EMPLOYING AGENT-BASED MODELING TO STUDY THE IMPACT OF THE THERAN ERUPTION ON THE MINOAN SOCIETY

A. CHLIAOUTAKIS[1,2], G. CHALKIADAKIS[1] & A. SARRIS[2]

[1] School of Electrical and Computer Engineering, Technical University of Crete (ECE-TUC)
angelos@intelligence.tuc.gr, gehalk@intelligence.tuc.gr
[2] Laboratory of Geophysical - Satellite Remote Sensing and Archaeo-environment (GeoSat ReSeArch), Foundation for Research and Technology, Hellas (IMS-FORTH)
asaris@ims.forth.gr

Περίληψη

Ο σκοπός αυτής της εργασίας είναι να εμβαθύνει την κατανόησή μας για την παρακμή του Μινωϊκού πολιτισμού, χρησιμοποιώντας ένα υπάρχον πολυπρακτορικό μοντέλο προσομοίωσης (ABM) για να μελετήσει σε ποιο βαθμό η κατακλυσμική έκρηξη του ηφαιστείου της Θήρας επηρέασε την κοινωνική εξέλιξη του Μινωϊκού πολιτισμού. Λαμβάνοντας υπόψη τη γεωργία ως κύρια παραγωγική δραστηριότητα για την διατήρηση του ανθρώπινου πληθυσμού, αξιολογούμε τις επιπτώσεις της έκρηξης του ηφαιστείου πάνω σε διαφορετικά μοντέλα κοινωνικής οργάνωσης, εστιάζοντας στην ευρύτερη περιοχή των Μαλίων της Κρήτης. Τα παραδείγματα κοινωνικής οργάνωσης που εξετάστηκαν είναι εμπνευσμένα από ένα μοντέλο αυτο-οργάνωσης μιας κοινότητας πρακτόρων καθώς και ιδέες από την εξελικτική θεωρία παιγνίων. Οι επιλογές παραμέτρων του πολυπρακτορικού μοντέλου βασίζονται σε αρχαιολογικές θεωρίες και ευρήματα, αλλά δεν είναι μεροληπτικές προς οποιαδήποτε συγκεκριμένη παραδοχή. Αποτελέσματα από διαφορετικά σενάρια προσομοίωσης επιδεικνύουν μια εντυπωσιακή βιωσιμότητα των νοικοκυριών (πρακτόρων). Ωστόσο, μερικά σενάρια οδηγούν σε αισθητές αλλαγές στην κατανομή των οικισμών, σχετιζόμενες με μια παρατηρούμενη σημαντική αύξηση των ποσοστών μετανάστευσης αμέσως μετά την έκρηξη του ηφαιστείου της Θήρας. Επιπλέον, η έκρηξη φαίνεται ότι είχε ισχυρό αντίκτυπο στην κοινωνική οργάνωση, μετατρέποντας την αρχικά συνεργατική συμπεριφορά των πρακτόρων σε μη συνεργατική. Το γεγονός αυτό παρέχει στήριξη σε αρχαιολογικές θεωρίες που δηλώνουν ότι η έκρηξη του ηφαιστείου της Θήρας οδήγησε σε μία σταδιακή (και όχι άμεση) κατάρρευση του Μινωϊκού κοινωνικο-οικονομικού συστήματος, εν μέρει λόγω συγκρούσεων στο εσωτερικό των τοπικών κοινοτήτων.

Abstract

The purpose of this work is to deepen our understanding of the Bronze Age Minoan civilization's decline, by utilizing an existing agent-based model (ABM) to study the extent by which the cataclysmic volcanic eruption of Thera (Santorini) impacted the Minoan social evolution. Considering agriculture as the main production activity sustaining the human population, we evaluate the volcanic eruption impact on different social organization models, focusing on the wider area of Malia in the island of Crete. The social organization paradigms examined are inspired by a framework for self-organizing agent organizations, and ideas from evolutionary game theory. Model parameter choices are based on archaeological theories and finds, but are not biased towards any specific assumption. Results over a number of different simulation scenarios demonstrate an impressive sustainability of household agents. However, in some scenarios we observe noticeable changes in the settlements' distribution, relating to significantly higher migration rates immediately after the eruption. Moreover, the eruption appears to have had a strong impact on social behaviour, transforming the initially cooperative agents' behaviour to a non-cooperative one. This provides support for archaeological theories suggesting that the Theran eruption led to a gradual (and not immediate) breakdown of the Minoan socio-economic system, partly due to inner community competition and conflicts.

Λέξεις Κλειδιά/Keywords: agent-based modelling, computational archaeology, social organization, Minoan civilization

1. Introduction

Over the last 15 years archaeological simulation models are associated with a particular modelling paradigm, namely agent-based modeling (Lake 2014). Agent-based models incorporate ideas from multi-agent systems (MAS) research, mainly to enhance agent sophistication, while information processing is achieved among interaction of entities (agents) that also consider their environment, with a view to assess their effects on emergent properties of the system as a whole. Agent-based archaeological simulation can be viewed as the means of modelling long-term social change by tracing individual or collective entities and its actions, allowing us to understand the feedback between decision-making and the environment in which decisions are made (Kohler and Gumerman, 2000). Many archaeologists have commented on the coming of age for agent-based modelling in archaeology and the utility of archaeological simulation considering the degree of its methodological maturity (McGlade 2005; Lake 2015); others provide proper introduction on archaeological simulation, focusing on agent-based simulation (Railsback and Grimm, 2012). In addition, by the turn of the millennium archaeological simulation has already included considerable examples of spatial agent-based modelling, since many ABM contributions include a spatial component (Westervelt, 2002; Chliaoutakis and Chalkiadakis, 2015).

