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Towards a Multi-Agent-Based Modelling of Obsidian Exchange in the Neolithic Near East

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Abstract This paper examines an alternative approach to previously proposed models of prehistoric exchange such as the law of monotonic decrement or the down-the-line exchange model developed by Renfrew (Proceedings of the Prehistoric Society 34: 319–331, 1968, Renfrew 1977) to explain the distribution of obsidian across the Near East during the Neolithic period. Renfrew's down-the-line model, which results in a very regular and clustered network, does not permit the circulation of obsidian to regions of the Near East that are further than 300 km from the source zones, as is shown in the archaeological data available. Obsidian exchange is a complex system where multiple factors interact and evolve in time and space. We therefore explore Agent-Based Modelling (ABM) so as to get a better understanding of complex networks. ABM simulations of an exchange network where some agents (villages) are allowed to attain long-distance exchange partners through correlated random walks are carried out. These simulations show what variables (population density, degree of collaboration between villages…) are relevant for the transfer of obsidian over long distances. Moreover, they show that a type of small-world exchange network could explain the breadth of obsidian distribution (up to 800 km from source) during the Near Eastern Neolithic.

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Introduction

In economic terms, the transition from hunter–gatherer to farming societies in the Near East is characterised by the beginnings of agriculture and animal husbandry. Following the process of sedentarization, the important shift towards a settled agro-pastoral lifestyle was accompanied by other socio-economic and ideological changes, such as the first villages, cultic buildings, and long-distance exchange in exogenous resources. It is likely that all of these cultural shifts were interrelated, forming a complex and dynamic cultural system that was continually changing.

Archaeologists have sought to explain the origin of the Neolithic as a process linked to environmental adaptation (Bar Yosef and Meadow 1995), growing socio-economic complexity (Kuijt and Goring-Morris 2002) or as a revolution of symbols (Cauvin 2000). However, the emergence of long-distance trade in resources has played a minimal role in debates on the process of neolithisation and its socio-economic consequences, despite the fact that intensified inter-regional interaction was likely to have had a part in enabling the transition to farming societies.

It has become increasingly evident that cultural interaction between distant regions of the Fertile Crescent can be crucial to explaining the transition into the Neolithic (Bar Yosef and Belfer-Cohen 1989; Watkins 2008). The exchange of items is present in all human societies. Exchange is primarily an economic behaviour that is intended to assure the supply of needed or valued commodities not accessible or produced by the groups being supplied. However, exchange is also a way of establishing and maintaining social relationships, whereby exchange networks can also be avenues for social exchange (experiences, values, beliefs. etc.) or tools of political relations. Therefore, the study of exchange dynamics is also an analysis of social interaction between communities.

This paper proposes new approaches to modelling the complex workings of past human exchange networks so as to better understand their characteristics. Using Agent-Based Modelling and Complex Network theory (Barrat *et al.* 2008), we take a step beyond Renfrew's seminal models to explore the complexity of the exchange networks that were inextricably linked to the spread of agriculture and animal husbandry in the Fertile Crescent. We test the importance of a number of variables, in order to begin reconstructing the mechanisms of exchange between Neolithic villages in the Near East.

Obsidian Circulation in the Neolithic

Obsidian is a volcanic glass that was widely used in prehistory for the making of utilitarian tools and elite objects. Though it forms in few volcanic areas and in varying quantities and qualities, the properties of obsidian from different outcrops can be precisely geochemically distinguished so that the geochemical properties of a tool found on a site can be matched to an exact source origin (Gratuze 1998, 1999). Obsidian is therefore an excellent tool for tracking prehistoric exchange.

Many scholars have worked on the question of obsidian distribution in the Near East (Barge and Chataigner 2003; Cauvin *et al.* 1998; Cauvin 2002; Carter *et al.* 2011). The sources of obsidian in Cappadocia, eastern Anatolia and the Caucasus are well characterised and the spread of obsidian from these sources to the Fertile Crescent is extensively documented. However, most models used to explain the mechanisms of obsidian exchange continue to be based on the down-the-line model proposed by Renfrew in the 1960s. Since the 1960s, few viable alternatives for modelling obsidian exchange in the ancient Near East have been presented, severely limiting our capacity to understand the phenomenon of prehistoric exchange and its role in the origins of the Neolithic.

In this paper, we evaluate the down-the-line model, pointing out some of its weaknesses. This model does not explain the appearance of obsidian at long distances from sources of origin and does not take into account certain important variables that affected the distribution of this commodity. We therefore explore multi-agent modelling which allows us to approach the topic of obsidian exchange as a complex system composed of autonomous, interacting agents (in this case Neolithic communities). As an alternative, we propose a type of small-world network in which agents from some villages are able to move (with goods) longer distances to reach new exchange partners than is possible in Renfrew's model, so as to better replicate the archaeological data. Finally, we present the first results of the multi-agent simulation. In addition to discussing the critical variables for simulating long-distance transfer of obsidian, we illustrate the tremendous potential of small-world exchange networks for explaining obsidian distribution in the Near East.

Our geographical focus constitutes the western wing of the Fertile Crescent and includes the northern, central and southern Levant, northern Mesopotamia, and central Anatolia. Chronologically, we focus on the Pre-Pottery Neolithic B period (8300–7000 cal. BC) (Aurenche *et al.* 1987, 2001), during which time obsidian exchange networks appear to have been well established in the Near East (Fig. 1).

Discussing Renfrew's Model: the Law of Monotonic Decrement and Down-the-Line Exchange

Renfrew's Model

The Law of Monotonic Decrement and the down-the-line exchange model, which were proposed by Renfrew, were modelled empirically on the archaeological data that was available at the end of the 1960s. In Renfrew's 1968 article, the author observed that there was a linear diminution in the quantity of obsidian with distance from the source of origin. Renfrew called this the Law of Monotonic Decrement. By plotting the proportion of obsidian to flint against the distance to the obsidian source of origin on a logarithmic scale, an exponential fall-off curve appeared (Renfrew *et al.* 1968; Renfrew 1975). Renfrew first explained the fall-off in frequency with distance as a reflection of what the energy spent implied in transport. However, Renfrew later emphasized that the number of transactions made was the crucial parameter responsible for the decay, as local communities consumed one part of the obsidian received, transferring the other part to other communities (Renfrew 1975, p. 78).

