

Networks for the Minoan Aegean

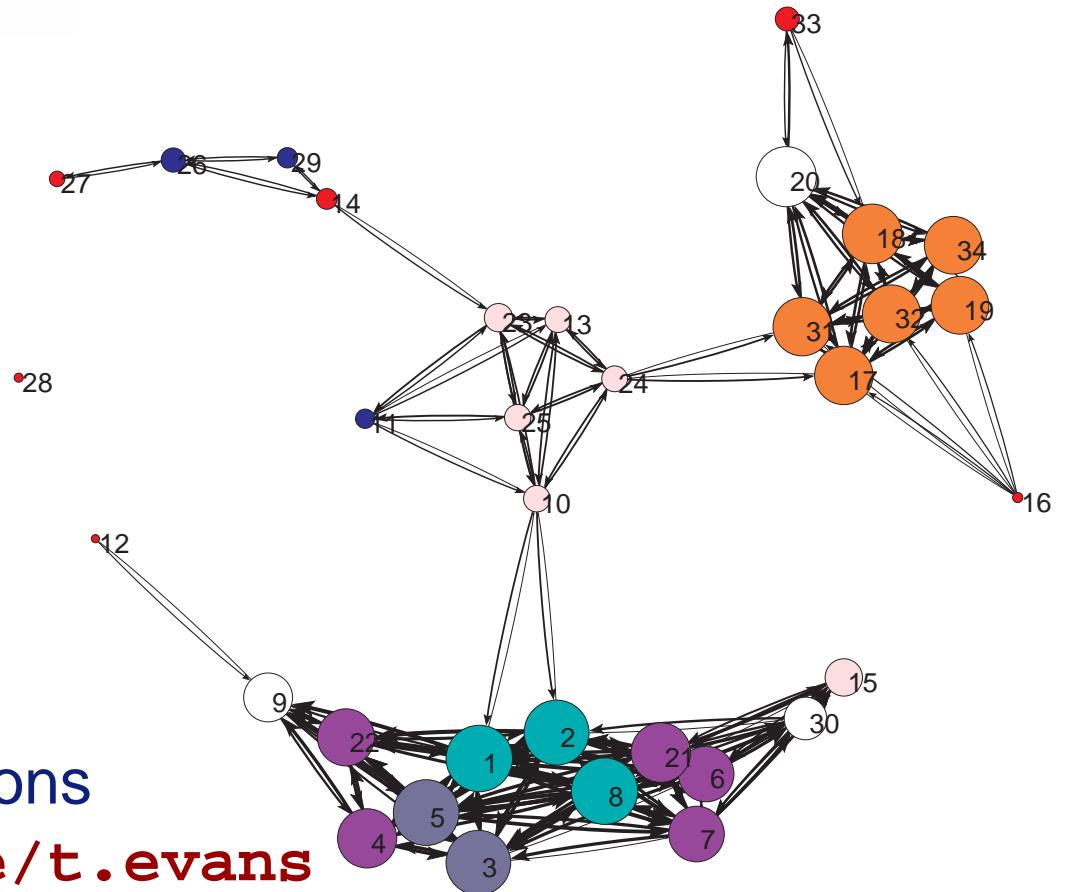
Tim Evans (Imperial),
Carl Knappett (Exeter),
Ray Rivers (Imperial)

See web site for publications

www.ic.ac.uk/people/t.evans

- e.g. see **ISCOM** project *D.Lane et al. (ed.s) 2007*

“Physical and Relational Networks in the Aegean Bronze Age”



‘Minoa’

A reconstruction on show in Chania, Crete



See commentary on the modern context of this reconstruction

Approaches to Modelling

Several approaches when studying settlement patterns,
many take *settlements* as the core unit.

- e.g. see EU ISCOM project D.Lane et al. (ed.s) 2007

Agent Based Modelling

People/Goats as agents e.g. MASS group

Cities as agents e.g. SIMPOP2 (Pumain et al.)

Increasing Detail

Network Optimisation

TSE, CJK, RJR ariadne

Coarse Graining Increasing

Equations
e.g. West et al.

Site-Site Interactions

- In archaeology relatively little attention has been given to the potential of interactions between sites being involved in the generation of those sites

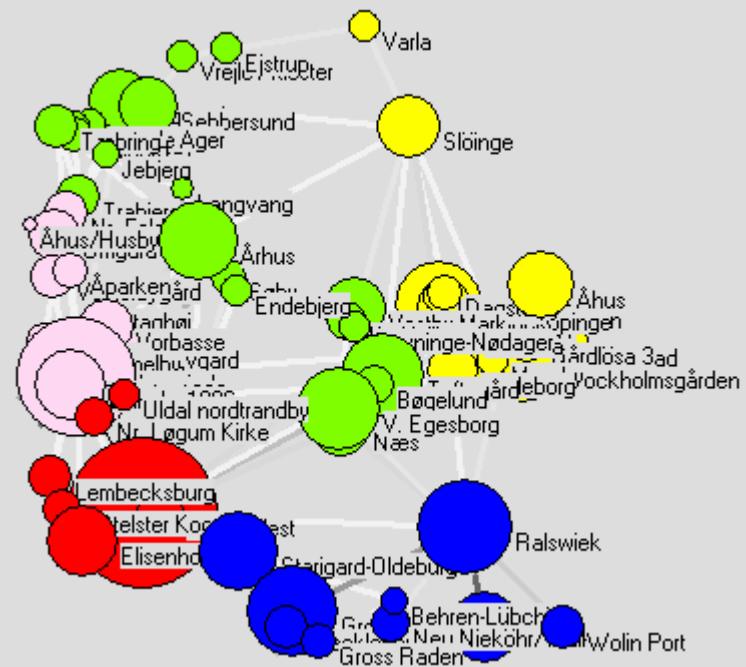
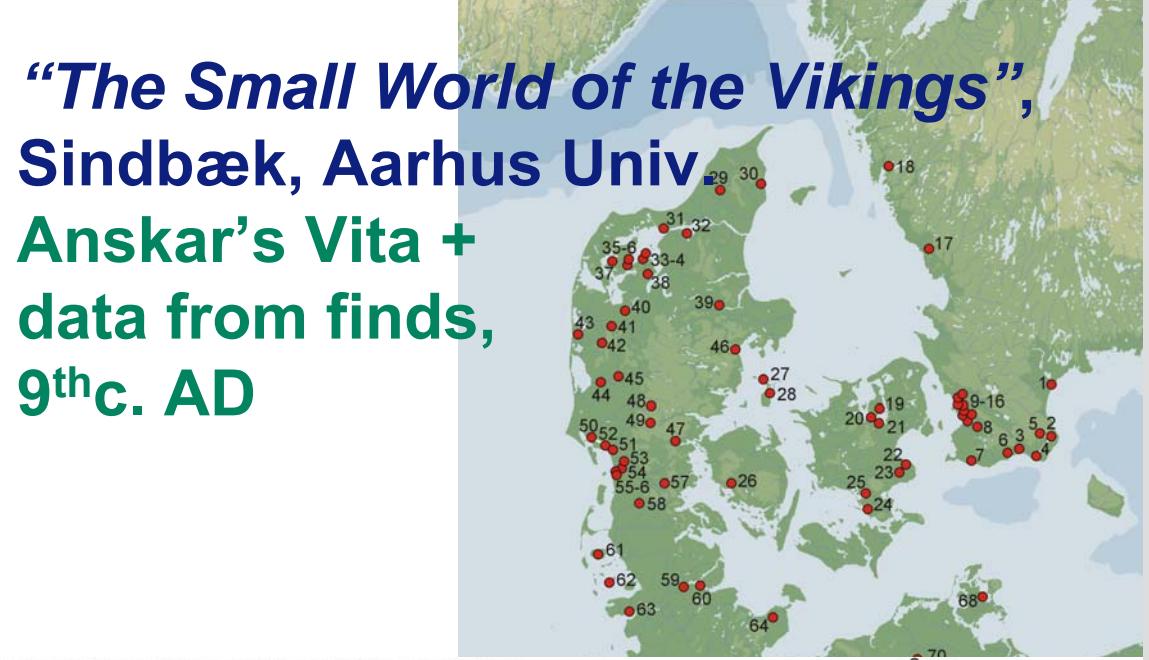
⇒ Network models may prove to be useful

- Most models fixed site sizes, focused on local interactions, often just nearest neighbour interactions
 - Malta (*Renfrew & Level, 1979*);
Geometric Greece (*Rihll & Wilson, 1991*);
Proximal Point Analysis (*Terrell 1977; Irwin 1983; Hage and Harary, 1991, 1996; Broodbank 2000; Sindbæk (in prep.); Collar (in prep.)*)

“The Small World of the Vikings”, Sindbæk, Aarhus Univ.