In this work, we adopt such an approach of agent-based modelling and utilize a recently developed ABM with autonomous agents, able to explore alternative hypotheses regarding the social organization of ancient societies (Chliaoutakis and Chalkiadakis, 2016). The purpose is to deepen our understanding of the Bronze Age Minoan civilization's decline by incorporating a natural disaster sub-model in order to study the extent by which the natural phenomenon affected the ancient society's social evolution. Specifically, we simulate the interactions of agents, corresponding to households in early Minoan settlements located in the Malia area at the island of Crete, for studying and evaluating the impact of the volcanic eruption of Thera on different agent social organization models. The social organization paradigms examined are inspired by a framework for self-organizing agent organizations, and ideas from evolutionary game theory (EGT). Considering agriculture as the main production activity sustaining household agents' population, we try to assess the imminent social crisis in terms of household and settlement sizes, migration behaviour and agents strategic behaviour evolution, before and after the natural disaster.

Results over a number of different simulation scenarios demonstrate an impressive sustainability of household agents, even for scenarios with relatively high mortality. At the same time, higher settlement numbers and fewer agents per settlement after the volcanic eruption are observed. Additionally, even higher migration rates are recorded immediately after the eruption. However, the serious decline in population size and change in settlement distribution patterns, appear to transform the initial cooperative agents' behaviour towards a non-cooperative one, thus, providing support to archaeological theories suggesting that the Theran eruption led to a gradual breakdown of the Minoan socio-economic system.

2. Archaeological background

Some of the most interesting questions one may ask about early societies are about people and their relations, the nature and scale of their organization, about social change and decline of past civilizations. Specifically, in this work, we attempt to incorporate natural disaster scenarios into archaeological simulations about social change, based on archaeologically traceable environmental and human impact of the mid-2nd millennium BCE Santorini eruption to the Minoan civilization.

The Theran eruption of Santorini continues to trouble scientists, especially on questions surrounding the volcanic eruption absolute date and its impact on the ecosystem of the Ancient Mediterranean. A series of changes in the Aegean, in particular in Cretan Bronze Age society, were triggered by the LM (Late Minoan) IA or ca. 16th c. BCE Santorini eruption (Driessen and Macdonald, 1997). These changes would have caused the breakdown of the Minoan system over the course of a few generations, during LM IB (15th c. BCE). Archaeologists hypothesize that the eruption would have initially caused major problems in food production and distribution, undermining central authority and leading to a process of decentralization; this fragmentation would then have led incrementally to internal conflict. However, despite the many destructions and abandonments documented, Minoan culture survived.

There is still no agreement on the absolute date of the eruption. Quite a few earth scientists take the late 17th c. BCE date (between 1630 and 1600 BCE) for granted, whereas many archaeologists remain to the traditional late 16th c. BCE date, roughly around 1530-1520 BCE (Driessen 2018). Despite the absolute date of the eruption, there is little doubt that the eruption was preceded and probably even triggered by one or more earthquakes. However, considering the archaeological record of Bronze Age Crete, careful analysιs of old and new archaeological data suggest that earthquake evidence is patchy, frequently ambiguous, and generally less spectacular than what popular accounts of Minoan society would expect (Jusseret and Sintubin, 2017).

Moreover, there is also no doubt that during the eruption large amounts of ash and pumice were emitted. Deposits of tephra originating from the Minoan Santorini eruption have been found dispersed in many Cretan sites. However, distinct volcanic ash layers are not apparent in the open hilly landscape of Crete (Bruins et al., 2008). While ash veils from a volcanic eruption normally clear up within a few years, dendrochronological work suggests limited plant growth for up to a decade (Baillie and Munro, 1988), rendering its impact detrimental to farms, at least on the eastern half of island of Crete. It may further be assumed that the eruption was accompanied by one or more tsunamis (Sakellariou et al., 2012). Tsunami generation and simulations suggest that the north coast of Crete was struck by highly variable wave amplitudes, ranging from a few to almost 30m with inundations of up to 300m inland, considering caldera collapse (Novikova et al., 2011). However, new evidence suggests that tsunamis can only have been caused by pyroclastic flows, where reasonable estimates reach up to a maximum of 10-12m height (Nomikou et al., 2016).

Based on the above, we may now form and describe the conceptual natural disaster sub-model incorporated in our ABM, in an attempt to provide insights to whether the effects of the Santorini eruption set in motion the process that led to the breakdown of Minoan society in ca. 1450 BCE.

3. The Agent-based model

In this work we incorporate a natural disaster sub-model on an existing ABM for simulating an artificial ancient society of household agents evolving within a grid environmental topology (Chliaoutakis and Chalkiadakis, 2016).

Agents and resources in the model are located within a 20 x 25 km area with a 100 x 100 m cell size for the grid space (Fig. 1). Environment's spatial information is derived from modern data concerning the topography – *i.e.*, today’s elevation, slope and aquifer (rivers and springs) locations. Thus, the landscape consists of 50K cells, while the time slot investigated is 2000 years (3100 to 1100 BCE), with annual time steps.

