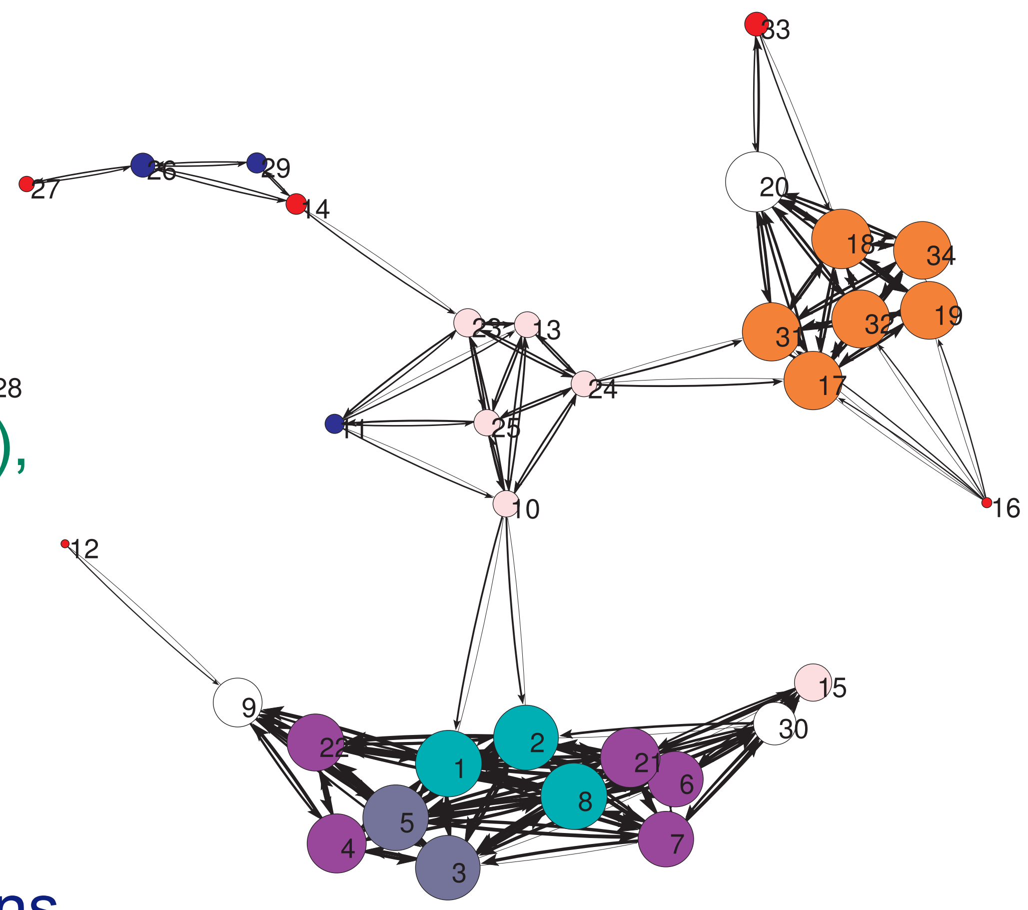
Århus 8th May 2008
Tim Evans
Theoretical Physics

Imperial College London

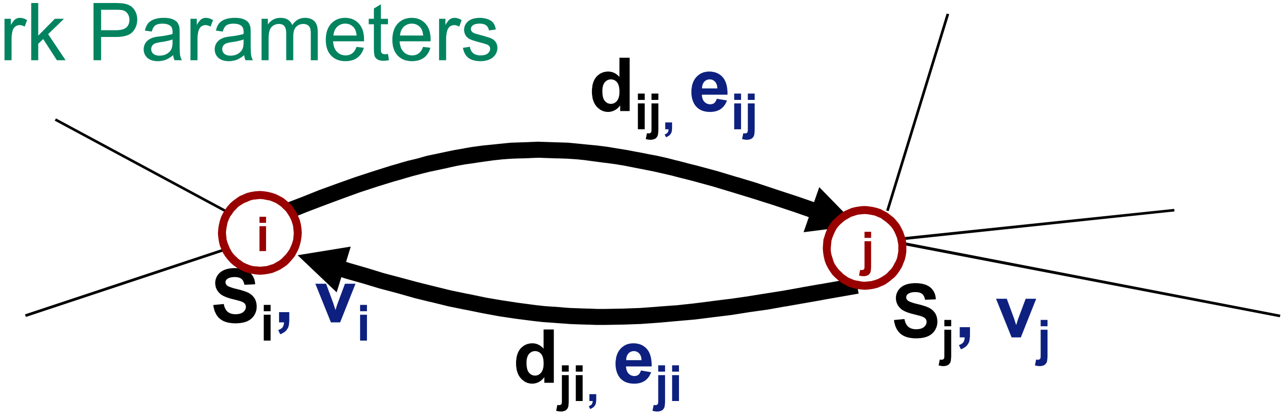
Networks for the Minoan Aegean



Carl Knappett (Exeter/Toronto),
Ray Rivers (Imperial),
Tim Evans (Imperial)

See web site for publications
www.ic.ac.uk/people/t.evans

Network Parameters



- We want to find our optimal network given:-

Inputs:

- **Site sizes** S_i
- **Site separation** d_{ij}

Outputs:

- **Site occupation** v_i
- **Interaction levels** e_{ij}
- **Total population** $\Sigma_j (S_i v_i)$
- **Trade activity** $\Sigma_j (S_i v_i e_{ij})$

Optimal Networks

- Adjust site and edge variables to optimise the **‘cost’** H of the network:

$$H = -\lambda E - \kappa L + j P + \mu T$$

where

- **E – all exchange/trade**
  Increase parameter λ and interaction produces more benefits
- **L – all local production**
  Increase parameter κ and internal processes more profitable
- **P – total population**
  Increase parameter j and cost per person is increased
- **T – total strength of links**
  Increase parameter μ and interaction links more expensive to maintain

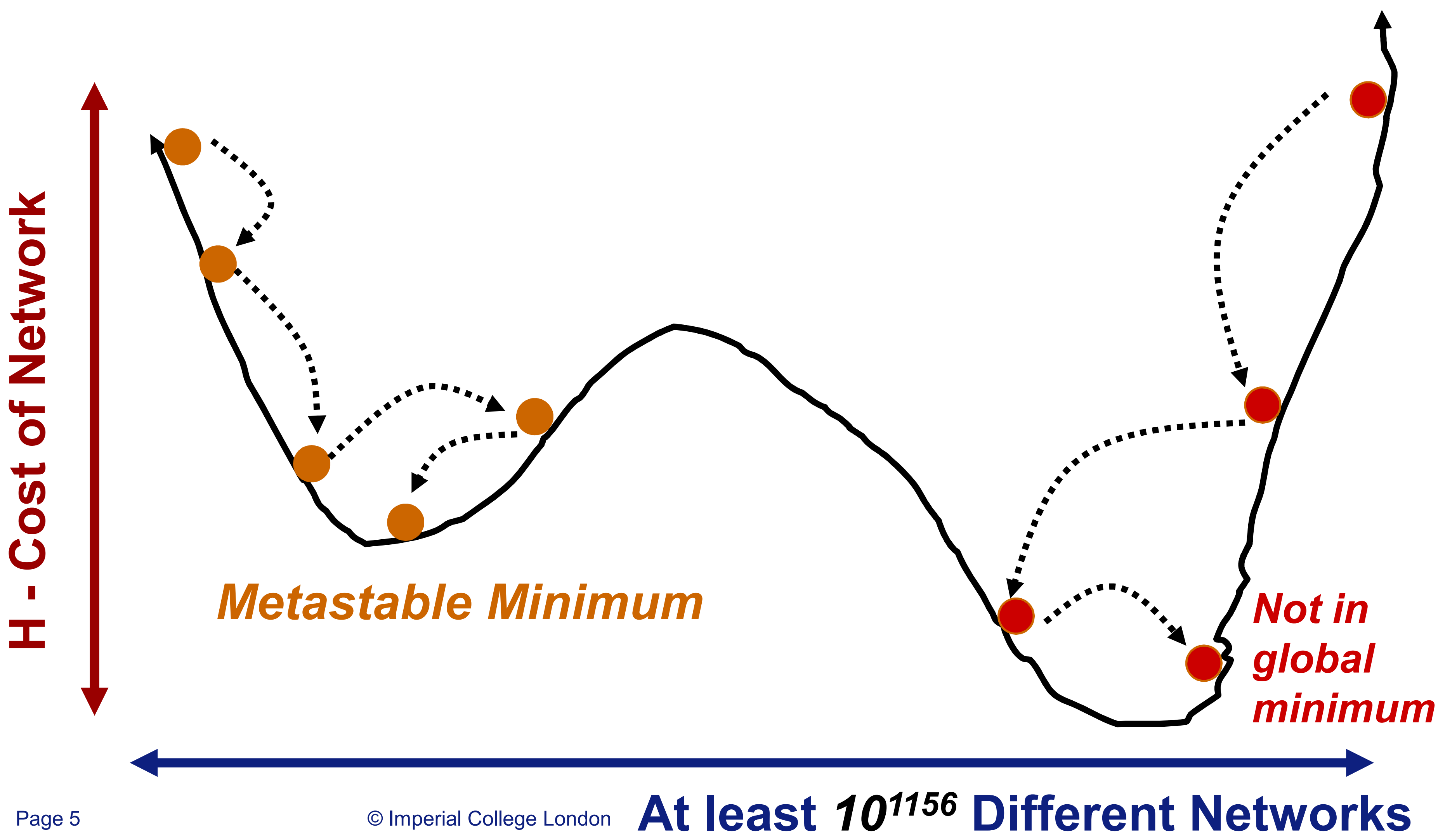
But not always perfectly optimal…

- We find networks which are only *approximately* optimal using standard stochastic methods (*simulated annealing* implemented using *Monte Carlo* techniques)

- We never find exactly the same network twice

- Usually networks are similar and have similar ***H*** values, but sometimes may find very different networks *(metastability)*

Stochasticity and Metastability



Choosing the numbers

How do we choose the numbers to use in our model?