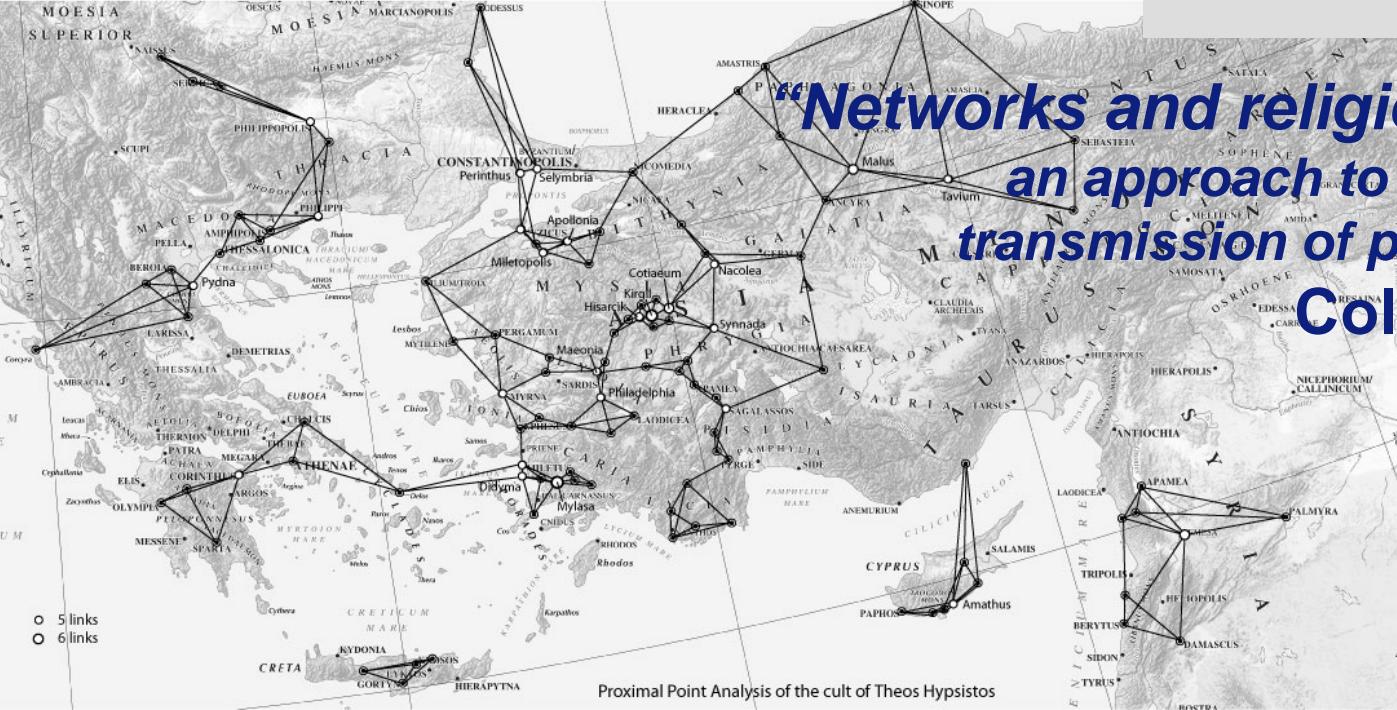
Anskar’s Vita + data from finds, 9thc. AD

<img alt="Map of Scandinavia and North Sea showing Viking find locations numbered 17, 18, 29, 30, 31, 32, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48, 27, 28, 19, 20, 21, 22, 23, 24, 25, 26, 29-31, 32-34, 36-38, 40-42, 44-46, 48-50, 52-54, 56-58, 60-62, 64-66, 68-70, 72-74, 76-78, 80-82, 84-86, 88-90, 92-94, 96-98, 100-102, 104-106, 108-110, 112-114, 116-118, 120-122, 124-126, 128-130, 132-134, 136-138, 140-142, 144-146, 148-150, 152-154, 156-158, 160-162, 164-166, 168-170, 172-174, 176-178, 180-182, 184-186, 188-190, 192-194, 196-198, 199-201, 203-205, 207-209, 211-213, 215-217, 219-221, 223-225, 227-229, 231-233, 235-237, 239-241, 243-245, 247-249, 251-253, 255-257, 259-261, 263-265, 267-269, 271-273, 275-277, 279-281, 283-285, 287-289, 291-293, 295-297, 299-301, 303-305, 307-309, 311-313, 315-317, 319-321, 323-325, 327-329, 331-333, 335-337, 339-341, 343-345, 347-349, 351-353, 355-357, 359-361, 363-365, 367-369, 371-373, 375-377, 379-381, 383-385, 387-389, 391-393, 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“Networks and religious innovation: an approach to understanding the transmission of pagan monotheism”

Hypsistos cult inscriptions, 1-4c.AD



Island Archipelagos as an Ideal Network

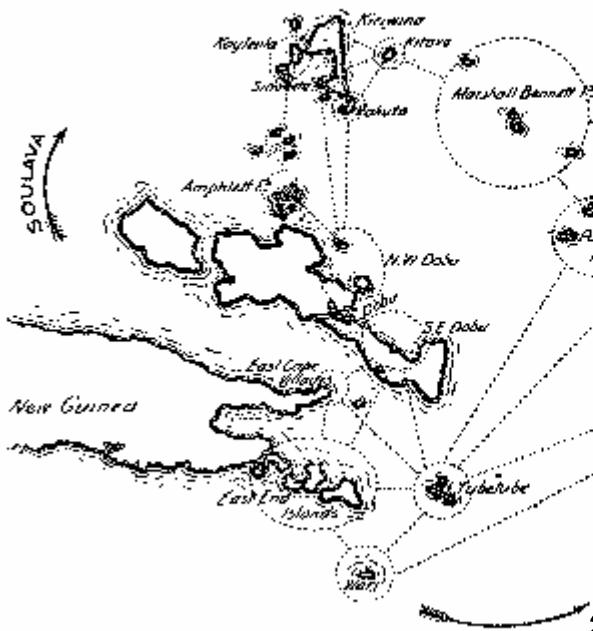
- Vertices = Major Population or Resource Sites
- Edges = Exchange between sites
 - physical trade of goods *or* transmission of culture
 - direct contact *or* island hopping links
- Sea isolates communities → **Natural Vertices**
- Interactions controlled by physical limitations of ancient sea travel → **Simple Links**
- Coastal Sites often isolated like islands due to geography and difficulty of ancient land travel

Earlier Island Network:- The Kula Ring

Malinowski (1922)

necklaces

SOULAVA



armshells

Hage and Harary (1991)

SOULAVA (necklaces)

2 Kiriwina

19

20

1

Kitava

18

Merrell

Bennetts

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Woodlark

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Lauighlin

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Misima

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Tubabola

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Merrell

Bennetts

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Woodlark

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Lauighlin

14

Misima

13

Tubabola

12

Wari

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Kiriwina

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Kitava

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Merrell

Bennetts

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Woodlark

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Lauighlin

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Misima

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Tubabola

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Wari

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Merrell

Bennetts

16

Woodlark

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Lauighlin

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Misima

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Tubabola

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Kitava

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Merrell

Bennetts

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Woodlark

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Lauighlin

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Misima

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Tubabola

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Merrell

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Tubabola

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Kitava

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Merrell

Bennetts

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Woodlark

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Lauighlin

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Misima

13

Tubabola

12

Focus: Middle Bronze Age (MBA) Aegean

- Clear temporal delineation
clear gaps ('dark ages') or shifts in record
 - c.2000BC distinct Minoan culture starts, and sail replaces oar
 - c.1500BC end of Minoan cultural dominance
- Physically largely self contained
 - questions regarding relationship to Egyptian culture

Some Questions

- **The Knossos Question**

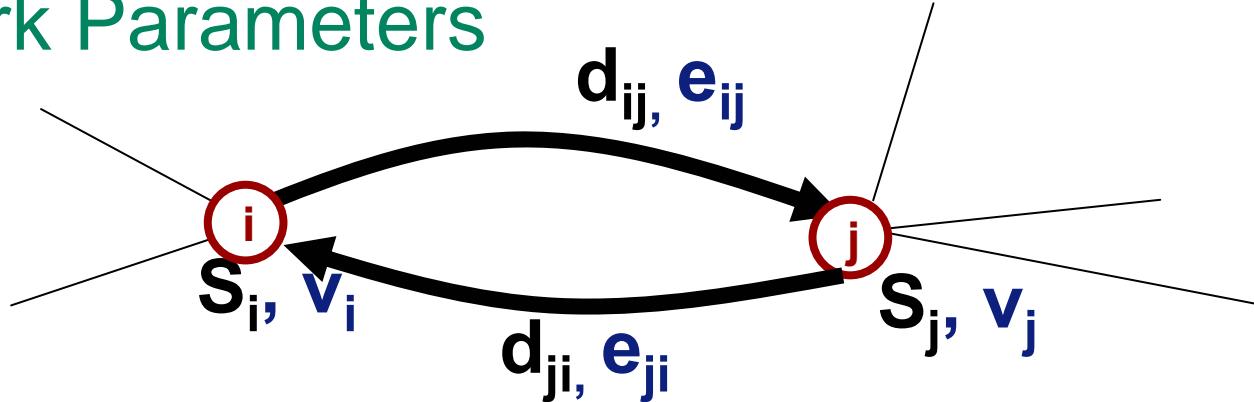
What is the connection between macro-scale development of regional networks and the emergence of a primary centre?

The palace at Knossos does not have the best local environment

- **Minoanisation**

What can explain the spread of and the variability in Minoan influence across the southern Aegean c.1700 BC?