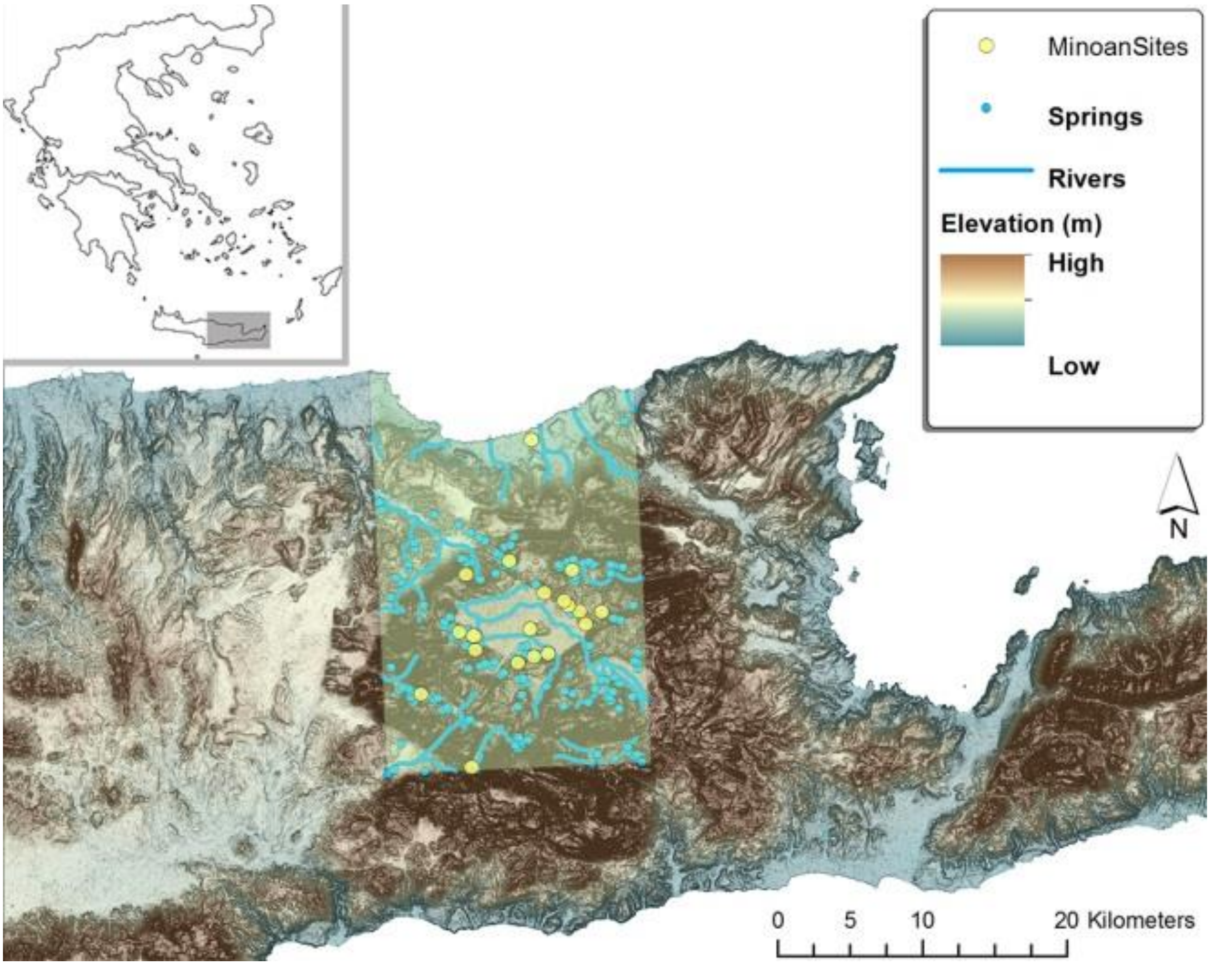

Figure 1. *Map indicating the area near Malia that was used in the ABM simulations. Environmental data included: elevation information, aquifer locations and known (Minoan) site locations.*

An agent in the model represents a household, containing up to a maximum number of individuals (inhabitants), and resides in a cell within the environmental grid, with the cell potentially shared by a number of agents. Adjacent cells occupied by agents make up a settlement — and there is at least one occupied cell in a settlement. Estimated population per hectare (cell) in an agricultural settlement was set by default to 100 based on population estimates by Isaakidou (2008). Households are *utility-based autonomous* agents who can settle (or occasionally re-settle) and cultivate nearby environmental cells. Household agents also possess an explicit representation of the environmental grid, allowing them to choose the best available location they can migrate to, in order to improve their utility. An agent moves to another location only when it finds a location within its perception radius that is better than its own location.

The agent calculates its expected utility for the new location as the average agricultural production of the neighboring cells, considering the agent moved to the respective unused cell. If the expected utility of the agent for the new location is higher than the agent's current utility, the location is considered to be an option for migration. If there are many such locations, the agent migrates to the one perceived to be the most favorable. We note, that we do not argue that utility is the main factor driving human behaviour or the advance of human societies. Nevertheless, utility theory has long been adopted as a useful tool in Artificial Intelligence (Russell and Norvig, 1995).

The total number of household agents in the system fluctuates over time, as individuals are born or die. The annual levels of births of individuals within a household are based on the amount of resources harvested and consumed by the household agent during the year. These rates produce a population growth rate of 0.1%, when households consume adequate resources (Chliaoutakis and Chalkiadakis, 2016). This assumption corresponds to estimated world-wide population growth rates during the Bronze Age (Cowgill, 1975). Resources harvested affect agent's utility, $U_x = f(population; location)$, a function inspired by the logistic map equation, the discrete version of the logistic differential equation, widely used to model population growth (Law et al., 2003). This naive function captures the fact that labour applied on a cultivated cell increases crop yield up to a point, but at the same time a household agent cannot use productively a specific location forever due to soil depletion. Cultivation area is also affected by the cell's geomorphological characteristics, i.e. as a decay of agricultural land suitability with increasing slope, given its location on the grid. Moreover, when individuals in a household exceed a critical number, new households (agent offsprings) are created; and when the agent overall utility levels are not high enough to sustain its individuals, households are "abandoned" and agents die. We refer to Chliaoutakis and Chalkiadakis (2016) for details.