- S_i - Site capacities (sizes) and locations
- D - Distance Scale in potential
- d_{ij} - The distances between each pair of sites
- H - The coefficients:
  - j population cost
  - μ trade cost
  - κ population benefits
  - λ trade benefits

Choosing the Site Locations and Capacities (sizes) - S_i

- Locations based on research.
  Currently 34 most significant sites included (see next slide).
- Capacities S_i based on research but only very crude estimates
  - Big $S_i = 1.0$
  - Medium $S_i = 0.667$
  - Small $S_i = 0.5$

The 34 Sites Used

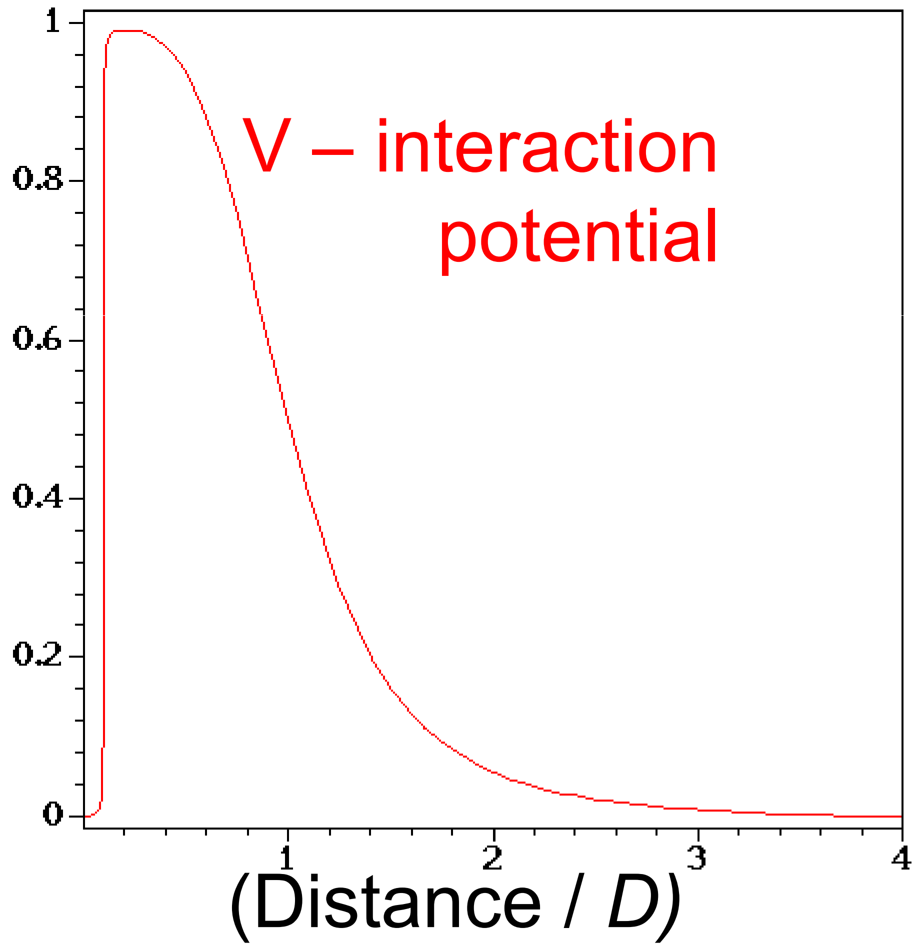
Choosing the Distance Scale *D*

We use: *D=100*km for sail, *D=10*km for rowing

(after 2000BC) (pre 2000BC)

Exchange/Trade/Interaction term ***E*** for each pair of sites depends on distance d_{ij} between sites such that for distances much longer than a scale ***D*** the benefit is zero

i.e. no effective direct interaction

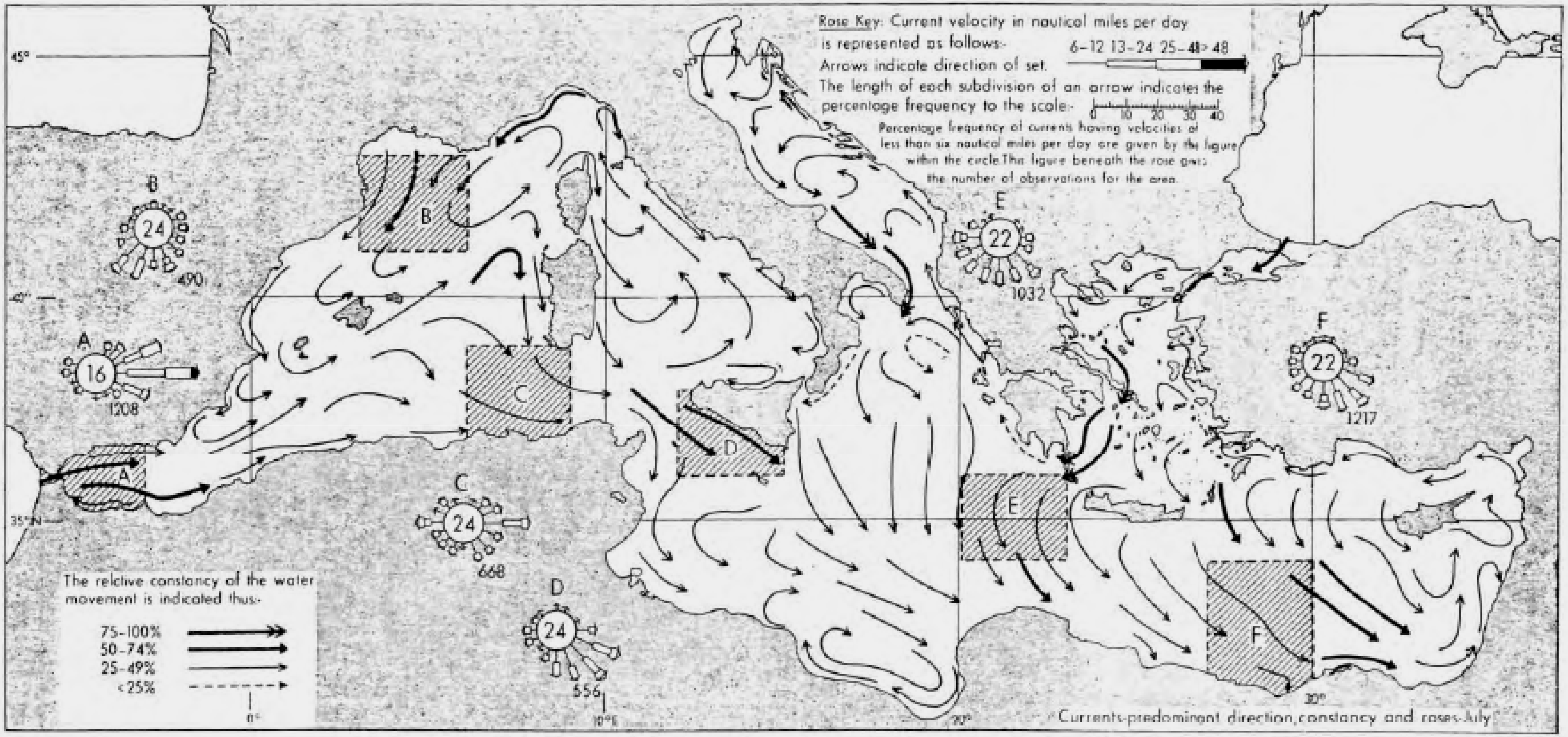


Choosing the Effective Distances d_{ij} – Travel Time, Relative Costs, …

- We take account of land vs. sea
  Examples here assume land distances travel are effectively three times as long as sea. Other choices also tried.

- Different site capacities (s_i) large, medium and small

- *In future* could allow for prevailing winds and currents. The effective distance from site i to site j need not be the same as from site j to site i.



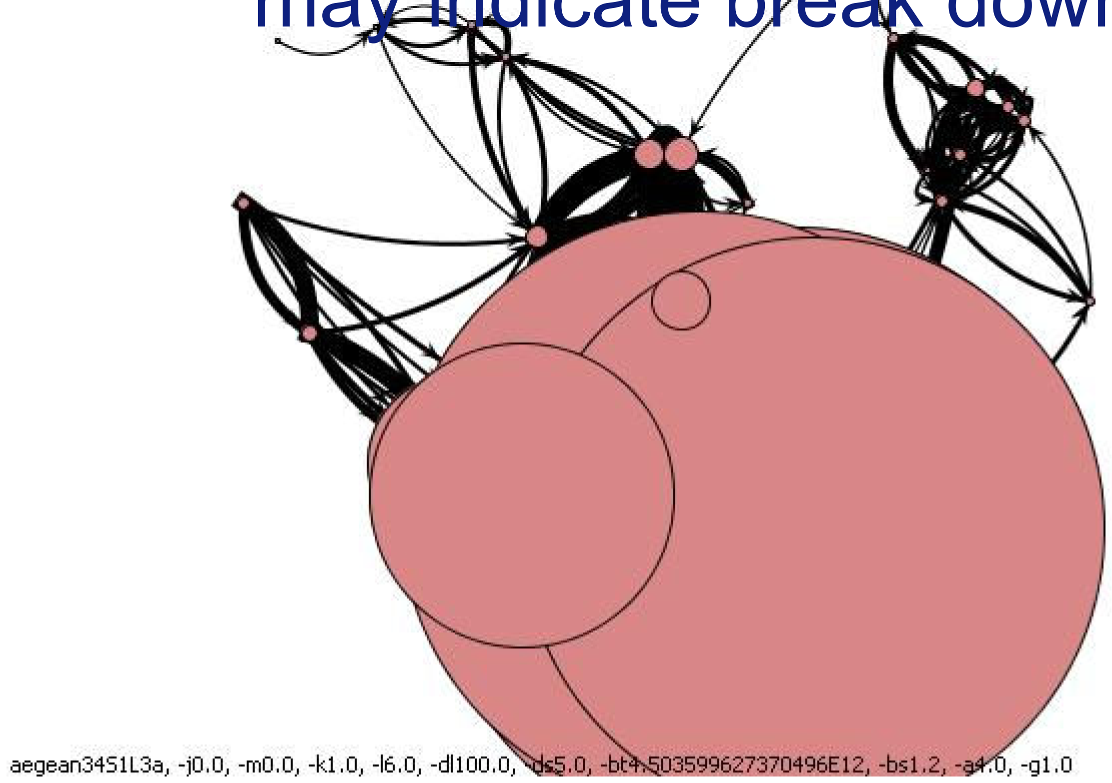
Currents—predominant direction, constancy and roses—July.

Lambrou-Phillipson, 1990

Choosing the coefficients of $\boldsymbol{H}$ ($\boldsymbol{j}, \mu, \kappa, \lambda$)

- Analytic and numerical calculations show regions of simple behaviour

e.g. large λ $(\lambda > 4\kappa)$ Runaway Sites (Boom) may indicate break down of model

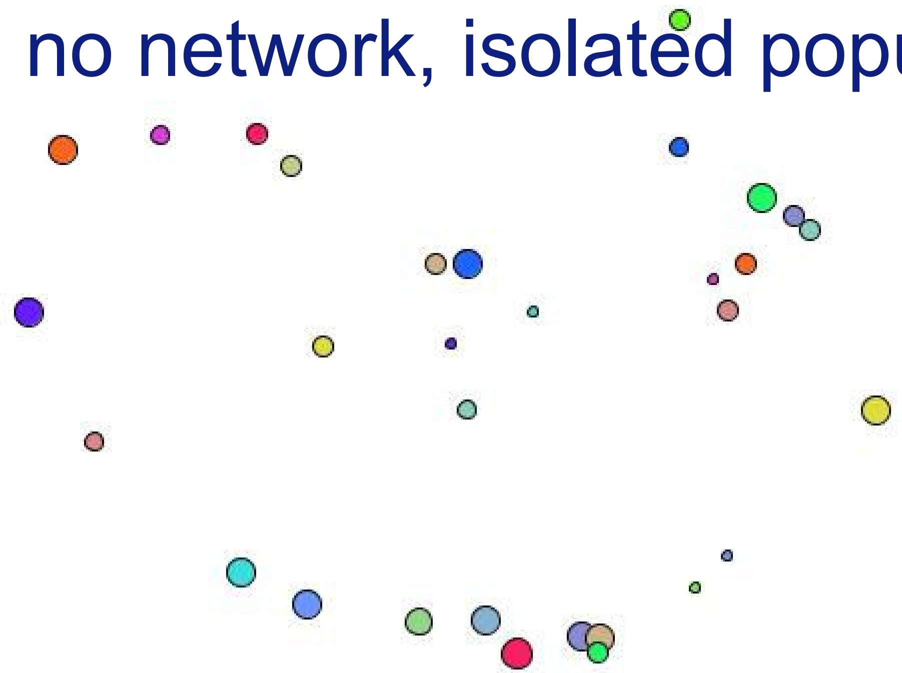


$(j,\mu,\kappa,\lambda)=(0,0,1,6)$
largest weights = 100
= numerical limit in this run

Choosing the coefficients of $\boldsymbol{H}$ ($\boldsymbol{j}, \mu, \kappa, \lambda$)

e.g. large $\boldsymbol{j}$ (roughly $j>4\kappa$)
"collapse", no population at all

e.g. low λ, large μ
no network, isolated populations



$(j,\mu,\kappa,\lambda)=(0,4,1,1)$
site weights 0.0 – 0.49

aegean34S1L3a, -j0.0, -m4.0, -k1.0, -l1.0, -dl100.0, -ds5.0, -bt33554.432, -bs1.2, -a4.0, -g1.0

Choosing the coefficients of $\boldsymbol{H}$ ($\boldsymbol{j}, \mu, \kappa, \lambda$)

- We scan through parameter ranges and select those that pass some basic criteria
  - e.g. non-trivial network and population
  - e.g. with reasonably sized populations

- We are therefore using some of our archaeological knowledge to apply some selection.