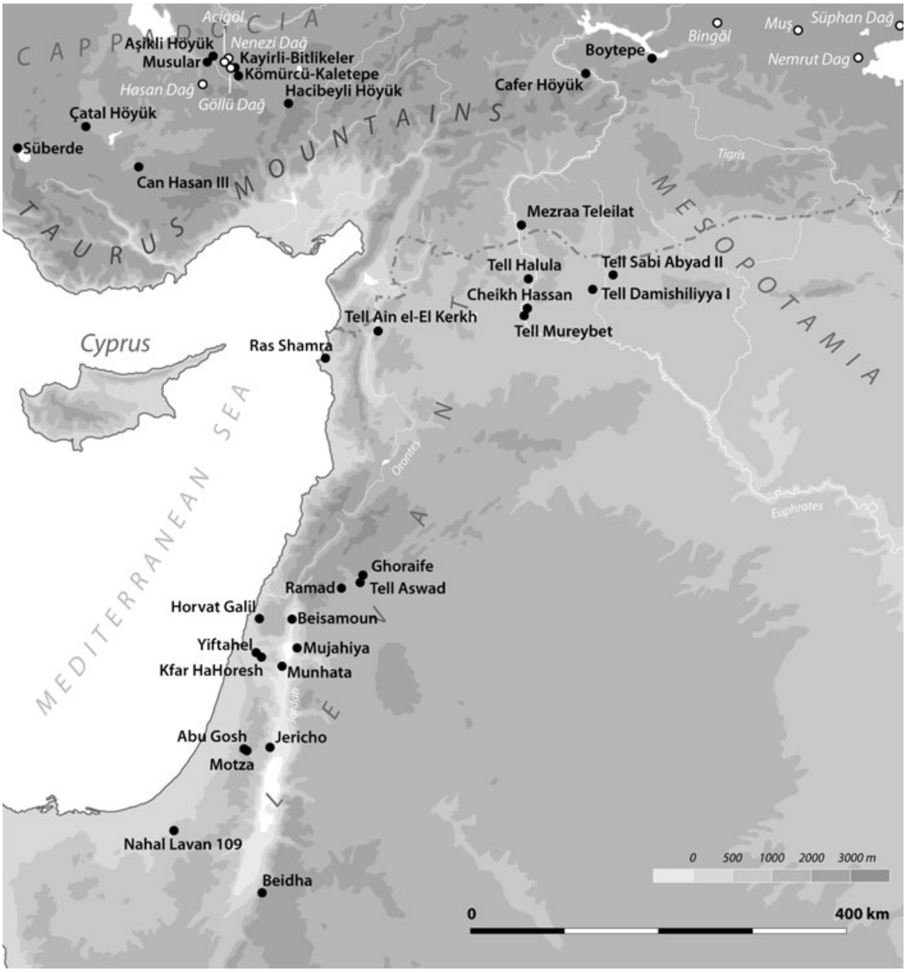

Fig. 1 Map of the Near East illustrating obsidian sources (*white dots*) and PPNB archaeological sites with information on the proportion of obsidian vs. flint tools (*black dots*). The location of the obsidian sources are taken from Obsidatabase (Varoutsikos and Chataigner 2012)

When contrasting this model with the archaeological data, Renfrew distinguished a first zone near the obsidian sources (the supply zone) where the quantity of obsidian was high and decreased slowly. Obsidian represented more than 80 % of the lithic materials present on sites in this zone. This was interpreted as an area where communities were supplied directly from the obsidian outcrops. Renfrew observed that this supply zone stretched 250 km from the sources of Cappadocia in central Anatolia towards the western wing of the Fertile Crescent, and as much as 350 km from eastern Anatolian sources towards the eastern wing of the Fertile Crescent. Renfrew also distinguished a very large contact zone, where the exchange of obsidian among communities resulted in a quick decay in the proportion of obsidian. The author suggested that this fall-off was due to a model of down-the-line exchange, where one part of the obsidian available at one site was used for making tools while the other part was transferred to a neighbouring site.

In order to fit this model to the archaeological data, Renfrew specified that sites would have been 90 km equidistant and that the rate of obsidian consumption/exchange by communities would have been 50 %.

Critique of the Model

Despite early critics (i.e. Hodder 1974; Earle and Ericson 1977) and inconsistencies between the model and the archaeological record, which are becoming increasingly evident as more archaeological data is obtained, the down-the-line model is the one currently used to explain obsidian distribution in the Near East and it is also commonly used to explain exchange systems in many other prehistoric contexts (Torrence 1986). Soon after Renfrew's proposal, Hodder observed that different systems of exchange and distribution of commodities produced similar fall-off curves, which he described as a phenomenon of *equifinality* (Hodder 1974). While different exchange models can generate more or less similar fall-off curves, it is very unlikely that they would produce exactly the same fall-off curve. Mathematical simulation might therefore be a useful way to delineate the point at which obsidian distribution models are affected by equifinality in their results.

However, other weaknesses of the down-the-line model are proving to be more relevant. Analysis of the archaeological data reveals that obsidian exchange was likely more complex than the simple chain transfer of material from one site to a neighbouring one. Soon after testing his down-the-line model against the archaeological data, Renfrew observed that the site of Jericho in Palestine (located at considerable distances from the source area that supplied it) had consumed larger quantities of obsidian than was predicted by his model. These sorts of anomalies in the archaeological record, which present higher quantities of obsidian than predicted by the down-the-line model, have been observed at a number of sites such as Tell 'Arqa (Thalmann 2006) or Nahal Lavan 109 (Burian and Friedman 1988), though no alternative model has been proposed to explain them.

A model for obsidian exchange should explain the distribution of obsidian in space, as it spread from its source of origin, rather than its distribution along one dimension (Ericson 1977). Renfrew argued that the application of the model in two dimensions would produce similar Gaussian (normal) distributions (Renfrew 1977). However, this is a question that remains untested.

Diachronic changes in obsidian distribution have been noted by several scholars working on the Neolithic (tenth to sixth millennium cal. BC) Near East (Cauvin and Chataigner 1998; Chataigner and Barge 2005) and are emblematic of the major socio-economic and cultural transformations that occurred during the period of neolithisation. A temporally static model cannot therefore explain a phenomenon that is dynamic in nature.

Furthermore, a large number of variables could have affected the nature and routing of exchange networks during this period. For example, Renfrew's model assumed only terrestrial transport of obsidian, excluding maritime and fluvial transport. However, maritime transport was used during the earliest stages of the Neolithic, as the archaeological data for Cyprus demonstrates. Not only were plant and animal species transported to Cyprus during the PPNA, but obsidian from Anatolian sources is also found on early Neolithic Cypriot sites (Briois *et al.* 1997; Guilaine *et al.* 2011;

Peltenburg 1998). Moreover, the use of animals for transport (i.e. oxen) is probable, at least from the Middle PPNB (eighth millennium BC) onward (Helmer *et al.* 2005). In sum, transport systems are likely to be relevant variables when trying to understand past exchange systems (Hodder and Orton 1976; Torrence 1986: p. 122–123; Sidrys 1977: p. 103–105; Ammerman 1979; Ammerman *et al.* 1978; Wright 1970).

Another relevant variable for modelling obsidian exchange is population density (Ericson 1977). In structuring his model, Renfrew assumed that population density was homogeneous. However, many decades of survey and excavation in the Near East have successfully demonstrated that population density was quite variable, and depended in part on ecological and geographical factors which may have changed in different periods of the neolithisation process. Certain areas were more ideal for settlement and were therefore more densely populated such as the Middle Euphrates, the Jordan valley and the marshy areas in the steppic north–south belt (Kiujt 2000; Goring-Morris and Belfer-Cohen 2011).