Any interaction between a pair of household agents within a settlement, takes place based on their relation type: acquaintance, peer or authority (superior - subordinate) related agents; and these relations give rise to a social structure reflecting the flow of resources during exchanges among the agents. The authority relation depicts a "superior status" of an agent *x* over the subordinate agent *y* in the context of their social organization, reflecting that higher amounts of resources flow from *x* to *y* during exchanges, than those flowing in the opposite direction. The peer relation holds between agents who are considered more-or-less equal in status (i.e. flows involve resource transfers of almost equal amounts in both directions); while acquainted agents are aware of each other's presence, but have no interaction (Chliaoutakis and Chalkiadakis, 2016). Agents use the information about all their past and current year resource allocations to re-evaluate and possibly alter their relations with others. These relations determine the way resources are ultimately distributed among the agents. This re-organization stage is performed within the framework of an (extended) agent self-organization algorithm (Kota et al., 2009), that results to the continuous targeted redistribution of wealth, i.e., resources flow from the more wealthy agents to those more in need, maintaining a dynamically "stratified" social structure.

Specifically, in our simulation experiments we consider the following differentiated social organization paradigms for household agents:

Hierarchical (static): Agents distribute resources based on a fixed hierarchical social structure. The agents are linked to each other via static social relations, which determine the amount of resources each agent acquires via the distribution scheme. In short, there is no re-organization stage.

Self-Organization (dynamic): Agents autonomously re-arrange their relations, and hence the underlying social (network) structure describing these relations, without any external control. They do so in order to adapt to changes in requirements and environmental conditions. They constantly re-evaluate and possibly alter their relations with other agents, employing the aforementioned self-organization algorithm.

Evolutionary self-organization: Each household agent is "genetically" programmed to play originally some pure strategy and agent offsprings inherit the strategy the agent currently plays. An agent playing repeated stage games with opponents, sticks to some pure strategy for some period consisting of several years, and then reviews its strategy, which sometimes results in a change of strategy. We assume three simple player strategic behaviours: a cooperative one (C), willing to share resources with another player; a “defection” one (D), refusing to share resources; and one which starts with cooperation and then behaves as the other player did in the previous game round, namely Tit-for-Tat (Axelrod and Hamilton, 1981). Considering these different strategic agent types as playing games against each other, we explore the evolutionary dynamics that arise. Agents’ payoff is interpreted as fitness, depending on the relative proportions of the different strategies in the population. Success in game playing improves utility, and is translated into reproductive success; strategic agents that do well over time reproduce more, while the ones that do poorly are outcompeted. As such, self-organization is now driven by the interactions of strategic agents operating within a given social organization group and the replication mechanism is based on imitation and reinforcement of successful behaviours (Chliaoutakis and Chalkiadakis, 2017).

The above agent behaviours are evaluated before and after the natural catastrophe, to assess the social crisis in terms of household and settlement sizes, social structure adaptation to environmental changes, migration rates and strategic behaviour evolution.

3.a The natural disaster sub-model

We assume that the natural disaster sub-model takes effect at 1630 BCE, that is, approximately the date of the eruption estimated by earth scientists (Driessen 2018). In order to conceptualize the model, we considered tsunami and volcanic ash impact on the artificial society and their effects on agriculture and human life. To that end, we assume the following simple processes based on archaeological estimates (cf. section 1):

Tsunami: We assume a 10 meters sea-level rise (including 2m rise on today elevation), with inundations of 300 meters inland in order to define tsunami affected areas on the model’s environmental grid. The agricultural impact to the respective areas is assumed to be rendering associated agricultural fields useless for up to 20 years. Human (immediate) impact is also assumed to create 10-15% fatalities (mortality) at the tsunami affected areas, linearly decreasing with distance to coastline.

Volcanic ash: Considering that the volcanic ash layer is smaller at higher elevations and clears up within 2-3 years, we assume the environmental impact of the eruption to be a limited growth to all agricultural fields in the model area for up to 10 years. The agricultural impact is considered to affect environmental cells inversely linear to elevation. For simplicity, no immediate human impact is assumed by the volcanic ash emission process.

The above simple natural disaster model is incorporated to the aforementioned ABM for studying and evaluating the impact of the volcanic eruption of Thera on different social organization paradigms of Minoan household agents located in the wider area of Malia at the island of Crete (see Fig. 1).

4. Simulation experiments and results

Model parameters were initialized to values that correspond to archaeological records or estimates found in archaeological studies relevant to the period of concern, such as estimated per hectare population in an agricultural settlement, resources amount required per individual per year, agricultural strategy and production per year, etc. (Isaakidou, 2008; Bevan, 2010). The number of initial settlements per scenario was set to 2, and the number of household agents in a given settlement was initialized to a random number between 1 and 10.[1] Moreover, a cell’s initial resources amount at a given run is multiplied with a sample from a standard normal distribution, and thus varies across runs. In all simulation experiments below, an intensive agricultural regime is employed, and it is required that settlements are built near aquifer locations. Mortality rates for the natural disaster sub-model – that is, the probability of annual deaths among the individuals located at the tsunami-affected area – were initialized to 10% and 15%.

Furthermore, the random number generators introduced in parts of the model are obviously “pseudo-random”. Thus, via using the same random “seeds”, one may introduce the same opportunities for agents in the model simulations (i.e., same “random” initial agent locations etc.). In this way, our simulations are reproducible.[2] In our base experiments, we evaluate the performance of agents that use self-organization against those that self-organize but do not change their relations (hierarchical), in terms of population growth achieved. In total, 12 experimental scenarios were simulated, and each scenario was simulated for 30 runs, for a total of 360 simulation runs = 30 x 2 (agent organization paradigms) x 3 (volcanic eruption scenarios) x 2 (mortality rates). In figures below, we depict shaded areas that correspond to

[1] We further experiment with 20 settlements; however, their initial number in the ABM simulations does not change substantially the conclusions drawn from the simulation results (Chliaoutakis and Chalkiadakis, 2016).