- Only remaining aspects can form part of the predictive power of our model
  - e.g. look at comparisons of model results for various acceptable values

Analysis

- Can not assign parameter values in model from physical data so make *comparisons* between different data sets
  - e.g. vary one parameter, hold rest fixed.

- For any given set of (reasonable) values:

  a) can analyse intrinsic network measures

  e.g. degree of vertices

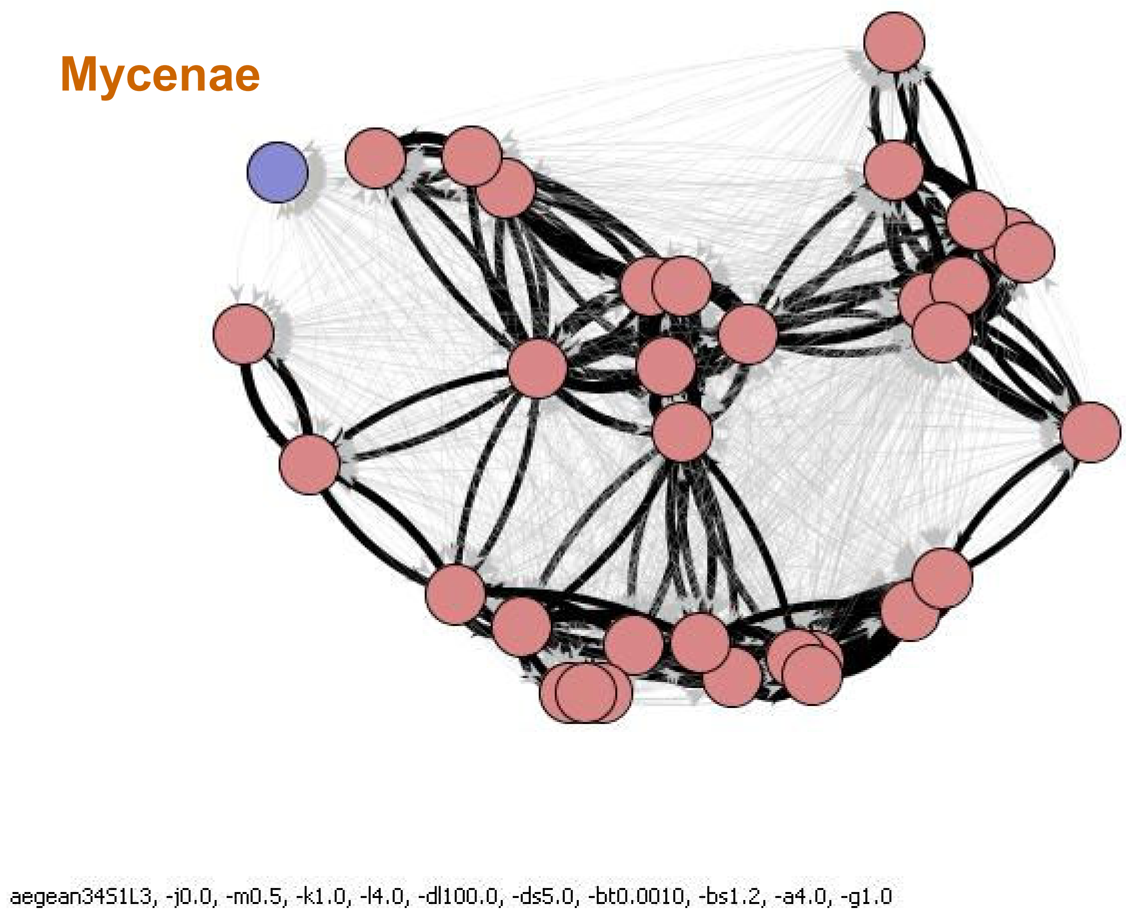
  b) can perform further `games' to analyse properties

  e.g. simulate trade in physical objects,
  apply cultural transmission models.

Physical Substrate of our Networks

- Can analyse this as a network in its own right
- Connect all vertices separated by less than a specified distance

Physical Substrate of our Networks (cont)



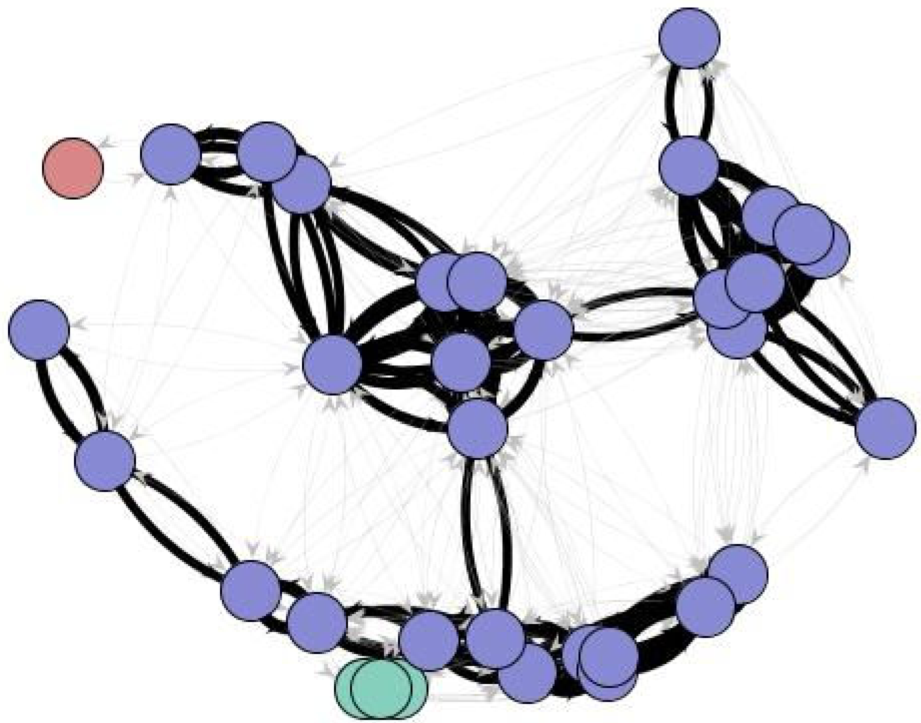
Connect all sites which are separated by

150km

or less

All sites (except Mycenae) are connected via a few hops along network links

Physical Substrate of our Networks (cont)



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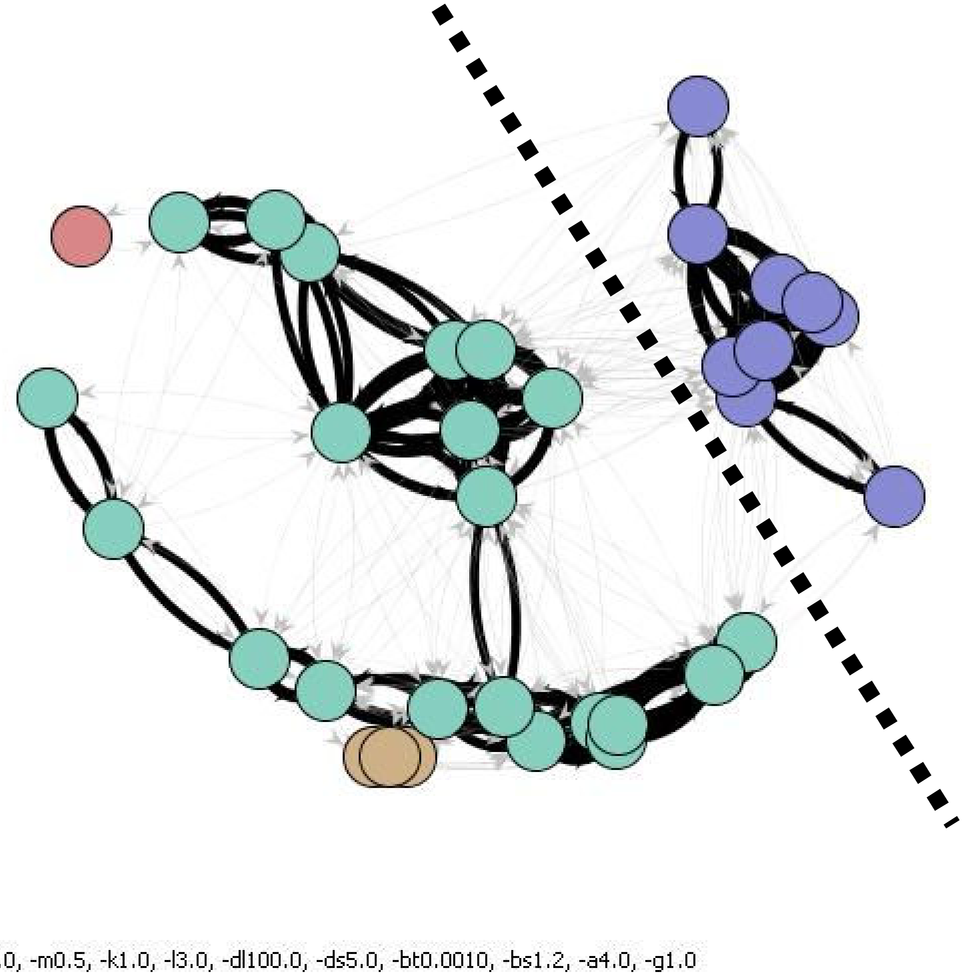
Connect all sites which are separated by

127km

or less

Still mostly connected

Physical Substrate of our Networks (cont)



