The Theran eruption and Minoan palatial collapse: new interpretations gained from modelling the maritime network.

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What was the effect on Late Minoan civilisation of the catastrophic destruction of Akrotiri on Thera (Santorini) by volcanic eruption? Not much, according to the evidence for continuing prosperity on Crete. But the authors mobilise their ingenious mathematical model (published in Antiquity *82, 1009-24), this time to show that the effects of removing a major port of call could have impacted after an interval, as increased costs of transport gradually led to ever fewer routes and eventual economic collapse.*

Keywords: Bronze Age, Aegean, Minoan, Crete, Thera, Santorini, Akrotiri, maritime communications, network analysis

Introduction

We seek in this paper to provide a novel perspective on the possible causes for the demise of Cretan Bronze Age palatial society c. 1500 BC using a mathematical model developed from a previous study (Knappett et al 2008). Various explanations have been proposed for the collapse - a tsunami generated by the Theran eruption destroying the Minoan fleet, an invasion by Mycenaean mainlanders, or internal socio-political turmoil and unrest (Rehak & Younger 2001). Today many scholars would see many such factors, natural and social, combining in some way. And although most do see some role for the Theran eruption, the fact that it took place some 50-100 years before the collapse makes it difficult to envisage what that role might have been. One persuasive argument sees indirect though insidious effects, both economic (such as ashfall polluting water supply and compromising crop yields in east Crete) and social, such as ideological uncertainty (Driessen & Macdonald 1997: 89-98). However, this accounts for neither the apparent continuing prosperity at some sites, nor the robust exchange activity across the Aegean; for these and other reasons some scholars have resisted the above interpretations (Warren 2001).

We tentatively put forward a new explanation that has the advantage of accounting for both the continued prosperity post-Thera, and the eventual collapse. Our approach is based on network modelling and sees the dynamics of network exchange at the regional level as critical to the ongoing success or otherwise of the Cretan Bronze Age palatial system. We argue that the strong continuing economic activity subsequent to the eruption is in reaction to it, yet also ultimately contains the seeds of instability and collapse (cf. Renfrew 1980).

Background

The Theran eruption—one of the largest volcanic eruptions globally of the last 10,000 years—buried the Bronze Age site of Akrotiri, the main settlement on Thera, beneath metres of ash and pumice, effectively ending occupation on the island for generations (Doumas 1983). This cataclysmic event had much wider impact too, with ash-fall over a very large area of the South-east Aegean (Friedrich 2000) and a possible devastating tsunami (Bruins et al. 2008). While a great deal of controversy surrounds the absolute dating of this event—with a 'scientific' high chronology favouring 1627 BC (Manning et al. 2006) and a 'traditional' low chronology 1525 BC (Wiener 2009)—there is general consensus that in relative dating terms the Theran eruption occurs at the end of the Late Minoan IA period, and is followed by Late Minoan IB. And what we see in Late Minoan IB in the region around Thera, and particularly on Crete, is quite remarkable. First, 'civilisation' carries on much as before, to the extent that Late Minoan IB has often been seen as the acme of Minoan culture (Hood 1971; Warren 1975; Cadogan 1976). Secondly, Late Minoan IB is brought to an end through violent destructions by fire, quite possibly caused by human agency. In the periods following this destruction horizon, Crete is never quite the same again, coming under pronounced influence, and perhaps even invasion, from Mycenaean mainlanders (Preston 2008).

The abundant evidence from the volcanic destruction levels of the site of Akrotiri on Thera indicates that it was a significant trade gateway between North Crete and the rest of the Aegean (see Figure 1 below, where Knossos carries label (1) and Thera (10)). Almost certainly, the island's destruction jeopardised an important exchange route. It has been argued that there is a reorientation to overcome the destruction of Akrotiri on Thera, with the mainland increasingly favoured by the new network structure (Mountjoy 2008). However, as far as can be told from current data, the Late Minoan IB period immediately following the destruction appears to see no let up in overall exchange across the southern Aegean. Crete appears to obtain the metals and other rare resources it demands without difficulty, and evidence for continuing inter-regional exchange is apparent at numerous sites, with ivory tusks and oxhide ingots at Zakros, for example (Wiener 1991: 341).

