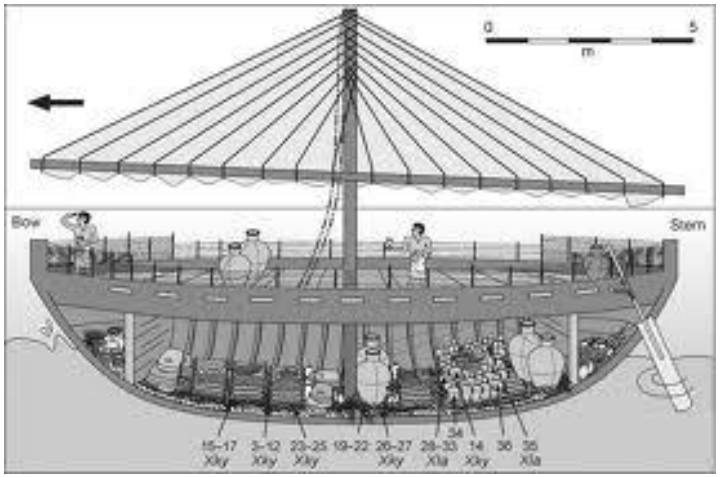
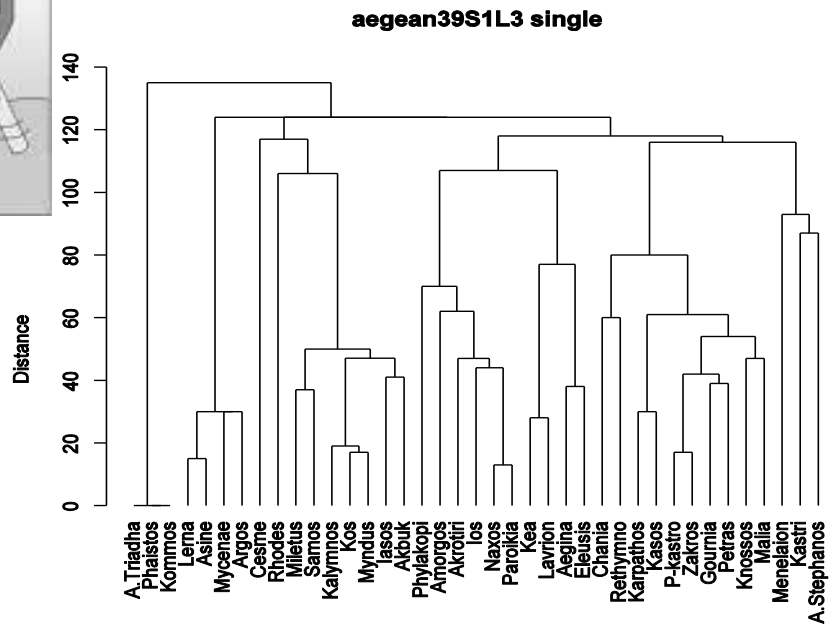
Imperial College London

How technology and geography influence network dynamics



Ray Rivers (Physics, Imperial College London)



Collaboration with

Tim Evans (Physics, IC)

Carl Knappett (Art, Toronto)

International Workshop ERC World Seastems,
16 June Paris 2014

Maritime Spatial Networks:

- Vertices/Nodes = Major Population or Resource Sites

- Edges/Links = Exchange between sites

  - physical trade of goods
  - soft power and hard power/social cohesion
  - transmission of culture

- Links controlled by physical limitations of sea travel -- 'Simple' Links

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- Links controlled by physical limitations of sea travel -- 'Simple' Links

  - very schematic overview
  - pictographic presentation

This talk: Bronze Age Mediterranean Networks

1. EBA Cyclades (3000 – 2000 BCE)
2. MBA Aegean (2000 – 1500 BCE)
3. LBA E. Mediterranean (1500 – 1000 BCE)

Only LBA has any relation to contemporary networks!

- Very different scales
- Very different maritime technologies

Networks too small (N < 80) for statistical analysis!

1. The EBA Cyclades (3000 – 2200 BCE)

‘Isolated’ with cultural continuity

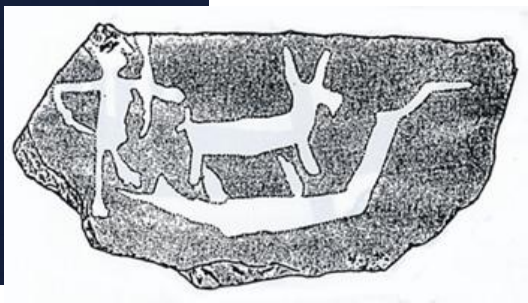
Many small habitable islands – ‘roughly homogeneous’

Agriculturally marginal

L ≈ 200km

Travel by

- canoe
- longboat



2. MBA Aegean (2000 – 1500 BCE)

– rise and fall of Minoan culture

a ‘heterogeneous’ whole

L ≈ 400km

Travel by:

- rigged sail
- oar

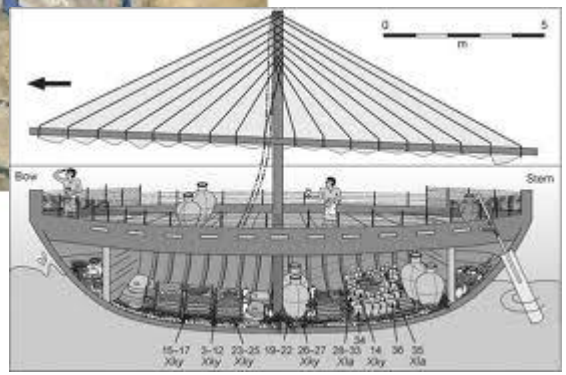
3. LBA E. Mediterranean (1500 -1000 BCE)

- totally inhomogeneous

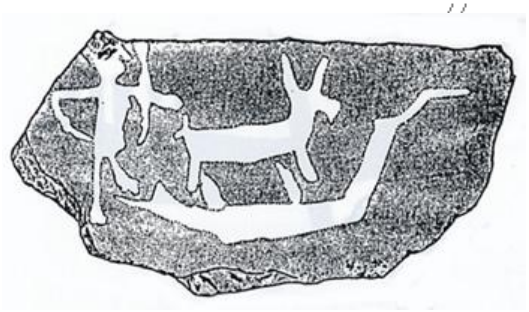
- Mycenean culture

L ≈ 2000km

Travel :
-rigged sail/oar
- tramping



Modelling Cycle



ARCHAEOLOGICAL DATA

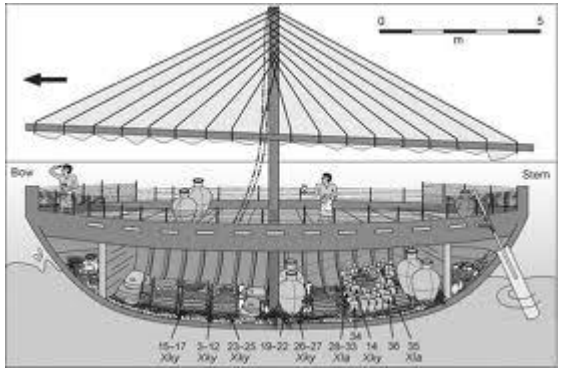
Set ‘geophysical’ input parameters

MODEL

Set ‘sociophysical’ input parameters

Consistency check

‘Predictions’

