronze Age. However, the fact that our sites are dated by allocating them to large, discretely-expressed but fuzzily bounded, time-blocks of varied duration has unfortunate consequences for what we can and cannot say. For the Mirabello surveys, the smallest temporal unit to which any given site can be allocated is determined by ceramic phases, and while all three surveys use mostly similar chronological conventions, these time periods are not of equal length (**Table 1**), making assessment of diachronic change difficult. Being able to identify different tempos of change and being able to identify whether a transformation in human-environment relationships was rapid or gradual can be problematic when we depend on such modern coarse-grained categorisations of prehistory. While we cannot necessarily improve our chronological certainty without taking many scientific dates or developing a major new programme of artefact study, several studies have shown that probability measures are nevertheless a useful way to retain, manage and interrogate temporal uncertainty in site survey datasets (e.g. Bevan et al. 2013b). One approach, in the case where site dating has already been assigned and cannot be easily reinvestigated, is to divide periods into equivalent time-blocks and assign likelihoods of site presence based on the number of time-blocks assigned to each period (*e.g.* Brughmans and Poblome 2016; Crema 2012; Crema et al. 2010; Fentress and Perkins 1988; Willet 2014). Here we go slightly further and use random sampling methods and simulations of spatial statistical models *within* periods; this works partially to counteract any incomplete patterning from temporal uncertainties and also acts as a barometer of confidence in interpretations of the changing nature of prehistoric settlement systems. This method also addresses intra-period variability and longevity of sites more indirectly, where smaller sites (with lower likelihoods of site longevity throughout a single period) are more variably chosen by the sampling method and thus play a more varied role across the simulated settlement models.

3. Data and Methods

Amongst a potentially huge range of possible variables to consider in relation to site location, we have prioritised those (**Figure 3**) that are likely to have impacted regional subsistence strategies (*e.g*. agricultural/pastoral, coastal/mountainous environments), and have already been highlighted in a more qualitative way by the published survey reports. However, such choices have been further limited by the practical constraints of available data. For example, it would be nice to consider the distance from a given site to the nearest freshwater source, but past spring locations are too uncertain and variable to be captured easily via modern proxies. Instead, we cautiously consider the border zone between hard limestone bedrock and other geologies both for its impact on soils and stone resources, and because this is a geological boundary at which freshwater springs often occur naturally (this association was noted in the Vrokastro study area, Hayden 2004: 105). For better or worse, similar compromises and decisions are embedded in the choice of the other variables in what follows. Each variable is a continuous number series that has been rescaled for better direct comparison of their relative effect (**Table 2** for list of changes; for further justification see Bevan and Conolly 2009).

Variable	***Source***	***Processing***
Elevation	15m horizontal resolution DEM (Chrysoulaki et al. 2004)	Square root transformation, rescaled to [0,1]
Slope	Derived from DEM (first derivative surface)	Log transformation, rescaled to [0,1]
Aspect	Derived from DEM (directionality of slope)	Converted into degree difference from south-facing, rescaled to [0,1]
Size of flat catchment	Reclassification and map algebra on Slope raster	Rescaled to [0,1]
Topographic Wetness Index value	Derived from DEM (second derivative surface), calculated in GRASS GIS using the *r.topidx* function	Square root transformation, rescaled to [0,1]
Euclidean distance to coastline (m)	Reclassification and map algebra on original DEM	Square root transformation, rescaled to [0,1]
Distance in or out of hard limestone outcrop (m)	Reclassification and map algebra	Rescaled to [0,1; 0.9 is limestone border]
Fuzzy classification of ridge landscape feature	Calculated from DEM using Landserf over geomorphometric windows up to 545 sq.m	Already [0,1]

Fuzzy classification of channel landscape feature	Calculated from DEM using Landserf over geomorphometric windows up to 545 sq.m	Already [0,1]
Local visibility	Cumulative calculations of results from ray-tracing algorithm on DEM	Rescaled to [0,1]
Long-distance visibility	Cumulative calculations of results from ray-tracing algorithm on DEM	Rescaled to [0,1]

Table 2. Transformations of environmental covariates used as input to fit the logistic regression models.

Figure 3.

3.1 Spatial logistic regression models

To consider the nature of human-environment relationships in each chronological phase, we build logistic regression models of site presence/absence data as dependent on a set of environmental covariates (Baddeley et al. 2016: 355-359). Regression analyses are used in our study to explore first-order trends to establish whether there are any correlations between site presence (or absence) and the values of the underlying landscape (our variables).

To address uncertainties in the survey data, we also adopt a bootstrap sampling method[3] (for wider discussion, Fox 2013) and generate not just one fitted model but 1000 different models, each with slightly randomised site and non-site locations. For the 'site' (i.e. presence) locations, points were simulated within the observed settlement polygons in an area-dependent way (**Figure 4a**): first, an initial sample point was assigned to each site to ensure all sites are represented at least once in the model, then additional points were simulated in each polygon for every extra 0.1 hectare of land. Although the behavioural assumption in this area-dependent sampling is not crucial, we might choose to think of it as a simulation of hypothetical households within each site, or a simulation of the density of human activity in the region. For the 'non-site' (i.e. absence) locations, we consider below two approaches to randomisation: (i) allowing non-sites to be chosen anywhere in the wider landscape and (ii) restricting non-site points to be randomly chosen from within the extents of sites occupied in any other period than the period in focus. These approaches produce starkly different site absence patterns that can tease out important differences when the models are contrasted. While the results are still ultimately limited by the quality and relevance of the chosen environmental variables, the above approach tests for robustness across different simulations rather than offering a single model for settlement locational logics.

Figure 4ab.

3.2 Pair correlation functions

Although the primary focus of this study is the modelling of settlement systems in relation to external environmental factors (first-order), we also briefly model the internal (second-order) structure of selected settlement distributions. Exogenous influences on settlement (the results of the regression models), such as a preference for rich alluvial soils, are very different to endogenous interactions between sites that affect how close or far apart communities choose to be from one another (e.g. within that preferred alluvial area). Not considering both effects together can produce misleading interpretations of patterns that are already complicated by several other spatial analytical challenges (for wider discussion, see Crema et al. 2013; Premo 2010). To consider second-order effects in any given chronological period, a hypothetical set of site locations is simulated at random across the study area.

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[3] Bootstrap sampling uses the observed settlement pattern to estimate the distribution of a complete settlement pattern in the region. In order words, each settlement pattern simulation is the product of randomly selected locations from within the extent of all the sites, and regression analyses were run on the locational characteristics of those locations against randomly selected locations in unoccupied areas within the survey region.