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 $\sum_j (s_i v_i)$
- Trade activity $\sum_j (s_i v_i e_{ij})$

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

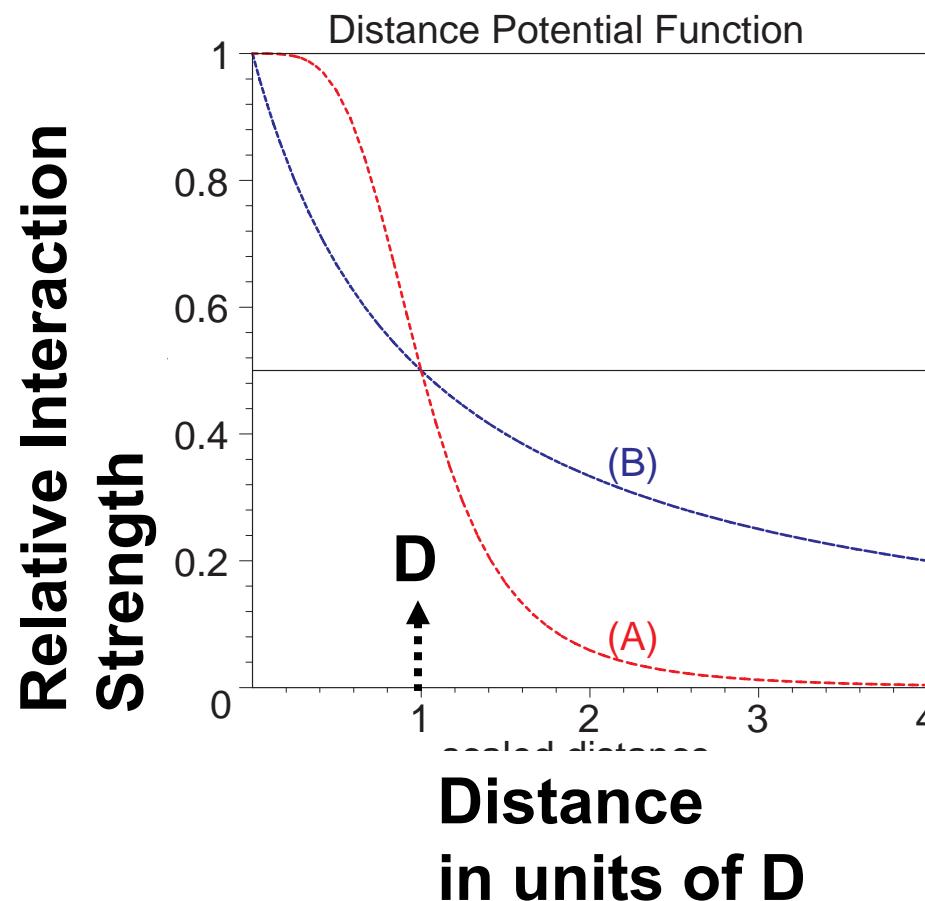
- **T – total strength of links**

Increase parameter μ and interaction links more expensive to maintain

Distance Scale D

We use: $D=100\text{km}$ for sail $D=10\text{km}$ for rowing
(after 2000BC) (pre 2000BC)

Interaction term for each pair of sites depends on distance d_{ij} between sites such that for distances longer than a scale D the benefit is zero i.e. no effective direct interaction

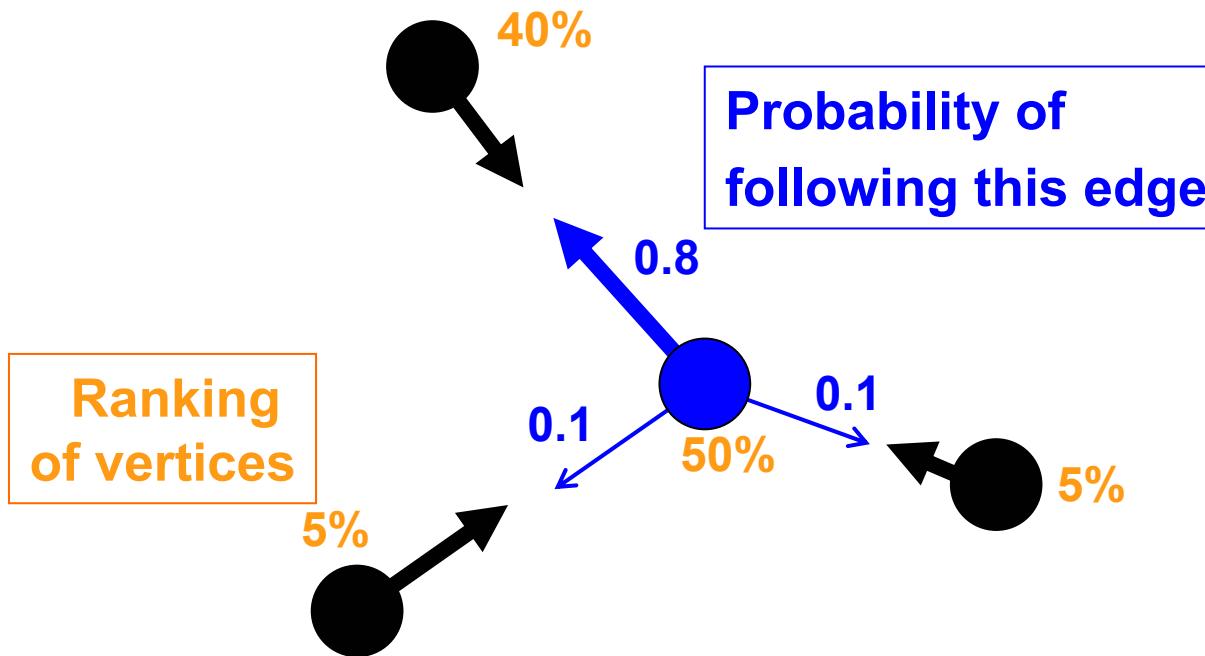


Analysis

- Working with 34 sites
- 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.
This represents slow evolution where system remains in effective equilibrium.
- For any given set of (reasonable) values:
 - a) can analyse intrinsic parameters
 - b) can perform further 'games' to analyse properties e.g. simulate trade in physical objects, cultural transmission models.

Analysis Methods: Ranking

- The percentage of time spent at each node by an *imaginary* random walker on the network. The walker moves from site to site, choosing to follow a link with probability proportional to its strength. (Other choices possible).
⇒ **Measure of GLOBAL network properties**



As used by
Hage &
Harary 1991,
and
GoogleTM
UK

The 34 Sites Used



Analysis of Single Network

- The new few slides show the analysis of one result of our model
- Look for sites which are off any general trends