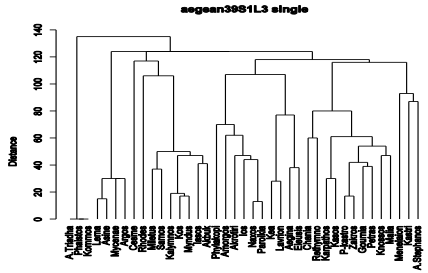



```
//      double [] [] distance  = new double [numberSites][num

        double DijkstraMaxDist;
      StatisticalQuantity siteDistanceStats;

      IslandCulture networkCulture;
      double culturePSiteCopy = 0.45;
      double culturePCopy =0.45;
      double culturePInnovate =0.05;
      double
      double influenceProb=0.5;

      // update records
      updateRecord edgeU = new updateRecord() ;
      updateRecord vertex R= new updateRecord() ;
      // General parameters
      TimMessage me
//infolevel=m ge.getInformationLevel();
      int updateMo
      int outputMode=255;
      double vertexMaximum;
//      double modelNumber;
      ModelNumber modelNumber;
//      int modelNumber.major;
//      int modelNumber.minor;
//      boolean modelNumber.bit0; // use these to record bits
//      boolean modelNumber.bit1;
//      boolean modelNumber.bit2;

      // Display factors
      double zeroColourFrac=0 3;
      double minColourFrac= 1;
      int siteWeightFacto = 20;
      int edgeWidthFact = 10;
      boolean newNetw xDisplaySyle = false;
      double DisplayMaxVertexScale=0.0; //<=0 then display ve
                                        // else display vertice
      double DisplayMaxEdgeScale=1.0;   //<=0 then display ed
                                        // else display edges r
      int DisplayVertexType=0; // 0=size, 1 = rank;
      int siteWindowMode=3; // 0=numerical, 1=size, 2=Rank, 3
```

Model:

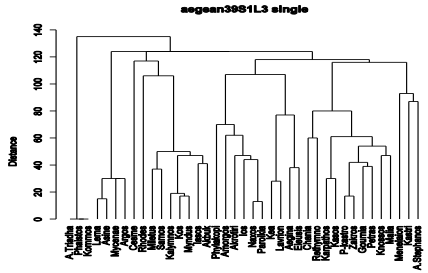
Model:

Settings



Model:

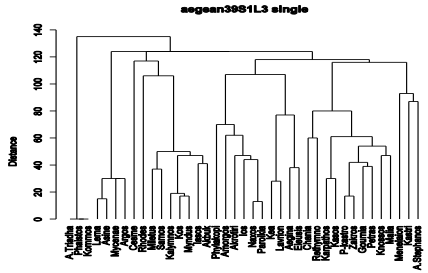
Settings



Variables

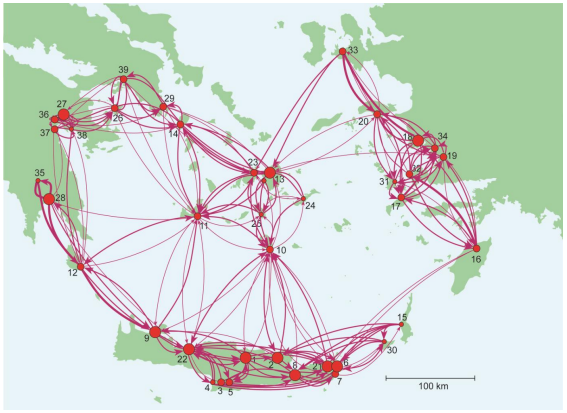
Model:

Settings



Variables

Output



Network distance scales:

1. **Settings:** Distance scale **S** for the network:

   - 'effective' distance you need to be able to travel to connect sites (not overall size **L**!)
   - essentially determined by 'geography'

2. **Variables:** Distance scale **D** for travel:

   - most simply (but not always) journey/journée
   - essentially determined by maritime 'technology'/techniques

3. **D/S** is a measure of the ease of establishing broad network

   D/S < 1; 'difficult'

   D/S > 1; 'easy'

   'ease of travel' ~ 'cost'

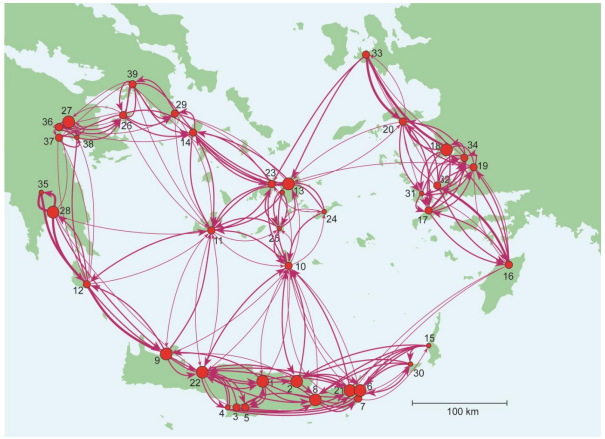
Output:

- ‘Exchange’: T_{ij}

Flattening of ‘exchange’ into a single measure

- Population (sometimes): P_i

- Centrality:



- ‘Betweenness’:

How to choose a model?

***ariadne suite*: Tim Evans**
http://figshare.com/articles/ariadne/97746

Optimisation: Assume networks are 'optimal' in some sense

Simple division:

- Most 'likely' models
- Most 'beneficial' models

‘Most likely’ models: ‘Maximum entropy’ $s = -\sum_{ij} T_{ij} \ln T_{ij}$

Basic idea: Identify most likely network commensurate with the limited knowledge that we possess (constrained entropy)

1. **Generalised gravity models (GGMs):** (*ariadne* acronyms)

- Simple Gravity Model (SGM/VP)
- Singly constrained Gravity model
- Doubly constrained gravity model (DCGM)

- Wilson ‘retail’ model (RW)

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- Wilson ‘retail’ model (RW)

The above are special cases of Alonso models (ALN)!

‘Most likely’ models:

2. Intermediate opportunity models (IOMs)

- PPA
- Directed PPA (DPPA)

- ‘Radiation’ model (RAD)

  Simini, Barabási *et al.*

- Other IOMs (Stouffer onwards) – not in *ariadne!*

Depend on distance rankings rather than distances themselves!

‘Most beneficial’ Networks:

‘Cost – benefit’ analysis (MC): $s = C(T_{ij}) - B(T_{ij})$

Some generalities but ultimately bespoke

- Considerable freedom in choosing ‘costs’ and ‘benefits’
- More like a construction kit than a black box!

‘Most beneficial’ Networks:

‘Cost – benefit’ analysis (MC): $s = C(T_{ij}) - B(T_{ij})$

Some generalities but ultimately bespoke

- Considerable freedom in choosing ‘costs’ and ‘benefits’
- More like a construction kit than a black box!

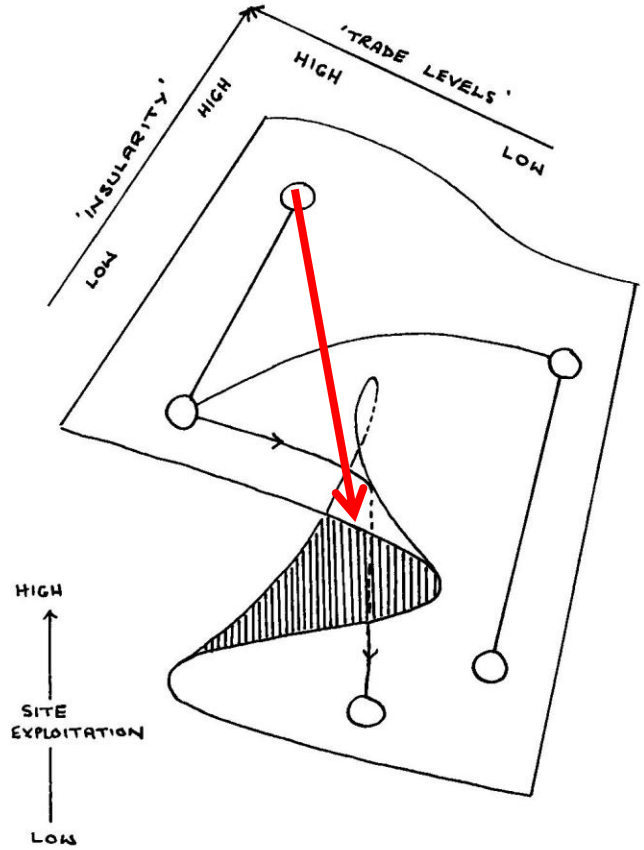
Aim:

Only use them in an environment that imposes structure

Our model is ‘ariadne’

becomes

when we have familiar catastrophe profile



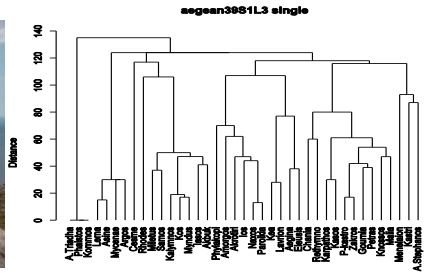
'Goldilocks' scenario:

Trading self-sufficiency against exchange

- not too 'cold'
- not too 'hot'
- 'just right'

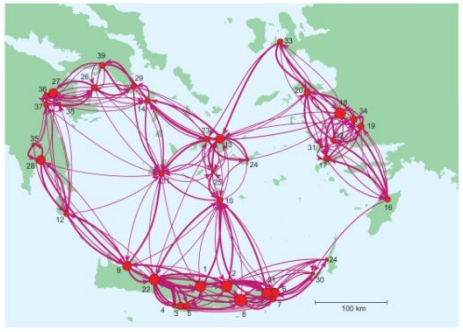
Treading the tightrope between 'boom' and 'bust'

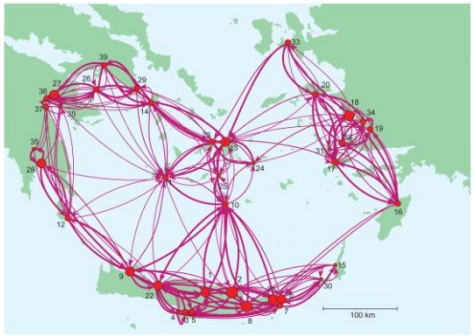
MBA Aegean: ***ariadne***



Model aims for ‘best’

Settles for the ‘good’



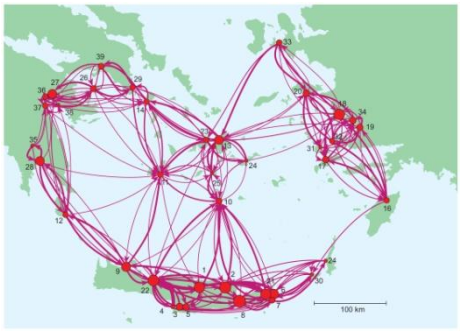
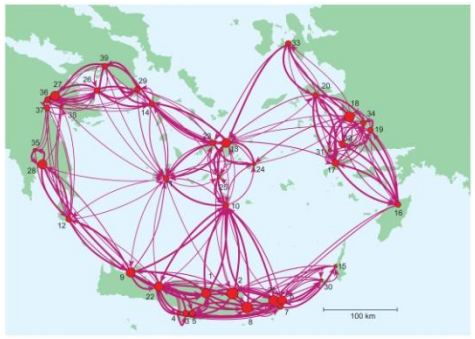


Bounded rationality

Contingency?

Question: How do we measure contingency?

Average?

$$\frac{1}{2}\left[\;\text{  }\;+\;\text{  }\;\right]\;?$$

Answer: **No!**

- If variation low, use discrete differences
- If variation high, model is useless!

Key point:

- GGMs and IOMs insensitive to D (except for SGM)

  - emphasise ‘social space’ enforcing connections physically difficult to achieve

- *ariadne* sensitive to D

  - sensitive to maritime technology

Very few variables!

- Don’t expect too much
  - very broadbrush!

or

- Delicate task of coarse-graining data

Very few variables!

- Don't expect too much

  - very broadbrush!

or

- Delicate task of coarse-graining data

E.g.

data

cf.

model

'Good' fit with little coarse-graining!

Very few variables!

- Don't expect too much
  - very broadbrush!

or

- Delicate task of coarse-graining data

However

data

cf.

model

'Bad' fit however much coarse-graining we adopt!

Very few variables!

- Don't expect too much
  - very broadbrush!

or

- Delicate task of coarse-graining data

- In practice, BA data is poor
  - very incomplete
  - it relies on material objects  as proxies for 'exchange'
  - very qualitative
  - makes coarse-graining easier!

Bronze Age Mediterranean Maritime Networks

1. EBA Cyclades (3000 – 2000 BCE)

2. MBA Aegean (2000 – 1500 BCE)

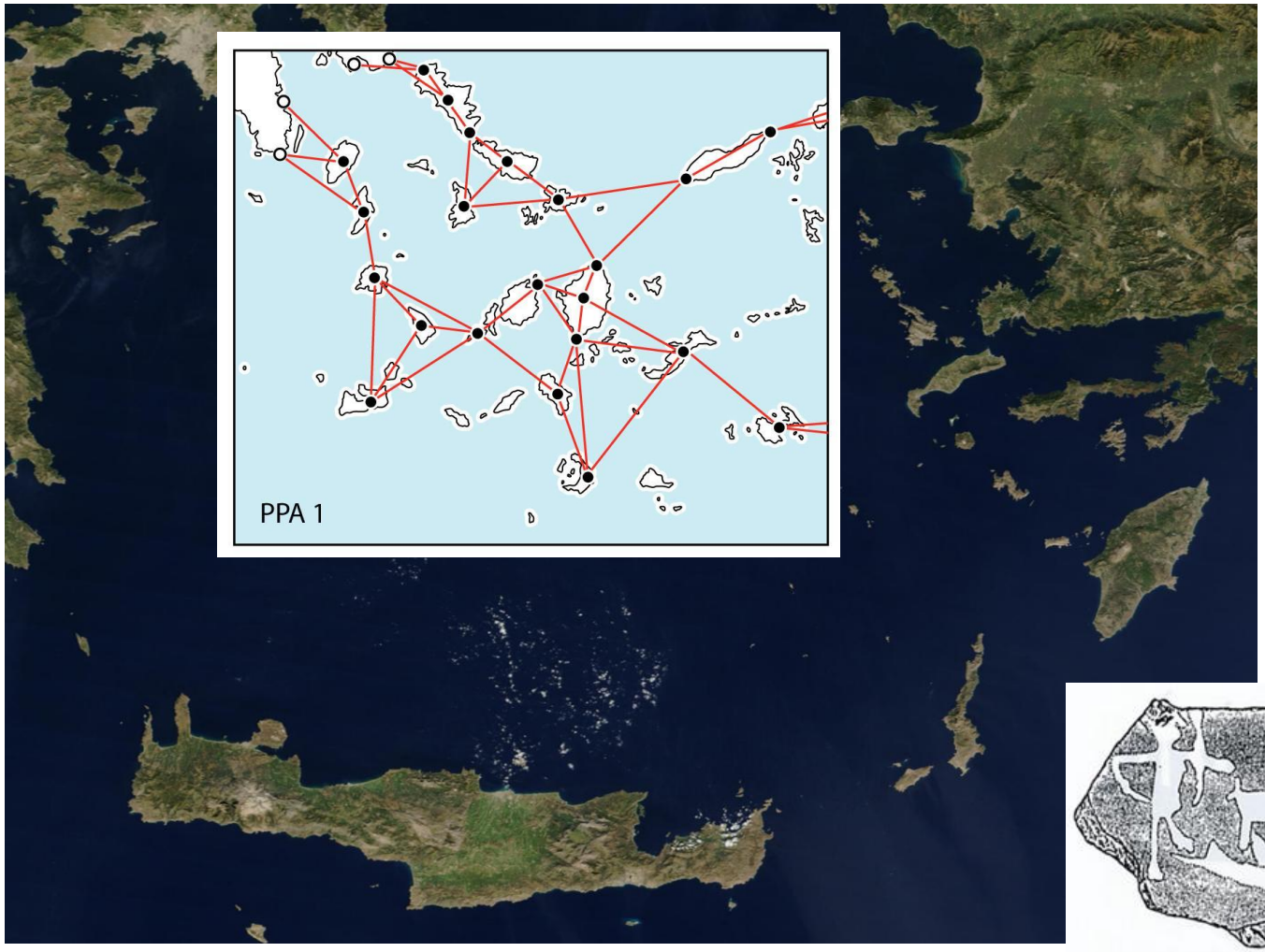
3. LBA E. Mediterranean (1500 – 1000 BCE)

1. The EBA Cyclades (3000 – 2200 BCE)

'Isolated' with cultural continuity

Many small habitable islands – 'roughly homogeneous'

L ≈ 200km



S: network 'distance scale'

S ≈ 40 - 55km

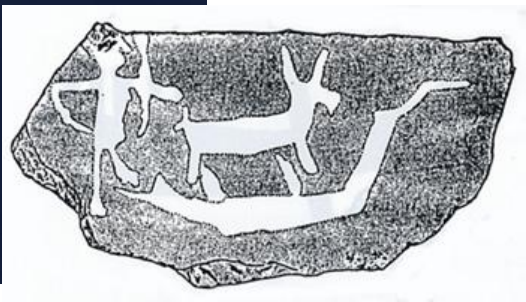
D: journey = journée

D ≈ 20km canoe

D ≈ 40-50km longboat - elite

Key point:

D < S or D ≈ S!

