Annex I. Description of the model

Spatial and time scales. The Near East was reproduced as a rectangular domain measuring 400x900 km. We randomly placed N villages within it according to a Poisson distribution. The evolution of obsidian quantities in each node (node=village) was computed over the course of a period of approximately 3000 steps (each time step corresponding to one annual period), so as to reproduce the real time scales for the period of interest.

Network topology. In order to construct the network that mediates obsidian exchange, all villages that are within a distance d_n (called the neighbor distance) from each other, are assumed to be permanently linked (Fig. 1). If applied to our random distribution of villages, this *criterion* gives rise to a regular network, similar to the down-the-line model. However, for the DL and ODL models, the complex network simulations, we additionally introduce a dynamic generation of long-distant links that are not fixed in time but evolve dynamically during the simulation.

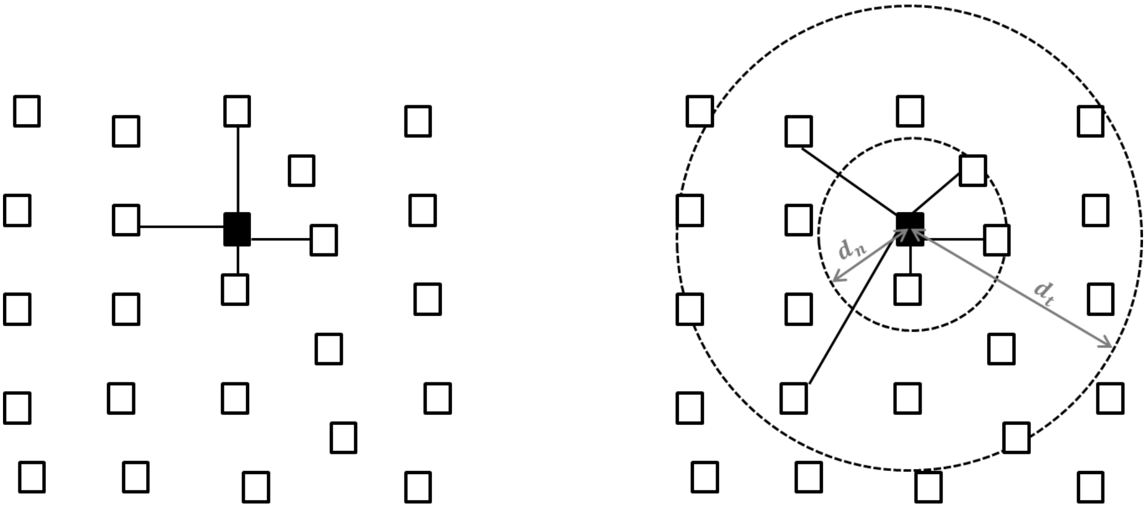

Figure 1. Comparison between the attachment dynamics in the original down-the-line scheme (left), where a specific node (emphasized in black) is connected to all of its neighbors independently of distances, and the model we present in this paper (right) where characteristic interaction distances d_n and d_t are considered.

Long-distance attachment dynamics. For the DL and ODL models (complex network simulations), for each time step, each node is given (with probability p_t) the possibility to create or renew one of the n distant links it has with any of the villages which are further away than d_n from it but within a distance d_t (which represents a maximum travel distance) (Fig. 1). Two types of attachment criteria for these long-distance nodes have been explored here. In the Distant Link (DL) case, whenever a village is given the opportunity to establish a longer node, a node is chosen at random, assigning the same probability to all potential candidates and the corresponding link is established, so this automatically replaces the long-distant node that the village may have had previously. In the Optimized Distant Link (ODL) case, the new link will only replace the previous one if the quantity of obsidian present in the new candidate is greater than that in the previous partner.

Obsidian production. Obsidian is introduced into the network from the northern boundary of the domain, so as to reproduce the presence of several natural obsidian outcrops north of the study region. Villages located at a distance of d_t (in km) from there were allowed to produce a fixed quantity of obsidian at each time step according to the expression $100 - r \cdot d$, where d represents the distance (in km) from the village to the northern boundary. This means that the transport costs associated with the resource reduce the production capacity of further villages according to the rate r. d_t (in km) is an estimate of the maximum radius that Neolithic societies would have moved from their homes in order to look for resources/partners.