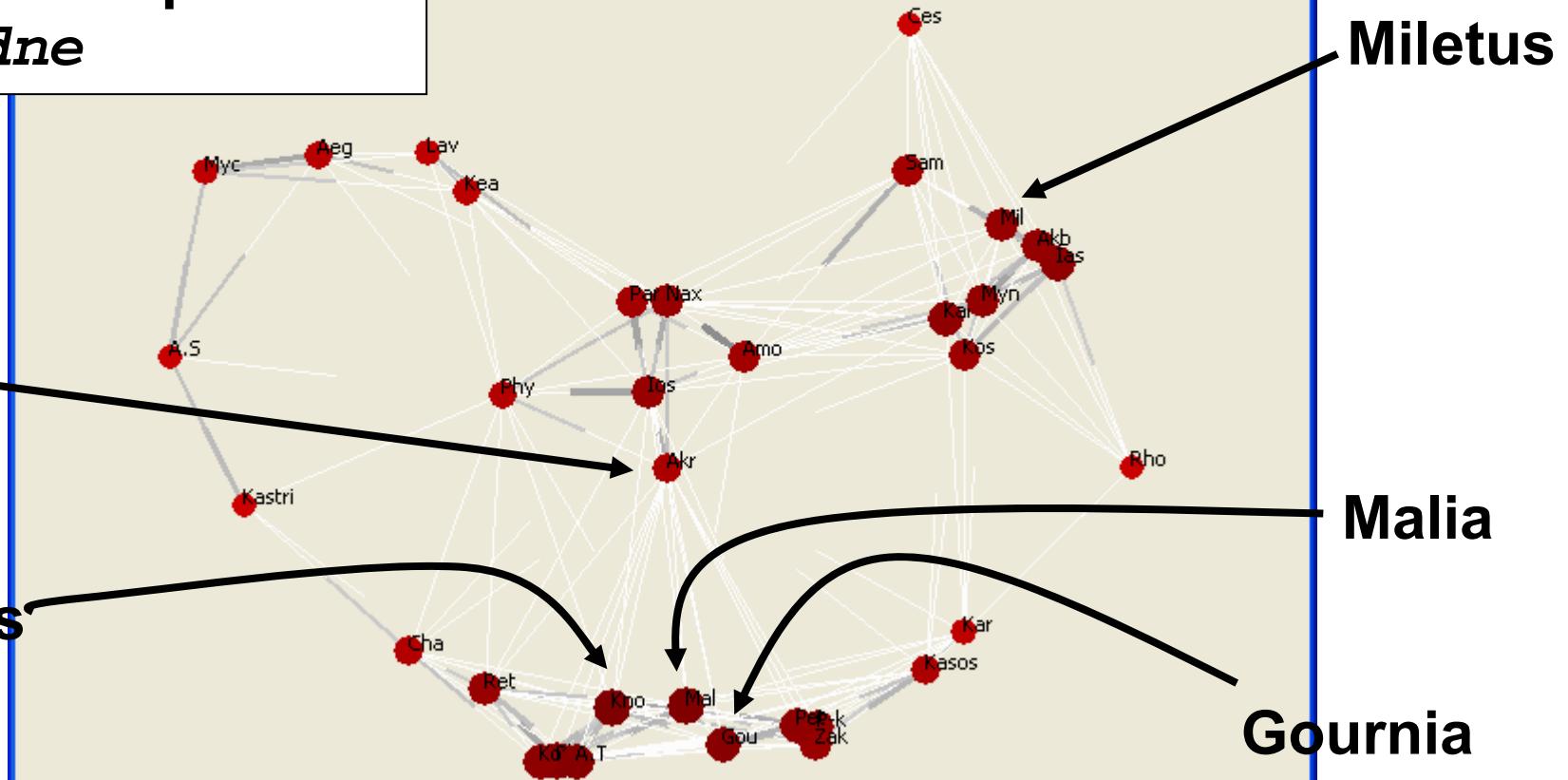
$j=0, m=0.5, k=1.0, l=4.0$

model number 1_3
 mu 0.5
 b 1.2
 beta 524288.0
 Absolute Edge Display, Max 1.0

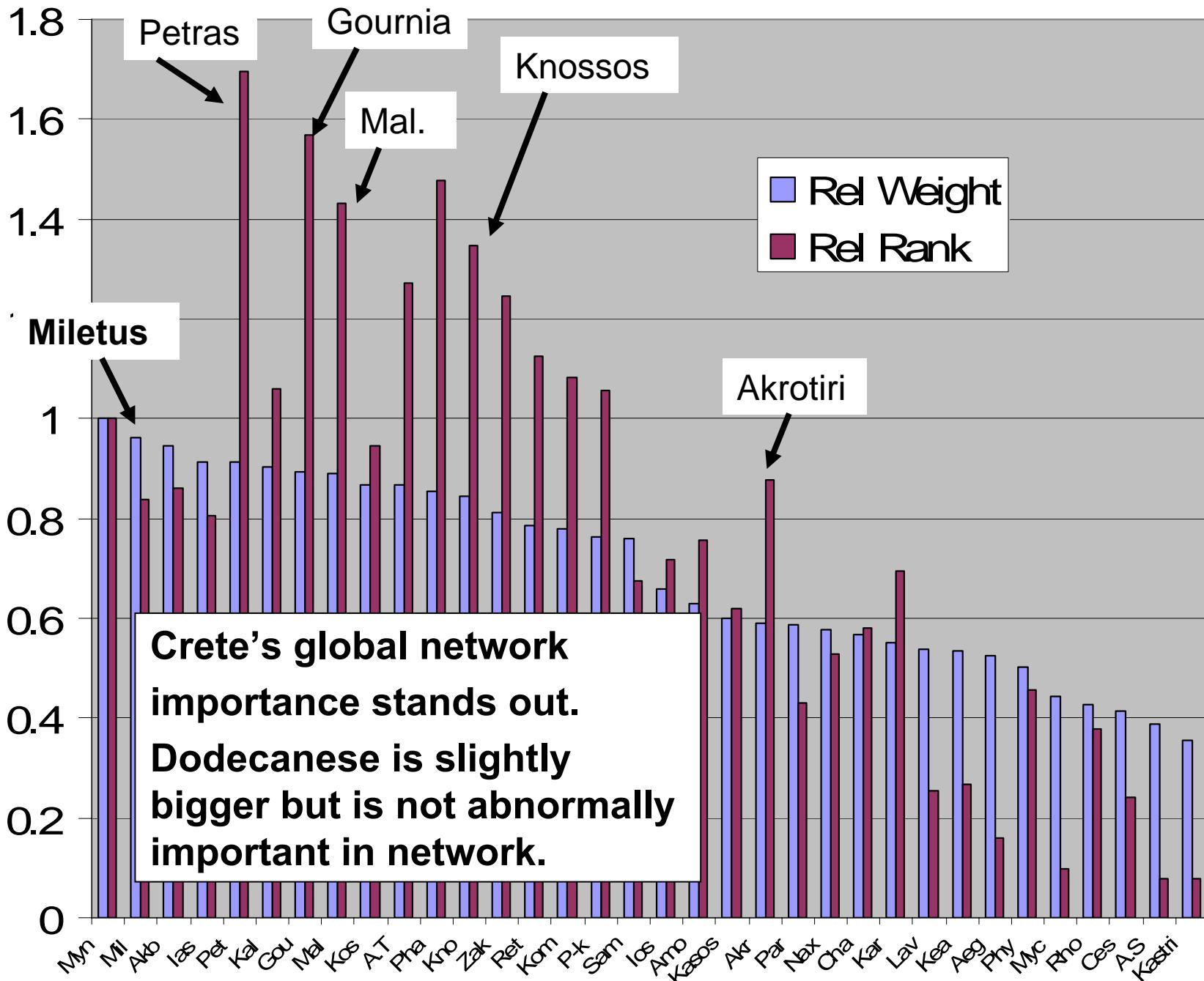
Monte Carlo Update
 j 0.0
 distance scale 100.0
 Zero Colour Frac 0.01
 Influence Range 1.0 (prob=0.5)

input file: aegean34
 output files: output/aegean34_v1_3e-1.0m0.5j0.0k1.0b1.2s100.0MCr0
 Model: Standard Hamiltonian+Gravity (source and target site in trade term)
 Limits on Out Strength 1.0
 kappa 1.0
 short distance scale 5.0
 Min. Colour Frac 0.2
 sites by Size
 max vertex value 5.0
 lambda 4.0
 metric number 5.0
 Relative Vertex Display

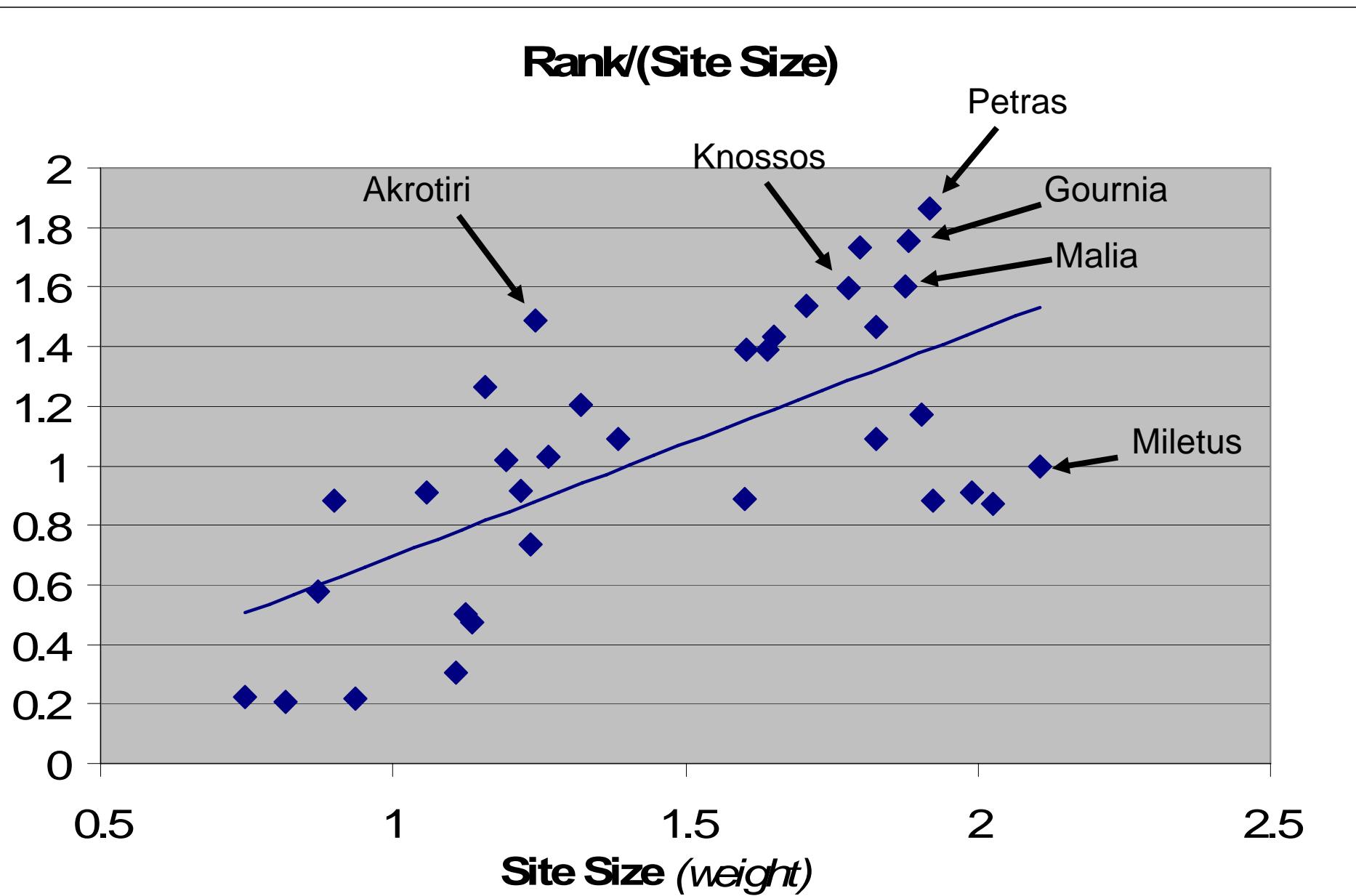
Typical Output from *ariadne*



| Quantity/Value | Average | Sigma | Minimum | Maximum |
|----------------------|---------|-------|---------|---------|
| Site Weight | 1.42 | 0.35 | 0.78 | 1.98 |
| Site Out W. Strength | 1.42 | 0.35 | 0.77 | 1.98 |
| Edge Weight | 0.04 | 0.08 | 0.0 | 0.45 |
| Edge Value | 0.03 | 0.06 | 0.0 | 0.34 |