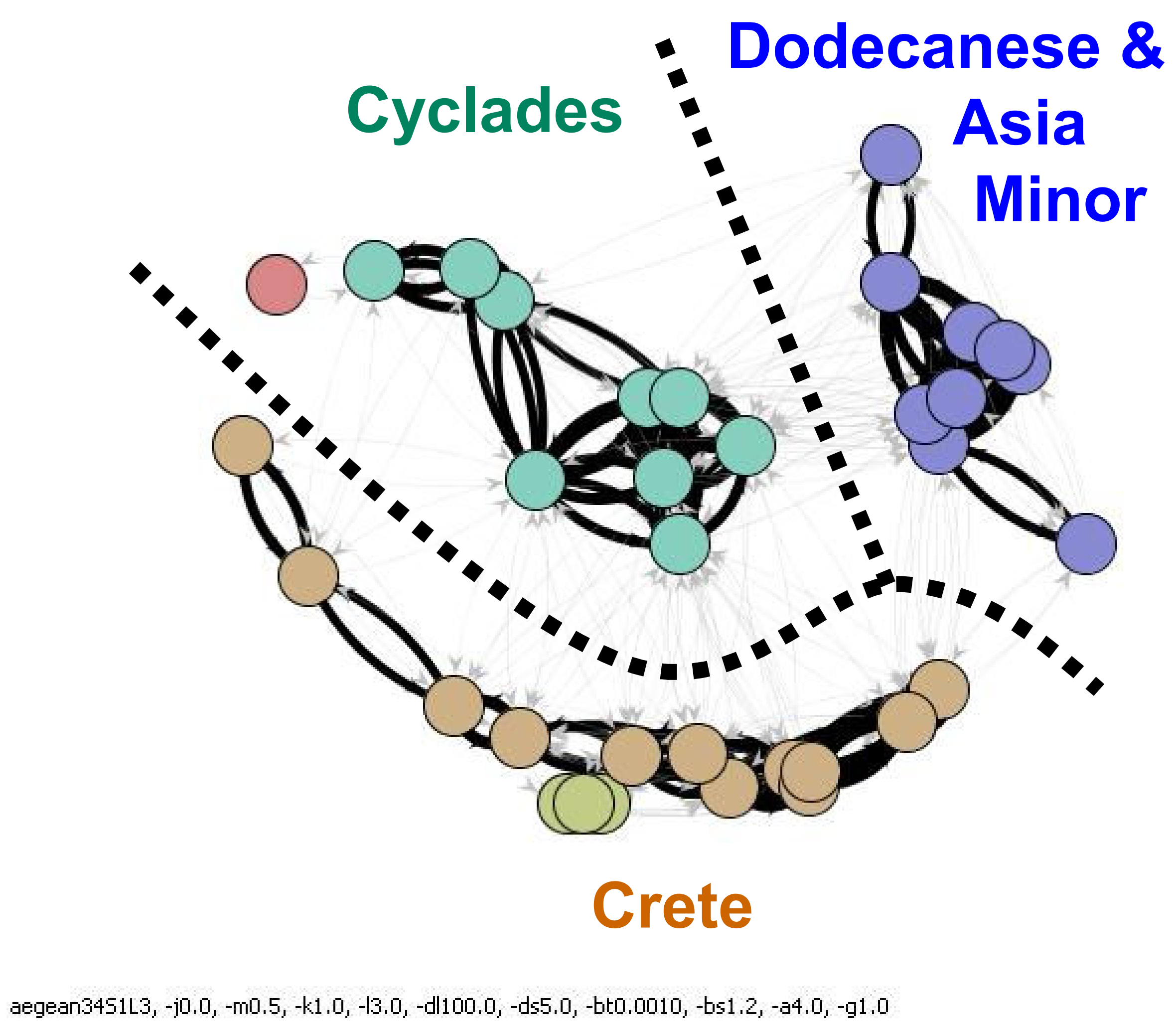
Connect all sites which are separated by

122km

or less

Now Dodecanese and Asia Minor disconnected

Physical Substrate of our Networks (cont)



Connect all sites which are separated by

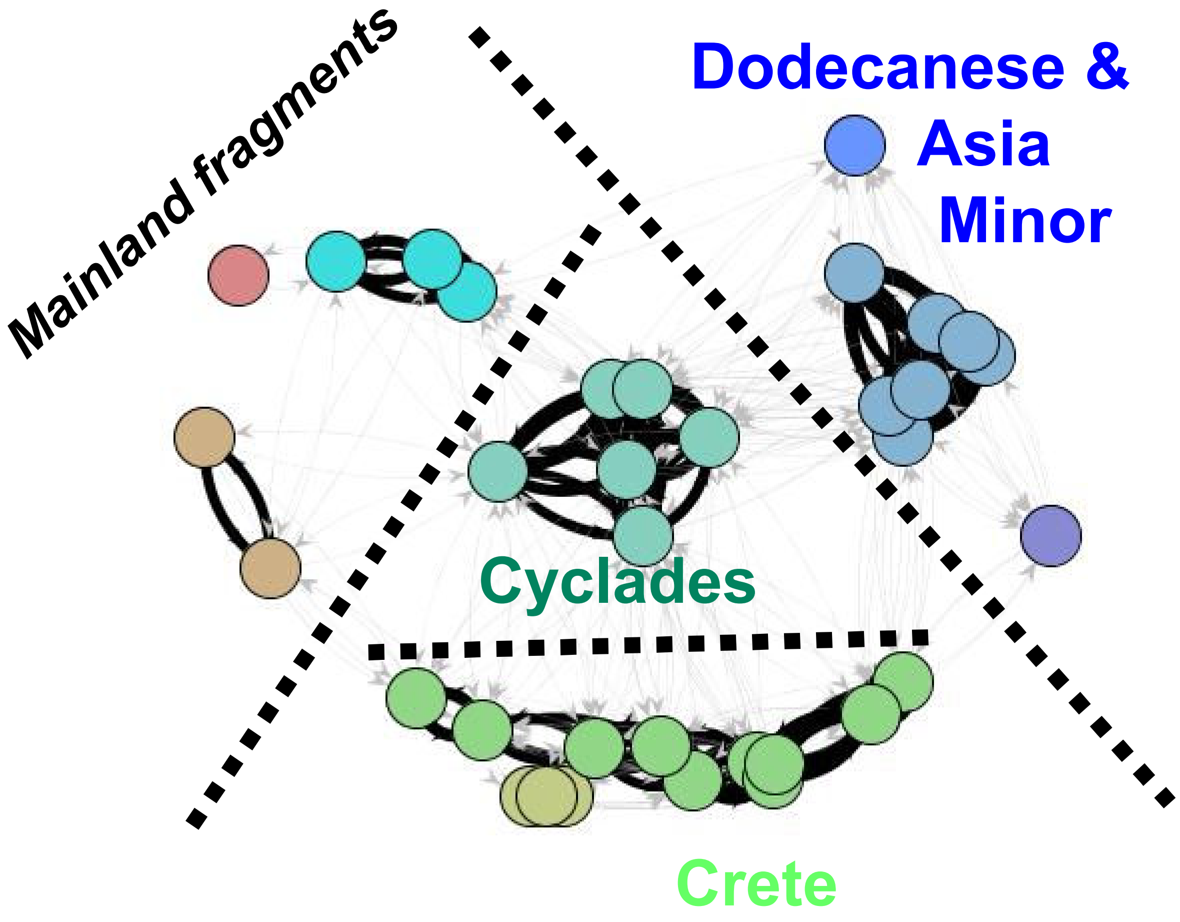
117km

or less

Network now shows

three primary regions in geographical substrate

Physical Substrate of our Networks (cont)



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Connect all sites which are separated by

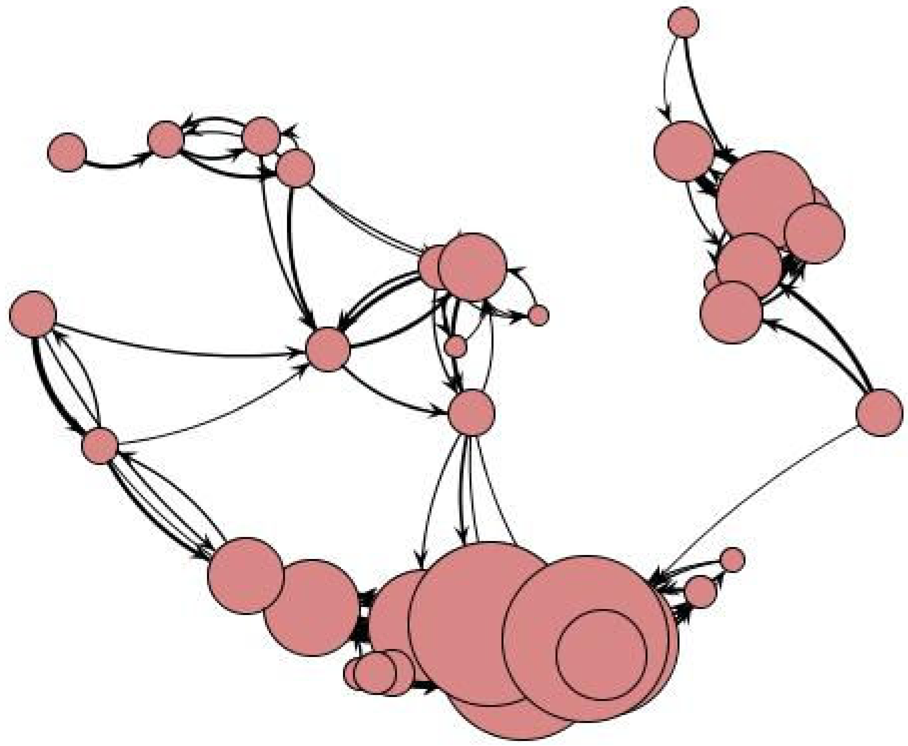
100km

or less

Simple application of 100km sailing distance gives disconnected regions

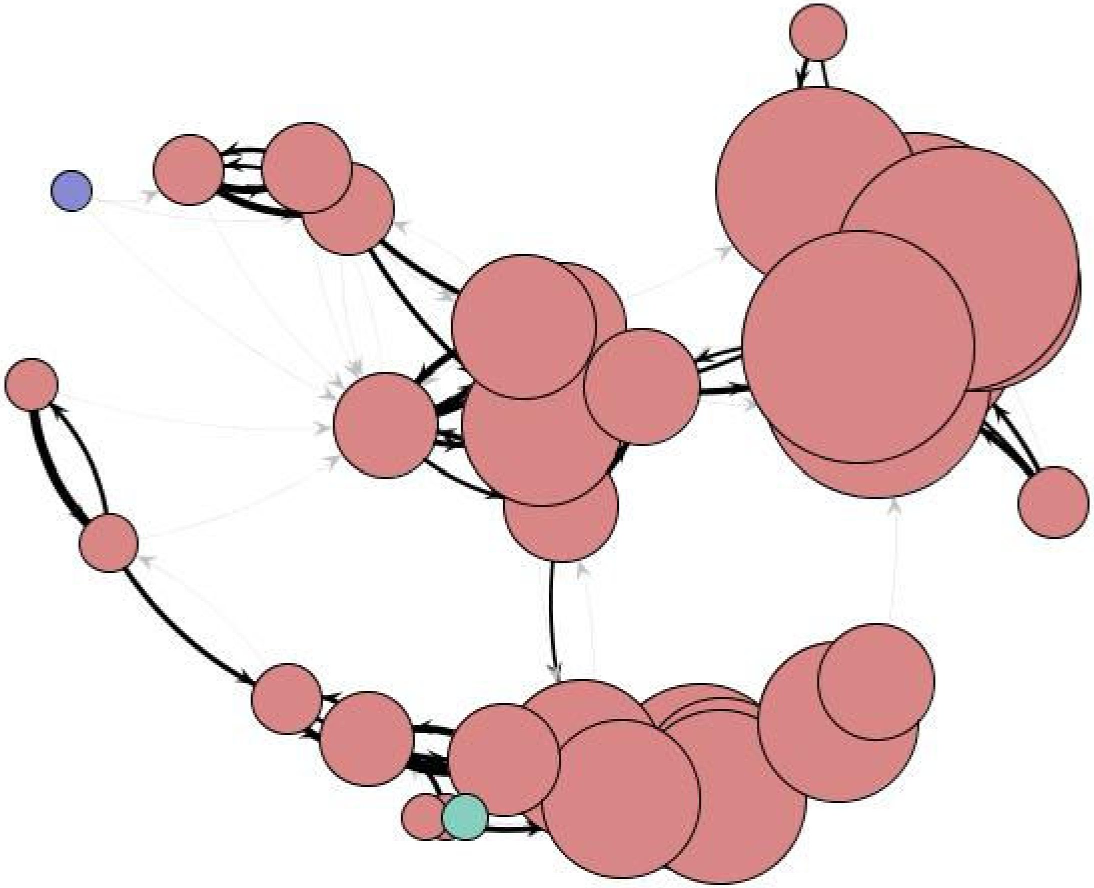
Effect of different choices for site capacities and separations

- Next two slides show changes when move from
  a) equal site capacities to unequal site capacities
  b) from direct “as-the-crow-flies” distances to realistic separations



aegean34S1L3a, -j-0.999, -m0.0, -k1.0, -l4.0, -dl100.0, -ds5.0, -bt2147483.647, -bs1.2, -a4.0, -g1.0

aegean34S1L3a
D=100km
High SCORE
(j,μ,κ,λ)=(-1,0,1,4)
slider 8%
Just connected
1.1 av (2.8 – 0.3) site weights



aegean34S1L3, -j-0.999, -m0.0, -k1.0, -l4.0, -dl100.0, -ds5.0, -bt2147483.647, -bs1.2, -a4.0, -g1.0