Finally, Refrew's model assumed that all villages were prepared to exchange. As Hodder points out, models of exchange would benefit from Sahlins' (1974) *generalized*, *balanced*, and *negative reciprocities*, while at the same time allowing for the existence of conflicts, tricking strategies and rule manipulations (Hodder 1982, p. 200).

Exploring Renfrew's Mathematical Function

By expressing Renfrew's model as a mathematical function and by changing several parameters, we can calculate how it behaves. The model can be summed up with the following equation:

$$c_0(1-\alpha)^{n-1}$$

The equation represents the amount of obsidian that reaches the nth node of the network, whereby c_o is the total volume of a commodity, α the rate of consumption and $n=1,2,\dots$ the order of the node. The ratio of consumption is the part of the commodity that is detracted from circulation in every node of the network. This equation can also be written as:

$$\frac{c_0}{1-\alpha}e^{n\ln(1-\alpha)}$$

which results in the exponential function proposed by Renfrew. Consumption in every node is calculated as follows:

$$c_0\alpha(1-\alpha)^{n-1}$$

In using a fixed ratio of consumption, the quantity of obsidian available for exchange declines drastically after very few exchange events (Fig. 2). This is especially true for high rates of consumption (0.9), but it is also the case for lower consumption rates. Following the down-the-line model, only very low consumption/exchange ratios (10 % consumption and 90 % exchange) would have allowed obsidian to arrive to the southern Levant in the quantities observed in the archaeological record (representing around 0.5 % obsidian in the lithic assemblages). However, it is not reasonable to

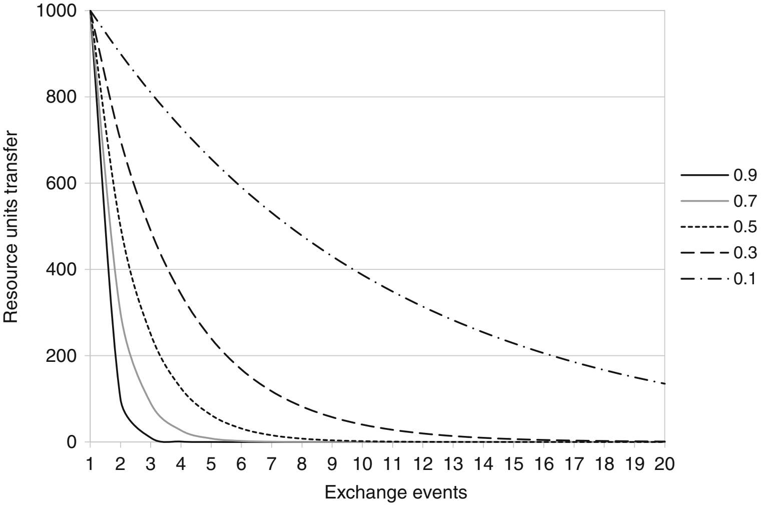

Fig. 2 Fall-off curve of quantity of obsidian in relation to number of exchange events, using fixed consumption/exchange ratios, as proposed in Renfrew's down-the-line model, for an initial volume of the commodity equalling 1,000 units of obsidian

significantly reduce the consumption to exchange ratio in each node, because it is unlikely that early Neolithic societies systematically exchanged nine times more than they consumed of a valued resource.

Renfrew tried to resolve the fact that his model did not fully conform to the archaeological data by establishing long distances between places (90 km), that is, by reducing the number of events of consumption/exchange. However, the proposed distance between nodes does not replicate the archaeological record as the density of Neolithic sites in the Near East was higher and the distances between sites much smaller in certain areas. For example, the distance between the contemporary PPNA period sites of Tell ‘Abr and Dja’de which are located along the Middle Euphrates is only 10 km.

As the down-the-line model does not adequately explain the distribution of this commodity across the Near East and as some relevant variables are not considered in Renfrew's model, a new type of approach—agent-based modelling—and a new model of obsidian exchange that functions through small-world networks of exchange, are needed to cope with these questions.

Agent-Based Modelling

Agent-Based Modelling (ABM) and simulation intends to artificially build systems composed of autonomous, interacting agents. This approach is especially useful for understanding the dynamics of complex systems, where multiple variables interact and evolve in time and space. By modelling systems involving agents and their interactions, self-organized patterns often emerge, which are not explicitly programmed into the models but arise through agent interactions. ABM has been used in many different fields of research and its use in the social sciences (Axelrod 1997; Epstein and Axtell

1996) and in archaeology is gaining momentum (Axtell *et al.* 2002; Brantingham 2006; Dean *et al.* 2000; Kohler and Gumerman 2000; Evans *et al.* 2009).

The distribution of obsidian in the Neolithic Near East can be described as the result of the interactions (exchange) of autonomous agents (Neolithic villages), who generated and used a complex network of obsidian distribution that evolved with time.

In a first instance, ABM will allow us to test the down-the-line model in a bi-dimensional scale. Due to the problem of the critical decrease in the quantity of obsidian intended for exchange in every consumption/exchange event, we are aware that regular networks issued from a down-the-line model will not supply obsidian to distant areas. We therefore test alternative models of obsidian exchange in which local exchange networks are complemented with the presence of villages that can benefit from an access to obsidian at a distance (small-world networks). We also test whether or not the application of a first set of variables to these models succeeds in moving obsidian over long distances. These variables include the proportion of villages which are allowed to access exchange partners at a distance, population density (number of villages per unit of surface), degree of collaboration between villages (degree of acceptance of exchanges), distance from which the villages can get direct access to obsidian sources and the ratio of consumption/exchange of obsidian. In this paper, we concentrate on reproducing obsidian distribution during the PPNB (Fig. 1 and Table 1). In order to do so, archaeological data pertaining to the proportion of obsidian versus flint in the lithic assemblages of PPNB sites was gathered from published literature, and inputted into a database specifically designed for this study (Table 1). Sites in Cyprus are not included here because only the terrestrial transport of obsidian is being considered in our first simulations. For the purposes of testing these new models, we assume that there was a similar consumption rate of lithic resources for tool making in each PPNB village, and use the proportion of obsidian to flint as a direct indicator of the quantity of obsidian consumed at a specific village.

Finally, the results of the different simulations are compared with the archaeological data, taking account of the degree of compatibility between the archaeological and simulated results in both the profile of the fall-off curve, and in the quantity/proportion of obsidian arriving to the southern Levant. Based on the archaeological data for the PPNB, an adequate model of obsidian exchange should supply a rate of 0.5 % obsidian to flint, to villages in the southern Levant.