[2] The source code will be available at http://www.intelligence.tuc.gr/~angelos upon publication.

95% confidence intervals around lines corresponding to average number of household agents, number of settlements and settlement sizes.

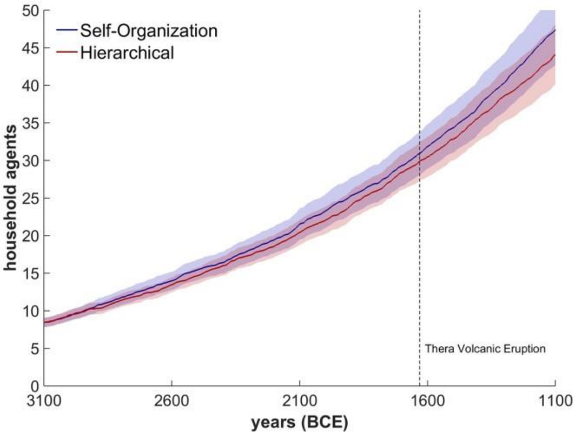

Figure 2. Number of household agents over 2000 (yearly) time-steps for the default scenario, considering 10% mortality rate.

Thus, in our default volcanic eruption scenario, we report that agent population size (number of households) increases with time, regardless of mortality rates, exhibiting similar viability potential for both the self-organization and hierarchical organization structures (Fig. 2). Additionally, we observe no human losses; during simulation runs, no household agent was settled at tsunami-affected areas at the time of the eruption, where fatalities are introduced by the model.

We do observe, however, an increase of ~60% on the average number of settlements (Fig. 3). This is due to higher migration rates observed immediately after the eruption, as further stated in our observations.

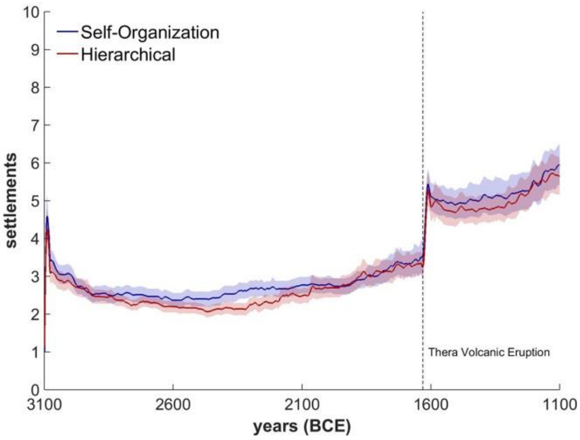

Figure 3. Number of settlements over 2000 (yearly) time-steps for the default scenario, considering 10% mortality rate.

Moreover, we report an overall decline of ~30% on the average number of household agents per settlement after the eruption (Fig. 4). Therefore, changes in settlement numbers and sizes are observed due to the agricultural impact of the eruption; more and smaller size settlements continue to cultivate the land after the eruption. Intuitively, one could assume that the layering of volcanic ash and the subsequent degradation of soil quality led to increased migration.

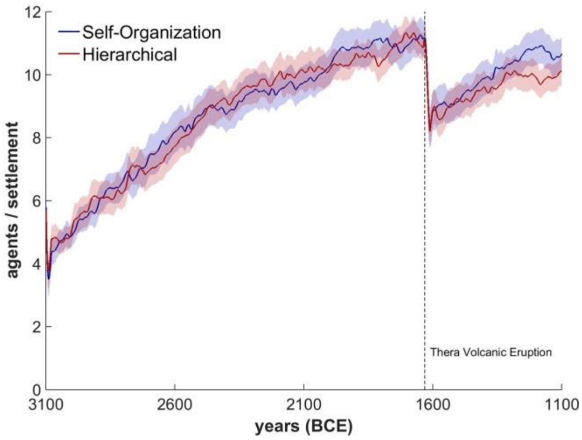

Figure 4. Number of agents per settlement over 2000 (yearly) time-steps for the default scenario, considering 10% mortality rate.

Since no human losses were observed to the default volcanic eruption scenario, we attempted to manually "move" (set) at the time of the eruption existing agent settlements to tsunami affected areas, in order to model human fatalities. We assumed the following two alternative scenarios: (i) moving the closest existing settlement to the geographical location of the archaeological site of Malia; and (ii) moving two closest existing settlements to randomly selected tsunami affected geographical locations.

In what follows, we refer to the former scenario (i) as scenario A, where the impact of the tsunami waves at the archaeological settlement of Malia presupposes an unrealistic parameterization to the natural disaster sub-model: the site is located in an elevation of 18m (wave height) and a distance from the coast 670m (inundation). We also refer to scenario (ii) as scenario B, where the default parameterization of the natural disaster sub-model was used. Simulation results of both scenarios exhibit similar effects; nevertheless, those are more intense and noticeable in the case of scenario B.

Specifically, the household agents' population size is now reduced, for both the self-organization and hierarchical organization structures, reaching up to ~8% death toll for scenario A and up to ~16% for the scenario B, respectively (Fig. 5). This is due the fact that 2 out of 3 settlements on average (over 30 runs) were struck by the tsunami waves.