Obsidian exchange. All of the obsidian produced by a village during each time step is divided into (i) a fraction c that is meant for consumption and (ii), a part that is shared between all neighbors possessing less obsidian at that particular time step (so as to prevent unlikely obsidian exchange with richer nodes in the network). The specific fraction that is given to each neighbor is proportional to the distance between the two villages. If we define d_{ij} as the distance between two nodes i and j, the fraction assigned by the node i to its neighbor j can be expressed as $d_{ij}/\sum_k d_{ik}$, where the sum is performed with all of the neighbors of i that are susceptible to receive the obsidian (to introduce the idea that costs associated with longer travel would be justified by larger exchange rates, which could also be interpreted as a mechanism to stimulate, maintain and strengthen links with distant partners). In the absence of long-distance links, this rule reproduces the dynamics used in the down-the-line model, making a comparison to that model possible.

Parameter estimation. The results provided in the main text are obtained for values of the parameters $N = 200$, $n = 1$, $r = 0.2$, $d_n = 50$ km, $d_t = 180$ km. These were considered to be reasonable choices according to (i) the presumed distribution of settlement during the Neolithic period in the Near East, and (ii) the typical and maximum travel capacities of a group of individuals in archaic farming communities as observed in the ethnographic record (see explanations in Annex 2)

Model outputs. To generate the results reported here we need to extract the following information from the model (in all of the cases, averages of over 100 different realizations of the network dynamics are used):

i) First, the obsidian to flint ratio at a given distance is calculated by grouping all nodes that are at a similar distance from the northern boundary of the domain and averaging all of their obsidian consumption. Specifically, we use a step length of 15 km, so that all nodes whose distance to the northern boundary is in the range (0.15) are grouped into one single class. The corresponding averages are then normalized with respect to the value obtained for the first class (that is in the range (0.15)), which is arbitrarily assigned a value of 100.

ii) The path length is estimated by measuring the minimum number of links that need to be covered to reach one node from the other, for each pair of nodes in the network. If we make $l_{ij}^{(\min)}$ the minimum path distance between nodes i and j, then the clustering coefficient is defined by the average

$$\frac{1}{2N(N-1)}\sum_{i,j} l_{ij}^{(\min)}$$

where the sum is performed over the $2N(N-1)$ pairs of nodes one can find in a network of N nodes.

iii) The clustering coefficient is defined as the probability that, if nodes j and k are each linked to i, then j and k are also linked to each other. Such a probability is calculated explicitly by accounting for all possible neighbor to neighbor combinations in the network. This average can be mathematically expressed as

$$\frac{1}{N}\sum_{i=0}^{N}\frac{1}{z_i(z_i-1)}\sum_{j,k} p_{ijk}$$

where z_i is the number of neighbors of the i-th node, and the second sum is performed over all the pairs j,k neighbors of the i-th node, with p_{ijk} denoting a bivaluate function that takes the value 1 if nodes i,j,k are all linked to each other, and otherwise takes the value 0.

Annex 2. Variables of the model: explanation of the magnitudes chosen and sensitivity analysis

In this Annex we explain the magnitudes of the variables that we have chosen because we judged them to be more realistic for our standard DL and ODL models. Moreover, we carry out a sensitivity analysis of the variables in the Optimized Distant Link (ODL) model in order to show how much the model shifts if alternative magnitudes to those of the standard model are chosen.

Number of villages (*N*): Distances of 10 to 15 km between villages are documented for the Early Neolithic in the areas of the Middle Euphrates or the Jordan Valley, while other regions were less populated. 200 villages have been distributed in the spatial domain of the model in our standard simulation, which means an average distance of 40 km between sites. Renfrew’s down-the-line model is very sensitive to this variable, as villages distribute obsidian between their neighbors irrespectively of the distance between them (Fig 1). However, our complex network models (DL and ODL) turned out to be largely insensitive to changes in village density (Fig. 2). This is a consequence of introducing characteristic distances d_n and d_t to quantify the level of interaction between villages.