In similar vein to the settlement patterns produced via logistic regression, simulated site distributions provide a background dataset whose propensity for the clustering or dispersion (second-order effects) can be compared against the clustering or dispersion of the real observed settlement pattern. As the published survey datasets do not have complete coverage (and thus do not record a complete settlement pattern), we have attempted to counteract any unreliability in the clustering results of the observed settlement pattern by comparing them to simulated settlement patterns that populate areas that were likely to have had activity (based on site-environment relationships) but were missed by the surveys. More specifically, a pair correlation function (PCF) was used to measure the degree of attraction/repulsion in both the real and simulated settlement data, over different interaction distances and for each of the simulations (Illian et al. 2008; Wiegand and Moloney 2004: 225).[4] PCFs use the frequencies of other sites located within successively larger bands around each site point to summarise how likely sites are to be clustered or dispersed at different spatial scales based on the number of sites located within each given distance. These different spatial scales potentially refer to different types of interaction between sites, from very localised community relations (as would be identified in traditional nearest neighbour analyses) to larger, more regional patterns, and can thereby potentially highlight different economic, social or political processes at the same time. For example, a settlement pattern can exhibit aggregation at smaller scales but dispersion at larger scales, where the small-scale clustering is around central places for local social groups while larger inhibition creates broader spatial boundaries between groups and beyond these clusters (e.g. spaced-out village clusters with separate resource hinterlands). Indeed, this multi-scalar pattern was noted in the eastern side of the Mirabello region (Haggis 2005: 67; Watrous et al. 2012: 35) in the Late Prepalatial period. As PCFs were computed for each simulated site pattern, for presentation purposes, each PCF result is grouped and summarised as a 'critical envelope'[5], Baddeley et al. 2016: 233-236, 391-403). When the PCF value from the observed (real-world) sites falls inside this summary envelope of PCF values, it might be consistent with a null hypothesis of location independence (where site locations are not affected by the location of other sites), as the simulations represent the degree of random variation in site locations expected based on landscape features. When the observed PCF falls outside this critical envelope – when the value is smaller or larger than the minimum or maximum value of the envelope - the observed site pattern can be assumed to exhibit more statistically significant patterning (at that particular spatial scale) then would be expected from the simulations which illustrate random variation. Furthermore, this form of second-order modelling can be powerful because it can be adjusted to account for first-order (in our case, environmental) effects that might otherwise distort a pure second-order analysis (often referred to as point process modelling in spatial statistics, discussed below and via **figures 8** and **9**).

4. Results

4.1 Site size and continuity

Figure 5 maps patterns of continuity and abandonment in the observed settlement distribution, with some clear visual differences between different periods. The Late Prepalatial shows strong continuity from the

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[4] This method belongs to a set of multi-scalar spatial statistics such as K functions that summarise second-order effects of spatial patterns at multiple scales (Orton 2004: 303). These have not been particularly common in archaeological studies (but see Bevan and Conolly 2006, 2009; Bevan et al. 2013a; Sayer and Wienhold 2012 for examples).

[5] A 95% critical envelope was used, which conservatively removes the most extreme PCF results. For the first statistical discussions on second-order simulation envelopes, see Besag and Diggle 1977; Ripley 1981; for more recent applications outside of archaeology, see Baddeley et al. 2016. An isotropic edge-correction method was applied which weights points within the search radius by probabilities (Ripley 1977).

earlier Prepalatial period in the Vrokastro area and significant growth along the Gournia coast and Kavousi plain (EM I-II, **Figure 5a**). Some earlier Prepalatial sites were abandoned in fairly equal measure across the study area, with slightly heavier losses in the south isthmus region, resulting in more sites clustering around the coast. The Late Prepalatial sees a slight decrease and increase in small (0.2-1 hectares) and medium (1-3 hectares) sites respectively, and reaches relative proportions that stay remarkably consistent in the Proto- and Neopalatial periods (percentages of total sites in **table 4**), despite changes in overall number of sites and total occupied area in subsequent periods (**Table 3**). Compared to the earlier Prepalatial period spanning approximately 800 years, the Late Prepalatial sees substantial growth in number of sites and total occupied area when raw counts are divided by period duration. Protopalatial settlement explodes in most areas of the study region (**Figure 5b**), encompassing the coastal and Gournia plains, the upland areas of Vrokastro and Kavousi, and farther south in the isthmus. While, as mentioned above, the mean site size and the proportion of sites in each size category remain constant, the total hectares of occupied area in the Protopalatial (**Table 3**) is far greater than any other phase in this study and correlates to the high number of *new* small and medium sites which appear in this period at rates unmatched (**Table 4**) in any other prehistoric period. In the Neopalatial period, sites continue to be present in fairly large numbers across the landscape, but there is a definite decline of small and medium sized sites in the Vrokastro uplands, the Kavousi plain and along the coast in the hinterland around the town of Gournia (**Figure 5c**). In contrast, the dynamics along the Kavousi slopes and in the middle of the Ierapetra isthmus are complex. While relative numbers of different-sized sites within the system remain stable, considering the relative length of the period, there is a clear decrease in Neopalatial settlement presence across the surveyed area (number of sites per century in **table 3**). Site sizes and numbers then fall drastically in the LM IIIA-IIIB period, where the majority of sites are now less than 0.2 hectares. Despite this, most (83%) LM IIIA-IIIB sites show evidence for continuity from the preceding Neopalatial: of these, a third were small Neopalatial sites, and another 40% were larger Neopalatial sites that then shrank in the Postpalatial period. Across the region, evidence for reoccupation in the Postpalatial is greatly reduced (**Figure 5d**), with pockets of continuing settlement nestled within the protected Kavousi plain the hilly slopes near the Vrokastro coast, and in the middle isthmus but are, overall, fairly well-dispersed across the landscape.

Figure 5a-d.

Period	***n* Sites**	**Total hectares**	**Mean site size**	**SE of site size**	**Number of centuries**	**Hectares/ century**	**Sites/ century**
EM I-II	110	40.87	0.37	0.05	8	5.11	13.75
EM III-MM IA	**94**	**42.55**	**0.45**	**0.09**	**2.5**	**17.02**	**37.6**
MM IB-II	**227**	**103.49**	**0.46**	**0.04**	**1.5**	**68.99**	**151.3**
MM III-LM I	**166**	**74.01**	**0.44**	**0.05**	**3.1**	**23.87**	**53.55**
LM IIIA-IIIB	**47**	**12.63**	**0.27**	**0.07**	**2.3**	**5.49**	**20.43**
LM IIIC-Geometric	63	41.59	0.66	0.22	5.2	7.99	12.12

Table 3. Settlement size and continuity indicators by chronological phase. Total (occupied) area is the sum of all given site sizes for that period, originally published to within 0.01 of a hectare. The values in

subsequent columns are derivatives of the number of sites and total area in hectares for each period. Periods discussed in this paper are shaded in grey.

	***n* Sites**		**< 0.2 hectares**		**0.2-1 hectares**		**1-3 hectares**		**3+ hectares**	
Period	***total***	***new***	***% total***	***% new***	***% total***	***% new***	***% total***	***% new***	***% total***	***% new***
EM I-II	110	na	61%	na	30%	na	6%	na	2%	na
EM III-MM IA	**94**	**20**	**55%**	**27%**	**36%**	**6%**	**15%**	**33%**	**2%**	**100%**
MM IB-II	**227**	**141**	**51%**	**69%**	**34%**	**60%**	**9%**	**48%**	**2%**	**0**
MM III-LM I	**166**	**27**	**55%**	**21%**	**32%**	**15%**	**6%**	**0**	**2%**	**0**
LM IIIA-IIIB	**47**	**8**	**70%**	**18%**	**23%**	**20%**	**4%**	**0**	**0**	**0**
LM IIIC-Geometric	63	42	62%	64%	27%	76%	5%	33%	6%	75%

Table 4. Proportion of sites in each size category by chronological phase. Percentage of total sites per phase are shaded in grey, new sites reflect the sites that did not have dated material from the previous period.