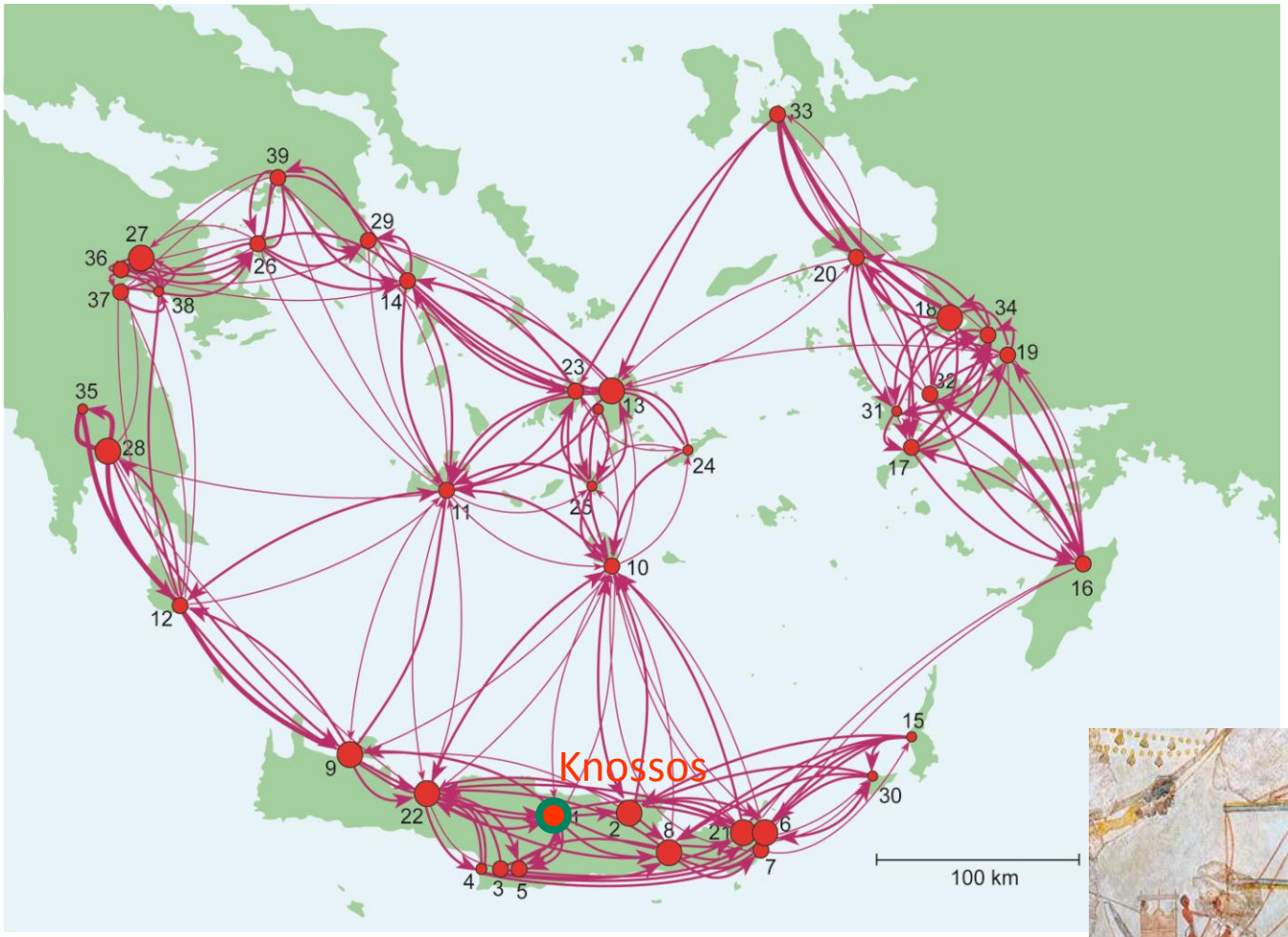


2. MBA Aegean (2000 – 1500 BCE)

- a ‘heterogeneous’ whole

a ‘heterogeneous’ whole

L ≈ 400km



S: ‘distance scale for network’

S ≈ 100km

D: journey = journée

D ≈ 100km

Key point:

D ≈ S !