Small-World Networks as an Alternative to the Down-the-Line Model

Small-world networks (Watts 2004; Watts and Strogatz 1998) are present in a great variety of natural and social systems. These networks lie midway between regular networks (Fig. 3a), where most agents are linked with their immediate neighbours, and *random networks*, where most agents are linked with distant ones. In small-world networks (Fig. 3b) neighbouring agents are interconnected, but some of them are also able to interact with distant agents by establishing shortcuts between the nodes. The characteristics of networks are defined by path length $L(p)$, the property measuring the mean separation between two nodes, and the clustering coefficient C(p), measuring the degree to which agents tend to group together in local neighbourhoods. *Regular networks* show a high mean path length, as many nodes must be crossed through to move from one extremity of the network to the opposite extremity, and a high

Table 1 A list of PPNB archaeological sites used for comparison to the simulation, including information on the proportion of obsidian vs. flint tools (found in publications) and on the distance to the nearest obsidian source

Id	Site	Level/loci	Km	Flint	Obsidian	Percent	Reference
1	Kayırlı-Bitlikeler		0	0	100	100.00	Balkan-Atli *et al.* 2001, p. 38
2	Kömürcü-Kaletepe	c. 4	0	0	828	100.00	Balkan-Atli *et al.* 1999, Table 1
3	Aşıklı Höyük		30	5	22,000	99.98	Esin *et al.* 1991, p. 145
4	Musular		30	20	5,000	99.60	Özbasaran 1999, p. 152
5	Hacıbeyli Höyük		60	1	121	99.18	Fujii 1995, Table 1
6	Boytepe		100	51	848	94.33	Balkan, 1989, Table 1
7	Can Hasan III		150	1,823	69,497	97.44	Ataman 1988, Fig. 15
8	Çatal Höyük	Pre-XII A–D	160	676	12,161	94.73	Carter *et al.* 2005, Table 11.1
9	Cafer Höyük	I–IV	160	10	90	90.00	Cauvin 1989, p. 80
10	Süberde	II–III	250	2,993	26,937	90.00	Bordaz 1966, p. 32
11	Tell Sabi Abyad II	ph. 2-1	310	480	657	57.78	Copeland 1989, Table 3.3
12	Tell Damishiliyya I	st 1-2	310	248	20	7.46	Nishiaki 2000, Table 5.1
13	Mezraa Teleilat	ph IV	340	1,551	151	8.87	Coskunsu 2007, Table V.1 and VII-3
14	Tell Ain el-Kerkh	c 3–6	370	9,710	1654	14.55	Arimura 2007, Table 3.147
15	Tell Halula	2A–2C	380	2,754	468	14.53	Molist *et al.* 2001, Table 1
16	Tell Mureybet	ph. IVB	400	2,165	90	3.99	Cauvin 2004, p. 325
17	Cheikh Hassan		400	5,000	35	0.70	Abbes *et al.* 2001, p. 13
18	Ras Shamra	Vc	410	19,579	593	2.94	Contenson 1992
19	Ghoraife	I–II	620	24,322	136	0.56	Contenson 1995
20	Ramad	I–II	640	16,422	149	0.90	Contenson, 2000, Tables 5 and 8
21	Tell Aswad	II	640	37,751	254	0.67	Cauvin 1995
22	Beisamoun	lev. 1–3	680	4,793	15	0.31	Lechevallier 1978a, p. 153
23	Horvat Galil		690	8,836	33	0.37	Gopher 1997, p. 195, 207
24	Mujahiya		710	8,311	17	0.20	Gopher 1990, p. 120, 132
25	Yiftahel	Area C	720	126,925	8	0.01	Yellin 2012, p. 243
26	Munhata	3–6	730	14,076	4	0.03	Gopher 1989
27	Kfar HaHoresh		730	120,170	7	0.01	Goring-Morris *et al.* 1995, Tables 1 and 114
28	Jericho		820	17,467	91	0.52	Crowfoot-Payne 1983, Tables 9–16
29	Motza	VI	830	9,152	432	4.51	Khalaily *et al.* 2007, Table 2
30	Abu Gosh		830	18,422	8	0.04	Lechevallier 1978b, p. 41
31	Nahal Lavan 109		930	10,944	144	1.30	Burian *et al.* 1999, Table 1
32	Beidha		980	44,248	3	0.01	Mortensen 1970

Sites in Cyprus are not included because only the terrestrial transport of obsidian is considered in the simulations presented here

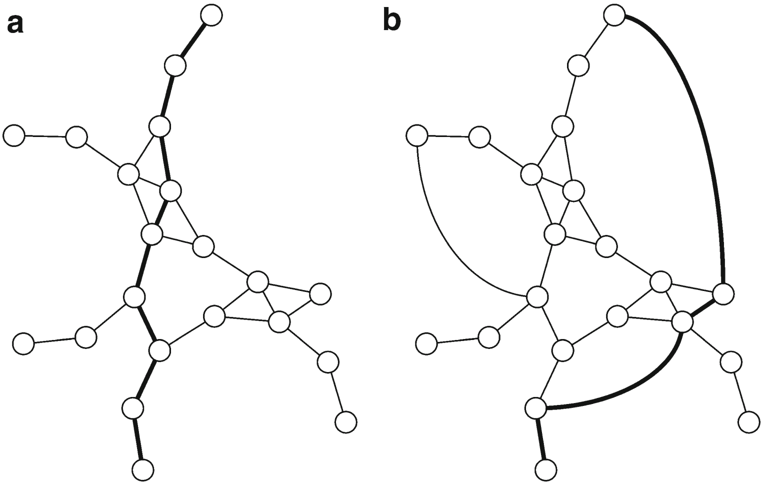

Fig. 3 Schematic representation of **a** a regular network resulting from a down-the-line model and **b** of a small-world network with shortcuts. The *thick black line* indicates the path followed by agents with obsidian when moving from one extremity of the network to the other, the regular network resulting in a higher path length (higher number of nodes/cells crossed) than with a small-world network

clustering coefficient, as abundant local connections of nodes results in local clusters. *Random networks* show a low mean path length, as extremities of the networks can be reached crossing through very few links, and a low clustering coefficient, as distant linking of the nodes results in a scarcity of local clusters. Small-world networks bear some characteristics of both types of networks as they are highly clustered, because local links are dominant, while having small characteristic path lengths, as a result of the distant linking of some of the nodes. This results in a very efficient network, as it allows for rapid linking between distant zones of the network, while showing a low proportion of distant links.

Based on a regular network of local interactions with neighbours, which we associate with the down-the-line model, a new network model can be obtained in which by a simple iterative algorithm with a probability *p*, some nodes are randomly selected to reconnect with other further ones. When in a regular network some "shortcuts" are created connecting distant parts of the graph, average path length is dramatically reduced, but clustering (measuring the degree of association in an agent's neighbourhood) is substantially preserved (Cassi and Zirulia 2008). These shortcuts are henceforth referred to as non-local exchange paths, while the links joining neighbouring agents are referred to as local exchange paths.