4.2 First-order effects

Beyond these simpler statistical summaries and visualisations, spatial regression models can give insight into the kinds of settlement and subsistence choices that lay behind settlement patterns, holding constant the similar environmental constraints faced by inhabitants throughout the Bronze Age. Similarity between periods is expected because of some enduring environmental factors that encourage or discourage human settlement, but a formal model can also tease out exceptions from an otherwise complicated archaeological record. A first glance at the results of such models for each period (**Figure 6**) suggest a consistency in specific environmental correlations across the four chronological periods, a pattern that has also been noted in the Vrokastro region (Hayden 2004: 112). Across the 1000 simulations of fitted regression models on randomised site presence/absence data, low-lying, flatter areas of the landscape (**Figure 6**: A, B, negative coefficient values) are a significant predictor in almost *every* simulation for *every* period, although this is less robust in LM IIIA-IIIB. This is at odds with one survey which cites more defensive positions on hilltops as a dominant pattern in the Late Prepalatial (Watrous and Schultz 2012: 34). The slightly positive coefficients of the ridge variable (**Figure 6**: H) are perhaps picking-up on sites being located on slightly elevated areas in low-lying parts of the landscape (areas that can be only locally defined as a ridge), although this relationship is also consistent across the later Middle and Late Minoan periods.

The frequency in which the variables were chosen across all simulations gives a strong indication of how powerful a predictor the variable is when random permutations (and thus uncertainties such as site longevity, site extent) are accounted for. Such a pattern corresponds well with the general landscape affordances of the Mirabello area, with certain areas naturally attractive to human settlement. It also points to a more general prehistoric emphasis on agricultural exploitation. A significant negative relationship with longer-distance visibility (**Figure 6**: K) in every period is more difficult to unpack, but probably relates to the fact that the majority of the surveyed area with the greatest visibility values are the slopes of the Sitia massif where there is consistently little settlement evidence in any period. The positive relationship to limestone boundaries in most fitted models for most periods (**Figure 6**: G) hints at a consistent positive correlation to potential spring locations but is not robust enough across all models to suggest clear inter-period changes[6]. The most variable relationship across each period is topographic wetness (TWI, **Figure 6**: E), an index measuring long-term surface moisture availability in the landscape and a potential proxy for more agriculturally-focused strategies. In the Proto- and Neopalatial periods, this variable exhibits a significant positive correlation with settlement intensity, while Late Prepalatial and Postpalatial periods have an insignificant but negative association. Although the topographic wetness index does not take into account soil types and thus may not actually reflect typical moisture availability along the isthmus, the robust positive correlation of Proto- and Neopalatial settlements to areas with higher TWI values seems to stem from the explosive growth (in the former) and subsequent continuity (in the latter) of a string of settlements from the alluvial plain of Kavousi down along the isthmus (**Figure 6**: B, C), a pattern that appears to break down in the Postpalatial period, resulting in a conversely negative relationship.

Figure 6.

To tease apart further differences between periods, a second set of regression models were computed for which non-site locations were sampled *only from the parts of the landscape that were settlements in other periods* from the Neolithic to Late Roman[7]. While the first method above (**Figure 6**) identifies the general location properties of settlement in any given period, this approach (**Figure 7**) focuses on picking out differences between periods and their apparent locational priorities. For example, Late Prepalatial and Protopalatial settlements tend to be found more often on south-facing ridges (**Figure 7**: C, H, positive values) than later Bronze Age settlements, which may reflect a greater focus on agricultural exploitation, or the fact these earlier settlements had effectively more of a first choice of site placement and therefore had already chosen some of the best locations for subsistence (with little room for further emphasis on these properties in the fitted models even if the same locales were occupied later on). Indeed, the surveyors noted sites dated from EM III-MM II had the strongest overall orientation towards rain-fed subsistence. Protopalatial settlements have a positive relationship with channel features above and beyond other periods of settlement (**Figure 7**: H) – again probably relating to expansion during this phase into the flat areas south of the Kavousi plain (**Figure 7**: B), a pattern that, while seen in LM IIIA-IIIB (Watrous and Schultz 2012: 65), did not involve the same scale of activity. Neopalatial settlements also show a positive relationship with channel landforms when we consider them against the landscape as whole (**Figure 7**: H). However, because these locations are first occupied during the Protopalatial, this variable is not significant when Neopalatial sites are compared to sites from other periods. The particularities of visibility measures (**Figure 7**: J, K) in the Neo- and Postpalatial period appear to stem from settlement continuity in the Vrokastro coastal hills and the protected Kavousi plain, where local and long-distance visibility values are highest and lowest respectively. This may stem from the overall loss of settlement along the coast and isthmus in LM IIIA-IIIB, coupled with the greatest survival rates of smaller settlements along the Vrokastro hills. Overall, EM III-LM IIIB settlement patterns (the focus of this paper) are consistently located closer to the coastline than earlier Neolithic/EBA or later Iron

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[6] In the survey area, limestone also tends to dominate more in upland areas, rather the more exposed conglomerates and marls along the coastal hills and ridges (Hayden 2004: 123)

[7] While including historic period data may act to homogenise differences between prehistoric phases (because the cultural and political environment affecting settlement patterns are likely very different), it was the choice of the authors to use all available data from the surveys to (i) contrast Bronze Age tendencies against how groups used the same (or very similar) landscape in other periods, (ii) pick up on similarities between phases that are not directly preceding or succeeding (e.g. EM IIIA-MM IA to LM IIIA-IIIB), and identifiable differences between prehistoric periods despite the overall similarities compared to pre- and post-Bronze Age patterns.

Age/Classical/Roman settlements (**Figure 7**: F), a pattern that is particularly robust for the Protopalatial and Neopalatial phases. Moreover, in 1000 simulations of Proto- and Neopalatial site presence and absence, a correlation with moisture-rich areas (again, above and beyond the pattern across all periods) is evident in every model (**Figure 7**: E). The palatial periods also share an association with higher elevations than other periods (**Figure 7**: A), likely relating to the growth of settlement inland in the Protopalatial and the relatively large reduction of lowland coastal sites in the Neopalatial (and noted by Hayden 2004: 112, Watrous and Schultz 2012: 52). These attributes together point towards both the significant continuity of practice identified in the first set of models (**Figure 6**), and a particularly strong connection in practice between the Protopalatial and Neopalatial periods. Unlike the Vrokastro survey which suggested this palatial period continuity (Hayden 2004: 115), this patterning was interpreted in the Gournia and Kavousi areas as a socio-politically driven shift in agricultural practices and economic interests towards intensification and control (Haggis 2005: 75, Watrous and Schultz 2012: 52).

Figure 7.

4.3 Second-order effects

To explore the question of social-spatial organisation of recorded sites, we also briefly consider results from pair correlation functions for the Protopalatial and Neopalatial periods, which we applied to the area-dependent site points (*i.e.* hypothetical households) adopted above for the first-order modelling. For the Protopalatial period (**Figure 8**), when external landscape influences (fitted regression variables) are not considered (***a***), the PCF find significant clustering in the observed settlement pattern at up to 1km interaction distances. This evidence corroborates the informal site clustering trends described in the original survey reports and is further discussed below. In contrast, when our simulation of points is conditioned on the first-order environmental relationships (***b***; so that the likelihood of a simulated site being present in any location is now weighted by the fitted models of environmental relationships), the observed clustering loses significance. This suggests that some of the small-scale clustering observed can be explained from the choice of attractive landscapes to settle, as the clustering falls within the range of expected variation for those environmental relationships. These results also indicate an inhibition process at larger scales, suggesting that sites (modelled as groups of hypothetical households) are located farther apart than would be suggested by locational priorities alone, and may be spacing out from one another (*e.g.* for the purposes of resource allocation, lineage affiliation, competition or some other socio-economic factor), a pattern corroborating with discussions in the Kavousi area (Haggis 2005: 67) and the middle isthmus (Watrous and Schultz 2012: 35). Similarly, in the Neopalatial period PCFs (**Figure 9a)**, a slightly dispersive process (although far less pronounced) is noted at the same scale (approximately 1.5 and 3 km apart), and probably suggests a legacy of Protopalatial patterns of local group formation (and/or the processes that drove it) that at least partially persisted into the succeeding Neopalatial period. However, when the simulated samples are conditioned on environmental relationships (**Figure 9b**), the Neopalatial settlement pattern fits more closely within the expected range, with similar implications of mapping onto landscape features as proposed for the Protopalatial.