Travel : Oar is supplemented or replaced by sail

3. LBA E. Mediterranean (1500 -1000) BC

- Mycenean culture

- totally inhomogeneous

L ≈ 2000km

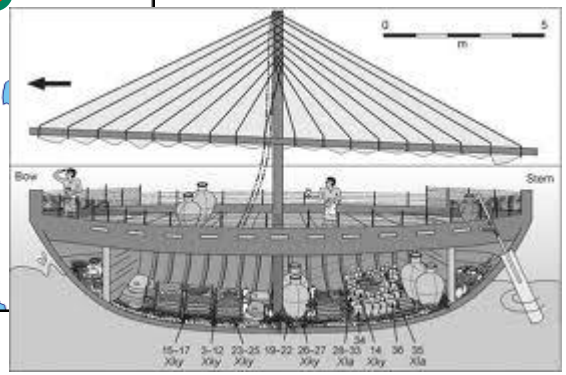
S: distance scale

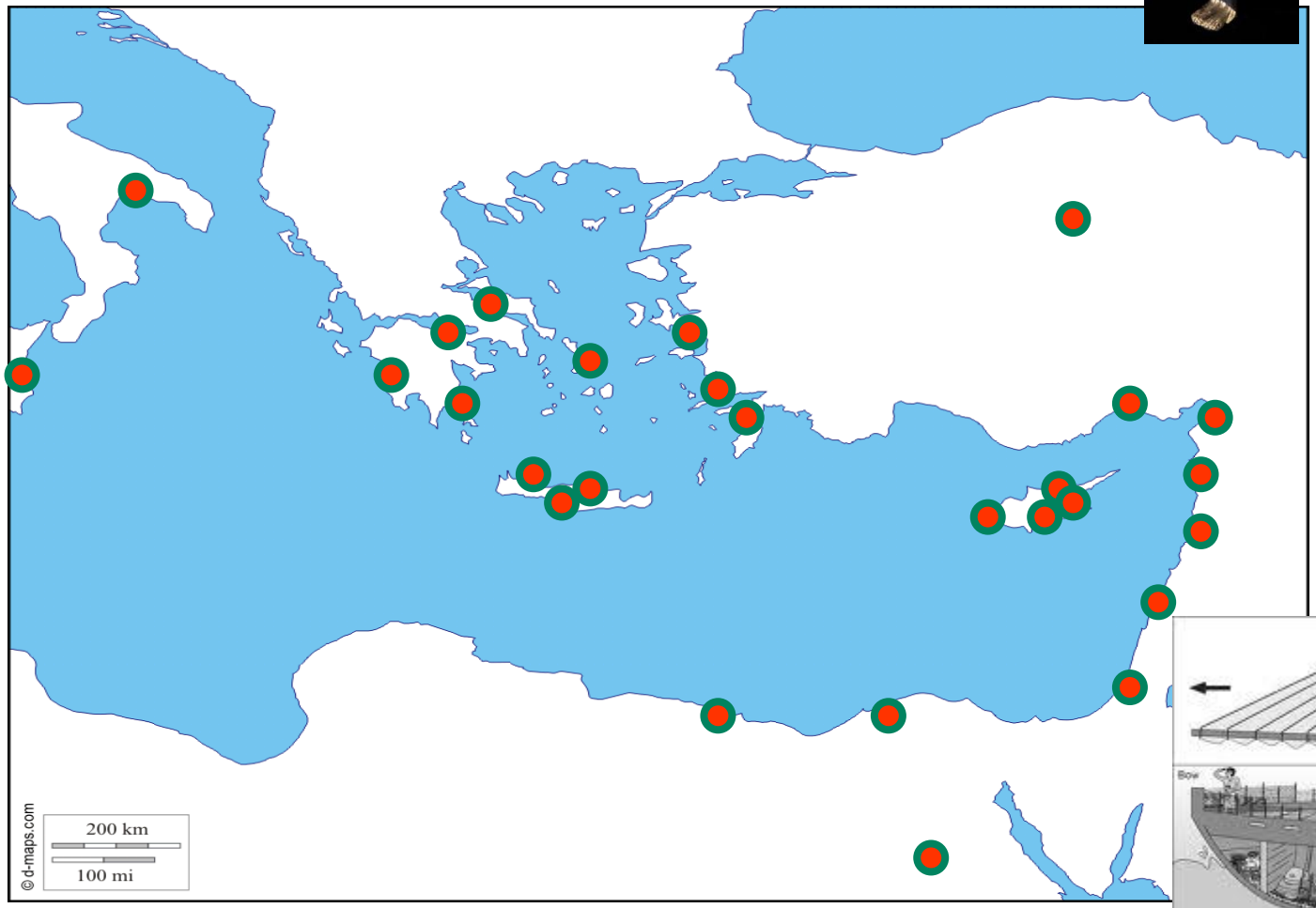
S ≈ 200 - 400km

journée ≈ 100km

D = journey > journée

D ≥ S





Travel : - sail/oar

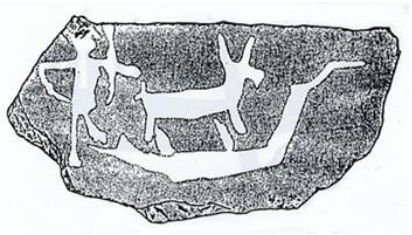
- better rigging
- variety of vessel types

Estimated journey of Uluburan ship (end of 14th C BCE) before wrecking

Summary: Three phases of BA network connectivity

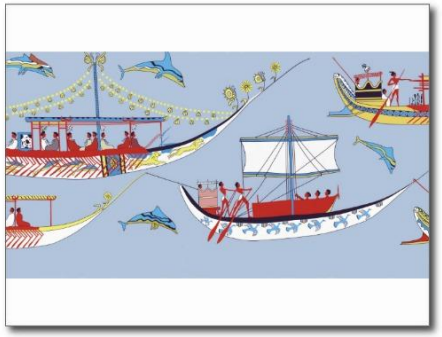
EBA: D < S or D ≈ S ≈ 50km

Small (L ≈ 200km) Cyclades network just achievable by rowing technology - but requires elite exchange



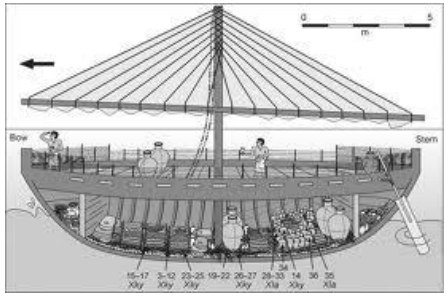
MBA: D ≈ S ≈ 100km

For the first time in the BA, mass technology is good enough to enable a fully connected Aegean-wide exchange network (L ≈ 400km) to form - does not require elite exchange to exist



LBA: D ≥ S ≈ 200-400km

Improved rigging and social organisation makes longer journeys possible with tramping in large (L ≈ 2000km) network



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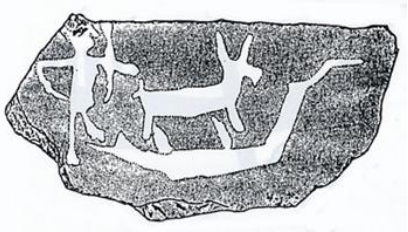

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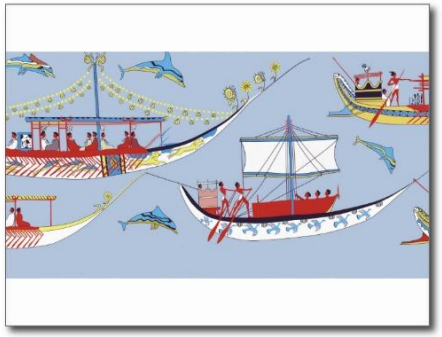

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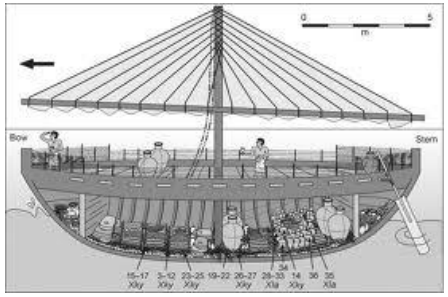


Still an embarrassment of choice!

Constrain models to match network temporal evolution over relevant era.

MBA Aegean (D ≈ S): Most straightforward!

Extreme event:

Eruption of Thera!

Network rearranges and thrives!

Tactics:

1. See which models describe the pre-eruption pattern of exchange?

2. Do surviving models help us understand the survival of the network?

- anticipate strong sensitivity to D!

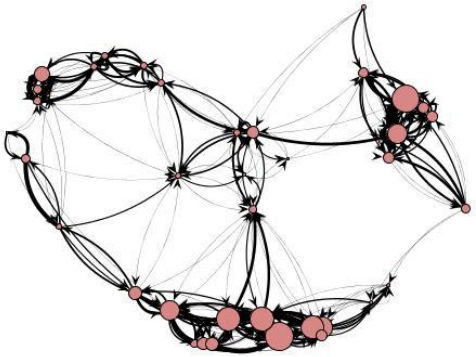
Pre-eruption:

SGM and *ariadne* survive

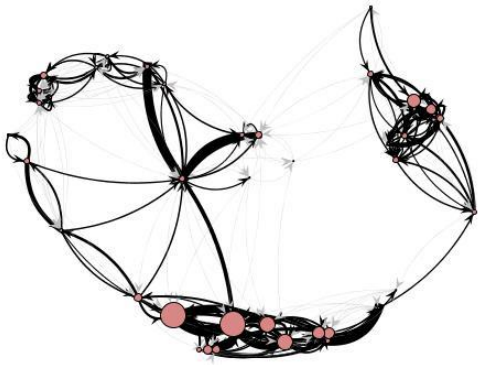
Post-eruption:

- SGM: No rearrangement – just deletion!
- Ariadne (cost-benefit)

Pre-eruption:



Post-eruption



EBA Cyclades (D ≤ S):

Continuous evolution

Question:

What determines a site's 'importance' as populations grow?

Some sites with very poor natural resources show high levels of activity e.g. obsidian

Key sites!

Grotta-Aplomata
Daskaleio-Kavos
Skarkos
Chalandriani
Ayia Irini

Not all 'central' sites!

Associated with elite exchange!