Thus, at first glance, it would seem that the disruption of exchange networks cannot have been a direct factor in Minoan collapse. But it seems unlikely that they were unconnected, since exchange was the basis of Cretan prosperity. We propose to pick apart the presumed stable situation of LM IB to search for some hidden patterns that might reveal some rather different, and more unstable, dynamics at play. In particular, we ask how resilient we expect LBA networks to be under removal of key nodes and which of their many characteristics may presage instability. To do this we adopt a network approach, building upon our earlier *Antiquity* paper on the maritime networks of the south Aegean (Knappett et al. 2008). But whereas that paper provided a demonstration of the validity in principle of a network model for the south Aegean, in this application we chose our inputs to reflect the consequence of Thera's removal. Details of these inputs and the analyses are given in the appendix, required reading for anyone immediately sceptical of our approach and its results.

Maritime Network Modelling for the Southern Aegean

We selected 39 sites that we considered the most important for the late MBA and early LBA (Figure 1, Table 1), and used their locations to create the maritime network. This raises initial questions about the completeness and interconnections of the chosen sample, which need to be addressed. Although a great deal of research over the past 100 years means we have a good idea where the main sites are, we cannot be completely sure that there is not another important trading settlement waiting to be found. To mitigate this problem, we use 'gravity modelling' - that is to say, if Knossos wants to exchange with Thera, it does not matter if there are two sites on Thera, or only one; only total resource availability matters and how a given island population is distributed is largely irrelevant. Thus the site of Akrotiri can represent a kind of 'centre of mass' for Thera, and likewise Knossos for its immediate area of north-central Crete (thus 'Knossos' may be seen to encapsulate the neighbouring sites of Poros and Archanes too). The whole is, to a good approximation, the sum of the parts. What this does is enable us to minimise our ignorance of the archaeological record. We discuss in full the details of gravity models elsewhere (Evans et al. 2009).

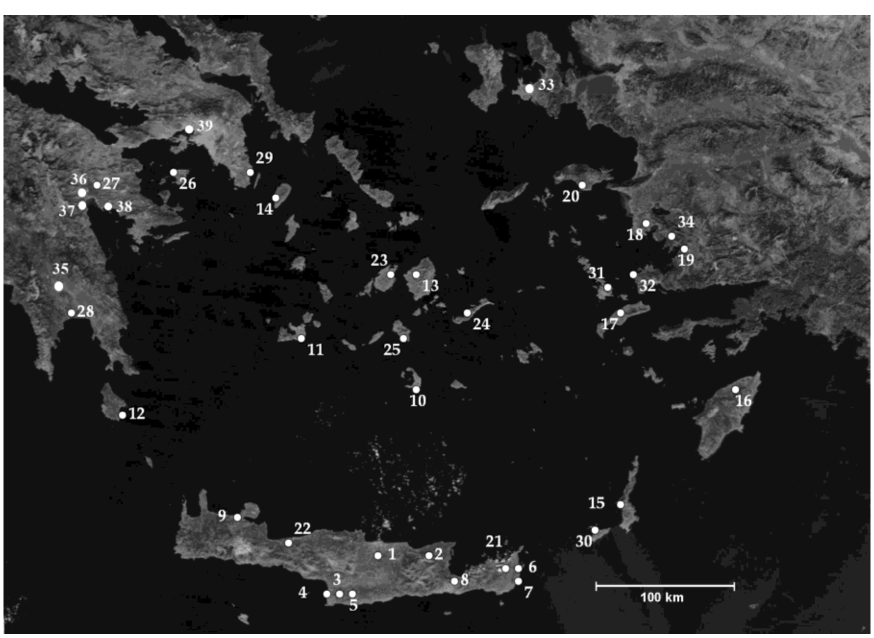

Fig. 1 The Aegean, showing the 39 sites selected for the generation of the maritime network. Important sites, for the discussion that follows, include Knossos (1) and Thera (10). The remainder are listed in Table 1. The outline of the Theran caldera is shown.