Small-world networks have been used by sociologists and economists, among others, to explore the effect of the network topology on processes of diffusion, and especially through social networks of technical knowledge (Cassi and Zirulia 2008), social norms (Santos *et al.* 2012), innovations (Delre *et al.* 2010) and prices in economic trade systems (Wilhite 2001).

Most of these studies resort to the algorithms of Watts and Strogatz (1998), which create fixed small-world networks, through which agents interact. In our case, we expect that the small-world network would appear as an emergent property of the dynamic connectivity in the model. Successive agent searches or explorations of the territory using correlated random walks (CRW, see below) would lead the communities to establish increasingly longer connections to distant territories through which supply of the commodity and exchange would take place. The small-world network model can allow some villages to obtain obsidian from distant partners, while at the same time, preserving their local networks of exchange. Shortcuts reduce the number of steps needed for a resource to arrive in regions at a given distance from its origin. Therefore, the problem of the drastic fall-off of the resource with every event of exchange would be partially corrected, as some villages would be allowed to access the commodity in distant places, outside of their neighbourhood.

Random Walk Search Strategies

A random walk (RW) is the standard method used to model the movement of autonomous agents who are searching for targets in contexts of partial information or uncertainty. The villages allowed to carry out a shortcut use a CRW in order to efficiently search for a target of unknown location. Simple random walks consist of a series of walks of fixed or varied amplitude with a random choice of the direction taken at every step.

Several scholars have previously explored the use of simple RW to reproduce the spatial distribution of archaeological items, including obsidian, around a centre of production (Hodder 1974; Hodder and Orton 1976; Renfrew 1977). For our purposes, we use a CRW in which agents start moving from their original cell to one of the eight neighbouring cells. They decide which cell to visit next by choosing at random among those cells that allow them to move further away from their starting point. This allows us to exclude the unrealistic possibility of backward trajectories that would be useless or inefficient from the point of view of search efficiency.

Obsidian Exchange Multi-Agent Model

We resort to a multi-agent model simulation to test a new exchange model (based on a small-world network of exchange) in order to correct one of the limitations of Renfrew's model: its inability to transfer obsidian over long distances. In this section, we present the parameters of our first simulations, which are simplified (in comparison to the archaeological evidence) for the purposes of establishing the effectiveness of the model and the relevance of a first set of variables.

The Spatial and Chronological Context

The spatial context is established as a flat area, 900 km long (on a north–south axis) and 350 wide (on an east–west axis). Agents are defined as sedentary farming communities (villages) in sites of equal size and hierarchy. These communities move to search for obsidian, interacting with other villages that they recognize as partners for exchange. The space is divided into 15×15 km cells that will host a community each with probability p_c, so that the random spatial distribution of farming communities in each realization of the model is determined from the beginning and is assumed to remain unchanged during successive cycles.

The production and exchange of obsidian takes place in successive cycles, each of them simulating one annual period. We replicate these cycles up to three thousand times.

Partner Search Strategies

Villages are able to get partners for exchange in their surrounding region. As a result, a local network is established in which partners exchange regularly in every chronological cycle with all neighbours present in the immediate vicinity (one cell distance). This allows us to reproduce the down-the-line model, where villages are joined to a network of local partners.

Later, in order to test the small-world hypothesis, some villages are allowed (with probability p_t: in each cycle) to travel outside of their local networks of exchange by journeying and obtaining information on the presence of potential partners or the presence of obsidian as they move. For this purpose, they use a CRW in which they start moving from their original cell to one of the eight neighbouring cells (at random in any direction) and decide which cell to visit next by choosing at random among those cells that allow them to move further away from their starting point. The length of the random walks is limited to a number of visited cells $n_{\max}$.

To reproduce the idea that network exchanges are not solely driven by obsidian but may pertain to networks that were present well before the introduction of the resource, we reserve the first five hundred cycles of the simulation for the formation of the pre-existing network. During this initial period (first five hundred cycles) the resource (obsidian) is not yet introduced in the lattice though search dynamics are being developed.

Matching Dynamics

If within $n_{\max}$ steps the travelling agent finds a partner with whom it had no previous exchange links, then a permanent link is established between the two agents with probability p_e, which introduces the possibility that exchanges may be rejected.

We also implement the idea that the exchange network is exposed to occasional alterations (e.g. environmental, situations of conflict, etc.) that may induce the rejection of exchange with partners whereby with a small probability p_b any non-local exchange path is assumed to be broken and no longer available to any of the partners.

Resource Production

Villages producing obsidian are those located in the northern area of the space, in a rough attempt to reproduce the area of Cappadocian obsidian sources. In each cycle, these villages produce more obsidian than the quantity needed for their own use in order to exchange it, thus inserting the resource into the exchange network. All villages within a distance d_p to the source region are labelled as 'producers' and introduce a fixed quantity of the resource into the system during each cycle (the specific value of this quantity is irrelevant, since the obsidian is measured in this study in relative units of obsidian with respect to flint, assuming that the total amount of annual consumption of lithic resources is similar in all the villages). Villages located on or adjacent to the sources produce the maximum of 100 units of obsidian per cycle. Transport costs are also taken into account by assuming that the quantity of resource production decays linearly with the distance to the source, so those ‘producers’ located at distance d_p to the source will be able to introduce just a fraction f_p of the resource compared to the ‘producers’ adjacent to the source region. For example, those villages located 3 cells away from the obsidian sources (45 km) produce $100-(2.5\times3)$, or 92.5 units of obsidian, those located 10 cells away produce $100-(2.5\times10)$ or 75 units of obsidian, up to distance d_p, which is the limit of the production area (12 cells/180 km in our standard simulation) and after which obsidian is only transferred through exchange.

Resource Consumption and Exchange

Obsidian is defined as a non-perishable commodity that can be divided into fractions. The presence of obsidian in an archaeological site is the result of consumption and discard of tools or knapping by-products (Torrence 1986, p. 5; Astruc *et al.* 2007). For the simulation, agents knap, use, and discard their entire stock of obsidian in each cycle. In the initial stages of our model that we present here, more complex behaviours of obsidian management (exchange and stocking of cores or blanks, recycling of tools…) are not considered. While in reality the situation is more complex, we initially condition that the quantity of material needed for making tools is equal for all of the communities. If the quantity of obsidian available in one community is not sufficient for their needs, other types of stone materials such as flint are used for making tools.

Communities consume a fixed proportion f_c of the resource available, while the rest is exchanged. In this way, different fixed ratios of consumption/exchange (i.e. 90 %/10 %) can be tested.

The exchange dynamics follow an egalitarian rule in which every village divides a fraction of the resources not used for their own consumption among exchange partners who have fewer resources than themselves. The same quantity of obsidian is therefore transferred to sites where resource availability is lower.