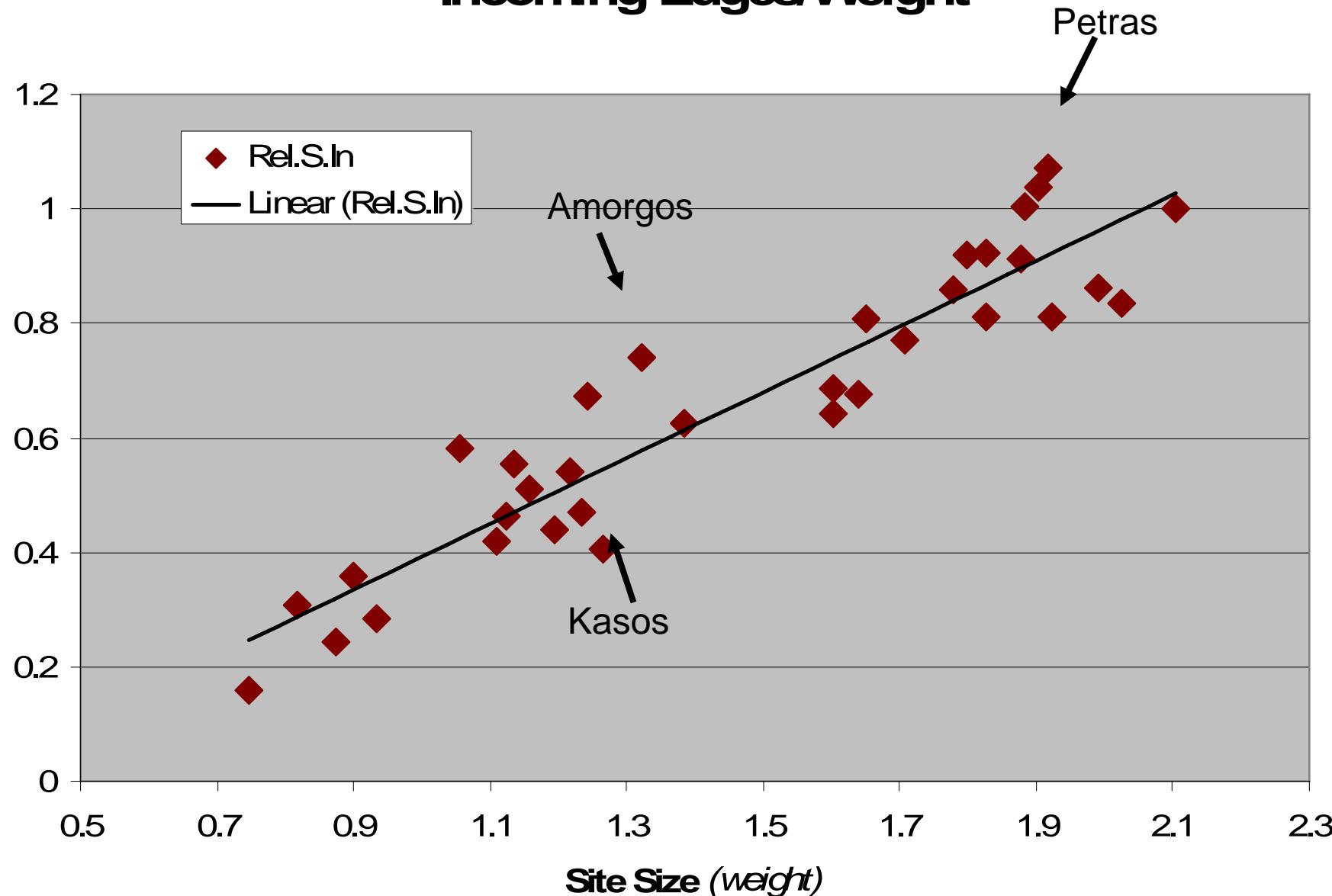


Rank vs. Size shows Crete's is more important to the global network than its size suggests, not so for Dodecanese

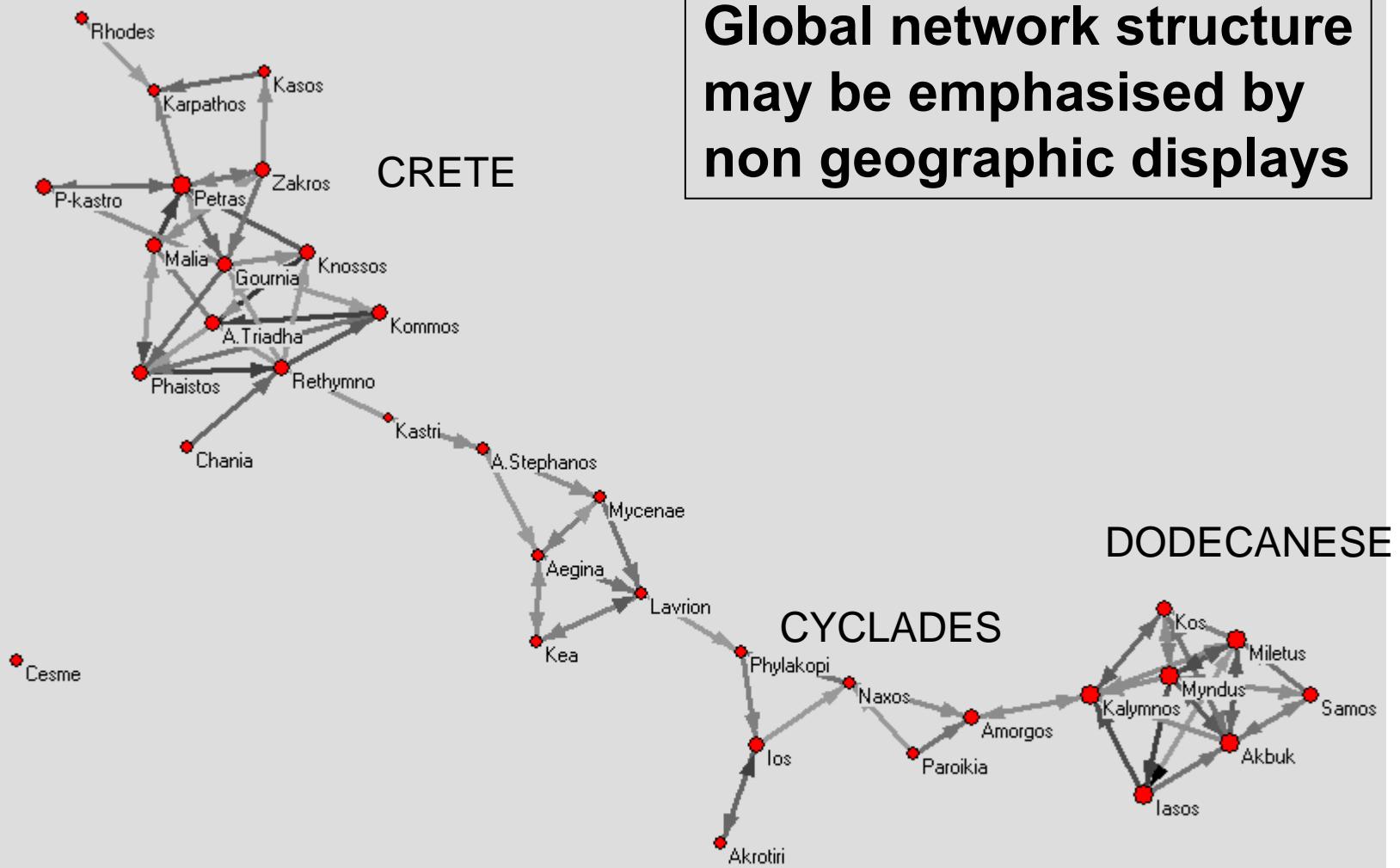


Local properties often scale closely with site size (weight)

Incoming Edges/Weight



**Global network structure
may be emphasised by
non geographic displays**



Increasing Edge Cost (μ)

Next 7 slides

- for large interaction benefits ($\lambda=4.0, j=0, \kappa=1.0$)
- Increasing μ causes edges to concentrate on decreasing profitable routes.
- The largest site size goes up while the smallest stays the same.
- Total cost in edges the same (as vertex out strength) but

model number 1_3

mu -1.0

b 1.2

beta 262144.0

Absolute Edge Display, Max 1.0

Monte Carlo Update

j 0.0

distance scale 100.0

Zero Colour Frac 0.01

Influence Range 1.0 (prob=0.5)

input file: aegean34

output files: output/aegean34_v1_3e-1.0m-1.0j0.0k1.0b1.2s100.0MCr0

Model: Standard Hamiltonian+Gravity (source and target site in trade term)