Figure 8ab.

Figure 9ab.

5. Discussion

In what follows, we try to draw out some of the above results to consider how they fit into wider Cretan dynamics over the Bronze Age.

5.1 Protopalatial

Excavated Protopalatial period sites in the Mirabello region show evidence of MM IA re-organisation. At Gournia, one building shows architectural differentiation from the rest of the site. This differentiation is also seen in the funerary evidence at Gournia, Myrtos-Pyrgos, Malia and Archanes in central Crete (Watrous 1994; Legarra Herrero 2014). Several MM IA building phases are represented at Vasiliki in the northern isthmus, which reached its largest extent in the Late Prepalatial period (Zois 1992), and although poorly published, is a contrast to the egalitarian interpretation of the agglutinated EM IIB houses before they were destroyed by fire. The excavated coastal settlement at Priniatikos Pyrgos shows the Late Prepalatial settlement flourished against the general backdrop of EM IIB destructions across the island (specifically Vasiliki, Mochlos, and Pseira in the region; Watrous 1994: 708), and the site continued into the Protopalatial period. This continuation of settlement at Priniatikos Pyrgos is in line with the widespread distribution of Mirabello pottery across the rest of Crete and is thought to have been exported from Priniatikos Pyrgos (Hayden 2014:16) and/or from Gournia.

Within the Gournia survey, the proliferation of small farms and field sites in relatively marginal environments has been argued as evidence for factional competition during the Protopalatial period, including in-migration of new groups whose opportunities were economically circumscribed by existing inhabitants (Watrous and Schultz 2012: 49). A more moderate interpretation in the Vrokastro reports sees Protopalatial expansion as resulting from both internally-driven and externally supplemented population growth forcing people to move south into areas less ideal for farming, while rural elites (represented by larger sites) retained access to the better resources (Hayden 2004: 84-100; Hayden 2014: 16). In further contrast, the Kavousi survey publication interprets the Protopalatial pattern as one of “peaceful and mutually beneficial social and economic interaction” with clusters of neighbouring small settlements forming semi-autonomous communities (Haggis 2005: 71-72), the multiplicity of similar social units and decentralised nature of the region as a scaled-down version of a less hierarchically-organised, more heterarchical system that certain researchers have also argued is a feature of Cretan Protopalatial society as a whole (Day and Wilson 1998; Haggis 2002; Knappett 1999; Schoep 2002). To recognise any of these competing interpretations of the same settlement pattern in the models requires one to think explicitly about their assumptions. For example, the Mirabello surveys posit hierarchies consisting of newly established small sites clustered around larger settlements (Watrous and Schultz 2012: 48; Haggis 2005: 73). If we re-plot Protopalatial settlements by site size, indeed the dataset does exhibit a trend towards the establishment of new sites (dark blue, **Figure 5c**) clustered around pre-existing sites that were also growing (in green) around Gournia and along the coasts. As previously noted, the regression models also suggested an infilling of the landscape with an agricultural emphasis (**Figures 6 and 7**). However, there are also other patterns of change observable across these two periods: in Vrokastro a distinct set of new sites appears further inland, forming clusters around both new large sites and growing Prepalatial sites (+1 hectare), and in Kavousi with whole new clusters of new small- and medium-sized sites. In the light of these observations, fitted regression models were generated separately for small sites (less than 0.2 ha, totalling 54% of all Protopalatial sites) and large Protopalatial sites to assess the particular relationships between different types of sites and the landscape. The models found significant variability in the locational characteristics of small sites, and a lack of correlation with more marginalised landscapes which does not support a systematic pattern argued for new Protopalatial sites in Gournia. Furthermore, the inhibition between Protopalatial sites noted in the PCF (**Figure 8**) could relate to dispersion processes of settlements around naturally inhabitable areas; this is a period of population expansion when the amount of available land, especially on the coastal plains, would be decreasing and there do appear to be spatial buffers between 1km-wide cluster groups that could reflect socio-economic inhibitory factors during this period (tenure arrangements, lineage affiliations, budding-off new households, etc.). Clearly groups in more ‘marginal’ areas would not have had the same opportunities as pre-existing sites, but there is no evidence to suggest that these groups were not exploiting the different advantages of upland (perhaps forested) landscapes and were interacting with lowland sites in economically complementary ways. Furthermore, the effects of MM IA re-organisation of settlement and funerary architecture on these temporally broad Protopalatial settlement patterns remain unclear. Therefore, while the fitted models do reflect a concern for subsistence strategies and an infilling of inland areas, and the PCFs indicate slight spatial repulsion between settlements, there are multiple possible causes, and neither cooperative processes at work amongst semi-autonomous communities, nor more competitive socio-economic circumscription amongst groups, can be substantiated from the second-order interaction models or the locational characteristics of sites alone.

5.2 Neopalatial

Systematic agricultural intensification promoted by a new regional hierarchical structure is thought to have been a driver for the intensification of exploitation of the coastal plains and the abandonment of upland areas in the Neopalatial period (Haggis 2005: 75-79), argued by some as centred around the LM I central building at Gournia (Watrous 2012: 52-4). The fitted regression models (**Figures 6, 7**) suggest a strong and continued concern with agricultural production, and the ostensible loss of satellite sites around the major coastal centres of Priniatikos Pyrgos, Gournia, and Tholos (**Figure 5c**) supports a trend towards nucleation. However, the majority of large Protopalatial sites that continue into the Neopalatial, including these centres, do not grow in sufficient size to offset the loss of smaller sites, lending credence instead to the probability of some decrease of visible human activity in the area.[8] Moreover, the Neopalatial period lasts longer than the Protopalatial, and whether we compare number of sites or sites-per-century (**Table 3**), the Neopalatial loss of sites jumps from a 26% to 64% decrease from the Protopalatial period, reminding us of the challenges in interpreting changes in settlement between unequal time blocks. In Kavousi, the majority of losses are from the smallest sites, but the greatest reduction across the surveyed areas comes from 0.2-1 ha sites in Vrokastro and Gournia, with evidence of site size reduction in the southern isthmus and Vrokastro uplands (**Figure 5c**). Of the 27 new sites in the Neopalatial period across the Mirabello region; 70% are under 0.2 hectares, and all are less than a hectare. In addition to the inevitability that not all of these sites were continuously occupied, this patterning suggests there while large sites remained

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[8] Although it must be noted that the actual extent of some sites (e.g. at Prinatikos Pyrgos, the dominant site in the Istron valley) are unknown, due to heavy alluvium covering certain areas.

stable, there was a considerable amount of instability of small and medium-sized sites as might be expected due to demographic processes.