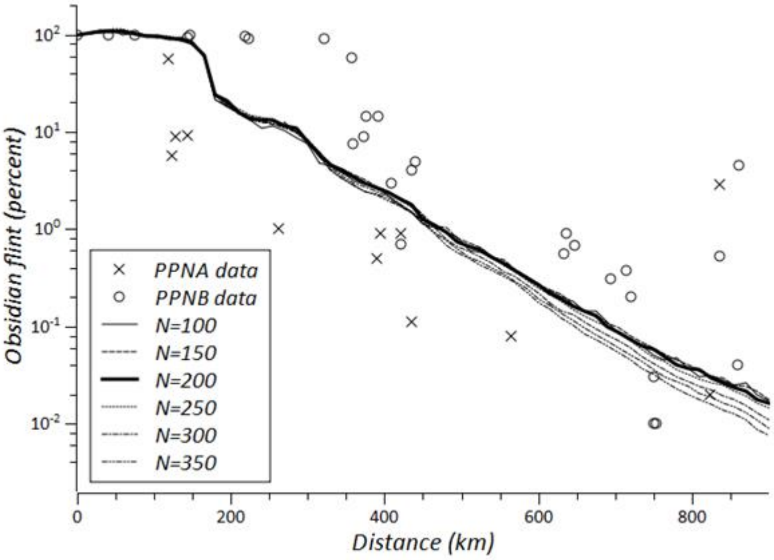

Figure 2. Optimized Distant Link (ODL) model results as a function of the total number of villages N.

The limit for distance of exchange link and for direct acquisition of obsidian from the outcrops (d_t): Ethnographic examples reveal long trade expeditions to reach contact partners located at distances between 4 and 10 days walking (44, 20, 56). Direct access to sources for acquiring salt or stone blades in ethnographic contexts of primitive trade in New Guinea implies expeditions of 4 to 7 days walking (57, 42). We have chosen 180 as d_t in our standard model. This is a very sensitive variable, as longer links result in a more efficient transfer of obsidian (Fig 3).

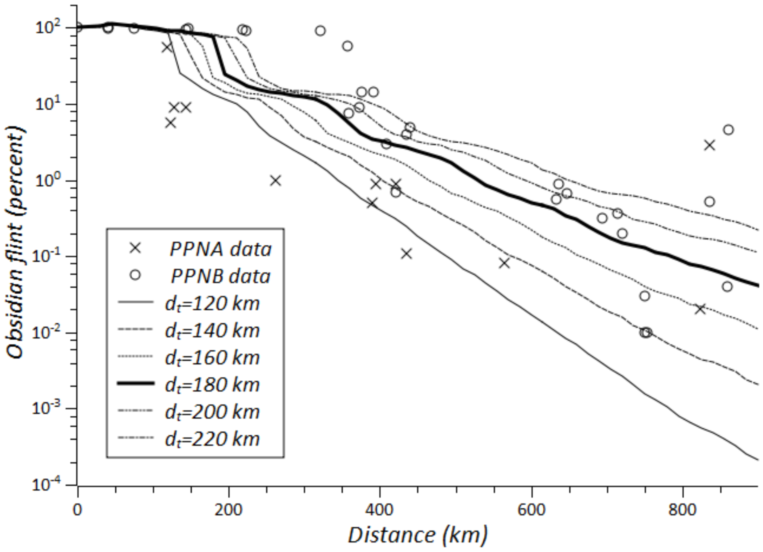

Figure 3. Optimized Distant Link (ODL) model results as a function of the maximum travel distance d_t.

The function of decrement in obsidian acquisition related to distance (*r*): This function simulates the higher cost of acquisition for the communities located at larger distances from the obsidian sources. As it is assumed (see previous point) that 180km is the limit of the area of direct access to the obsidian sources and given that quantities of obsidian in this area are around 80%, we have approximated -0.13/km as the function of friction. Nevertheless the model happens not to be sensitive to this variable (Fig 4).

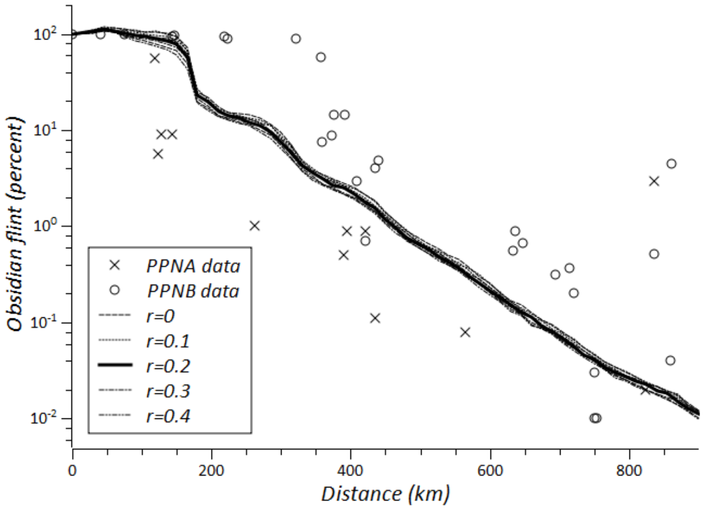

Figure 4. Optimized Distant Link (ODL) model results as a function of the decay rate in obsidian production r.