1. Knossos (L)	14. Kea (M)	27. Mycenae (L)
2. Malia (L)	15. Karpathos (S)	28. Ayios Stephanos (L)
3. Phaistos (L)	16. Rhodes (L)	29. Lavrion (M)
4. Kommos (M)	17. Kos (M)	30. Kasos (S)
5. Ayia Triadha (L)	18. Miletus (L)	31. Kalymnos (S)
6. Palaikastro (L)	19. Iasos (M)	32. Myndus (M)
7. Zakros (M)	20. Samos (M)	33. Cesme (M)
8. Gournia (L)	21. Petras (L)	34. Akbuk (M)
9. Chania (L)	22. Rethymnon (L)	35. Menelaion (S)
10. Thera (M)	23. Paroikia (M)	36. Argos (M)
11. Phylakopi (M)	24. Amorgos (S)	37. Lerna (M)
12. Kastri (M)	25. Ios (S)	38. Asine (S)
13. Naxos (L)	26. Aegina (M)	39. Eleusis (M)

Table 1: The sites enumerated in Fig.1 and the size of their local resource base, with (S), (M), (L) denoting 'small', medium' or 'large' respectively in terms of their resource base *(input).* This is to be distinguished from their 'populations', which are *outputs.*

Our knowledge of the links between one site and another relies largely on the evidence of ceramic imports; but if such finds are limited, so is our knowledge of connectivity. To bypass our lack of knowledge about actual links, we use modern distance as the determinant input. A threshold falling off rapidly from 110 km onwards (though we can easily vary it), was applied, based on a crude estimation of daily travel achievable with the sail, an important innovation c. 2000 BC (Broodbank 2010). We would argue that the southern Aegean forms a coherent whole and can be treated as an approximately autonomous region, even though we know that some external links are important e.g. the importation of tin from Anatolia. Other than this, we basically ignored any information we might have about connectivity in terms of inputs, and just let the connections grow as a feature of the model. Then we compared the outputs to the limited information we have for connectivity. For example, we know that there are strong connections between Crete and Akrotiri (Knappett and Nikolakopoulou 2008), as well as, to a lesser degree, between Crete and the Dodecanese and coastal Anatolia (Raymond 2001; Niemeier 2005; Marketou 2009; Momigliano 2009; Knappett and Nikolakopoulou 2005). We also know that links between the mainland and the Cyclades were relatively weak (until LM IB that is; Nikolakopoulou 2007), and that there were also relatively weak links between the Cyclades and Dodecanese and coastal Anatolia (Marthari et al. 1990). Since the relationship between sites is not necessarily symmetric, each pair is connected by *two* directional links. We make no prior assumption that the geographical substrate of itself determines network properties, but there is no doubt that they are conditioned by it and the prevailing maritime technology.

The framework in which we address these issues is one of ‘optimisation’, or ‘rational choice’. For *sites,* we input their *carrying capacities*, the availability of local resources, adopting a simple relative grading according as to whether available resources are large (L), moderate (M) or small (S) (see Table 1). For *links,* the input parameters are essentially the ease of travel between pairs of sites, allowing for passage around headlands and also taking into account the relative difficulty of travelling over land when this is inevitable. ‘Near neighbours’, which can connect in a single journey/single day communicate directly, sites further apart (‘distant neighbours’) tend to communicate through intermediaries. Empirically, we find a distance of about *100km* to be the pivotal scale that separates the two.

Working from a chosen cost-benefit/utility function our model hunts for the most 'efficient' networks, on taking into account the *benefits* accruing from both exploiting local resources and for developing links to other sites and the *costs* of sustaining these links and maintaining the population (see appendix). Altering the relative weighting of the costs and benefits allows us to generate a wide variety of network configurations characterized by site populations, flows of trade/people and other derivative attributes such as island ‘rank’.

The implementation is subtle. Most of us have personal experience of wanting to make the best choice in our actions, but finding very little to distinguish between several of the choices available, perhaps making a final choice with the toss of a coin. Our model reflects this, particularly as the quantification of ‘best’ can only be fuzzy. In practice, at each stage there are several candidate networks that are comparably good, from which the model chooses one and our results have to be interpreted statistically. The ‘imperfect’ nature of our ‘rational choice’ is in strong contrast to the explicit determinism of many other network methods (Evans et al. 2011), such as proximal point analysis (Broodbank 2000) and Euler method entropy minimisation models (Rihll and Wilson 1987,1991).