Trade is often seen as the root cause of the argued-for nucleative processes along the coast, both cross culturally and as argued closer to home for the Bronze Age Cyclades (Cherry *et al.* 1991: 221) and off-island Pseira (Betancourt and Hope Simpson 1992). In the Mirabello, it has been argued that Gournia was a major production and exchange centre for the region (Watrous and Heimroth 2011). In these examples and others elsewhere (Taafe *et al.* 1963), shifting tendencies between inland connectivity and coastal accessibility is a dynamic that has been charted in past settlement patterns, where the development of a coastal centre with exterior connections leads to other spatial processes as locational advantages of surrounding areas concordantly adjust. To offer one example, the Vrokastro study area contains most of the geologically-restricted granodiorite deposits in the region, which have been used as temper for (Protopalatial) Middle Bronze Age Mirabello wares found in sites from Malia[9] and Mochlos to Petras and Palaikastro, their importation dramatically increasing in Kavousi from the Late Prepalatial (Haggis 2005: 68), although whether the main production area was around Priniatikos Pyrgos or Gournia remains unknown[10]. As with other major coastal sites in east Crete where the presence of palatial architectural elements is accepted (although unproven) to reflect the importance of maritime-based activities and coastal interaction, Priniatikos Pyrgos is thought to have been a main distribution point for this trade, and running under previous assumptions of the reaches of a Malia state, is suggested to have been perhaps under Maliote control in the Protopalatial period (Hayden 2004: 99). By the Neopalatial period, however, granodiorite imports disappear outside the Mirabello region, and while granodiorite fabrics continue to be present in the Vrokastro area (Moody 2005: Pottery Catalogue 152), the temper of fabrics found within Gournia and Kavousi shifts to phyllite-quartzites, which are predominant in pottery production centres from Kavousi to Sitia (Haggis and Mook 1993:291; Haggis 1996: 408, 2006: 228; Hayden 2004: 121, n.58; Hayden and Tsipopoulou 2012: 542), strongly suggesting Gournia was not the primary production centre of Mirabello wares. Overall, the intensity and continuity of coastal occupation in the Neopalatial Mirabello does suggest an important configuring role for external contacts and a maritime-oriented society, but this coastal presence was also the case for the Protopalatial – the large 3+ hectare settlement in Tholos bay had already reached this size in the Protopalatial (**Figure 5b**). Recalling that the greatest loss of activity was seen in inland sites, the Neopalatial pattern can be interpreted as a continuation and perhaps further nucleation of coastal activity at well-connected sites on agriculturally advantageous fertile coastal plains.

We should legitimately ask what provokes these economic shifts in the Neopalatial period. Unfortunately, the low temporal resolution of the site survey data *within* the Neopalatial is likely masking important intra-period changes, such as the kinds of site-biographic difference noticed for palace centres in central Crete (perhaps hinted at locally by the impression that the central court building at Gournia developed relatively late) or the possible impact of the LMIA Theran eruption (evidence of which is found in coastal settlements across east Crete, including Priniatikos Pyrgos: Hayden 2005: 119; Watrous 2012: 55; Soles

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[9] Almost a quarter of oval mouthed amphorae from Quartier Mu are in Mirabello fabric (Pratt 2016: 30).

[10] There is generally a lack of evidence for kilns or pottery production evidence, a problem that is amplified in surface surveys (only 2 sites in Gournia survey found Bronze Age wasters), although Bronze age kilns are known at both Gournia and Priniatikos Pyrgos (Hayden 2004: 63, 83; Nodarou and Moody 2014: 91). One should be careful in assuming that Gournia was the producer of Mirabello ware simply on the basis of relatively well-documented kilns in one location.

1991: 21-31, Watrous and Schultz 2012: 58-60). If the Mirabello region parallels demographic changes elsewhere on Crete, can this be taken to indicate similar developmental trajectories and economic processes? Looking at the transition between the Proto- and Neopalatial periods, comparisons between the number of sites and site size indicate a marked change (**Table 3**): a reduction of sites and total occupied area contrasting with the relative stability of mean site size and their proportions within the system. In south-central Crete, the Mesara survey notes a contemporary loss of small sites (Watrous *et al.* 2004) and a possible decline of the specialised port complex at Kommos (Girella 2010: 402). In Malia, evidence for the loss of exploitation of upland areas in the Neopalatial is seen as a fundamental change in the relationship between the palatial centre and rural hinterland (Müller-Celka *et al.* 2014). By contrast, the reduction of upland Vrokastro sites is seen as a collapse of an unsustainable rural elite system, where the remaining sites better facilitated movement of agricultural products (Hayden 2003: 94, 2014: 17-20). Considering the transition between palatial periods, it becomes clear that similarity of process cannot be ascertained from high-level comparisons of settlement patterns and the question of whether parallel changes in settlement patterns indicate similar social trajectories needs further comparative work.

5.3 Postpalatial

Across Crete, change in the Postpalatial period has itself been explained either via exogenous causes such as a prolonged impact of the disruption after the Theran eruption or external Mycenaean conquest and/or with reference to internal processes of collapse within the existing palatial society on Crete (Cunningham and Driessen 2004; Knappett *et al.* 2011; Soles 1999). While a so-called Late Palace period is visible archaeologically at Knossos, Neopalatial centres in the Mirabello all suffer destruction at the end of LM IB (Watrous 2012: 65). Thereafter, LMIIIA-IIIB evidence across the region is meagre: this undoubtedly is in part be due to the difficulty in assigning phases to east Cretan pottery using north-central Cretan criteria (where type fossils are largely limited to fine wares, Haggis 2005: 80-81). Nevertheless, despite problems in archaeological visibility and site size estimation, declines in aggregate habitation area and mean site size do suggest an overall demographic decline (**Table 4**), as does the reduced visibility of human activity along the coast in stratigraphic layers above Theran ash deposits (Molloy *et al.* 2014: 53). Vrokastro is the coastal exception with the strongest case for continuity: it fortuitously has a chain of protected hills ringing the coast that facilitate its continued exploitation (Hayden 2004: 149), a feature of neither the steep cliffs of Kavousi nor the Tholos plain, although redevelopment at Gournia in LM IB is apparent from excavations. Small sites dominate the LM IIIA-IIIB regional settlement pattern indicating a dispersed, localised settlement system that mirrors broader patterns of social disintegration across Crete and the Cyclades (Bintliff 1999: 25), even if a certain degree of localised clustering is also a feature of the preceding Neopalatial period in the Mirabello. The observed shift towards dispersion could also have necessitated different subsistence strategies, while a continuation of the production of storage and cooking wares in with local granodiorite temper throughout Vrokastro and its' reappearance at some Kavousi sites (Hayden 2004: 146) and further east in LM IIIA2-B levels at Petras (Pratt 2016: 42), suggests at least partly restored connections to western Mirabello production centres after Gournia is abandoned with (whether this is viewed as necessity or a new expression of economic independence).

6. Conclusions

This paper has used intensive survey data to identify major transformations in settlement patterning across the Mirabello region that can tentatively be linked to wider inter-regional developments. Uneven site preservation, varying field methods, a spatially heterogeneous environment and fuzzy temporal resolution will always somewhat obscure the statistical relationships between site locations and quantified measures of the landscape, but it is encouraging that certain results appear robust and conform with the broad-scale interpretations previously offered by the original surveyors, even if the underlying causal processes remain unproven. That said, the Mirabello region's position at a unique geographic pinch-point on the island has often lent it a distinct character, reinforced by natural anchorages that also make it a stopping place for maritime traffic (Haggis 2005: 11; Hayden 2014: 15; Watrous *et al.* 2012: 9). These features, along with the omission of paleo-environmental reconstructions, should urge caution in our attempts to generalise from it about wider Cretan settlement trends. Ultimately, any sub-regional history of settlement in the Mirabello area should not be written in isolation, but should be compared and contrasted with the record in other regions, and in future the Mirabello can be resituated via new information from other recent surveys (Chalikis 2013; Nowicki 2008a, 2008b) and excavations (Betancourt 2013; Molloy and Duckworth 2014) and re-investigation of deposits across Crete more widely (Greco *et al.* 2002; Todaro 2013). Given this wider interpretative agenda, the fact that, in this paper, starting comparisons can be made satisfactorily across three different published surveys strongly advocates, in our view, for the further application of similar formal methods to other Cretan and Mediterranean survey data.