The number of distant links per village (*n*): Establishing and maintaining distant trade links must have represented an important social and economic cost for Neolithic communities. **As** this is not a sensitive parameter (Fig 5), we have chosen the more conservative option and kept only 1 distant link per village.

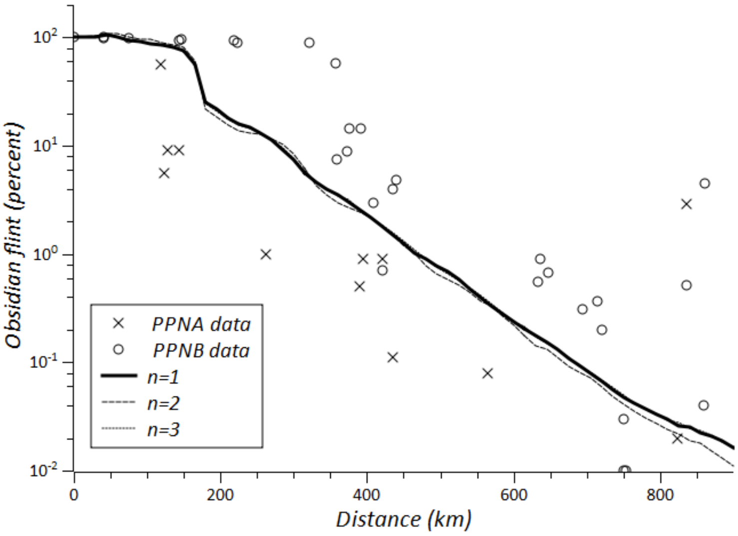

Figure 5. Optimized Distant Link (ODL) model results as a function of the number of distant links per node n.

The rate of obsidian exchange/consumption in each village (*c*): The study of archaeological remains has demonstrated beyond a doubt that obsidian was both consumed and exchanged, and therefore had a use and an exchange value. As ethnographic examples show, the proportion of one value with respect to the other was most likely contextual. For example among the Anga of New Guinea, the price of a commodity (which is directly related to the exchange value) depends on its rarity, on the political relationships between groups (the price is higher for enemies) and, in the case of utilitarian commodities (which obsidian was in the context we are researching), on the degree of necessity for its use. Another important element which influences the exchange value of a commodity is the likelihood of providing other commodities in exchange. Among the Kapau and Langimar groups from New-Guinea, Baruya salt is consumed but not exchanged because these groups own the production monopoly on stone axes and adzes, which are other commodities which can be used for exchange (57). Most obsidian remains are recovered from archaeological sites in the form of used and discarded tools, while very few obsidian caches that could represent material ready for exchange, have been found (19). This seems to indicate, generally speaking, that the exchange value was not higher than the use value. As both values were important, we have chosen a rate of 50% for each site in our standard model. This is a sensitive parameter (Fig 6).

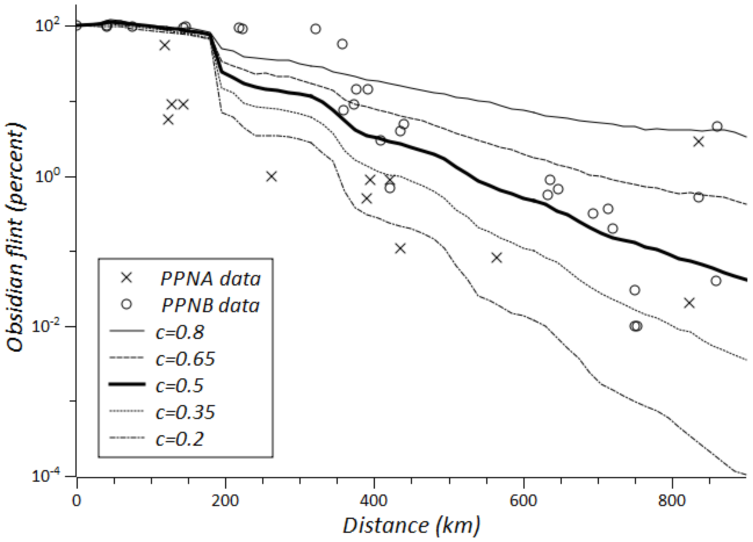

Figure 6. Optimized Distant Link (ODL) model results as a function of the exchange/consumption rate in each village *(c)*.