Results

The immediate outputs in this search for ‘efficient’ networks are the *site weights,* which reflect the respective ‘populations’ and the *link weights,* which reflect the annual traffic along the links. In the figures below, the sizes of the nodes are proportional to the former and the thicknesses of the lines to the latter. These outputs relate only to the *local* properties of the sites and links. More importantly, we can also construct outputs that reflect how the network impacts on individual sites. The most important of these is site *rank (*essentially the same as

PageRank™, used by Google). This is a measure of the *flow* of people/trade passing through a site, not simply related to the site population or site size but an attribute of how the network functions as a whole. It has no counterpart in models with no network structure such as the Xtent model of Renfrew & Level (1979). Sites with high ranking in comparison to their site weights have high impact and are, literally, punching above their weight. In fact, we use the ratio of *rank/weight* to define '*impact*.' Not visible directly in the figures, we shall discuss this where relevant. The analysis that follows explores the likely character of Aegean maritime connections before and after the eruption on Thera.

Pre-eruption Networks (Figures 2a-b)

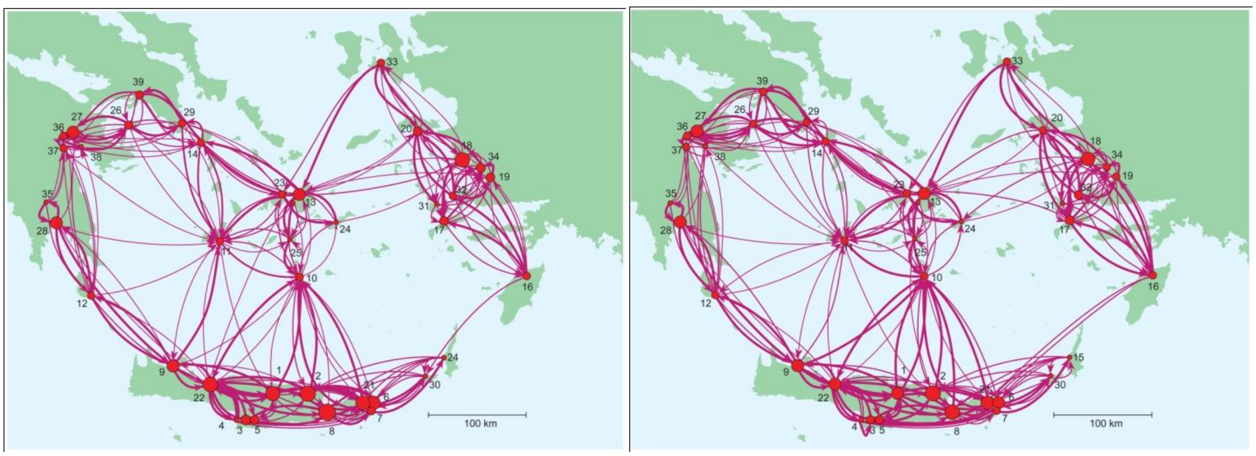

Fig. 2 (a & b). Two exemplary runs of the model for the identical parameter values λ= 4, κ = 1, μ = 0.1, j = -2, d = 110 (see Appendix for more detail). The size of the nodes, the *site weights,* reflects the respective 'population' and the thicknesses of the lines, the *link weights,* reflects the annual traffic along them. In each case the importance of Thera as a link between Crete and the rest of the Aegean is clearly visible.

In the period preceding the Theran eruption, exchange networks across the Aegean appear to have been thriving. There is fairly intensive trade within regional clusters—for example within Crete, and within the Dodecanese/coastal Anatolia area—with significant though less intense activity between clusters. Cretan imports at sites like Akrotiri are certainly substantial, though we should not forget that even here they only constitute c.10-15% of the total pottery consumed. Within our model we can mimic these circumstances by setting the parameters such that there is considerable benefit from trade, while incurring limited costs. We give two examples of pre-eruption networks below in Figure 2a-b. These exemplify the statistical nature of the model in that they arise from the *same* input as comparably 'efficient' networks. In each of these figures Knossos and the north Cretan sites have the highest, comparable, weights ('populations'). Thera has a much lower weight. Although Knossos and northern Crete are among the sites with highest rank, Thera has much higher rank than weight so that, in terms of 'impact', it is comparable with Knossos, which reflects its importance in the archaeological record. Competing sites with high impact are Kasos (30), Zakros (7), Knossos (1) (left hand figure); Kasos (30), Phylakopi (11), Ios (25) (Figure 2b) .