Model Summary and Rules

According to the model description given above, the initial version of our model contains eight different parameters:

p_c	Probability of cell occupation.
p_t	Probability of a village deciding to begin a new journey/search for new partners.
p_b	Probability of breakage of exchange link
n_max	Number of maximum cells visited during a journey.
p_e	Probability of exchange acceptance.
d_p	Size of production region.
f_p	Degree of the linear decrement in the quantity of obsidian which is directly acquired from the source of obsidian by each obsidian-extracting village. These obsidian-extracting villages are those located at a certain distance from the source (180 km for the standard simulation). The linear decrement depends on the distance between the village and the source.
f_c	Consumption/exchange ratio.

The practical rules that are used to run the model can be summarized in the following algorithm:

1. Assign an agent (village) to each cell in the lattice with probability p_c.
2. Establish local connections between each village and all villages present in the eight nearest squares of the lattice.

For the first five hundred cycles:

3. With probability p_t, each agent in the lattice can take a journey (of maximum size n_{max} cells) based on a correlated random walk (as described above) to search for new exchange partners.
4. If new partners are found during the journey, an exchange link is established between them with probability p_e.
5. Any of the existing non-local links can be broken with probability p_b.

For the remaining cycles (up to three thousand):

6. Apply rules 3 to 5.
7. Assume that all villages within a distance d_p from the source region acquire new resources in a proportion that decreases linearly with distance from source. The degree of the linear decrement is f_p.
8. All villages that have available resources consume a fraction f_c of them and exchange the rest, transferring the same quantity to all partners that have fewer resources.

First Results of the Simulation

The results of the simulation can be observed in Fig. 4 and the values of the parameters used are shown in Table 2. At the left of the graph we can observe the transfer of

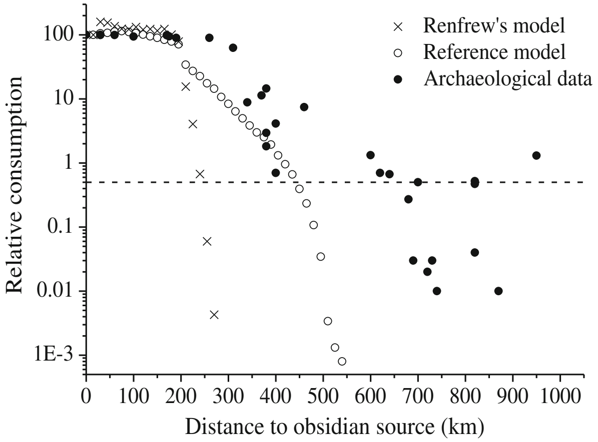

Fig. 4 Results of the simulation of the down-the line model (*left*), of a small-world type network using the parameters specified in Table 2 (*centre*), and of results of the proportion of obsidian to flint recovered from archaeological sites in the Levant during the PPNB (*right*). The *dotted line* represents 0.5 % obsidian, which is the mean quantity of obsidian reaching the southern Levant

Table 2 A list of the parameters used in the simulation represented in Fig. 4 onward

Parameter	
p_c	0.2 (280 agents)
p_t	0.1
p_b	0.001s
n_{max}	8 (120 km)
p_e	1
d_p	180 km
f_p	$100-(2.5\times$cell number)
f_c	0.5

obsidian obtained using Renfrew's model, where obsidian is transferred from one village to its neighbouring village (up to one cell of distance), and no village is able to establish contact with further villages ($p_t=0$).

In this scenario the quantity of obsidian transferred through such a regular network falls very quickly and quantities corresponding to 0.5 % of the lithic assemblage, are present only at 250 km from the source of origin. Thus, the 2D simulation of Renfrew's model (down-the-line transfer) results in the same conclusion obtained for the linear simulation (1D), which is that in both cases, obsidian does not reach the southern Levant.

In the middle of this same graph (Fig. 4), we can observe the results of the simulation when some villages (20 %) are allowed to jump and contact further partners for obsidian exchange using a CRW search strategy. In this case, obsidian is transferred in a more efficient way, and quantities of obsidian corresponding to 0.5 % of the lithic assemblage are present at around 450 km away from the source of origin. Finally, at the right of the same graph, the archaeological results of the proportion of obsidian to flint at PPNB sites in the Levant are shown. As noted by Renfrew, the quantity of obsidian in archaeological sites falls with distance following a logarithmic function. The archaeological data show more efficient distribution of obsidian than our model, as quantities corresponding to 0.5 % of obsidian in the lithic assemblage are observed at a distance of around 750 km from the source of origin.

Firstly, this simulation indicates the inadequacy of Renfrew's model to explain the distribution of obsidian in the Levant during the PPNB. Secondly, the simulation demonstrates that alternative small-world type networks result in a more efficient distribution of obsidian though the small-world model that we have designed for this simulation still does not adequately replicate the archaeological data. We shall discuss the implications of this conclusion later, after showing how the different variables used in this simulation behave with respect to the capacity of the model to transfer obsidian over long distances.

Figure 5 reflects how the fraction of villages allowed to jump using a random walk (parameter p_t; probability of a village deciding to begin a new journey) for the purpose of contacting further partners, influences the efficiency in the distribution of obsidian. As can be observed, this is not a very relevant variable, as the results obtained for 5 % are similar to those obtained when 50 % of the villages are allowed to carry out the random walk. This means that after the simulation model is left to run for some time, only a small quantity of villages able to jump are able to establish the distant links that in turn enable a better distribution of obsidian.

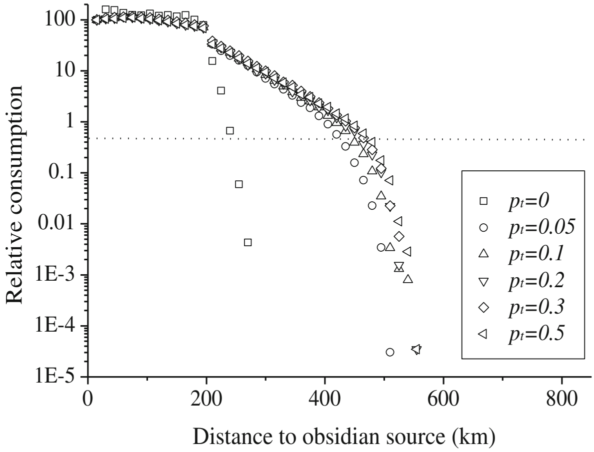

Fig. 5 Results of the simulation of obsidian distribution depending on the number of villages allowed to jump to contact distant exchange partners using a random walk (parameter p_t: probability of a village deciding to begin a new journey). The *dotted line* represents 0.5 % obsidian, which is the mean quantity of obsidian reaching the southern Levant

In Fig. 6 we can observe that the fraction of cells which are occupied by a village (parameter p_c; population density) is not important for the distribution of obsidian, as the results obtained with 5 % of the cells occupied is similar to those obtained with 50 %. In other words, a populated landscape is not necessary for explaining obsidian distribution during the PPNB. In addition, the existence of many villages, which are able to consume obsidian within a small-world network, does not affect the efficiency of obsidian transfer over long distances.