The proportion of obsidian assigned to local and to distant partners: Distant exchange partners are more profitable than local ones, as the former can offer more exotic commodities. As a result, distant exchange partners receive more obsidian than local ones in our DL and ODL standard models. To implement this rule we assume that the quantity exchanged should be proportional to the distance between nodes (the opposite strategy would be to consider that all neighbors receive exactly the same independently of distance). This rule is supported by ethnographic examples, whereby a continuous and small-scale exchange takes place between local neighbors, while distant trade mobilizes important quantities of commodities (42). The model is only relatively sensitive to this parameter (Fig 7) and it does not jeopardize the viability of the model.

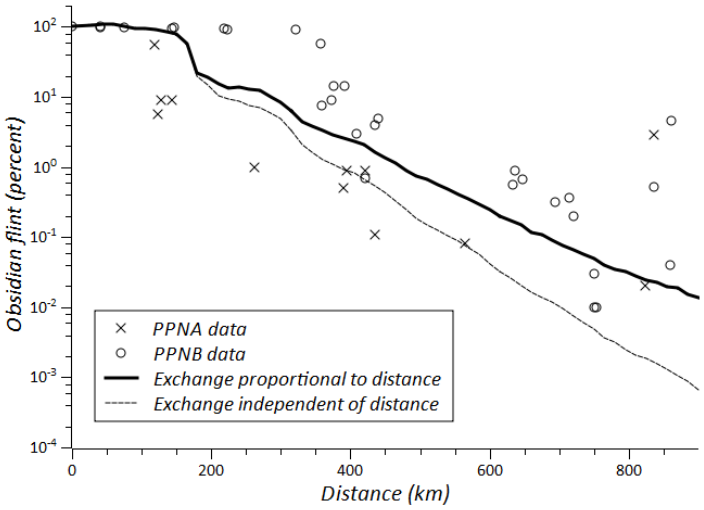

Figure 7. Optimized Distant Link (ODL) model results depending on whether obsidian is distributed in direct proportion to distance between partners or equitably between them.

The distance defining neighborhood (d_n): Ethnographic examples show (42) that most transactions take place between villages which are located at a distance of one or two days walking. Thus we have chosen 50 km as the limit of a "neighborhood". Longer neighborhoods result in a more efficient transfer of obsidian (Fig 8)

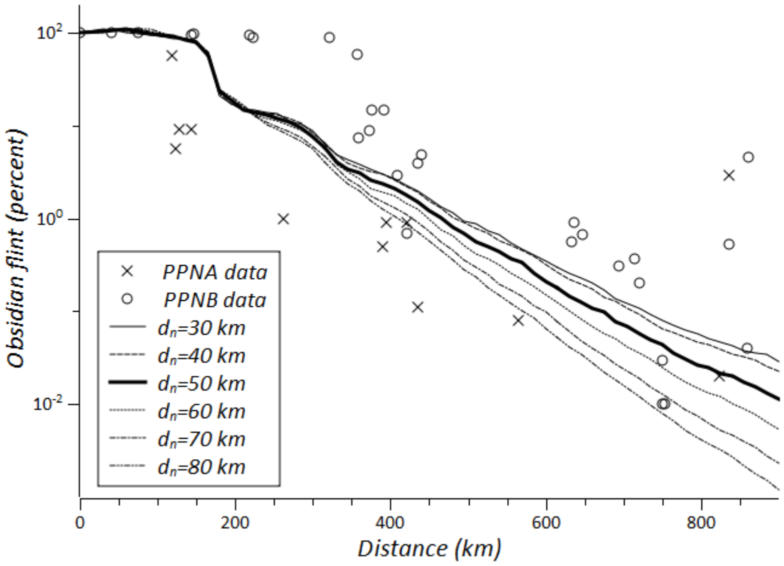

Figure 8. Optimized Distant Link (ODL) model results as a function of the neighbor distance d_n.

The duration of the exchange link with distant partners: As ethnographic examples show that exchange links are usually inherited, we have chosen 50 years (two generations) as the duration of a link. The model is not sensitive to this parameter as changing the magnitudes of this variable only affects how quickly the same results are obtained.

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