High SCORE
$(j,\mu,\kappa,\lambda)=(-1,0,1,4)$
slider 17%
Just connected
4.1 – 0.7 site weights

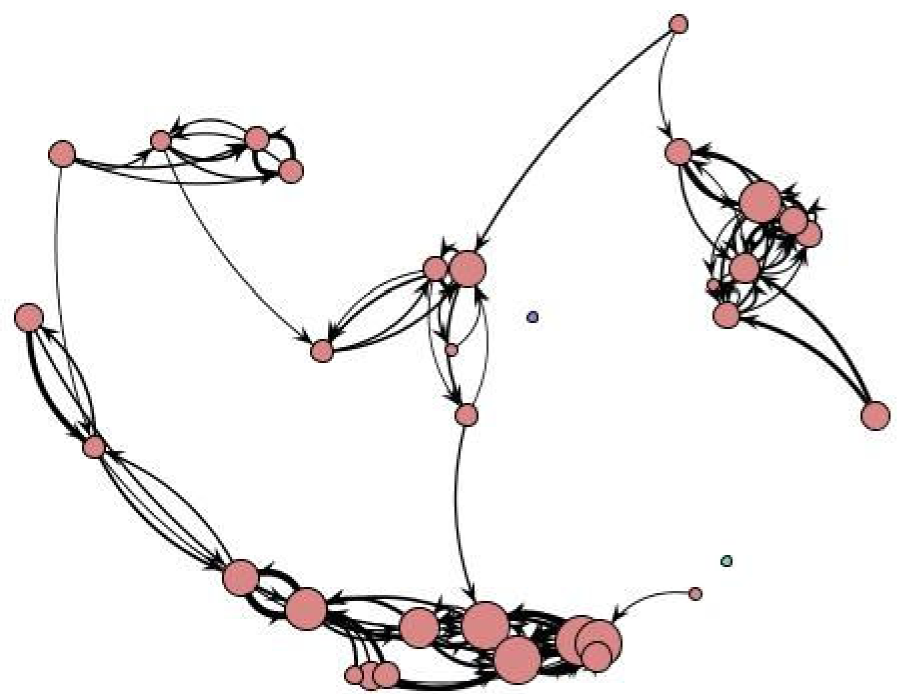
Effect of different choices for site capacities and separations

In general we find that

- With all site capacities equal and as-the-crow-flies distances, Crete dominates.
- With all site capacities equal but now realistic sites separations the Dodecanese/Asia-Minor group dominates
- With realistic site capacities and realistic sites separations, Crete again dominates

Increasing benefit of trade – λ increasing

λ=2.5



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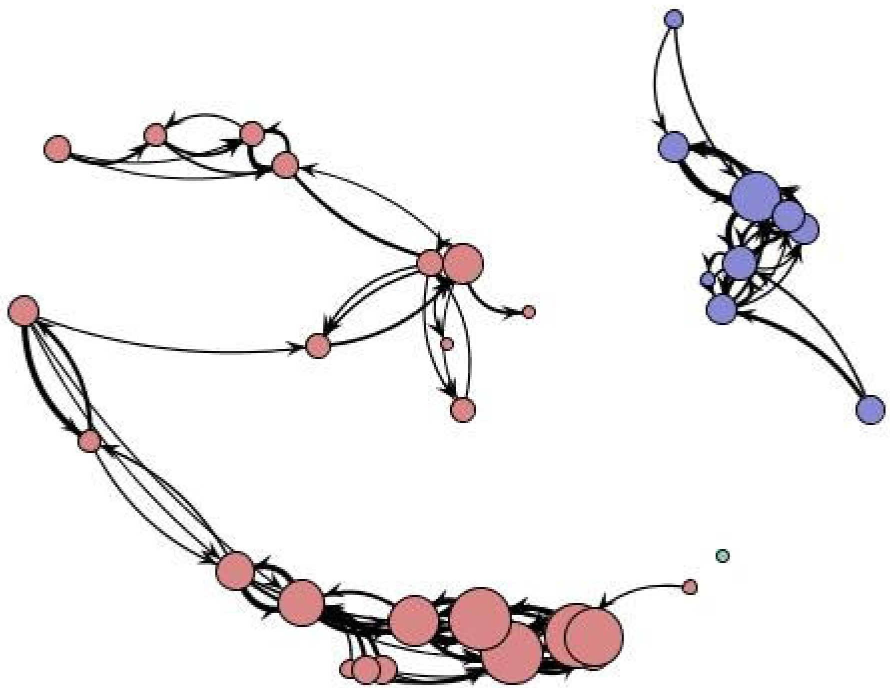
$(j,\mu,\kappa,\lambda)=(-1,0,1,2.5)$
slider 8%
0.69 (1.26 – 0.27) site weights

Increasing benefit of trade – λ increasing

λ=3.0

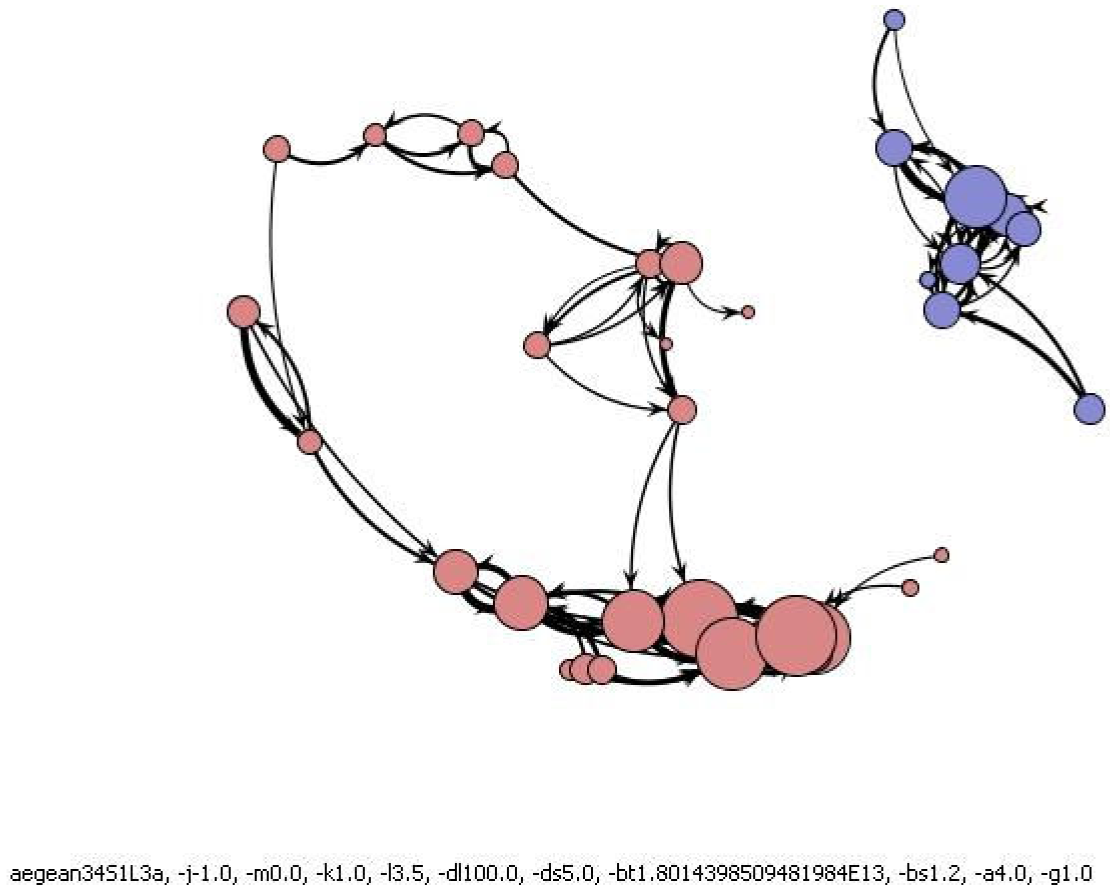


aegean34S1L3a, -j-1.0, -m0.0, -k1.0, -l2.0, -dl100.0, -ds5.0, -bt9.00719925474099 2E12, -bs1.2, -a4.0, -g1.0