Limits on Out Strength 1.0

max vertex value 5.0

kappa 1.0

lambda 4.0

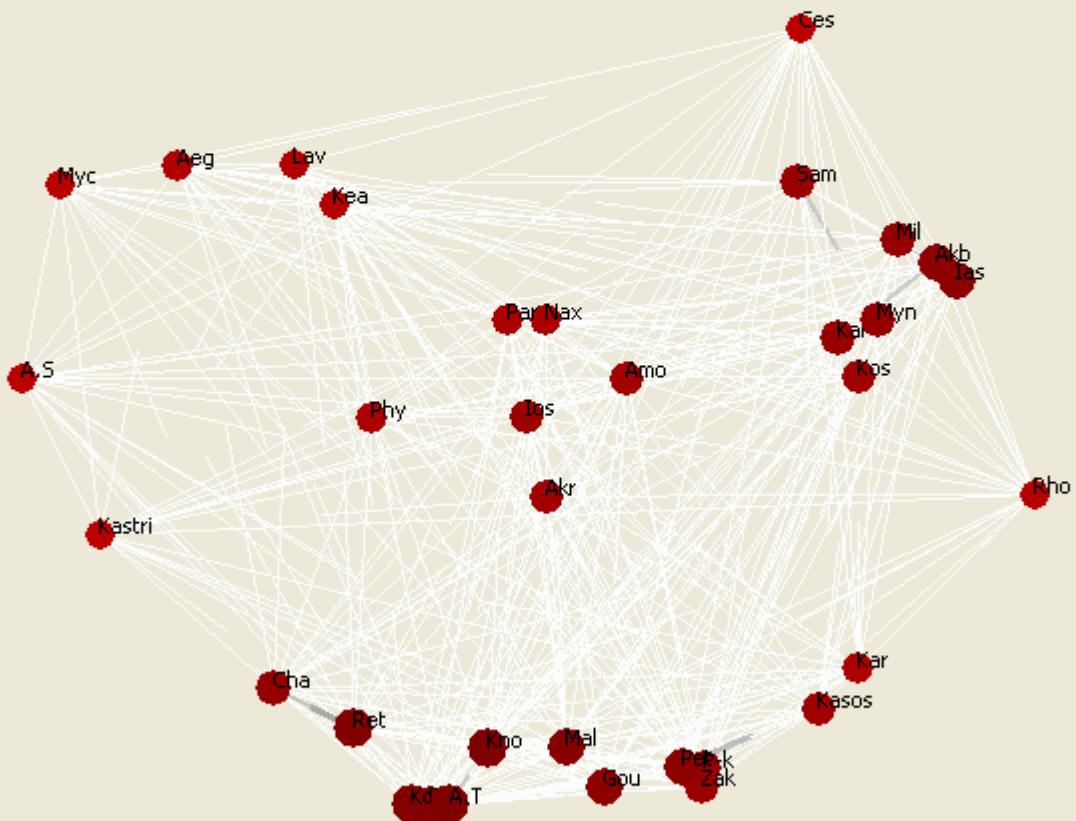
short distance scale 5.0

metric number 5.0

Min. Colour Frac 0.2

Relative Vertex Display

sites by Size



| Quantity/Value | Average | Sigma | Minimum | Maximum |
|---------------------|---------|-------|---------|---------|
| Site Weight | 1.07 | 0.2 | 0.74 | 1.4 |
| Site Out W.Strength | 1.07 | 0.2 | 0.74 | 1.4 |
| Edge Weight | 0.03 | 0.04 | 0.0 | 0.34 |
| Edge Value | 0.03 | 0.03 | 0.0 | 0.25 |

input file: aegean34
 output files: output/aegean34_v1_3e-1.0m0.0j0.0k1.0b1.2s100.0MCr0
 Model: Standard Hamiltonian+Gravity (source and target site in trade term)

model number 1_3

mu 0.0

b 1.2

beta 524288.0

Absolute Edge Display, Max 1.0

Monte Carlo Update

j 0.0

distance scale 100.0

Zero Colour Frac 0.01

Influence Range 1.0 (prob=0.5)

Limits on Out Strength 1.0

kappa 1.0

short distance scale 5.0

Min. Colour Frac 0.2

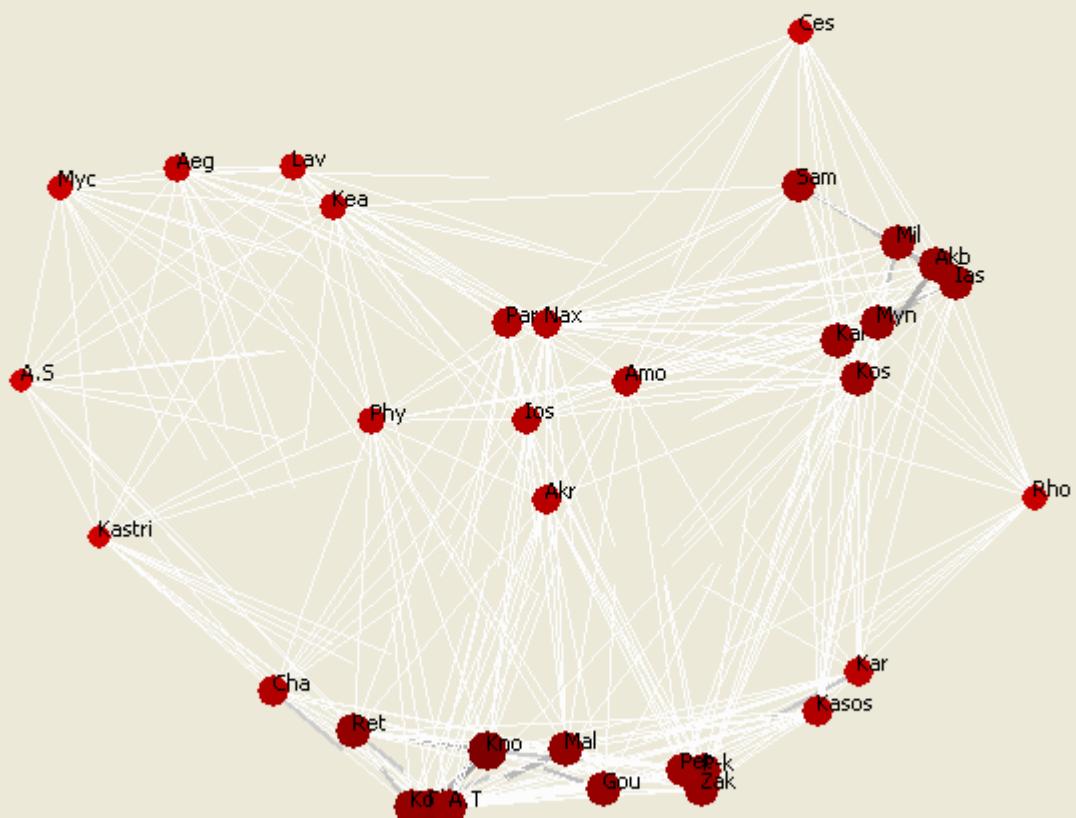
sites by Size

max vertex value 5.0

lambda 4.0

metric number 5.0

Relative Vertex Display



| Quantity/Value | Average | Sigma | Minimum | Maximum |
|---------------------|---------|-------|---------|---------|
| Site Weight | 1.17 | 0.3 | 0.64 | 1.76 |
| Site Out W.Strength | 1.17 | 0.3 | 0.64 | 1.76 |
| Edge Weight | 0.03 | 0.05 | 0.0 | 0.39 |
| Edge Value | 0.03 | 0.04 | 0.0 | 0.23 |

model number 1_3

mu 0.5

b 1.2

beta 524288.0

Absolute Edge Display, Max 1.0

Monte Carlo Update

j 0.0

distance scale 100.0

Zero Colour Frac 0.01

Influence Range 1.0 (prob=0.5)

input file: aegean34

output files: output/aegean34_v1_3e-1.0m0.5j0.0k1.0b1.2s100.0MCr0

Model: Standard Hamiltonian+Gravity (source and target site in trade term)

Limits on Out Strength 1.0

max vertex value 5.0

kappa 1.0

lambda 4.0

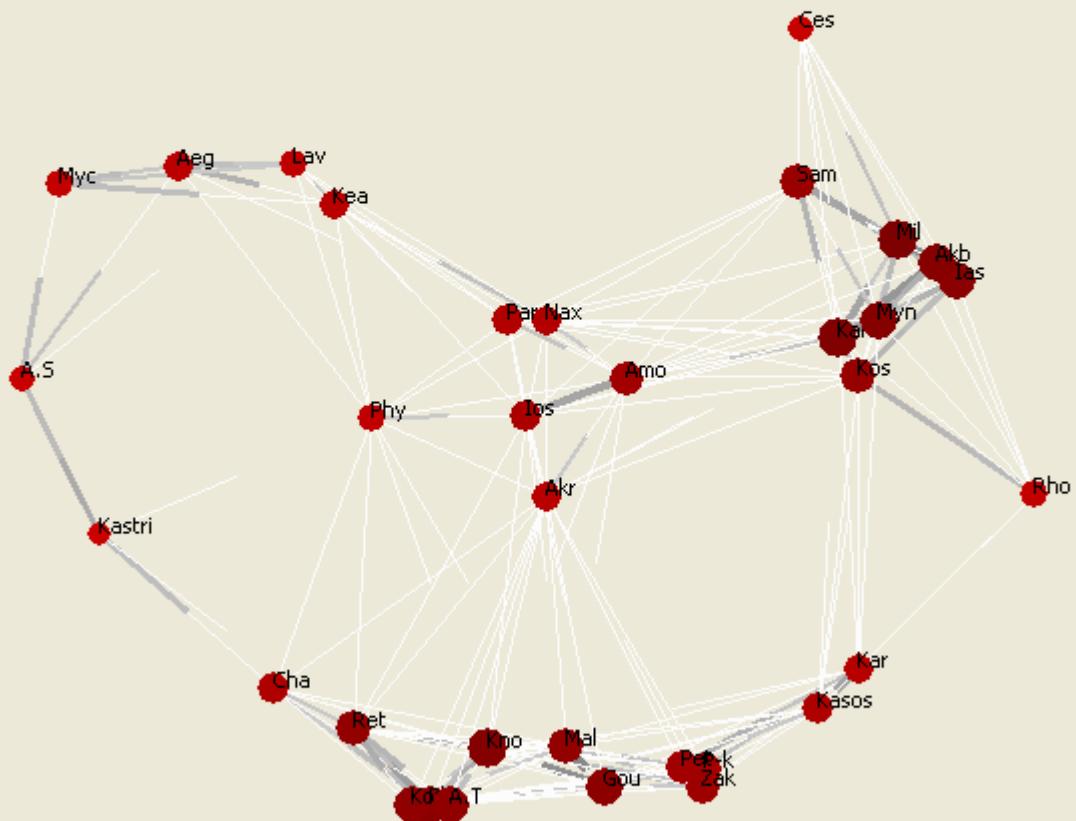
short distance scale 5.0

metric number 5.0

Min. Colour Frac 0.2

Relative Vertex Display

sites by Size



| Quantity/Value | Average | Sigma | Minimum | Maximum |
|----------------------|---------|-------|---------|---------|
| Site Weight | 1.43 | 0.37 | 0.79 | 2.03 |
| Site Out W. Strength | 1.43 | 0.37 | 0.79 | 2.03 |
| Edge Weight | 0.04 | 0.08 | 0.0 | 0.47 |
| Edge Value | 0.03 | 0.06 | 0.0 | 0.42 |

model number 1_3

mu 1.0

b 1.2

beta 524288.0

Absolute Edge Display, Max 1.0

Monte Carlo Update

j 0.0

distance scale 100.0

Zero Colour Frac 0.01

Influence Range 1.0 (prob=0.5)

input file: aegean34

output files: output/aegean34_v1_3e-1.0m1.0j0.0k1.0b1.2s100.0MCr0

Model: Standard Hamiltonian+Gravity (source and target site in trade term)