We should not attach too much importance to the details. What is important is that, as exemplary networks, they show regional clusters that are strongly linked within themselves, but linked with each other by weak links and a few strong links. This is actually quite difficult to achieve in the model: it is all too easy, with a small adjustment in the parameters, to flip either towards disconnectivity, with links between the clusters very weak (which happens when benefits of interaction between sites are small in comparison to the benefits from exploiting local resources), or towards hyperconnectivity, with an abundance of strong links, with large sites expanding their populations and trade preferentially. Thus the archaeological scenario of LM IA can be generated as an output from the model, but only with a fairly narrow range of inputs. This is commensurate with the following observation (Broodbank et al. 2005: 95):

'*For the southern Aegean islands in the late Second and Third Palace periods, an age of intensifying trans-Mediterranean linkage and expanding political units, there may often have been precariously little middle ground to hold between the two poles of (i) high profile connectivity, wealth and population, or (ii) an obscurity and relative poverty in terms of population and access to wealth that did not carry with it even the compensation of safety from external groups*'.

If we consider the model outputs in a little more detail, they do show the importance of Thera and north Crete, with a strong Knossos competing with, and often exceeding, neighbouring sites. Perhaps surprisingly, these outputs will turn out to be very resilient to the removal of Thera, as we shall see now.

Immediate Post-eruption networks

The volcanic eruption of Thera is of such a scale that the large Theran site of Akrotiri is completely destroyed. The island sees no signs of reoccupation for centuries thereafter. Thus in our model we can mimic the scenario immediately following the eruption by removing this node from the list of sites and repeating the analysis. Given how much of a hub it was before the eruption, one might expect its removal to create considerable change to the network outputs. In Figure 3, we show examples of networks derived after eliminating Thera from the analysis, but otherwise leaving everything else in the model *unchanged*. As before, the networks have identical inputs.

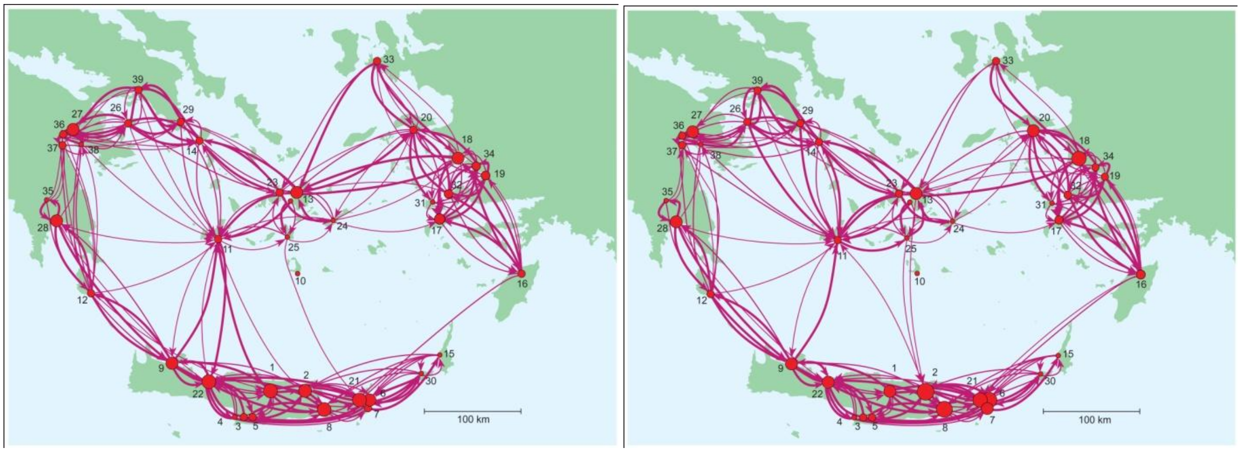

Fig. 3 (a & b). Two exemplary runs of the model for the identical parameter values λ= 4, κ = 1, μ = 0.1, j = -2, d = 110 (as in Figs 2.) on removing Thera from the network. With regard to both weight and rank Knossos and N. Crete dominate. For impact, Kasos, Zakros, Kalymnos, Knossos, and then N. Crete are most important in Figure 3a, Kasos, Karpathos, Kalymnos, Zakros, ..N. Crete in Figure 3b. Total population and Trade are essentially unchanged from pre-eruption averages.