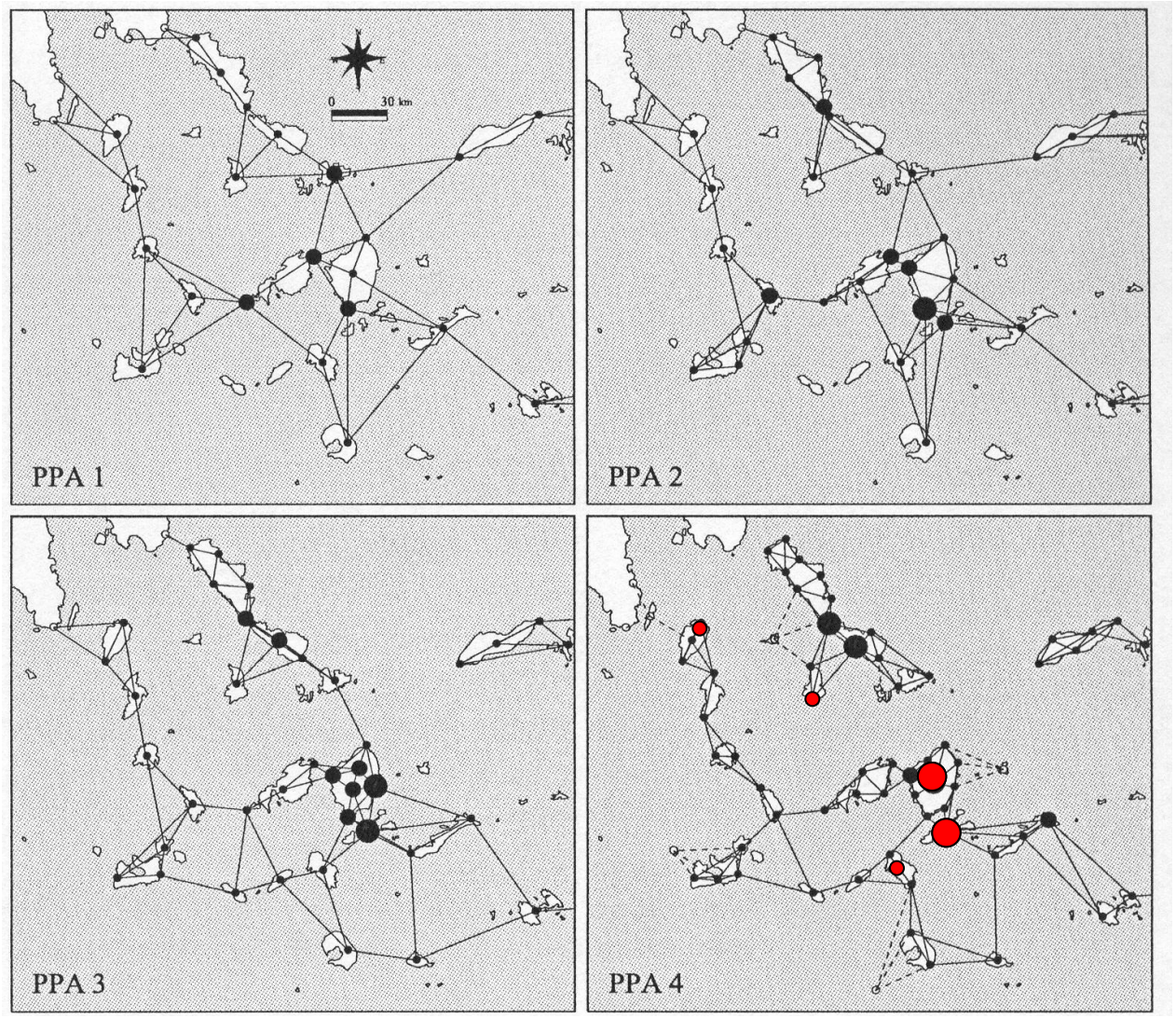
EBA Cyclades: Evolution = Continuous growth in number of sites

Sites equal: # increases

Null models:

- PPA (Broodbank 2000)
- SGM

- PPA too insensitive to D/S !
- SGM too sensitive to D/S !



Size of 'blob' = level of activity – not 'population'

EBA Cyclades:

Possible solution:

Twin-track exchange:

- **Short journeys (≤ 20km):**

  geography v. important.

  network disconnected!

  - ariadne

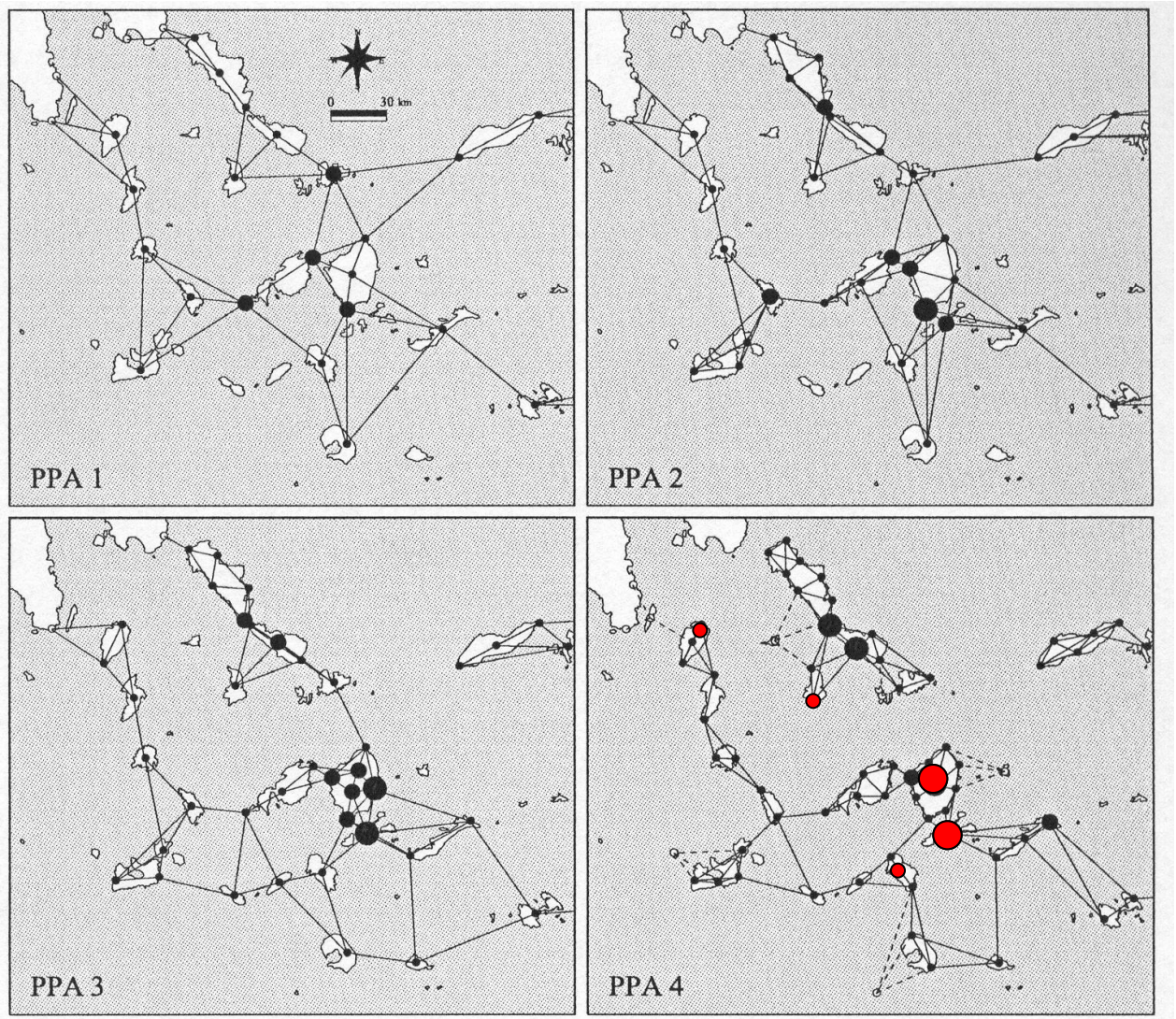


Fig. 75 Nodes of intense communication in the Cyclades as modelled by PPAs 1–4 (five and six linkages only).

EBA Cyclades:

Possible solution:

Twin-track exchange:

- **Long journeys (≥ 30km):**

-'retail model'

Although **D ≈ S** geography less important because of elite exchange

Need better data!