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References

Adams, E. (2006). Social strategies and spatial dynamics in Neopalatial Crete: an analysis of the north-central area, *American Journal of Archaeology* 110: 1-36.

Amato, V., Longo, F., Bredaki, M., Rossi, A., Ghilardi, A., Psomiadis, D., Colleu, M., Sinibaldi, L., Delanghe-Sabatier, D., Demory, F. and Petit, C. (2014). Geoarchaeological and palaeoenvironmental researches in the area of ancient Phaistos (Crete, Greece): preliminary results. In G. Touchais, R. Laffineur and F. Rougemont (Eds), *Physis. L'environment naturel et la relation home-milieu dans la monde egeen protohistorique*, pp. 129-40. Aegaeum 37. Liège, Université de Liège.

Baddeley, A., E. Rubak, R. Turner (2016). *Spatial Point Patterns: Methodology and Applications with R.* Boca Raton: CRC Press.

Barnard, K. A. (2001). Transition, Production and Standardization in Minoan Ceramics: A View from Neopalatial Mochlos. *PhD dissertation*. University of Pennsylvania.

Besag, J., P. Diggle (1977). Simple Monte Carlo Tests for Spatial Pattern, *Journal of the Royal Statistical Society. Series C (Applied Statistics)* 26(3): 327-333.

Betancourt, P.P. (2013). *Aphrodite's Kephali: an early Minoan I defensive site in Eastern Crete*. Philadelphia: INSTAP Academic Press.

Betancourt, P.P., R.H. Simpson (1992). The Agricultural System of Bronze Age Pseira, *Cretan Studies* 3: 47-54.

Bevan, A. (2010). Political Geography and Palatial Crete. *Journal of Mediterranean Archaeology* 23(1): 27-54.

Bevan, A., J. Conolly (2004). GIS, archaeological survey and landscape archaeology on the Island of Kythera, Greece, *Journal of Field Archaeology* 29: 123-138.

(2009). Modelling spatial heterogeneity and nonstationarity in artifact—rich landscapes, *Journal of Archaeological Science* 36, 956–964.

Bevan, A. and A. Wilson (2013). Models of settlement hierarchy based on partial evidence, *Journal of Archaeological Science* 40.5: 2415–2427.

Bevan, A.H., E.R. Crema, X. Li, A. Palmisano (2013). Intensities, interactions and uncertainties: some new approaches to archaeological distributions. In A.H. Bevan, M.W. Lake (Eds.), *Computational Approaches to Archaeological Spaces*, pp. 27-51. Walnut Creek: Left Coast Press.

Bintliff J. (1999). Regional field surveys and population cycles. In: Bintliff J.L., Sbonias K. (Eds.), *Reconstructing Past Population Trends in Mediterranean Europe*, pp. 21-33. Oxford: Oxbow Books.

Borgna, E. (2003). Regional Settlement Patterns, Exchange Systems and Sources of Power in Crete at the end of the Bronze Age: Establishing a Connection, *Studi micenei ed egeo-anatolici* 45: 153-183.

Brughmans, T., J. Poblome (2016). Roman bazaar or market economy? Explaining tableware distributions through computational modelling, *Antiquity* 350: 393-408.

Cadogan, G. (1994). “An Old Palace Period Knossos State?”. In D. Evely, H. Hughes-Brock, N. Momigliano (Eds.), *Knossos: A Labyrinth of History: Papers Presented in Honour of Sinclair Hood*, pp. 57-68. London.

Chalikias, K. (2013). *Living on the Margin: Chryssi Island and the Settlement Patterns of the Ierapetra Area (Crete).* Oxford: Archaeopress.

Cherry, J. F. (1978). Generalization and the Archaeology of the State. In D. Green, C. Haselgrove, M. Spriggs (Eds.), *Social Organisation and Settlement: Contributions from Anthropology, Archaeology and Geography,* BAR International Series Suppl. 47(2), pp. 411-437. London.

(1983). Evolution, revolution and the origins of complex society in Minoan Crete. In O.Kryszkowska & L.Nixon (Eds.), *Minoan Society*, pp. 33-45. Bristol: Bristol Classical Press.

(1984). The emergence of the state in the prehistoric Aegean. *Proceedings of the Cambridge Philological Society* n.s.30 (210): 18-48.

(1986). Palaces and polities: some problems in Minoan state formation. In C.Renfrew, J.F.Cherry (Eds.), *Peer Polity Interaction and Sociopolitical Change*, pp. 19-45. Cambridge: Cambridge University Press.

Cherry, J. F, J. L. Davis, E. Mantzourani (1991). *Landscape Archaeology as Long-Term History: Northern Keos in the Cycladic Islands.* Los Angeles: Institute of Archaeology, University of California.

Chrysoulaki, N., M. Abrams, H. Feidas, D. Veliantis (2004). Analysis of Aster multispectral stereo imagery to produce dem and land cover databases for Greek islands: the Realdems Project. *EARSeL Workshop on Remote Sensing for Developing Countries, Cairo, 2004.*

Crema, E. (2012). Modelling temporal uncertainty in archaeological analysis. *Journal of Archaeological Method and Theory* 19: 440-461.

Crema, E., A. Bevan, M. Lake (2010). A probabilistic framework for assessing spatio-temporal point patterns in the archaeological record, *Journal of Archaeological Science* 36(4): 1118-1130.

Cunningham, T. (2001). Variations on a Theme: Divergence in Settlement Patterns and Spatial Organization in the Far East of Crete during the Proto- and Neopalatial Periods, In. K. Branigan (Ed.), *Urbanism in the Aegean Bronze Age*, pp. 72-86. Sheffield: Sheffield University Press.

Cunningham, T. and J. Driessen (2004). Site by site: combining survey and excavation data to chart patterns of socio-political change in Bronze Age Crete. In S.E. Alcock and J. F. Cherry (Eds.), *Side-by-Side Survey: comparative regional studies in the Mediterranean World*, pp. 101-113.

Day, P., D.E. Wilson (1998). Consuming Power: Kamares Ware in Protopalatial Knossos, *Antiquity* 72: 350-358.

Déderix, S. (2017). Communication networks, interactions and social negotiation in Prepalatial south-central Crete, *American Journal of Archaeology* 117.1: 5-37.

Driessen, J. (2001). “History and Hierarchy. Preliminary Observations on the Settlement Pattern of Minoan Crete”. In K. Branigan (Ed.), *Urbanism in the Aegean Bronze Age (Sheffield Studies in Aegean Archaeology)*, pp51-71. London: Sheffield Academic Press.

Driessen, J., J.A. MacGillivray (1989). The Neopalatial Period in East Crete. In R. Laffineur (Ed.) *TRANSITION: Le monde égéen du Bronze moyen et Bronze récent*, *Aegeaum* 3, pp. 99-111. Liège.

Driessen, J., I. Schoep, R. Laffineur (2002). *Monuments of Minos: Rethinking the Minoan Palaces.* Leuven: Peeters.

Fentress, E. and P. Perkins (1988). Counting African Red Slip Ware. *Antiquités Africaines* 24, 205-214.