$(j,\mu,\kappa,\lambda)=(-1,0,1,3)$
slider 8%
0.79 (1.6 – 0.28) site weights

Increasing benefit of trade – λ increasing

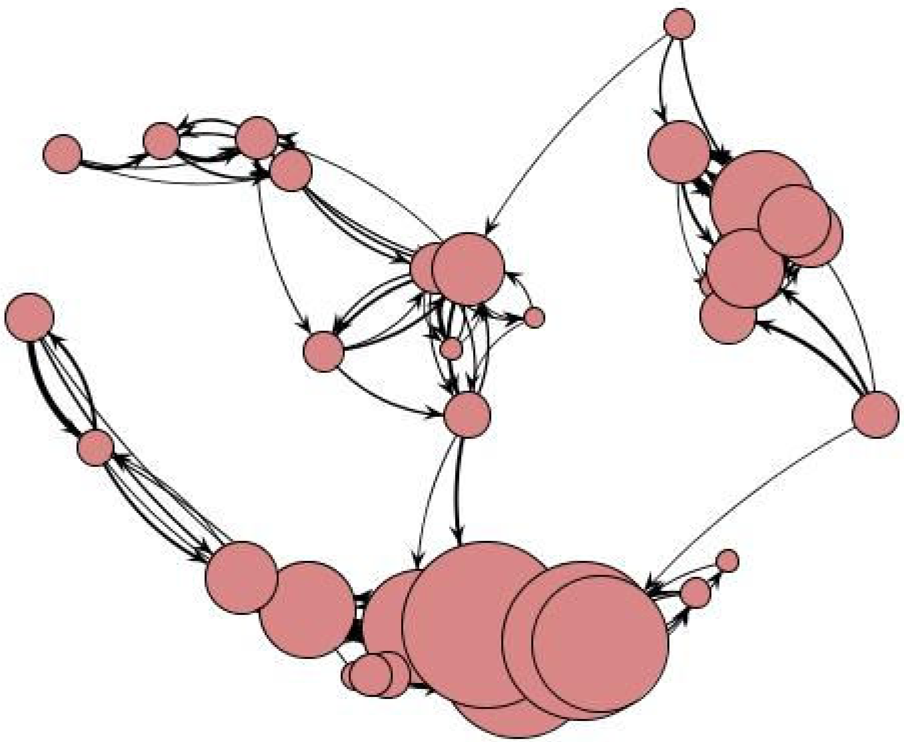
$\lambda=3.5$



$(j,\mu,\kappa,\lambda)=(-1,0,1,3.5)$
slider 8%
0.9 (1.99 – 0.3) site weights

Increasing benefit of trade – λ increasing

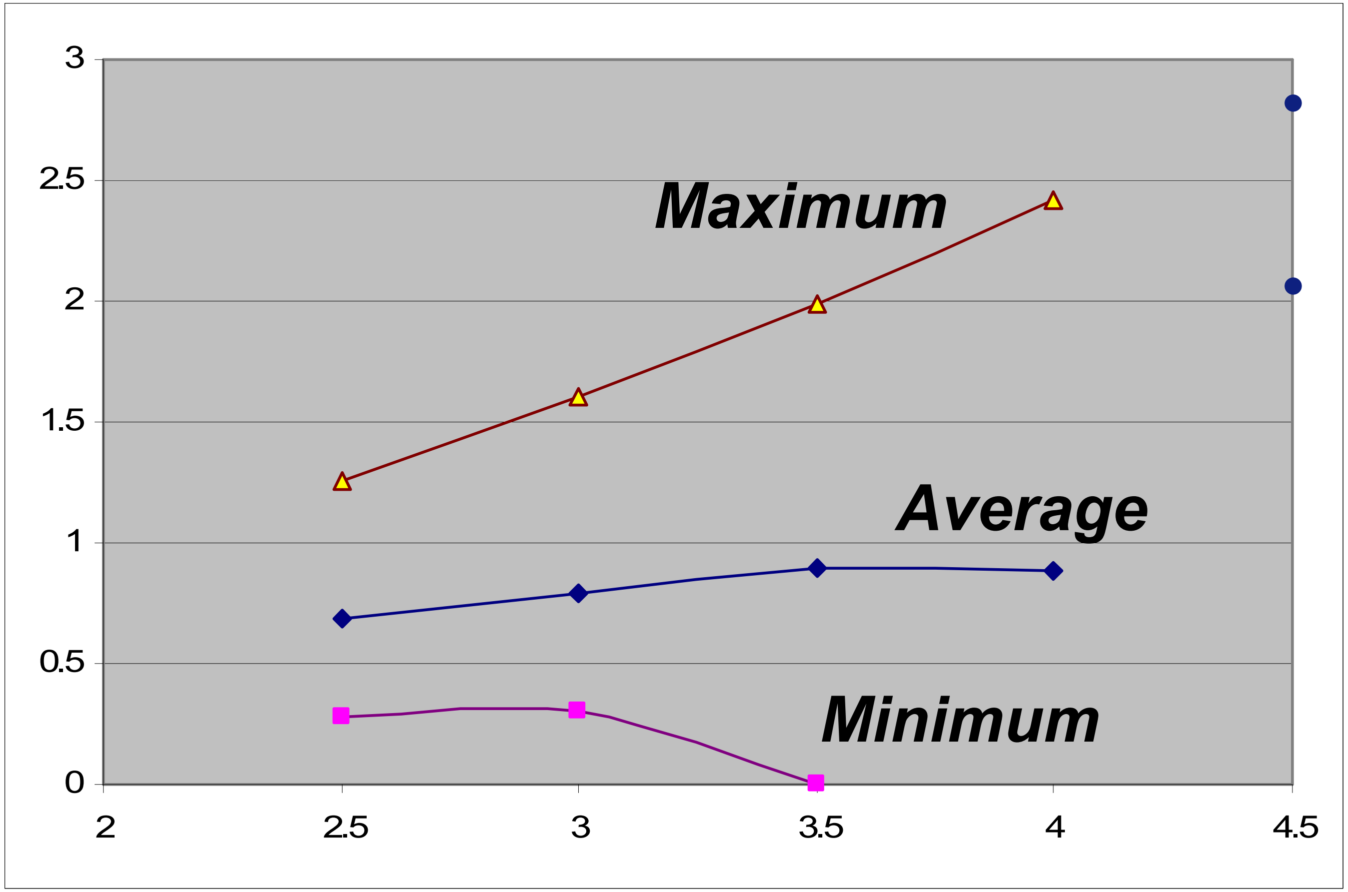
λ=4.0



aegean34S1L3a, -j-0.999, -m0.0, -k1.0, -l4.0, -dl100.0, -ds5.0, -bt2147483.647, -bs1.2, -a4.0, -g1.0

$(j,\mu,\kappa,\lambda)=(-1,0,1,4)$
slider 8%
0.88 (2.42 – 0.0) site weights

Increasing benefit of trade – λ increasing



- Population/Sites sizes grow
- Largest Site and differential between large and small grows faster

Analysis of Single Network

- The next few slides show the analysis of one result of our model
- Look for sites which are off any general trends
- Rank = probability of random walker arriving at location, c.f. Hage & Harary 1991, Google PageRank
- Total Site Size (Weight) = $(S_i v_i)$

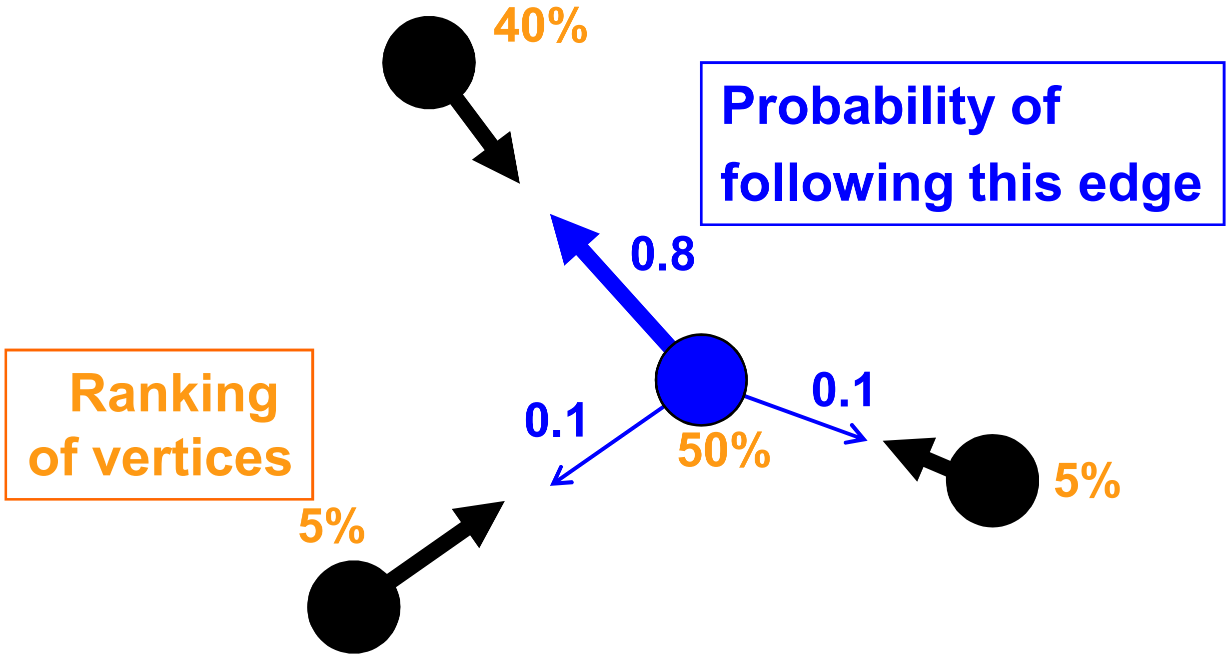
$j=0, \mu=0.5, \kappa=1.0, \lambda=4.0$

Analysis Methods: Ranking

- The percentage of time spent at each node by a random walker on the network.

  The walker chooses to follow a link with probability proportional to its strength. (Other choices possible).

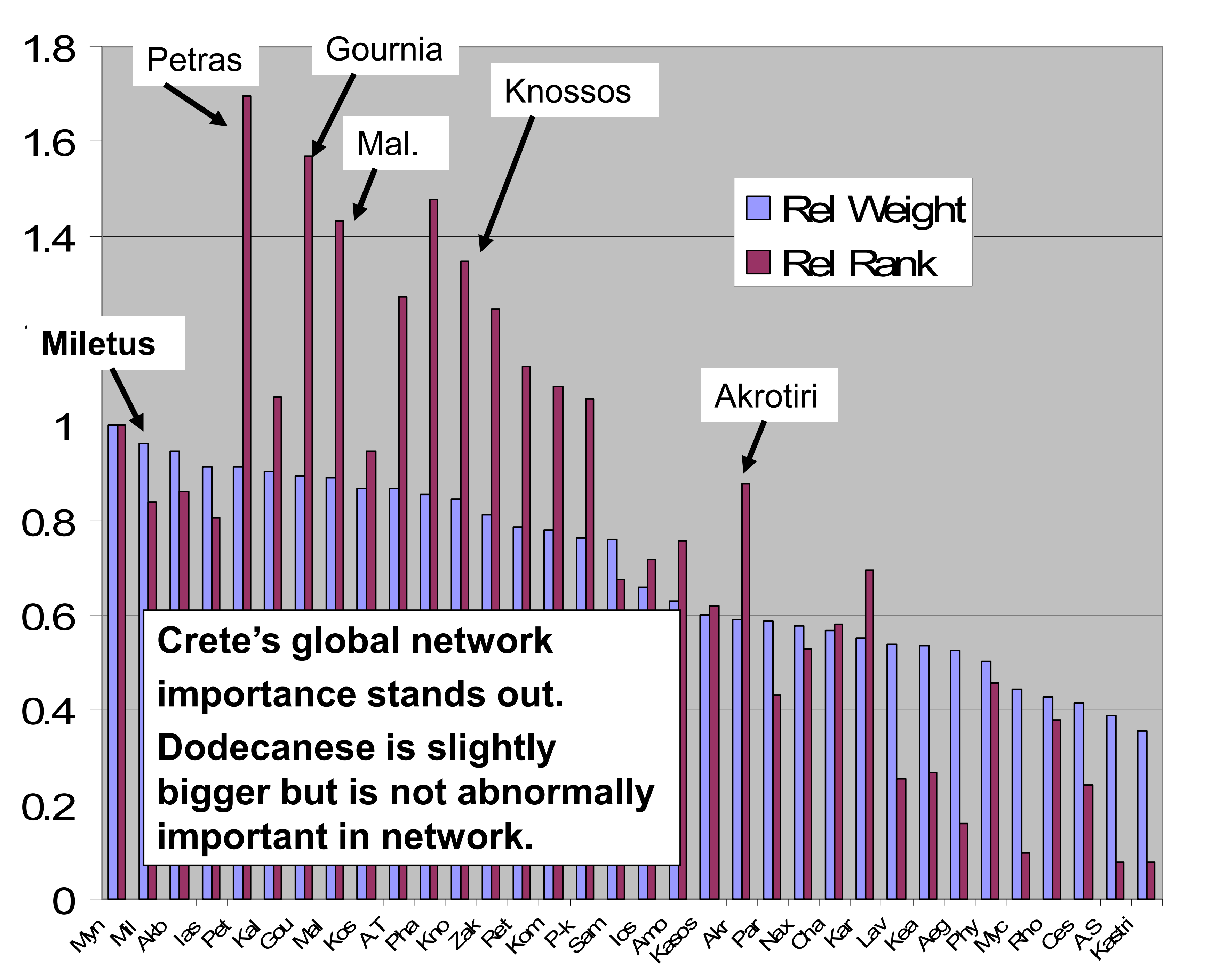
  $\Rightarrow$ **Measure of GLOBAL network properties**