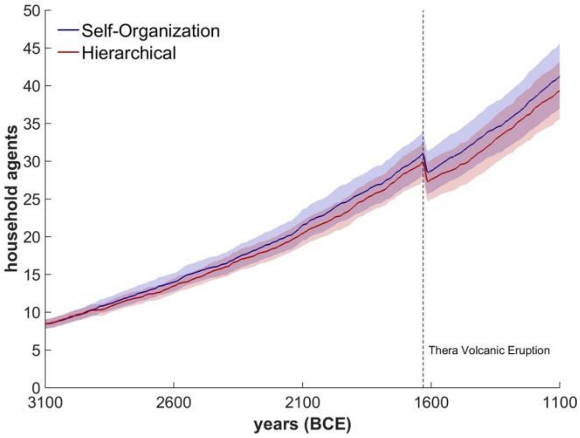

Figure 5. Number of agents over 2000 (yearly) time-steps for scenario B, considering 15% mortality rate.

However, we observe an increase on the average number of settlements, of ~90% for scenario A and of ~150% for scenario B, respectively. The latter is shown in Fig. 6.

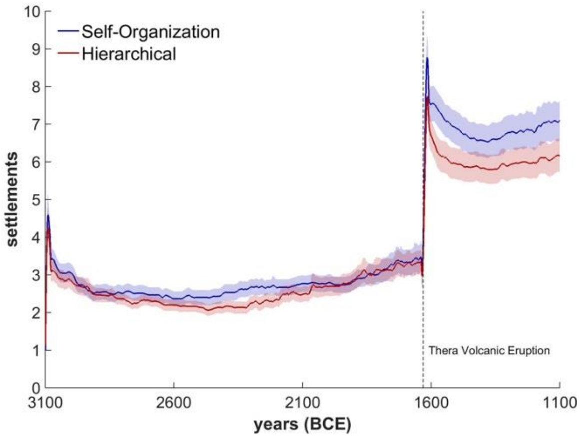

Figure 6. Number of settlements over 2000 (yearly) time-steps for scenario B, considering 15% mortality rate.

Moreover, we observe more settlements after the volcanic eruption for household agents adopting the self-organized social behaviour, rather than the hierarchical (static) one.

In addition, we observe an even more abrupt decline on the average number of household agents per settlement (settlement size) after the eruption, of ~40% for scenario A (Fig. 7) and of ~55% for scenario B (Fig. 8), respectively. Therefore, we observe a totally changed landscape consisting of many “small-size” settlements after the eruption rather than a few and higher in size communities before the eruption. This major change is a result of the environmental impact by the volcanic ash and pumice, as well as the human impact attributed to the tsunami waves that struck settlements located near to the coast. This is because of “forced” migration due to soil degradation. We report that before the eruption, migration rate for the agents – that is, average number of households out of the total of households that migrate annually to other locations – was ~1%, while immediately after the eruption migration rate was increased to ~15%, ~20% and ~25% for the default, A, and B scenarios respectively.

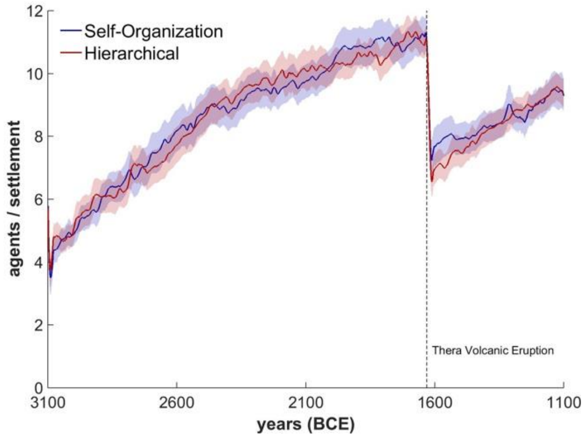

Figure 7. Number of agents per settlements over 2000 (yearly) time-steps for scenario A, considering 15% mortality rate.

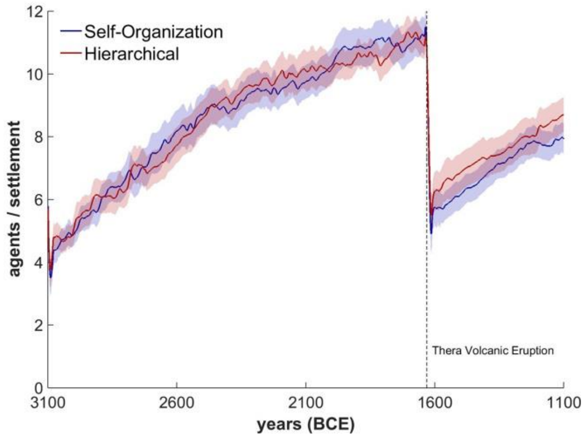

Figure 8. Number of agents per settlements over 2000 (yearly) time-steps for scenario B, considering 15% mortality rate.

Higher migration rates are the result of the high number of household agents being undernourished: immediately after the eruption, about 70% of household agents are below their utility threshold, a fact which means that the agents possess insufficient resources for sustaining themselves.

Since household agents are able to store any surplus resources in their storage, for up to several years (default: 5), we report on the average amount of resources stored before and after the time of the eruption, in order to further examine the high migration rates and percentage of household agents being undernourished. The average amount of resources stored by household agents during the simulation period is similar for all scenarios, however, agents adopting the self-organized social behaviour appear to have an advantage on the amounts they were able to store after the volcanic eruption. Storage average values drop to ~95% immediately after the time of the eruption; however, self-organizing strategies succeed to store even more than before the eruption, after a few decades from the time of the eruption until the end of the Minoan period, while hierarchically organized agents also manage to bounce back in terms of food stored (Fig. 9). Moreover, we observe that after the eruption, storage values are higher for agents adopting a self-organization social behaviour than agents employing a static hierarchical social paradigm.