With the removal of Thera, north Crete (including Knossos) still dominates, both in weight and rank. In general, Phylakopi (11) takes over as the link between the Cyclades and other regions, with these islands now strongly connected to the mainland; but there is variation in where the stronger inter-regional links go. Warren notes that the palace building at Zakros (7)—which occurs with consistently high 'impact' in our analysis after the eruption—makes 'little sense on its own in its relatively isolated and circumscribed landward position ... Its wealth makes better sense as part of a larger structure, plausibly as a, or even *the*, eastern port of Knossos in LM IB' (Warren 2001: 116). Thus, there may well have been some adjustments after the eruption to the destruction of the trading hub of Thera. Nonetheless, according to our model outputs, such adjustments can occur without affecting total population and trade which, for the runs above, only fluctuate slightly around the same level as pre-eruption figures. This shows how the removal of a key node has little immediate effect on **overall** activity.

Looking at the archaeological evidence, Cretan centres did not cease to participate in exchange networks in LM IB (Wiener 1991; Warren 2001). Yet, it has been argued that Cretan influence in the Cyclades post-eruption (Late Minoan IB) is less than it was pre-eruption (Late Minoan IA) (Mountjoy 2004: 399-404). Chemical analysis of LM IB/LH IIA Marine Style pottery from Melos (11) and Kea (14) seems to show it is imported from the Greek mainland rather than Crete (Mountjoy and Ponting 2000). If not for Melos directly, inspection of Figure 3 (replicated in further runs of the model for the same parameters) shows links between the northern Cyclades and the mainland as strong as before (on average), and perhaps with greater connections to the N. Dodecanese. We now turn to how such links may evolve.

Later Post-eruption: network collapse

In the post-eruption scenario outlined above, the network is quite stable, no less so than pre-eruption. Other than the removal of Thera, we did not touch the model. But this is unrealistic, because it is likely that the removal from the network of a trading hub would have increased the overall costs of trade. What we imagine is that the costs did not increase immediately after the eruption, but took a little while to kick in. These costs concern the greater distance needed to travel from Crete to trade with the Cyclades, and perhaps a concomitant need for more ships, more crew: generally, more investment. So, we need to incorporate these projected increasing costs of sustaining the network in the cost-benefit assumptions of our model. In this way our networks evolve in time.

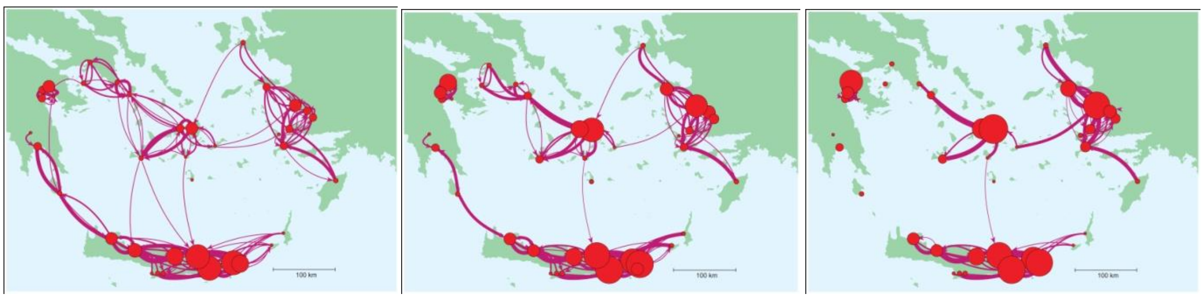

Fig. 4 (a, b & c). Three exemplary runs of the model in which, beginning from the parameter values $\lambda = 4$, $\kappa = 1$, $\mu = 0.1$, $j = -2$, $d = 110$ of Figs. 3, we increase the costs of sustaining links, implemented by increasing the parameter μ (see Appendix).

We show what happens when we increase exchange costs in Figure 4. Taking the map in Figure 4a as our starting point, we can see that the network continues to show significant activity. Increasing the costs of sustaining links (increasing the network parameter ***μ)*** has not substantially reduced total activity. Thus, within our simple approximations, we see an active Ayia Irini prior to the eruption, maintaining its strength after the eruption, in accord with the observation that:

'the evidence points to, if anything, an increase in Minoan trading activity in LM IB, particularly in our excavations at Ayia Irini, Keos (14) where we literally had thousands of LM IB vases imported from outside' (Davis 1980: 336; Cummer & Schofield 1984).