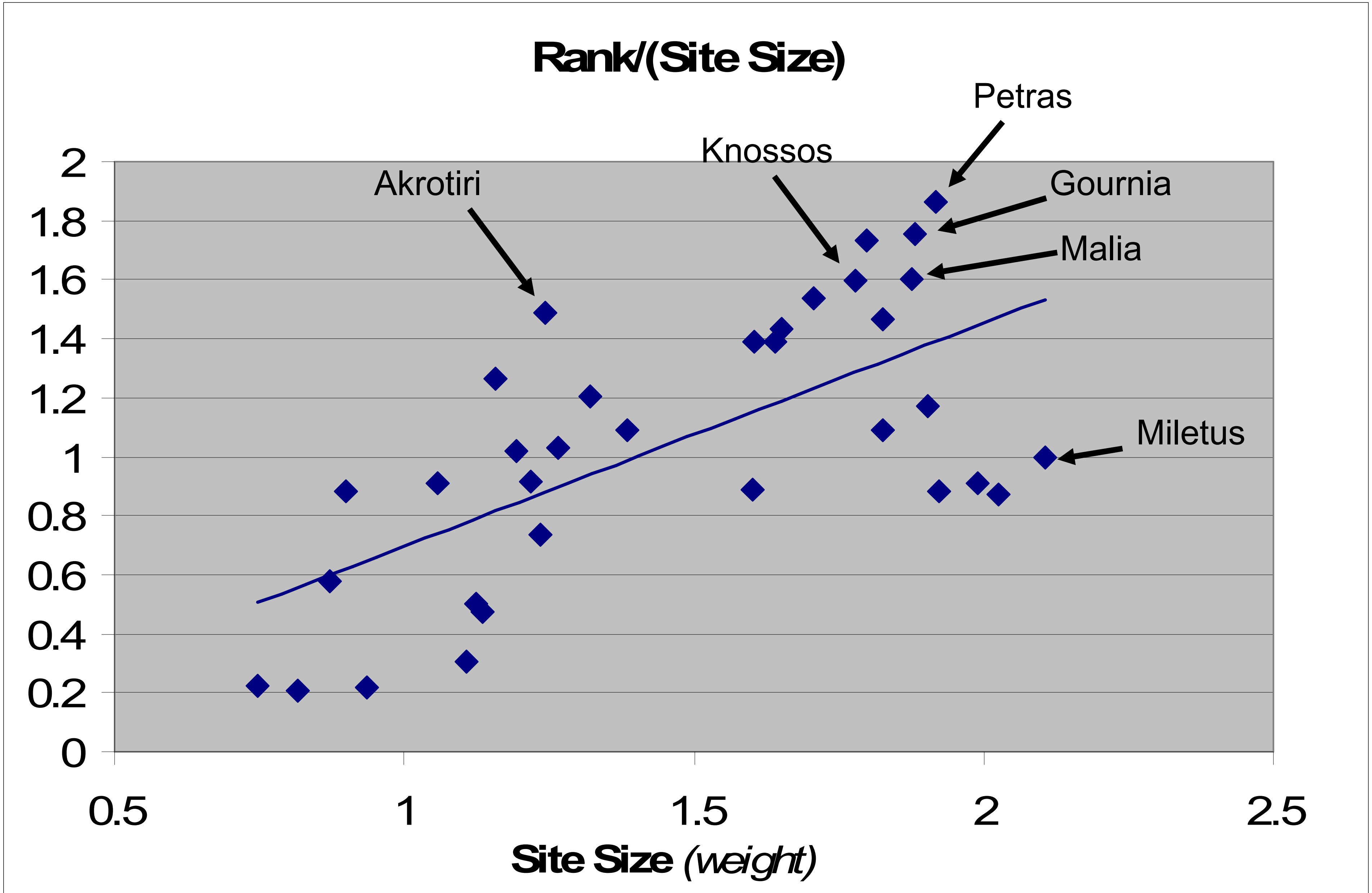
As used by Hage & Harary 1991, and Google UK

Influence – towards Minoanisation

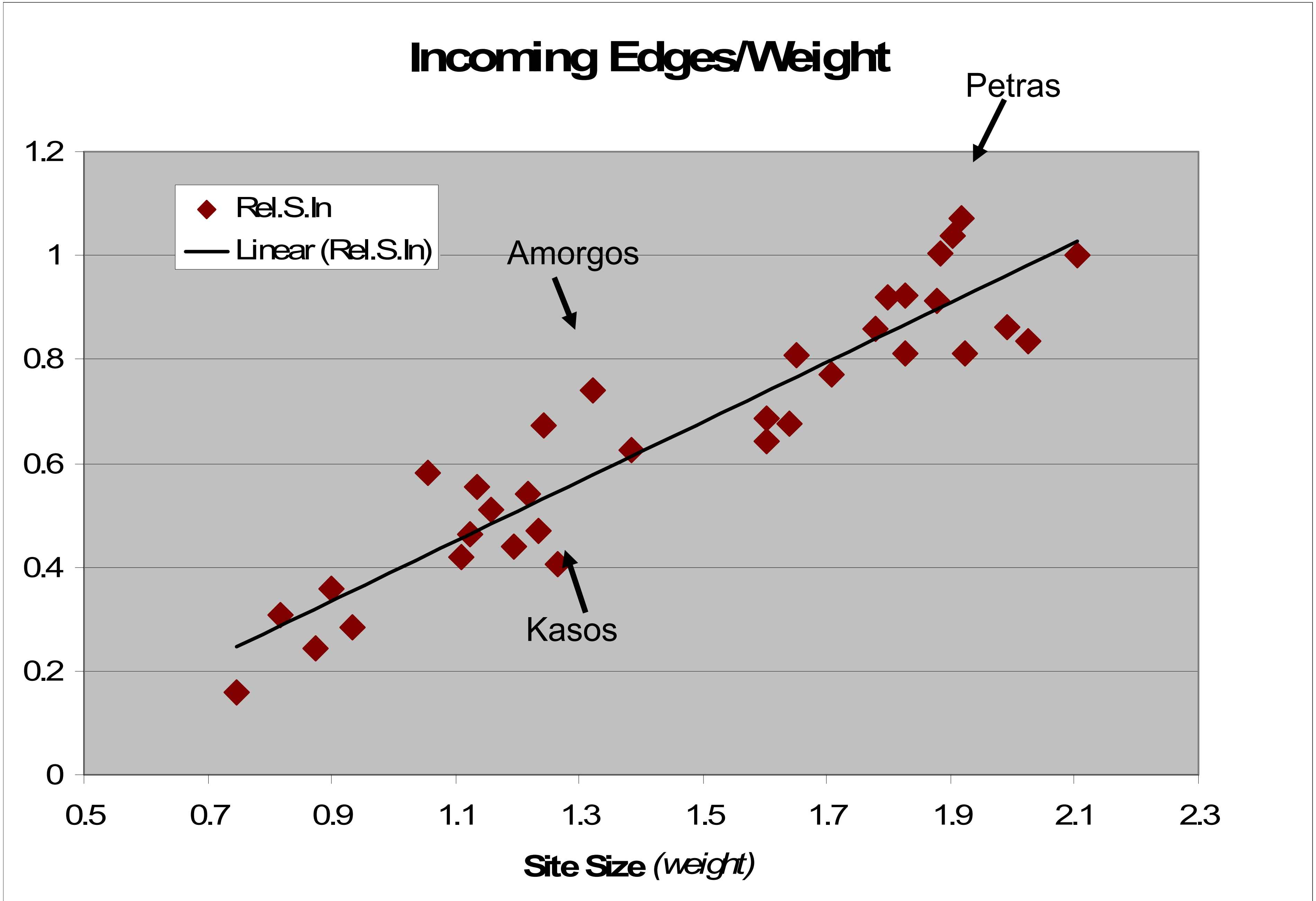
- Start walkers from one site i in proportion to its `population' $S_i v_i$.
- The stronger a link the more likely a walker is to follow that edge.
- After each step a fraction (say 25%) are killed off so on average they make limited number of steps (e.g. 3)
- Each time a walker arrives at a site j add its population $S_j v_j$ to the `influence' of site i.


1.8
1.6
1.4
1
0.8
0.6
0.4
0.2
0
Petras
Gournia
Mal.
Knossos
Miletus
Akrotiri
Rel Weight
Rel Rank
Crete's global network importance stands out. Dodecanese is slightly bigger but is not abnormally important in network.
Myn
Mil
Akb
Ias
Pet
Kal
Gou
Mal
Kos
A-T
Pha
Kno
Zak
Ret
Kom
P-k
Sam
Ios
Amo
Kasos
Akr
Par
Nax
Cha
Kar
Lav
Kea
Aeg
Phy
Myc
Rho
Ces
A-S
Kastri

Rank vs. Size shows Crete's is more important to the global network that its size suggests, not so for Dodecanese



Local properties often scale closely with site size (weight)

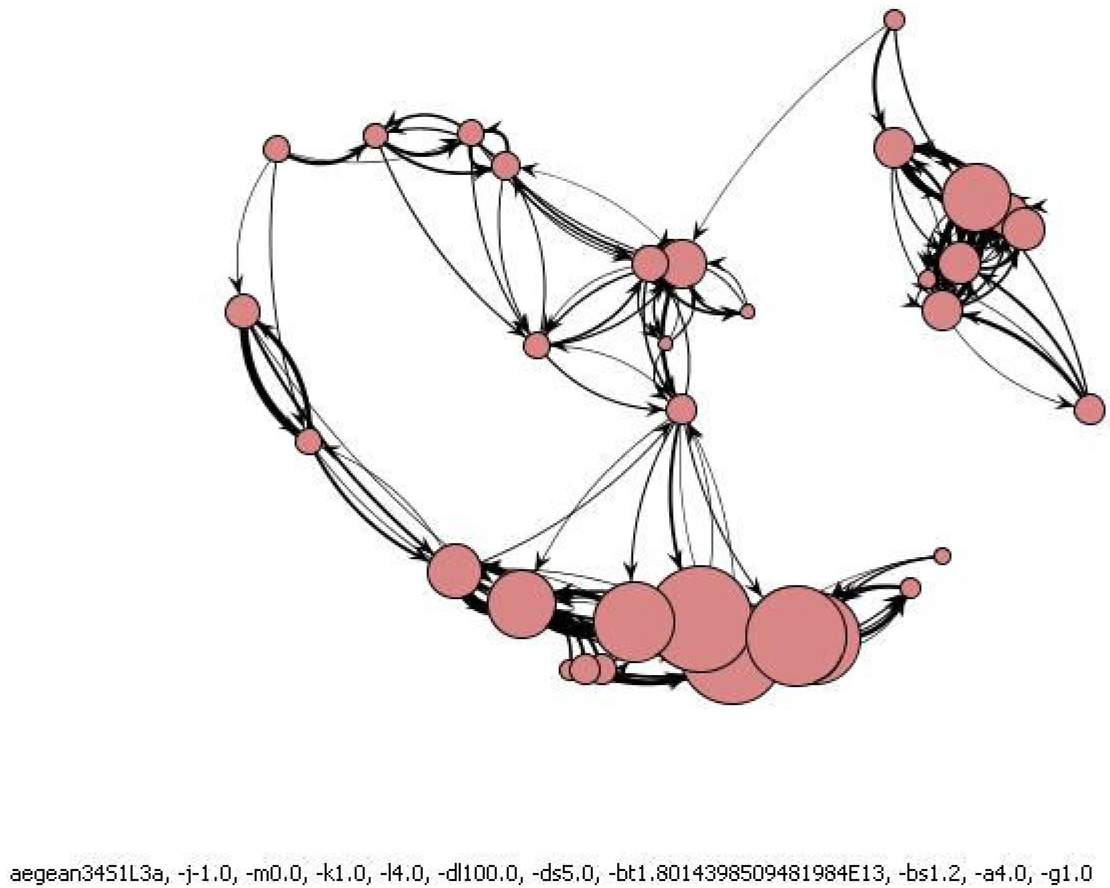


General analysis of our networks

- Big problem is that many measures of network properties are for unweighted graphs

- Fine for PPA, not for more realistic networks appropriate for more complex civilisations