Figure 7 illustrates how the change in degree of collaboration between villages (parameter p_e; probability of exchange acceptance) affects obsidian distribution in our model. Twenty percent of villages accepting non-local exchange produces similar

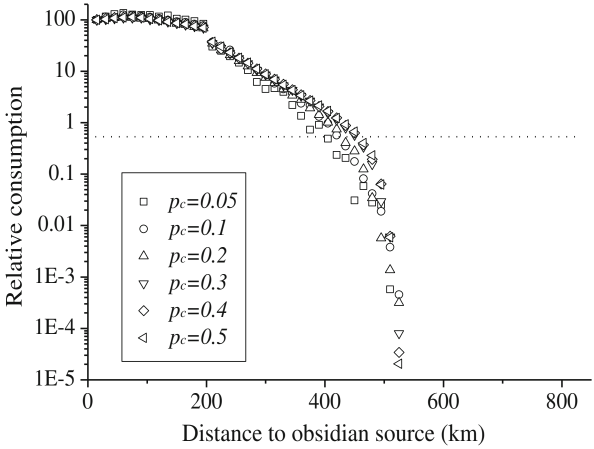

Fig. 6 Results of the simulation of obsidian distribution depending on the quantity of villages occupying each cell (parameter p_c: population density). The *dotted line* represents 0.5 % obsidian, which is the mean quantity of obsidian reaching the southern Levant

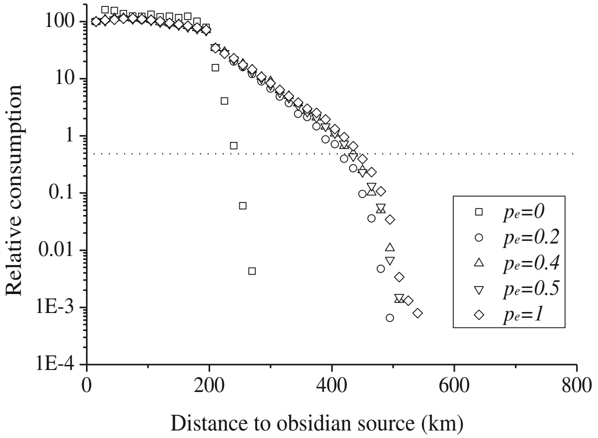

Fig. 7 Results of the simulation of obsidian distribution depending on the degree of collaboration between villages (parameter p_e: probability of exchange acceptance). The *dotted line* represents 0.5 % obsidian, which is the mean quantity of obsidian reaching the southern Levant

results to higher collaboration rates, demonstrating that this variable is not relevant in this case.

It would seem logical that the increase in distance from which a village can get direct access to an obsidian source (parameter d_p: size of production region) would considerably increase the distances over which obsidian could be transferred. In Fig. 8, we show the results of the simulation carried out with variations (from 75 to 180 km) in the size of the area in which villages could have had direct access to obsidian outcrops. This variable has limited influence on the final results of obsidian transfer. With a 180-km radius of direct access to the sources, obsidian arrives further (around 450 km for quantities corresponding to 0.5 % obsidian) than with a 75 km radius of direct access (around 350 km for the same quantity). However, this variable seems not to affect the efficiency of the mechanisms of exchange, as the increase in the distance at which a

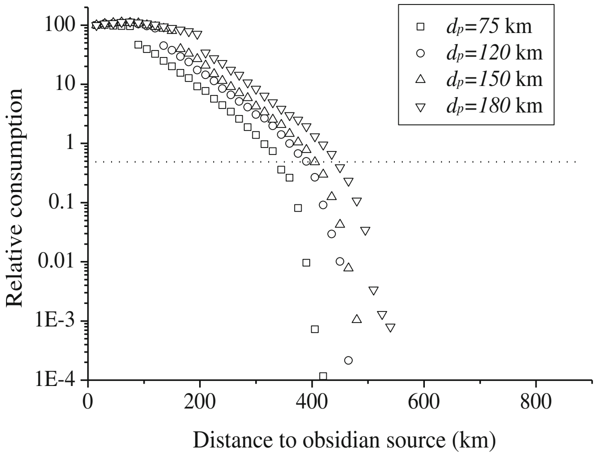

Fig. 8 Results of the simulation of obsidian distribution depending on the distance from which villages can have direct access to obsidian sources (parameter d_p: size of production region). The *dotted line* represents 0.5 % obsidian, which is the mean quantity of obsidian reaching the southern Levant

certain quantity of obsidian is transferred (450–350=100 km) is similar to the increment in the radius of direct access itself (180–75=105 km). In other words, a higher radius of direct access only nears the start line to the finish line, without qualitatively affecting the distribution of obsidian. That means that in order to transfer obsidian to the southern Levant, the type of exchange network is critical, while the influence of the distance from which Neolithic communities can obtain obsidian directly from the source is secondary.

The length of the journey carried out by agents of villages allowed to find non-local partners by CRW (parameter $n_{\max}$: number of maximum cells visited during a journey), is relevant for the distribution of obsidian over long distances, as can be observed in Fig. 9. Longer journeys to search for exchange partners result in a more distant distribution of obsidian. If journeys are longer than 14 cells (210 km), quantities of obsidian (around 0.5 %, see dotted line) can reach distances of 650 km (southern Levant), as was the case during the PPNB. However, it is difficult to assume that such distant exchange links (210 km), implying approximately 1 week's walk, could have been established and regularly maintained during the Neolithic. Though it is difficult to estimate the maximum length of these distant links, we think that 120 km (around 4 day's walk) is a reasonable limit for maintaining a regular exchange relationship during the PPNB.

In inputting different ratios of obsidian consumption/exchange (parameter f_c: consumption/exchange ratio), we observe (Fig. 10) that this variable is extremely significant. 80 % obsidian consumption, which implies only 20 % obsidian exchange to other villages, results in 0.5 % of the obsidian of the total lithic assemblage reaching a maximum of 350 km from the source of origin. As we saw above, 50 % obsidian consumption/exchange results in obsidian reaching 450 km from the source of origin, while to achieve a transfer of 0.5 % of the obsidian as far as the southern Levant, very low ratios of consumption (10 %) and very high ratios of transfer (90 %) in each node of the network are needed. Without completely ruling out this possibility, it is nonetheless unlikely that PPNB societies would have regularly transferred most of the obsidian they had obtained to their exchange partners.