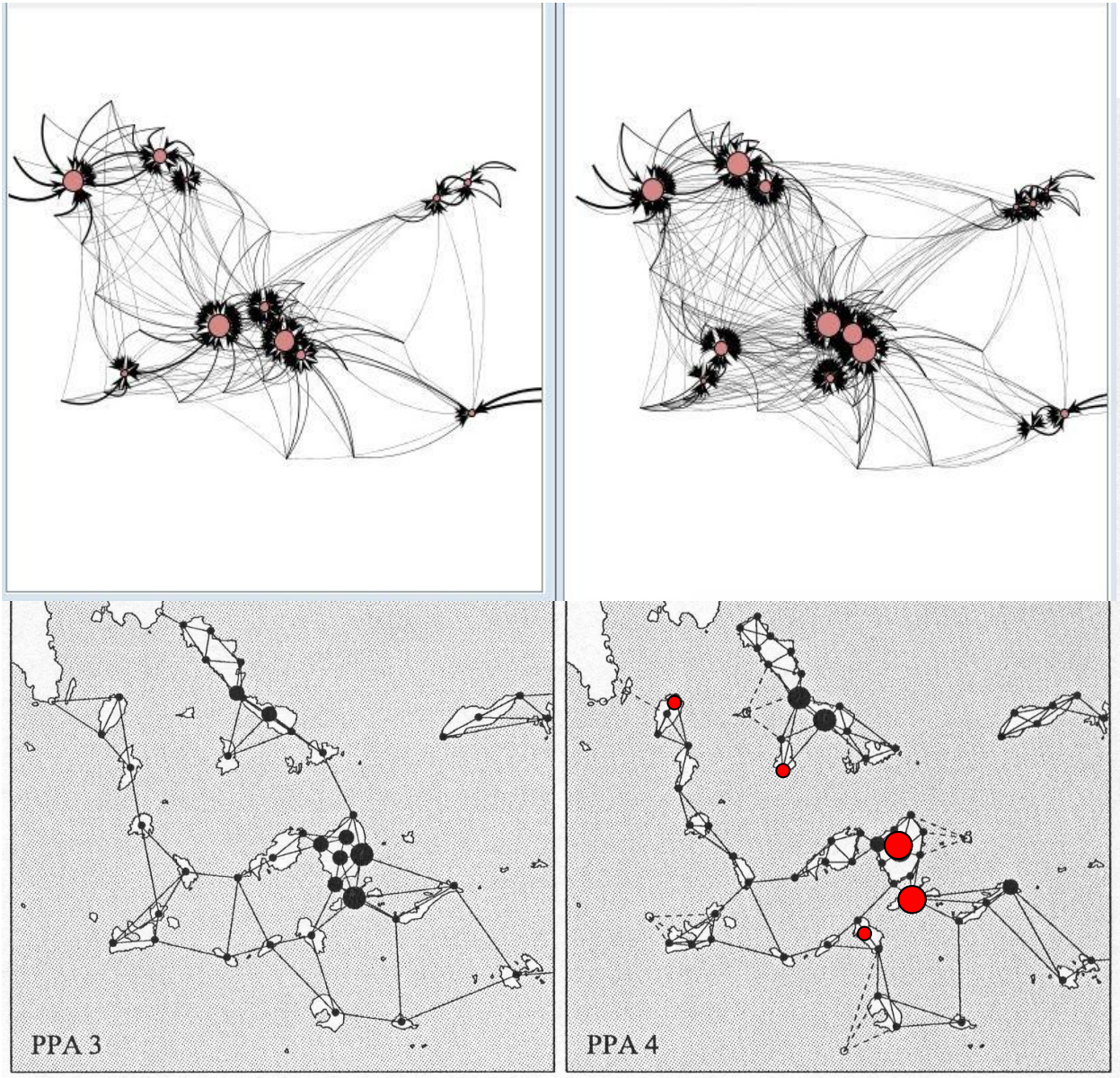
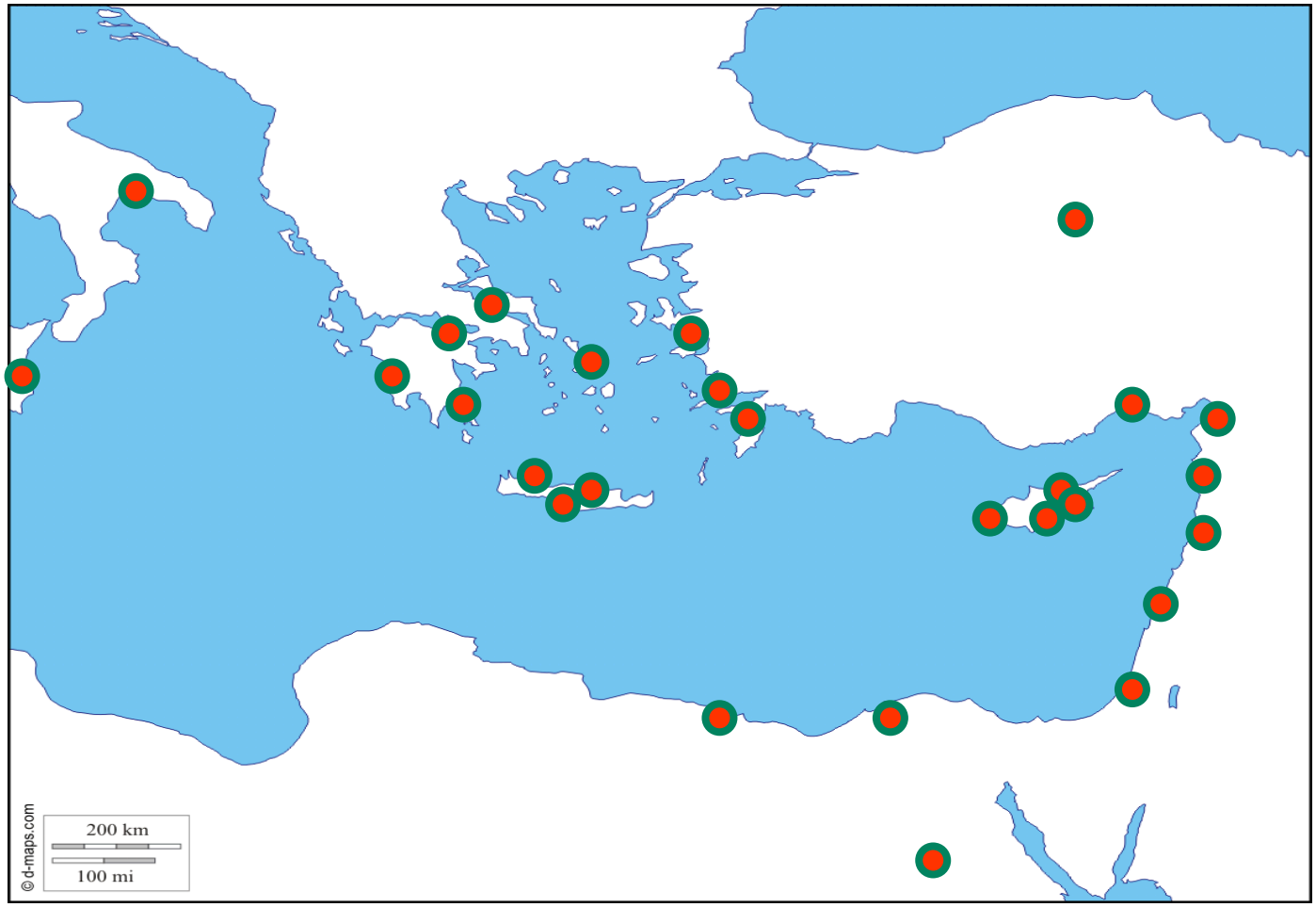


Fig. 75 Nodes of intense communication in the Cyclades as modelled by PPAs 1–4 (five and six linkages only).

LBA E. Mediterranean

- Mycenean culture



D ≥ S

'Geography' not important

Only IOMs begin to work

Preliminary conclusions:

Crudely,

- ‘geography’ sets network distance scale S
- ‘technology’ sets the travel distance scale D

Different periods require different approaches according to the values of D/S

- **EBA: $D \leq S$**
  short distance exchange unclear, Wilson ‘retail’ model longer distances

- **MBA: $D \approx S$**
  cost-benefit (*ariadne*) throughout

- **LBA: $D \geq S$**
  intermediate opportunities model throughout (’radiation’ model ?)

Need better understanding of data, better data!