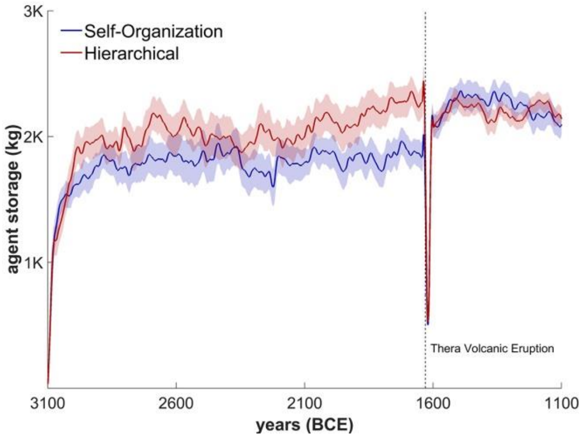

Figure 9. Agent storage over 2000 (yearly) time-steps for scenario B, considering 15% mortality rate.

Certainly, the impact of a natural disaster on a human society tends to affect also aspects of its community life, since essential functions of the society (such as the allocation of resources) are interrupted or destroyed. Therefore, in order to assess the social crisis potentially caused by the volcanic eruption impact, we also provide results on an alternative agent self-organization social paradigm that is driven by the interactions of strategic agents operating within a given social organization group, namely *evolutionary* self-organization.

Thus, we simulated 6 additional experimental scenarios, where each scenario was simulated for 30 runs, for a total of 180 simulation runs, considering all three social organization paradigms and mortality rates of 10% and 15%. However, the number of initial settlements per scenario was now set to 20. In this way the evolution of strategic agents' behaviour during the simulation can be better observed. To this end, we evaluate the performance of agents that play games and self-organize, in terms of population growth achieved.

In particular, we examine the evolutionary self-organization social behaviour setting that was able to achieve the most cooperative behaviour observed. In previous work, we have shown that agent populations converge to adopting cooperative strategies, despite this behaviour being in contrast to that prescribed by the stage game Nash equilibrium. In particular, cooperative behaviour was more widespread when agent fitness was evaluated with respect to their overall utility rather than their immediate reward, and the adoption of alternative strategies was stochastic (Chliaoutakis and Chalkiadakis, 2017)

The viability results are similar with the previous ones. This is because of the migration due to soil degradation. The intuition and conclusions drawn from the previous results do not change. Interestingly, however, we observe that the average number of household agents adopting a defective behaviour D after the eruption is increased and exceeds those that adopt a cooperative one (Fig. 10).

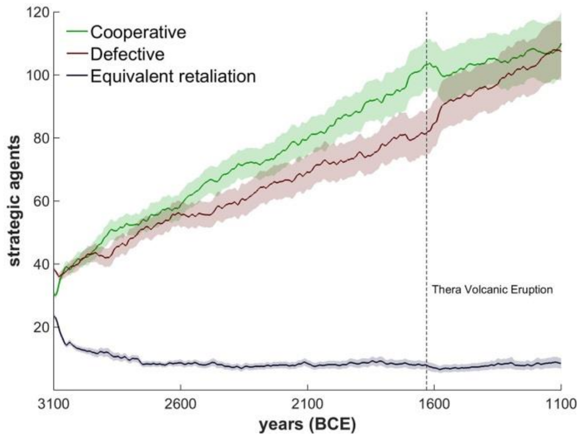

Figure 10. Strategic agent population over 2000 (yearly) time-steps for the default scenario, considering 15% mortality rate.

This indicates that the eruption also had a strong impact on the social behaviour of the household communities. This observation is in line with the fact that conflict usually arises due to problems with the allocation of resources for rehabilitation after a disaster, given its impact on natural resources (Driessen 2018).

5. Conclusions and future work

In this work, we attempted to deepen our understanding of the Bronze Age Minoan civilization's decline by incorporating natural disaster scenarios in an ABM for archaeological simulations. Specifically, we explored whether the Minoan eruption of the Thera volcano was a catalyst, through its environmental and human impact, which triggered a disintegration process in early Minoan communities. Household agents were assumed to be located in Malia area at the island of Crete, and different (household) agent social organization paradigms are employed, inspired by MAS and EGT, and in particular, a framework for self-organizing agent organization. We tried to assess the imminent social crisis in terms of household and settlement sizes, migration behaviour, and evolution of agent strategic behaviour, before and after the eruption.

Simulation results over a number of different scenarios show higher non-cooperative household agent numbers after the eruption. This result may provide support to archaeological hypotheses of decentralization, which led to political fragmentation and internal conflict with increasing competition, largely related to the acquisition of resources (Driessen and Macdonald, 1997).

Moreover, we observed a significant change in settlement distribution patterns, an effect of high mobility and starvation rates, rendering a landscape with higher number of “small-size” settlements at the end of the LM IB period. Archaeologists argue that the number of settlements or households, of ritual sites and of funerary sites that were abandoned during LM IA is considerable, however, they cannot yet distinguish archaeologically between a mature (i.e. prior the eruption) and final (i.e. contemporary to the eruption) abandonment (Driessen, 2018). Interestingly, in our simulations increased food storage is also observed after the eruption, suggesting collection of resources organized on a greater scale. Surprisingly, recent excavations have brought evidence pinpointing towards an increase in storage space in the mature LM IB phase, while the reduction in population size, change in the distribution of human groups, including their mobility patterns, and the conversion of food into direct and indirect storage, are all features evidenced during LM IB (Driessen and Macdonald, 1997). Therefore, results may provide support to archaeological hypotheses suggesting that the Theran eruption led to a gradual breakdown of the pre-eruption Minoan socio-economic system.