Fernandes, R., G. Geeven, S. Soetens, V. Klontza-Jaklova (2012). "Mapping the probability of settlement location for the Malia-Lasithi region (Crete, Greece) during the Minoan Protopalatial Period". In S. Kluiving, E. Guttman-Bond (Eds.), *Landscape Archaeology between Art and Science: From a Multi- to an Interdisciplinary Approach*, pp. 353-368. Amsterdam: Amsterdam University Press.

Fox, J. (2013). *Applied Regression Analysis and Generalized Linear Models*. SAGE Publications.

Girella, L. (2010). Depositi ceramici del Medio Minoico III da Festòs e Haghia Triada. *Studi di Archeologia Cretese* 8. Padova, Bottega d'Erasmo.

Greco, E., T. Kalpaxis, N. Papadakis, A. Schmapp, D. Viviers (2002). Itanos (Crète orientale), *BCH* 126: 577-582.

Haggis, D. (1996). Archaeological Survey at Kavousi, East Crete: Preliminary Report, *Hesperia* 65: 373-432.

(1999). Staple Finance, Peak Sanctuaries, and Economic Complexity in Late Prepalatial Crete. In A. Chaniotis (Ed.), *From Minoan Farmers to Roman Traders: Sidelights on the Economy of Ancient Crete*, pp. 53-86. Stuttgart: Steiner.

(2002). Integration and complexity in the late Prepalatial Period. A view from the countryside in Eastern Crete. In Y. Hamilakis (Eds.), *Labyrinth Revisited: Rethinking Minoan Archaeology*, pp. 120-142. Oxford: Oxbow Books.

Haggis, D., G. C. Gesell, and L. Day (2005). *Kavousi I: the archaeological survey of the Kavousi Region.* Philadelphia: INSTAP Press.

Hamilakis, Y. (2002). *Labyrinth Revisited: Rethinking Minoan Archaeology.* Oxford: Oxbow Books.

Hayden, B. (2003). *Reports on the Vrokastro area, eastern Crete. Vol. 1, Catalogue of pottery from the Bronze and early Iron Age settlement of Vrokastro in the collections of the University of Pennsylvania Museum of Archaeology and Anthropology and the Archaeological Museum, Herakleion, Crete*. Philadelphia: University of Pennsylvania, Museum of Archaeology and Anthropology.

(2004). *Reports on the Vrokastro area, eastern Crete. vol. 2, The settlement history of the Vrokastro area and related studies*. (University Museum Monograph 119) Philadelphia: University of Pennsylvania, Museum of Archaeology and Anthropology.

(2005). *Reports on the Vrokastro area, eastern Crete. Vol. 3, The Vrokastro regional survey project: sites and pottery*. (University Museum Monograph 123) Philadelphia: University of Pennsylvania, Museum of Archaeology and Anthropology.

(2014). Priniatikos Pyrgos and Its Territory: Results of Survey and Excavation. In B. Molloy, C. N. Duckworth, 2014 (Eds.), *A Cretan Landscape through Time: Priniatikos Pyrgos and Environs*, pp. 15-22. Oxford: Archaeopress

Hayden, B. and M. Tsipopoulou (2012). The Priniatikos Pyrgos Project: Preliminary Report on the Rescue Excavation of 2005-2006, *Hesperia* 81(4):507-584.

Hope Simpson, R., P. Betancourt, P. Callaghan, D. Harlan, J. Hayes, J. Shaw, M. Shaw, L.V. Watrous (1995). The Archaeological Survey of the Kommos Area. In J. Shaw (Ed.), *Kommos: An Excavation on the South Coast of Crete, Volume I: The Kommos Region and Houses of the Minoan Town. Part I: The Kommos Region, Ecology, and Minoan Industries*, pp. 325-402. Princeton: Princeton University Press.

Illian, J., A. Penttinen, H. Stoyan, D. Stoyan (2008). *Statistical Analysis and Modelling of Spatial Point Patterns*. New York: John Wiley & Sons.

Knappett, C. (1999). Assessing a Polity in Protopalatial Crete: The Malia-Lasithi State, *American Journal of Archaeology* 103(4): 615-639.

(2012). A Regional Network Approach to Protopalatial Complexity. In I. Schoep, P. Tomkins, J. Driessen (Eds.), *Back to the Beginning: Reassessing Social and Political Complexity on Crete during the Early and Middle Bronze Age*, 384-402. Oxford: Oxbow Books.

Knappett, C., C. Ichim (2017). "East Cretan Networks in the Middle Bronze Age". In M. Tsipopoulou (Ed.), *Petras, Siteia: The Pre- and Proto-palatial cemetery in context*, pp. 399-412. Monographs of the Danish Institute of Athens 21.

Knappett, C., R. Rivers, T. Evans (2011). "The Theran eruption and Minoan palatial collapse: new interpretations gained from modelling the maritime network", *Antiquity* 85(329): 1008-1023.

Legarra Herrero, B., (2014). *Mortuary Behavior and Social Trajectories in Pre- and Protopalatial Crete.* Philadelphia: INSTAP Academic Press.

Manning, S.W., (1995). *The Absolute Chronology of the Aegean Bronze Age: Archaeology, Radiocarbon and History.* Sheffield: Sheffield Academic Press.

(1997). Cultural change in the Aegean c.2200BC. In H.N. Dalfes, G. Kukla and H. Weiss (Eds.), *Third millennium BC climate change and old world collapse*, pp. 149-171. NATO ASI Series I, vol.49. Berlin: Springer.

(1999). *A Test of Time*. Oxford: Oxford University Press.

Momigliano, N. (2007). Introduction. In N. Momigliano (Ed.) *Knossos Pottery Handbook: Neolithic and Bronze Age (Minoan)*, pp. 1-8. Athens: British School at Athens.

Molloy, B., F.W. McCoy, R. Megarry, D.J. Govantes Edwards and M. Pavlacký (2014). Of Tephra and Tsunamis: A Secondary Deposit of Tephra Sealing LM IA Activity at Priniatikos Pyrgos. In B. Molloy, C. Duckworth (Eds.), *A Cretan Landscape through Time: Priniatikos Pyrgos and Environs*, pp. 43-53. Oxford: Archaeopress.

Molloy, B., C. N. Duckworth (2014). *A Cretan Landscape through Time: Priniatikos Pyrgos and Environs*. Oxford: Archaeopress.

Müller-Celka, S., D. Puglisi, F. Bendall (2014). Settlement Pattern Dynamics and Natural Resources in the MM-LM I Crete: The Case of Malia. In G. Touchais, R. Laffineur, F. Rougemont (Eds.), *PHYSIS: l'Environnement naturel et la relation homme-milieu dans le monde égéen protohistorique*, pp. 431-440. Leuven: Peeters.

Nowicki, K. (1999). Economy of Refugees: Life in the Cretan Mountains at the Turn of the Bronze and Iron Ages. In A. Chaniotis (Ed.), *From Minoan Farmers to Roman Traders: Sidelights on the Economy of Ancient Crete*, pp. 145-172. Stuttgart: Steiner.

(2008a). The Final Neolithic (Late Chalcolithic) to Early Bronze Age Transition in Crete and Southeast Aegean Islands: Changes in Settlement Patterns and Pottery. In V. Isaakidou and P. Tomkins (Eds.), *Escaping the Labyrinth: the Cretan Neolithic in context (Sheffield Studies in Aegean Archaeology)*, pp. 201-228. Oxford: Oxbow Books.

(2008b). *Monastiraki Katalimata: Excavation of a Cretan Refuge Site, 1993-2000.* Philadelphia: INSTAP Press.