Again, within our simple approximations, we see Kastri on Kythera (12) active both prior to and after the eruption. Indeed, it even seems to flourish in LM IB, with Coldstream and Huxley talking of an 'Indian summer' (Coldstream & Huxley 1984: 110). Fine wares in LM IA were largely locally produced, but in LM IB seem to be almost all imported, including examples of Cretan 'Alternating Style' (Coldstream & Huxley 1984: 110; Coldstream & Huxley 1972).

However, we can see further changes in Figure 4 b to c, as increased exchange costs are progressively input**.** Increasing the costs of sustaining links appears to lead to fewer stronger links as the major sites respond by putting what eggs they have in fewer baskets. In one sense this may seem to be a valid response, in that there can be *more* total trade passing through the limited number of links to keep the network functioning until the collapse. This is in accord with Renfrew's (1980: 337) suggestion that:

'a centralised economy which may be working under some adversity which might be increased population … people coming in from Thera … What I think you would expect to see is not a gradual decline, but an increasing intensity in the various subsystems of the culture system, including an **increasing** level of trade, until the system breaks down altogether.'

But as Renfrew posits, the ultimate result may well be collapse, as concentrating exchange resources in a few links is an unstable solution. We can see the onset of collapse Figure 4c, when the different regional clusters are no longer interconnected. Of course, this is not the only possible outcome. Other, and less dramatic, choices of parameter change do enable a trading network to continue to thrive, or go into gentle decline, perhaps requiring the *deus ex machina* of an earthquake or external invasion to bring it to an end.

This requires a little elaboration. If we treat the numerical value of the cost/benefit function as an 'altitude', for which the model parameters provide 'latitude' and 'longitude', we can usefully think of the function describing a 'cost/benefit landscape'. Each network corresponds to a 'point' in this landscape. Instability occurs when the response of the system is disproportionate to the change in circumstances, a 'tipping-point' from which we roll 'downhill' into one extreme behaviour or another e.g. 'boom' or 'bust'. The 'landscape' of our model is very hilly and, although it is possible to negotiate stable ridges down from its peaks, unstable behaviour is generic for many types of change in external circumstances, presaging collapse. This is an almost inevitable consequence of models in which the non-linear benefits of large sites exchanging with large sites, and thereby making large sites larger, is in precarious balance with the non-linear costs of over-exploitation of local resources.

Conclusions

In this paper we have viewed the events from the eruption of Thera to the destruction of the palaces through the prism of network theory, in arguing that both the rise and decline of Cretan influence can be understood as due to a varying trade-off between the costs and benefits of maintaining a maritime exchange network in a resource-rich environment.

Knossos and Akrotiri are naturally important within our network, but the removal of Akrotiri because of volcanic eruption does not cause the network to collapse, despite the site's importance as a gateway between northern Crete and much of the south Aegean. The network is sufficiently resilient to sustain its overall levels of activity by readjusting links to maintain overall activity. However, what *does* lead to network change is an increase in exchange costs, which we have introduced to mimic the probable increased cost of exchange in the aftermath of the removal of the key trading hub of Akrotiri. This has the effect in our model of encouraging sites to invest their resources in just a handful of seemingly key exchange links, putting their eggs in a few baskets. While this may initially seem a sensible solution in that it can maintain overall trade levels, our model shows it to be an unstable solution that can easily lead to the breakdown of the network. This, then, allows us to untangle the paradox outlined at the start of the paper: the continued exchange post-eruption, and yet collapse within just a few generations. Both are explicable as outcomes of the Theran eruption, if considered in terms of the costs and benefits of regional exchange networks.

This is certainly not to say that our model predicts the destruction of the Minoan palaces as an inevitable outcome of the Theran eruption. There are many possibilities for the longer-term behaviour of the network, too many to map easily. But our model generically leads to network instability under many types of pressure for change. In the scenario outlined here, the system is vulnerable to increasing the costs of maintaining the network, whereby sites concentrate their exchange/trade into fewer, stronger links at the expense of the weaker links. Similar instabilities arise if the benefits of local resources diminish (e.g. bad harvests), but not if the only change is an increase in population pressure.

As many scenarios of ancient societal demise or collapse are currently attracting attention (Tainter 1988; Turchin 2003; Diamond 2005; Schwartz and Nicholls 2006; Railey and Reycraft 2009), with tensions between 'natural' and 'social' explanations, we believe that fuller attention to the kinds of dynamics outlined here may help scholars create more satisfactory interpretations based not on environmental determinism but modelling of local decision-making and their influence on regional/global dynamics.