In terms of future work, we need to enhance the ABM with additional geomorphological information and archaeological evidence of interest. In addition, we intend to examine and incorporate further models of exchange for inter-settlement trading behaviour; and potentially address other specific archaeological questions and gain new insights into existing theories. The use of our agent-based model bears the potential of assisting archaeologists to come up with entirely novel explanations and paradigms regarding the ancient society being studied.

Acknowledgements
The authors wish to thank the Laboratory of Geophysical - Satellite Remote Sensing & Archaeo - environment of the Foundation of Research & Technology for providing archaeological data for the ABM.

References

Axelrod, R., & Hamilton, W. D. 1981. The evolution of cooperation. *Science*, 211(4489): 1390-1396.

Baillie, M. G., & Munro, M. A. R. 1988. Irish tree rings, Santorini and volcanic dust veils. *Nature*, 332(6162): 344-346.

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

Bruins, H. J., MacGillivray, J. A., Synolakis, C. E., Benjamini, C., Keller, J., Kisch, H. J., Klügel, A. and Van Der Plicht, J., 2008. “Geoarchaeological tsunami deposits at Palaikastro (Crete) and the Late Minoan IA eruption of Santorini.” *Journal of Archaeological Science*, 35(1): 191-212.

Chliaoutakis, A., & Chalkiadakis, G. 2015. Interpreting the Past through Agent-Based Modeling and GIS. In Sarris, A. (Ed.), *Best Practices of GeoInformatic Technologies for the Mapping of Archaeolandscapes*, pp. 159–171. Oxford: Archaeopress.

Chliaoutakis A. & Chalkiadakis G. 2016. Agent-Based Modeling of Ancient Societies and their Organization Structure, *Journal of Autonomous Agents and Multi-Agent Systems (JAAMAS)*. 30(6): 1072-1116.

Chliaoutakis, A., & Chalkiadakis, G. 2017. Evolutionary game-theoretic modeling of past societies' social organization. In *Proceedings of the European Conference on Artificial Life*. Volume 14, pp. 98-105. Cambridge, USA: MIT Press.

Cowgill, G. L. 1975. On the causes and consequences of ancient and modern population changes. *American Anthropologist*, 77(3):505–525.

Driessen, J. 2018. The Santorini eruption. An archaeological investigation of its distal impacts on Minoan Crete. *Quaternary International*. Volume 2018 (4): 121-131.

Driessen, J. and Macdonald, C. F. 1997. The Troubled Island. Minoan Crete before and after the Santorini eruption, pp. 106-113. *Aegaeum* 17. Liège-Austin: University of Texas Press.

Jusseret, S., & Sintubin, M. (Eds.). 2017. *Minoan Earthquakes: Breaking the Myth Through Interdisciplinarity* (Vol. 5). Leuven University Press.

Isaakidou, V. 2008. "The fauna and economy of Neolithic Knossos" revisited. In *Escaping the Labyrinth. The Cretan Neolithic in Context.* Sheffield Studies in Aegean Archaeology, pp. 90–114. Oxbow Books, Oxford.

Kohler, T. A., & Gumerman, G. G. (Eds.). 2000. *Dynamics in human and primate societies: Agent-based modeling of social and spatial processes*. Oxford University Press.

Kota, R., Gibbins, N., & Jennings, N. R. 2009. Self-organising agent organisations. In *Proceedings of AAM'S'19*. Volume 2, pp. 797-804. IFAAMAS.

Lake, M. W. 2014. Trends in archaeological simulation. *Journal of Archaeological Method and Theory*, 21(2): 258-287.

Lake, M. W. 2015. Explaining the past with ABM: on modelling philosophy. In *Agent-based modeling and simulation in archaeology*, pp. 3-35. Springer, Cham.

Law, R., Murrell, D. J., & Dieckmann, U. 2003. Population growth in space and time: spatial logistic equations. *Ecology*, 84(1): 252-262.

McGlade, J. 2005. Systems and simulacra: Modeling, simulation, and archaeological interpretation. In H. D. G. Maschner & C. Chippindale (Eds.), *Handbook of archaeological methods*, pp. 554–602. Oxford: Altamira Press.

Nomikou, P., Druitt, T. H., Hübscher, C., Mather, T. A., Paulatto, M., Kalnins, L. M., Kelfoun, K., Papanikolaou, D., Bejelou, K., Lampridou, D., Pyle, D. M., Carey, S., Watts, A. B., Parks, M. M., 2016. Post-eruptive flooding of Santorini caldera and implications for tsunami generation. *Nature Communications*, 7(13332).

Novikova, T., Papadopoulos, G. A., McCoy, F. W., 2011. Modelling of tsunami generated by the giant late Bronze Age eruption of Thera, south Aegean Sea, Greece. *Geophysical Journal International*, 186(2): 665–680.

Railsback, S. F., & Grimm, V. 2012. *Agent-based and individual-based modeling: a practical introduction*. Princeton: Princeton University Press.

Russell, S. J. A. and Norvig, P. A. 1995. *Artificial Intelligence: Modern Approach*. Prentice Hall Series In Artificial Intelligence.

Sakellariou, D., Rousakis, G., Nomikou, P., Bell, K. C., Carey, S., & Sigurdsson, H. 2012. Tsunami triggering mechanisms associated with the 17th cent. BC Minoan eruption of Thera volcano, Greece. In *The Twenty-second International Offshore and Polar Engineering Conference*. International Society of Offshore and Polar Engineers.

Westervelt, J. D. 2002. Geographic information systems and agent-based modelling. In H. R. Gimblett (Ed.), *Integrating geographic information systems and agent-based modeling techniques for simulating social and ecological processes*, pp. 83–104. Oxford: Oxford University Press.