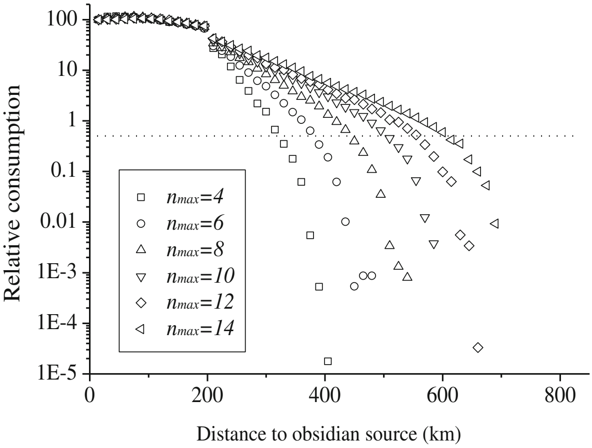

Fig. 9 Results of the simulation of obsidian distribution depending on the length of the journey (parameter $n_{\max}$: number of maximum cells visited during a journey). The *dotted line* represents 0.5 % obsidian, which is the mean quantity of obsidian reaching the southern Levant

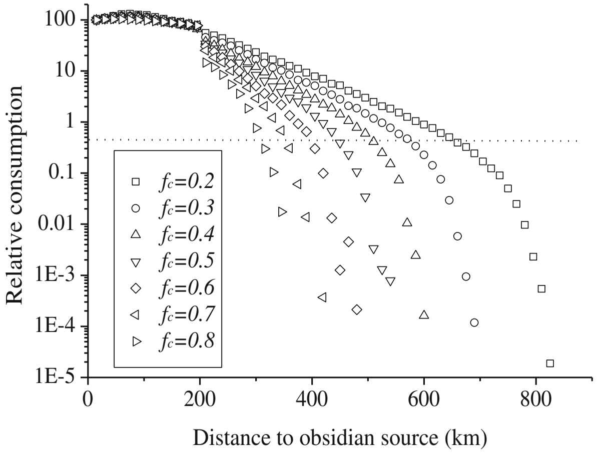

Fig. 10 Results of the simulation of obsidian distribution depending on the ratio of obsidian consumption/exchange (parameter f_c: consumption/exchange ratio). The *dotted line* represents 0.5 % obsidian, which is the mean quantity of obsidian reaching the southern Levant

In summary, our first simulation results confirm that obsidian does not reach distant regions such as the southern Levant, using the down-the-line model. Therefore, this model of exchange is not pertinent for explaining how obsidian was exchanged during the PPNB period. Simulations also indicate that a small-world network model of exchange offers a more realistic scenario, as the results of the simulation better resemble the archaeological data. Inside this small-world network model of obsidian exchange, two variables are critical for the distribution of obsidian over very long distances (up to 800 km), as is observed in the archaeological record. These include: (1) the variation in the ratio of consumption/exchange (parameter f_c) and (2) the length of the links established by the villages to carry out their exchanges (parameter n_{max}). If the consumption is low in relation to the exchange (around 20 % consumption and 80 % exchange) or if some villages establish distant links for exchange with partners (at least 200 km), obsidian can be transferred over very long distances, matching the archaeological data. However, as we have previously stated, it is not reasonable to assume a significant reduction of the consumption/exchange ratio in each node or a massive extension of the distance at which exchange links can be established and maintained in this period.

Even if our first results indicate that a type of small-world exchange network could explain the characteristics of obsidian exchange during the PPNB, our model has not yet succeeded in precisely replicating the archaeological data. Our results have demonstrated that there is great potential in continued experimentation with other types of small-world networks in order to improve our results regarding the distance of obsidian transfer. In our current simulation, all villages are able to undertake a random walk. In forthcoming simulations, we shall test networks where only some villages are able to establish further links and where these links are preferentially established with villages that also possess further links. We believe that this type of network would allow for a more fluent transmission of obsidian between villages that are interconnected with further links, while the remaining villages would form regional clusters that would be supplied by local networks.

Conclusions and Perspectives

The emergence of long-distance trade in resources has played a minimal role in debates on the process of neolithisation and its socio-economic consequences, despite the fact that intensified inter-regional interaction was likely to have had a part in enabling the transition from hunter–gatherer to farming societies. In order to understand the relationship between long distance exchange and neolithisation, it is altogether necessary to understand the mechanisms of exchange in the region.

The analyses of the origin of obsidian and its distribution give us access to accurate information on certain aspects of prehistoric long-distance exchange. In the last few decades, a great deal of obsidian data has been gathered from pre-Neolithic and Neolithic sites and a considerable effort has been made to precisely characterise the numerous geological sources of obsidian in the Near East. In the meantime, however, there has been little effort to reassess or to rebuild the main model used to explain the mechanisms of exchange of this material (Earle 2010). The down-the-line model continues to be commonly used to explain obsidian distribution in the Near East as well as to explain exchange systems in many other prehistoric contexts (Torrence 1986). While Renfrew's Law of Monotonic Decrement and down-the-line model were seminal, allowing for new theoretical and methodological perspectives, their capacity for explaining obsidian exchange in the Near East is limited. Despite their weakness and an increasing imbalance with growing archaeological datasets, no alternative model has been proposed that explains how obsidian can be found at extremely long distances from its source origin.

ABM is a promising approach to understanding exchange and the mechanisms of obsidian distribution in the Neolithic Near East. By simulating the down-the-line model, a very regular network emerges with high clustering and a high average path. This network only permits supply of obsidian to the areas near the obsidian sources. As an alternative to this outcome, our model allowed some villages to carry out shortcuts in the network, so that a small-world network emerged. This type of network shows high clustering, whereby local networks are respected, and low average paths, whereby information and objects can more efficiently flow through the system and supply the whole region.

Our simulations have shown that the major variables sufficiently influencing long distance transfer are the variation in the rate of consumption/exchange (f_c) in each village and the length of the links established by villages to carry out their exchanges (n_{max}). Other variables such as the quantity of villages in the system (p_c), the degree of collaboration between long distance villages (p_e) and the distance from which villages have direct access to the obsidian sources (f_p) are of minimal relevance. If we heavily reduce the consumption ratio in each node in order to augment the quantity of obsidian exchanged or if we allow agents to establish very distant links for exchange, obsidian can reach very long distances. However, such scenarios are unlikely given the archaeological evidence. The type of exchange network remains the most relevant variable for explaining how obsidian arrived to the southern Levant from the sources of origin, which lie approximately 800 km away. A small-world network that permits certain villages to establish distant exchange links seems to be the most effective way of reducing the average path of the network, so as to permit a more fluid transmission of obsidian through the network.

For now, the comparison of our simulation results to the archaeological data have confirmed that during the early Neolithic in the Near East, a type of small-world network rather than a down-the-line model, was responsible for obsidian exchange at long distances. While the model we have proposed and tested is clearly more effective and realistic than previous ones, the archaeological evidence shows that obsidian arrived even further and with more fluidity than even our simulations have been able to replicate. This demonstrates that certain detailed characteristics of the PPNB exchange network remain untapped and untested at this preliminary stage. Judging from the archaeological evidence available for the period, it is likely that a more hierarchical network is needed, whereby only certain privileged interlinked villages are able to establish long distance links. More complex networks that take hierarchical structures and multiple variables into account (e.g. integrating supply from more than one obsidian source zone) are currently being modelled so as to fine-tune our results and better approach our reconstructions of past nascent exchange networks in the Neolithic Near East.

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