Limits on Out Strength 1.0

max vertex value 5.0

kappa 1.0

lambda 4.0

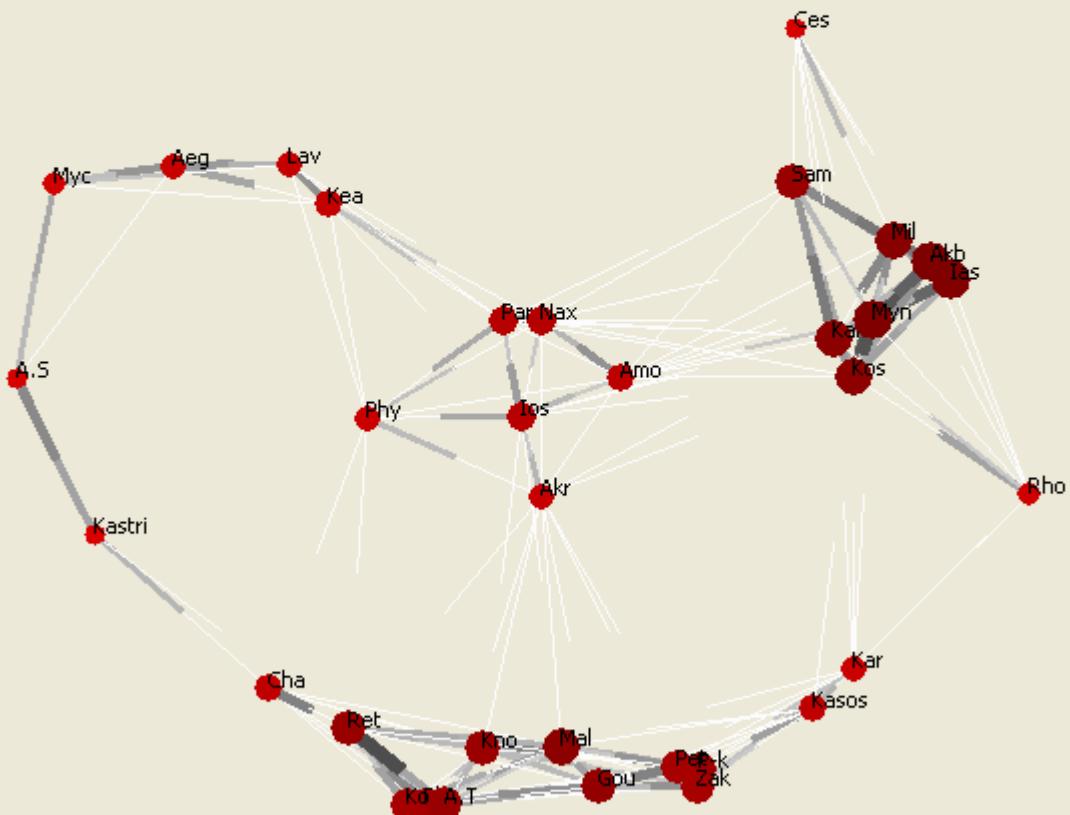
short distance scale 5.0

metric number 5.0

Min. Colour Frac 0.2

Relative Vertex Display

sites by Size



| Quantity/Value | Average | Sigma | Minimum | Maximum |
|---------------------|---------|-------|---------|---------|
| Site Weight | 1.77 | 0.61 | 0.81 | 2.79 |
| Site Out W.Strength | 1.77 | 0.61 | 0.81 | 2.79 |
| Edge Weight | 0.05 | 0.12 | 0.0 | 0.7 |
| Edge Value | 0.03 | 0.07 | 0.0 | 0.53 |

model number 1_3

mu 1.0

b 1.2

beta 524288.0

Absolute Edge Display, Max 1.0

Monte Carlo Update

j 0.0

distance scale 100.0

Zero Colour Frac 0.01

Influence Range 1.0 (prob=0.5)

input file: aegean34

output files: output/aegean34_v1_3e-1.0m1.0j0.0k1.0b1.2s100.0MCr0

Model: Standard Hamiltonian+Gravity (source and target site in trade term)

Limits on Out Strength 1.0

max vertex value 5.0

kappa 1.0

lambda 4.0

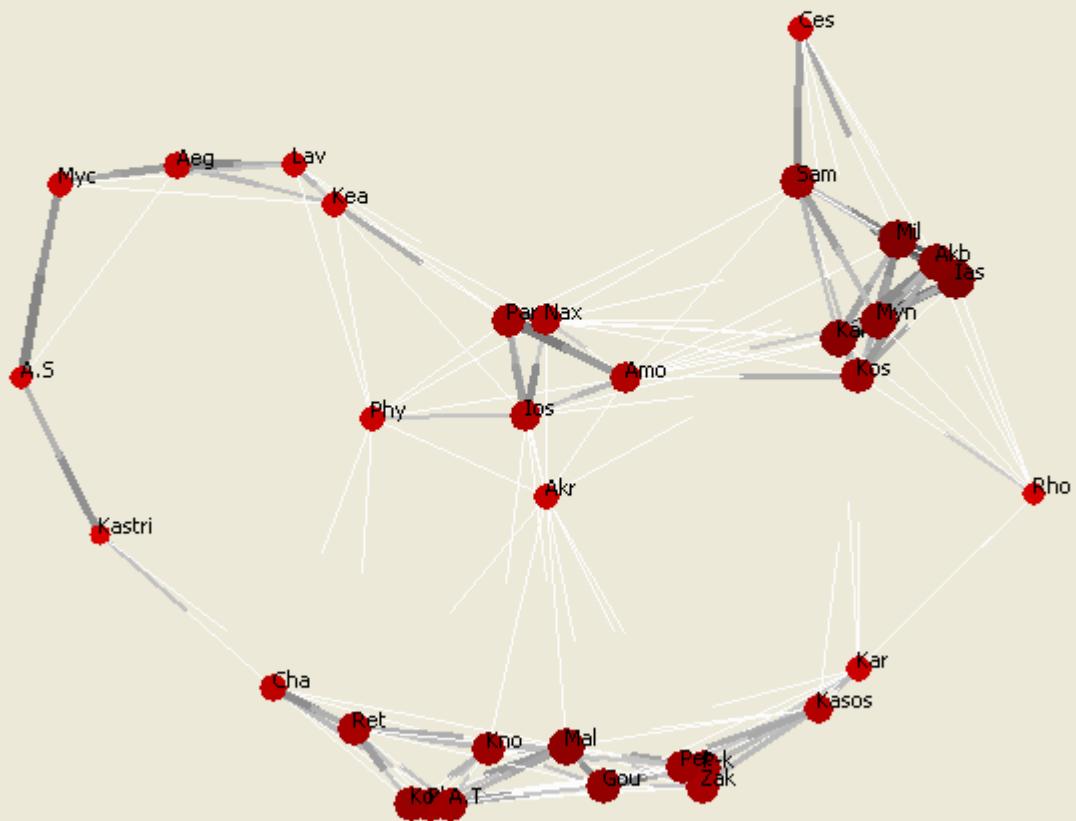
short distance scale 5.0

metric number 5.0

Min. Colour Frac 0.2

Relative Vertex Display

sites by Size



Quantity/Value

Average

Sigma

Minimum

Maximum

Site Weight

1.72

0.54

0.77

2.66

Site Out W.Strength

1.72

0.54

0.77

2.66

Edge Weight

0.05

0.11

0.0

0.81

Edge Value

0.03

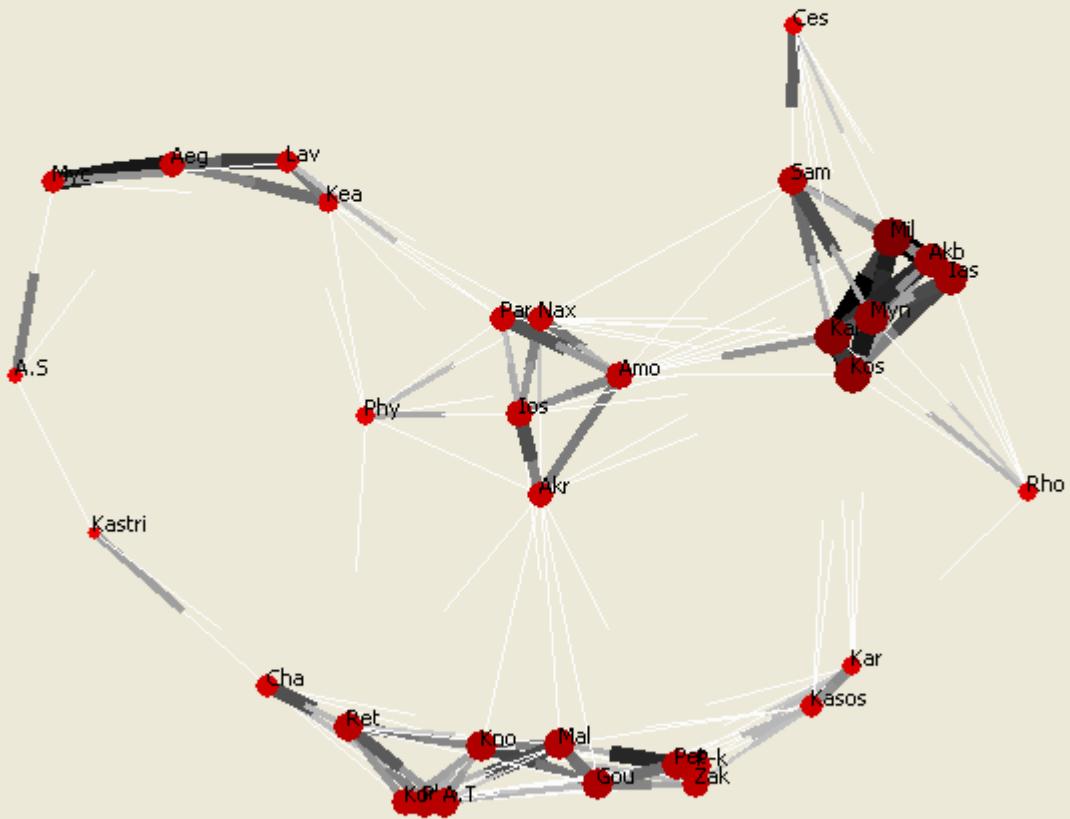
0.07

0.0

0.56

input file: aegean34
output files: output/aegean34_v1_3e-1.0m1.5j0.0k1.0b1.2s100.0MCr0
Model: Standard Hamiltonian+Gravity (source and target site in trade term)