Thank you!

r.rivers@imperial.ac.uk

References:

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Appendix A: Glossary of models:

1. Generalised gravity models (GGMs):

Simple gravity model (SGM):

- O_i = *outflow from i*
- I_j = *inflow to j*
- f_{ij} = *deterrence function from i to j e.g.* $f_{ij} = V(d_{ij}/D)$
- S_i = *population of i*

'physical parameter: D

$$T_{ij} = A_i O_i B_j I_j f_{ij}$$

No constraints: typically take $A_i O_i \equiv S_i$, $B_j I_{ij} \equiv S_j$

Appendix A: Glossary of models:

1. Generalised gravity models (GGMs):

Doubly constrained gravity model (DCGM):

- O_i = *outflow from i (now given as input)*
- I_j = *inflow to j (now given as input)*
- f_{ij} = *deterrence function from i to j e.g.* $f_{ij} = V(d_{ij}/D)$

'physical parameter: D

As before $\boldsymbol{T_{ij} = A_i O_i B_j I_j f_{ij}}$

Fixing $\boldsymbol{\sum_j T_{ij} = O_i}$, $\boldsymbol{\sum_i T_{ij} = I_j}$

constrains A_i B_j by self-consistent equations

$$\boldsymbol{(A_i)^{-1} = \sum_j B_j I_j f_{ij} \qquad (B_j)^{-1} = \sum_i A_i O_i I_j f_{ij}}$$

Appendix A: Glossary of models:

1. Generalised gravity models (GGMs):

Wilson 'retail' model (RWGM):

- O_i = *outflow from i (now given as input)*
- I_j = *inflow to j (now determined as output)*
- f_{ij} = *deterrence function from i to j e.g.* $f_{ij} = V(d_{ij}/D)$
- Υ = *'attractiveness' coefficient (given as input)*

'physical parameters: D and Υ

Now $T_{ij} = A_i O_i (I_j)^{\Upsilon} f_{ij}$

Fixing $\sum_j T_{ij} = O_i$, $\sum_i T_{ij} = I_j$

constrains A_i B_j by self-consistent equations

$$(A_i)^{-1} = \sum_j (I_j)^{\Upsilon} f_{ij} \qquad I_j = \sum_i A_i O_i (I_j)^{\Upsilon} f_{ij}$$

Appendix A: Glossary of models:

2. Intervening opportunity models (IOMs):

Simplest IOM:

- S_i = *population of i*
- S_{ij} = *population/resources between i and j as measured by 'effective' distance without including resources of i and j themselves*

  - # of intervening opportunities

'physical parameter: ranking scale

- f_{ij} = *site ranking deterrence function from i to j e.g.* $f_{ij} = V(S_{ij})$

$$T_{ij} = S_i S_j f_{ij}$$

No constraints as it stands but can be imposed as before:

PPA: $S_i = S_j = 1$

$f_{ij} = 1$, $S_{ij} = 1,2,...k$

$f_{ij} = 0$, otherwise

Appendix A: Glossary of models:

2. Intervening opportunity models (IOMs):

Simini Barabasi 'radiation' model (simplest form)

- S_i = *population of i*
- S_{ij} = *population/resources between i and j as measured by 'effective' distance without including resources of i and j themselves*

- # of intervening opportunities

$$T_{ij} = \frac{S_i S_j}{(S_i + S_{ij})(S_i + S_j + S_{ij})}$$

Appendix A: Glossary of models:

3. Cost benefit model: *ariadne*

Input parameters:

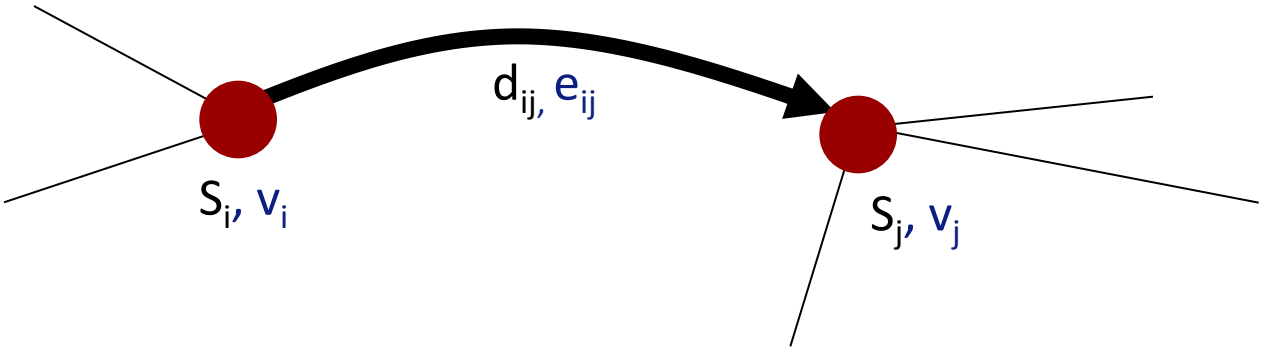
- d_{ij} : fixed distance between sites
  - may be physical but may include penalties for land travel etc.
- S_i : fixed site size = maximum local resources

Output parameters:

- v_i : variable site occupation fraction - if $v_i > 1$ then site needs external resources
- Site **Weight** ($S_i v_i$) = Site `*population*'
- e_{ij} : fractional Edge values $0 \leq e_{ij} \leq 1$
- Edge **Weights** ($S_i v_i e_{ij}$) = '*Trade*' (interaction) going from site i to site j

ariadne: description of networks:

- Site Strength = Σ_j (S_i v_i e_{ij}) = Total Trade Going Out



We find the values of site occupation (v_i) and trade levels (e_{ij}) that give us the most efficient use of resources (lowest energy) for given input of site size (S_i) and distances (d_{ij})

ariadne: Optimisation of 'social potential' ('Hamiltonian')

`Energy', resources

Isolated sites have optimal size $v_i = 0.5$

Trade (interactions) bring benefits

Increasing 'population' has a cost

Each trade link has a cost

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

Appendix B: Contingency

Optimisation:

Simple division has a thermodynamical analogy:

- Most ‘likely’ networks (microcanonical – specify states)
- Most ‘beneficial’ networks (macrocanonical – specify averages)

Relevant for describing ‘contingency’

Appendix B: Contingency - stochastic outcomes:

Q. When is ‘good’ good enough?

Look for the ‘best’ – be satisfied with the ‘good’

- ‘Satisficing’ strategy
- Bounded rationality
- Stochastically Panglossian

Contingency:

Q. How susceptible are outcomes to equally good alternatives?

Appendix B: Contingency – the 'social 'landscape':

Optimisation ≡ minimising 'social potential'

Each point on landscape corresponds to a network: look for 'lowest' point

Contingency:

What penalties are incurred by making different choices!

- 'Swiss valley' landscape

  - high penalties in crossing from one 'valley' to the next
  - low contingency

- 'American mid-west' landscape

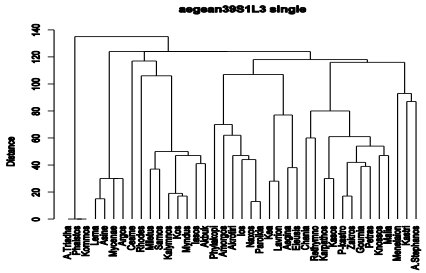
  - low penalties in roaming landscape
  - high contingency

Appendix C: How universal is a network exchange model?

How would we know that our output is not equally acceptable as a contemporary exchange network?

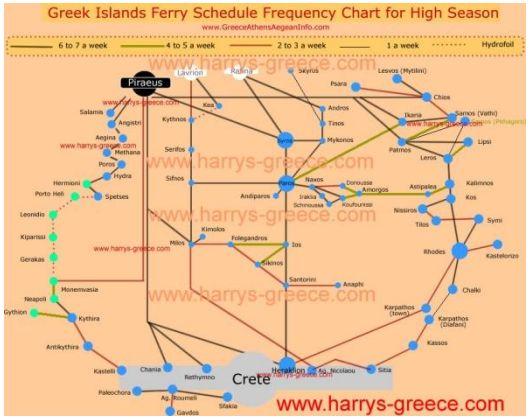
E.g 21C Aegean:

Settings



Variables

Output



Is this the new processualism?

Answer: Not simply!

- Different types of socio/geophysical data (e.g. D/S) require different models!
- Different models have different agency

Appendix D: MBA Model selection pre-eruption

Model	Sensitivity to D*	Directed	Weak links	Minoan
Standard Gravity model: D (NULL)	✓	×	✓	✓ Hi-B, Hi-W
Singly constrained gravity model: D	⁉	✓	✓	⁉ Hi-B, Lo-W
Doubly constrained (transport) gravity model: D	×	✓	✓	× Hi-B, Lo-W
Retail (Rihll & Wilson) gravity model: D + 'attraction'	×	✓ ×**	✓	× Lo-B, Lo-W
PPA (k=4) (NULL)	× ×	×	×	✓×***
Directed PPA (k=4)	××	✓	×	✓× ***
Ariadne : D + local resources + pop./network costs	✓	✓	✓	✓