Acknowledgements

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Technical Appendix: The Cost/benefit or Utility Function

Our primary principle was to work with the fewest and simplest functional forms that are required on general grounds. Details are given in (Knappett et al 2008) but, basically, our *utility, or cost/benefit*, function ***H*** separates into four terms (two benefits followed by two costs), as

$$H = -4\kappa \sum_{i} s_i v_i (1 - v_i) - \lambda \sum_{i,j} V(d_{ij}/D).(s_i v_i).e_{ij}.(s_j v_j) + j \sum_{i} s_i v_i + \mu \sum_{i,j} s_i v_i e_{ij} (1)$$

The summations are over the different sites or over all pairs of sites, labelled by *i* or *j*, which take the values 1 to 39. The aim is to find the configuration of the network that makes *H* as *small* as possible, for fixed values of the input parameters κ, λ, *j* and μ.

We understand *H* as follows:

The site *inputs* are the site carrying capacities, labelled s_I (with a simple relative grading of 1,1/2,1/3 according as to whether available resources are large, moderate or small). Different gradings cause little difference, unless we take sites to have identical capacities (as in Knappett et al. 2008), which favours the Dodecanese over Crete, at variance with the record. The immediate *output* for each site is its fractional resource exploitation v_i so that the total resource use $P_i = s_i v_i$ **,** the node *weight*, reflects population. For an isolated island $0 \leq v \leq 1$**,** but exchange with other islands enables larger populations ($v \geq \mathbf{1}$) to be sustained. The size of the nodes in the Figures of the main text is proportional to the respective ***P*,** the site *weight.*

The *input* parameters for links are essentially statements of how easy it is to travel between pairs of sites, determined by the 'neighbourhood function' $V(d_{ij}$ /D), determined by the ratio of the effective distance d_{ij} between two sites to the distance scale *D* that characterises the largest distance travelled in a single journey, which we take to be $100km < D < 120km$. $V(x) \approx 1$ for near neighbours ($x << 1$) and $V(x) \approx 0$ for distant neighbours ($x >> 1$) (we adopt an x^{-4} behaviour for large *x*). d_{ij} also takes into account the relative difficulty of travelling over land when this is inevitable (e.g. Knossos and Mycenae are inland) and negotiates promonteries. We have considered the effective distance over land as identical, double or triple to that of sea. The figures above assumed a double cost, essentially indistinguishable in output from adopting triple cost. [There is the slight qualification that *V* is truncated so as to be effectively minus infinity for very short distances, whose scale is set by the minimum separation needed for a split community to be treated as two.]

The immediate *output* for each directional link (from site i to site j) is, in the first instance, a directional probability e_{ij} , $0 \leq e_{ij} \leq 1$. This can be thought of most simply as proportional to the fraction of man hours, from the total available per unit of population, that are dedicated to maintaining the link or, perhaps equivalently, the likelihood that any individual will travel along that link in a year, say. The total effort in sustaining that link or, equivalently, the annual traffic along that link from site i to site j will then be $P_i e_{ij}$ (the link *weight*). *The thicknesses of the lines in the Figures of the main text are proportional to these weights.*

The first term proportional to κ describe the benefits from local resources. The second term describes the benefits from exchange. It is proportional to the total 'populations' at both ends of a link and to e_{ij}. For such models it is advantageous, in cultural exchange, or trade, for both a site and its exchange partner to have large resources.

The remaining terms describe the costs of sustaining the total population (the coefficient of j) and the total network activity (the coefficient of μ). As such they impose constraints on population size and total trading links (and/or journeys made).

These outputs relate only to the *local* properties of the nodes and edges. Equally, if not more importantly, we can also construct *global* outputs which, nonetheless, are represented by numbers attached to *individual* links or sites that require knowledge of *all* local variables. In particular, we construct site *rank*: Assuming that sailors continually travel along links with probabilities $\boldsymbol{e}$, this is a measure of the numbers of random sailors that would pass through a site in a given time. This definition of rank is essentially the same sense as PageRank. The ratio of rank to weight we have termed '*impact*'.

The minima are then found by performing Monte Carlo simulations with updates chosen according to the statistical Metropolis algorithm.