Orton, C. (2004). Point pattern analysis revisited, *Archeologia e Calcolatori* 15: 299-315.

Paliou, E., A. Bevan (2016). Evolving settlement patterns, spatial interaction and the socio-political organisation of late Prepalatial south-central Crete, *Journal of Anthropological Archaeology* 42: 182-197.

Premo, L. (2010). Equifinality and Explanation: The Role of Agent-Based Modelling in Postpositivist Archaeology. In A. Costopoulos and M. Lake (Eds.), *Simulating Change: Archaeology into the 21st Century*, pp. 28-37. Salt Lake: Utah Press.

Reid, J. (2007). *Minoan Kato Zakro: A Pastoral Economy.* Oxford: Archaeopress.

Relaki, M. (2012). The Social Arenas of Tradition. Investigating Collective and Individual Social Strategies in the Prepalatial and Protopalatial Mesara. In I. Schoep, P. Tomkins, J. Driessen (Eds.), *Back to the Beginning: Reassessing Social and Political Complexity on Crete during the Early and Middle Bronze Age*, 290-324. Oxford: Oxbow Books.

Renfrew, C. (1972). *The Emergence of Civilisation.* Oxford: Oxbow Books.

Ripley, B., (1977). "Modelling spatial patterns (with discussion)". *Journal ofthe Royal Statistical Society: Series B* 39: 172-212.

(1981). *Spatial Statistics.* London: Wiley & Sons.

Sayer, D., M. Wienhold (2012). A GIS-Investigation of Four Early Anglo-Saxon Cemeteries: Ripley's K-function Analysis of Spatial Groupings Amongst Graves, *Social Science Computer Review* 0: 1-19.

Sbonias, K. (1999). Social Development, Management of Production, and Symbolic Representation in Prepalatial Crete. In A. Chaniotis (Ed.), *From Minoan Farmers to Roman Traders: Sidelights on the Economy of Ancient Crete*, pp. 25-52. Stuttgart: Steiner.

(2012). Regional elite-groups and the production and consumption of seals in the Prepalatial period. A case-study of the Asterousia region. In I. Schoep, P. Tomkins, J. Driessen (Eds.), *Back to the Beginning: Reassessing Social and Political Complexity during the Early and Middle Bronze Age*, pp. 273-89. Oxford: Oxbow Books.

Schoep, I. (1999). Tablets and territories? Reconstructing Late Minoan IB political geography through undeciphered documents. *American Journal of Archaeology* 103:201-221.

(2001). Managing the hinterland: the rural concerns of urban administration. In K. Branigan (Ed.), *Urbanism in the Aegean Bronze Age (Sheffield Studies in Aegean Archaeology)*, pp. 87-102. London: Sheffield Academic Press.

(2002). Social and Political Organisation in Proto-palatial Crete: The Case of Malia in the Middle Minoan II Period, *Journal of Mediterranean Archaeology* 15(2): 101-133.

(2006). Looking beyond the First Palaces: Elites and the Agency of Power in EM III-MM II Crete, *American Journal of Archaeology* 110(1): 37-64.

(2012). Bridging the divide between the 'Prepalatial' and 'Protopalatial' Periods. In I. Schoep, P. Tomkins, J. Driessen (Eds.), *Back to the Beginning: Reassessing Social and Political Complexity on Crete during the Early and Middle Bronze Age*, 403-428. Oxford: Oxbow Books.

Schoep, I., C. Knappett (2004). Dual Emergence: Evolving Heterarchy, Exploding Hierarchy. In J. Barrett, P. Halstead (Eds.), *The Emergence of Civilisation Revisited*, pp. 21-37. Oxford: Oxbow Books.

Soles, J. (1991). The Gournia Palace, *American Journal of Archaeology* 95: 17–78.

(1992). *The Prepalatial Cemeteries at Mochlos and Gournia and the House Tombs of Bronze Age Crete*. Princeton: Hesperia Supplement 24.

(1999). The Collapse of Minoan Civilization: the Evidence of the Broken Ashlar. In R. Laffineur (Ed.), *POLEMOS. Le contexte guerrier en Égée à l'âge du Bronze*. Aegeaum 19.

Soles, J.C., C. Davaras (1992). Excavations at Mochlos, 1989, *Hesperia* 61: 413-445.

Taaffe, E. J., R. Morrill, P. Gould (1963). Transport expansion in underdeveloped countries: a comparative analysis, *Geographical Review* 53: 503–29.

Todaro, S., (2013). "The EM III Phase in South-Central Crete: New Data from Phaistos", *Aegean Archaeology* 10: 65-85.

Watrous, L.V. (1994). "Review of Aegean Prehistory III: Crete from the Earliest Prehistory through the Protopalatial Period", *American Journal of Archaeology* 98: 695-753.

(2001). "Crete from earliest prehistory through the protopalatial period". In T. Cullen (Ed.), *Aegean Prehistory. A Review*, pp. 157-223. AJA Suppl. 1. Boston.

(2004). "State formation (Middle Minoan IA)". In L.V. Watrous, D. Hadzi-Vallianou, H. Blitzer (Eds.), *The Plain of Phaistos: cycles of social complexity in the Mesara region of Crete*, pp. 253-276. Los Angeles: Cotsen Institute of Archaeology.

Watrous, L. V., D. Haggis, K. Nowicki, N. Vogeikoff-Brogan and M. Schultz (2012). *An Archaeological Survey of the Gournia Landscape.* Philadelphia: INSTAP Press.

Watrous, L. V, A. Heimroth (2011). Household industries of Late Minoan IB Gournia and the Socioeconomic Status of the Town. In K. Glowacki and N. Vogeikoff-Brogan (Eds.), *STEGA: The Archaeology of Houses and Households in Ancient Crete, Hesperia Supplement 11*, pp. 199-212. Princeton: The American School at Athens.

Wiegand, T., K. Moloney (2004). Rings, circles, and null-models for point pattern analysis in ecology, *Oikos* 104(2): 209-229.

Wilson, D., P. Day (2000). EM I Chronology and Social Practice: Pottery from the Early Palace Tests at Knossos, *British School at Athens* 89: 1-87.

Whitelaw, T. (2004). Alternative Pathways to Complexity in the Southern Aegean. In: J. Barrett and P. Halstead (Eds.), *The Emergence of Civilization Revisited*, pp.232-256. Oxford: Oxbow Books.

(2012) The urbanisation of Prehistoric Crete: Settlement Perspectives on Minoan State Formation. In I. Schoep, J. Driessen, P. Tomkins (Eds.), *Back to the Beginning*, pp. 114-176. Oxford: Oxbow Books.

(In press). Feeding Knossos: exploring economic and logistical implications of urbanism on Prehistoric Crete. In D. Garcia, R. Orgeolet, M. Pomadiere and J. Zurbach (Eds.), *The Country in the City*. Oxford: Archaeopress.

Whitelaw, T., P. Day, E. Kiriatzi, V. Kilikoglou, D. Wilson (1997). Ceramic traditions at EM IIB Myrtos, Fournou Korifi, *Aegaeum* 16: 265-274.

Willet, R. (2014). Experiments with diachronic data distribution methods applied to Eastern Sigillata A in the eastern Mediterranean, *HEROM - Journal on Hellenistic and Roman material culture* 3: 39-69.

Zois, A.A. (1992). Vasiliki. In J. Myers, E. Myers, G. Cadogan (Eds.), *An Aerial Atlas of Ancient Crete*, pp. 245-281. Berkeley.