Time Evolution

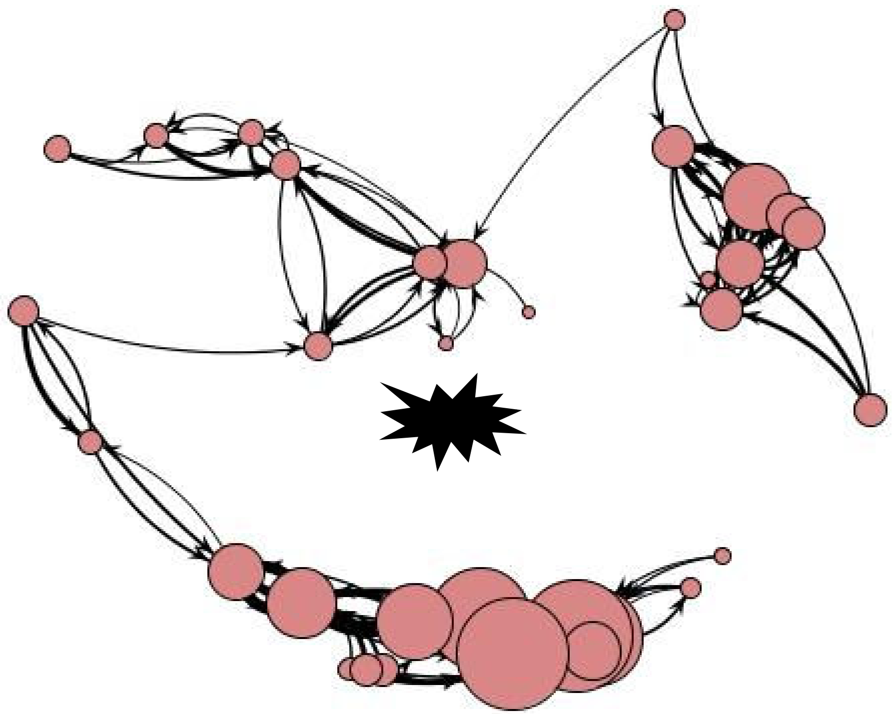


Before Eruption

$(j,\mu,\kappa,\lambda)=(-1,0,1,4)$
slider 5%
Just connected
1.07 (0.37-2.67) site weights

Time Evolution

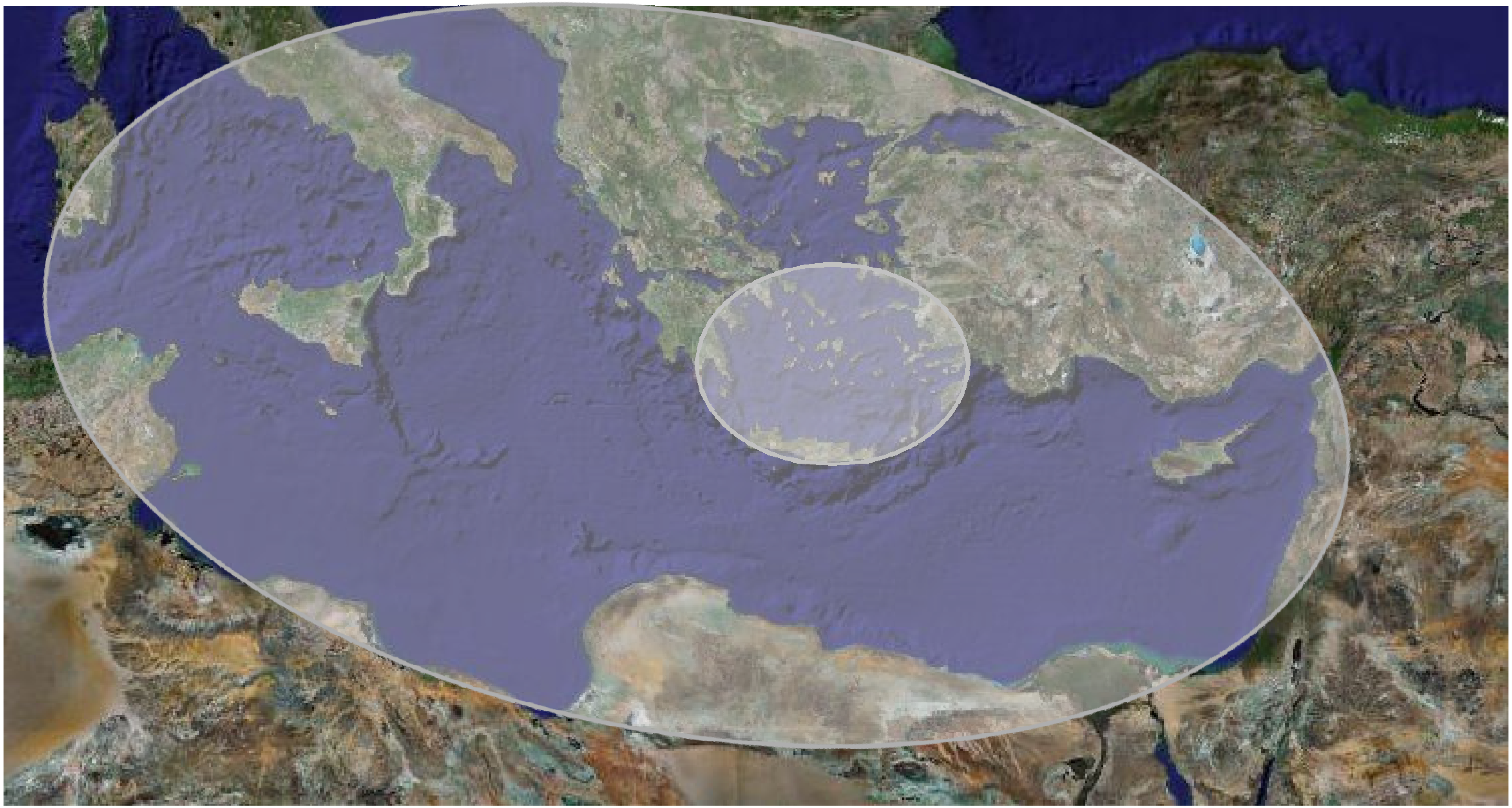
After Eruption



aegean33nTS1L3a, -j-1.0, -m0.0, -k1.0, -l4.0, -dl100.0, -ds5.0, -bt3.602879701896397E13, -bs1.2, -a4.0, -g1.0

$(j,\mu,\kappa,\lambda)=(-1,0,1,4)$
slider 8%
Just connected
1.07 (0.37-2.67) site weights

Future work …



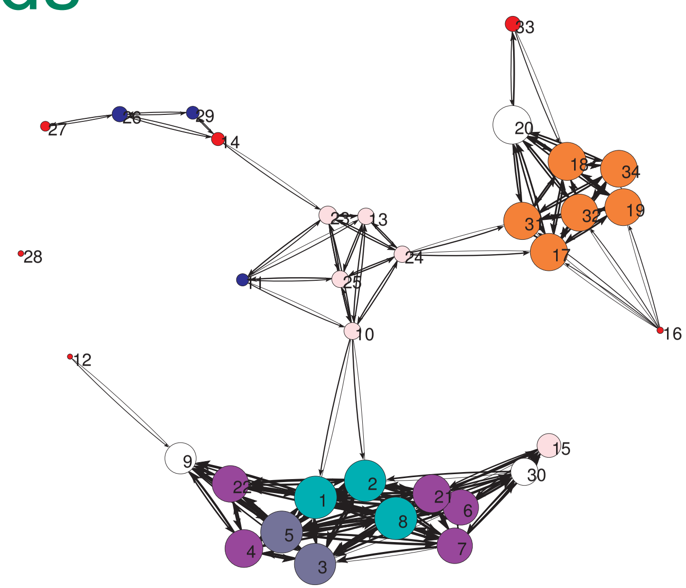
- **Extending spatial scale of networks**
- **Late Bronze Age 'international' trade and political collapse**

Conclusions

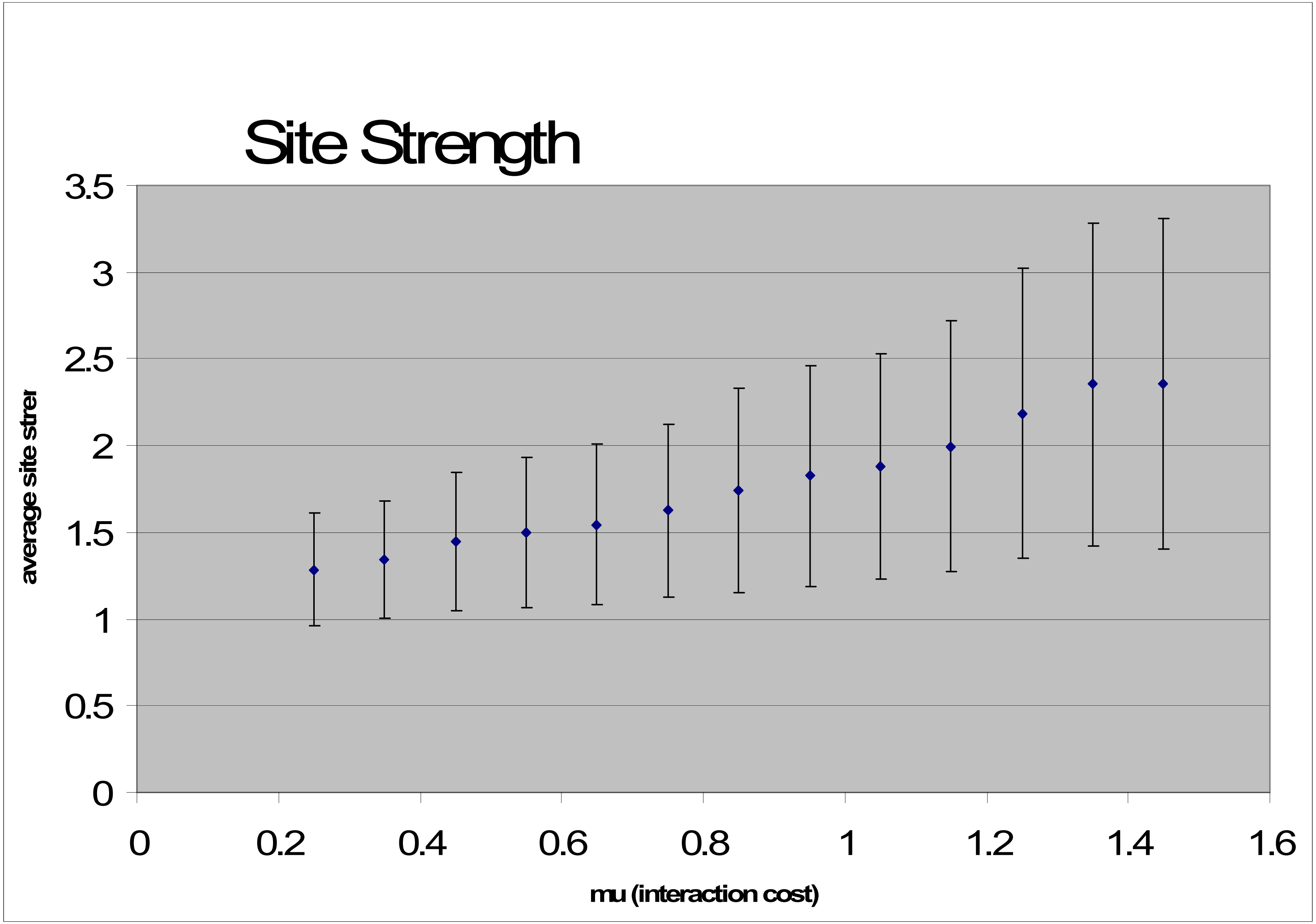
- Our model is stochastic going beyond earlier static network models
- Size of both edges and vertices of our network (small world or otherwise) emerges in response to cost function
- Physical substrate important but not overwhelmingly so
- Various *what if* scenarios can be modelled

End of Sequence

Minoanisation Analysis Methods



- **Diffusion**
  Use random walkers doing variable short range walks to assess how ideas can percolate through system.
- **Cultural Transmission**
  Use the networks produced here as substrate for well known models of cultural transmission (Bentley & Shennan 2003) and language transmission (Stauffer et al. 2006)
  - based on copying (drift) and innovation (mutation) processes


Site Strength
3.5
3
2.5
2
1.5
1
0.5
0
average site strer
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
mu (interaction cost)

- Archaeology and Physics
- Previous Models
  - Without networks
  - With Networks
- Our Model
  - The Middle Bronze Age Aegean and the Minoans
- Summary