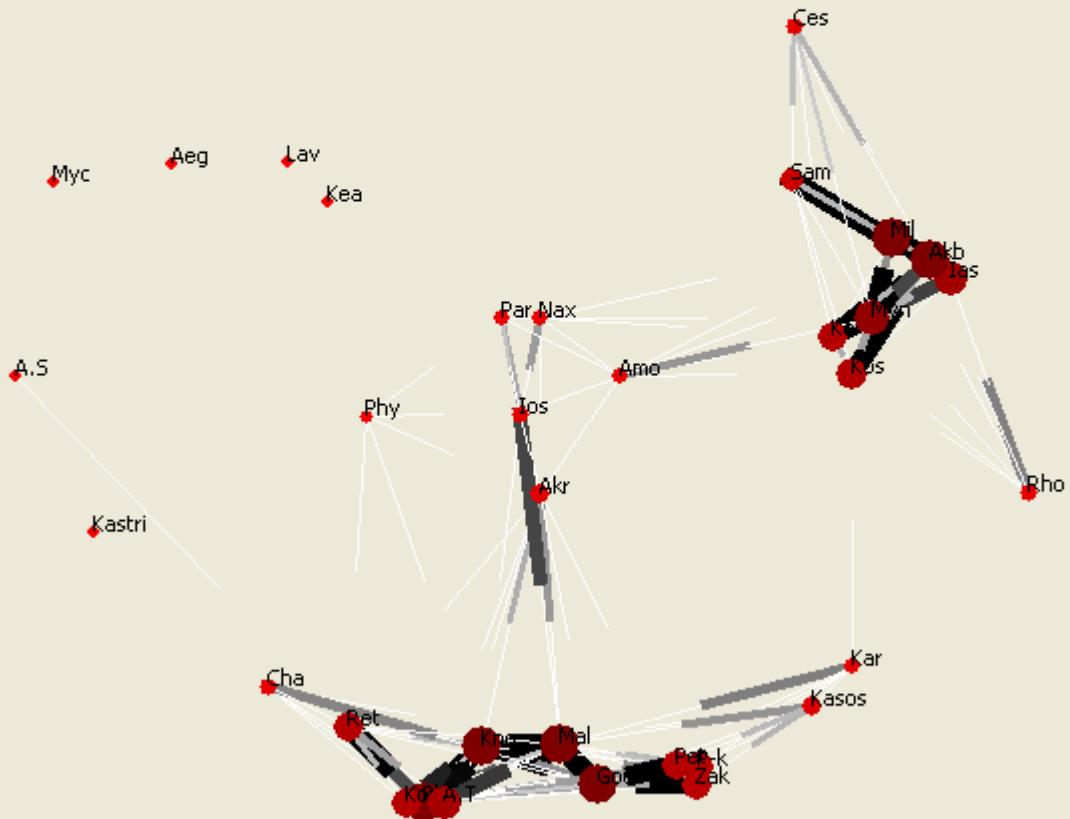
| | | | |
|--------------------------------|--------------------------------|----------------------------|-------------------------|
| model number 1_3 | Monte Carlo Update | Limits on Out Strength 1.0 | max vertex value 5.0 |
| mu 1.5 | j 0.0 | kappa 1.0 | lambda 4.0 |
| b 1.2 | distance scale 100.0 | short distance scale 5.0 | metric number 5.0 |
| beta 524288.0 | Zero Colour Frac 0.01 | Min. Colour Frac 0.2 | Relative Vertex Display |
| Absolute Edge Display, Max 1.0 | Influence Range 1.0 (prob=0.5) | sites by Size | |



| Quantity/Value | Average | Sigma | Minimum | Maximum |
|---------------------|---------|-------|---------|---------|
| Site Weight | 2.32 | 0.99 | 0.64 | 4.62 |
| Site Out W.Strength | 2.32 | 0.99 | 0.64 | 4.62 |
| Edge Weight | 0.07 | 0.18 | 0.0 | 1.4 |
| Edge Value | 0.03 | 0.08 | 0.0 | 0.63 |

input file: aegean34
output files: output/aegean34_v1_3e-1.0m2.0j0.0k1.0b1.2s100.0MCr0
Model: Standard Hamiltonian+Gravity (source and target site in trade term)

| | | | |
|--------------------------------|--------------------------------|----------------------------|-------------------------|
| model number 1_3 | Monte Carlo Update | Limits on Out Strength 1.0 | max vertex value 5.0 |
| mu 2.0 | j 0.0 | kappa 1.0 | lambda 4.0 |
| b 1.2 | distance scale 100.0 | short distance scale 5.0 | metric number 5.0 |
| beta 524288.0 | Zero Colour Frac 0.01 | Min. Colour Frac 0.2 | Relative Vertex Display |
| Absolute Edge Display, Max 1.0 | Influence Range 1.0 (prob=0.5) | sites by Size | |



| Quantity/Value | Average | Sigma | Minimum | Maximum |
|---------------------|---------|-------|---------|---------|
| Site Weight | 2.24 | 1.66 | 0.46 | 5.0 |
| Site Out W.Strength | 2.17 | 1.74 | 0.06 | 5.0 |
| Edge Weight | 0.06 | 0.27 | 0.0 | 3.47 |
| Edge Value | 0.03 | 0.09 | 0.0 | 0.78 |

End of increasing μ sequence

Minoanisation Analysis Methods

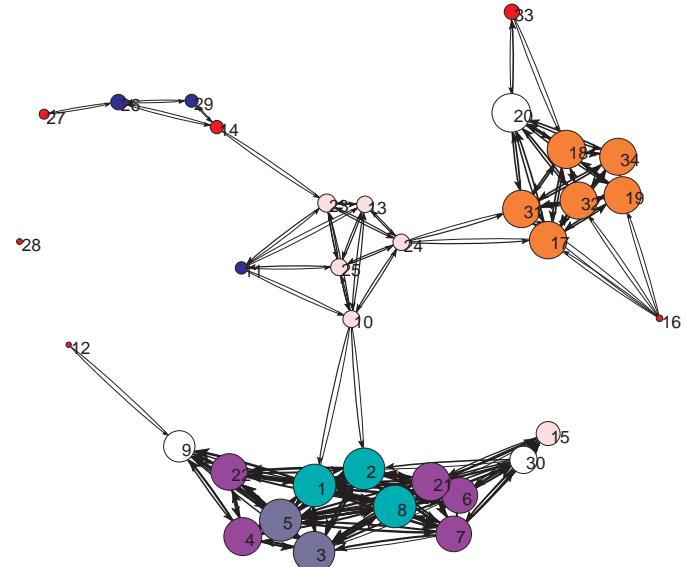
- **Diffusion**

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



Summary

- Starting to extract basic results systematically
- Some behaviour looks interesting to an archaeologist
 - Crete and Dodecanese usually form strongest clusters
- Some types of behaviour do not appear to be possible
 - Greek mainland rarely gives significant sized sites
- Some factors seem to be playing a key role
 - small differences in physical distance from Crete may be significant
- **Many options remain to be explored**
 - improve distance data, more analysis tools, more what if scenarios, EBA vs MBA, general time evolution, other data sets

Additional Material

More stuff ...

PPA - Proximal Point Analysis

Most models focused on local interactions,
often just nearest neighbour interactions

- Malta (*Renfrew & Level, 1979*)
- Geometric Greece (*Rihll & Wilson, 1991*)
- Proximal Point Analysis
 - Connect each vertex to 3 (or whatever) nearest neighbours
 - (*Terrell 1977; Irwin 1983; Hage and Harary, 1991, 1996*)
 - *EBA Aegean (Broodbank 2000)*
 - *Vikings (Sindbæk, in prep.)*
 - *Hypsistas Cult (Collar, in prep.)*

Increasing Interaction Benefits (λ)

Next 5 slides ...

model number 1_3

mu 0.5

b 1.2

beta 524288.0

Absolute Edge Display, Max 1.0

Monte Carlo Update

j 0.0

distance scale 100.0

Zero Colour Frac 0.01

Influence Range 1.0 (prob=0.5)

input file: aegean34

output files: output/aegean34_v1_3e-1.0m0.5j0.0k1.0b1.2s100.0MCr0

Model: Standard Hamiltonian+Gravity (source and target site in trade term)

Limits on Out Strength 1.0

max vertex value 5.0

kappa 1.0

lambda 0.5

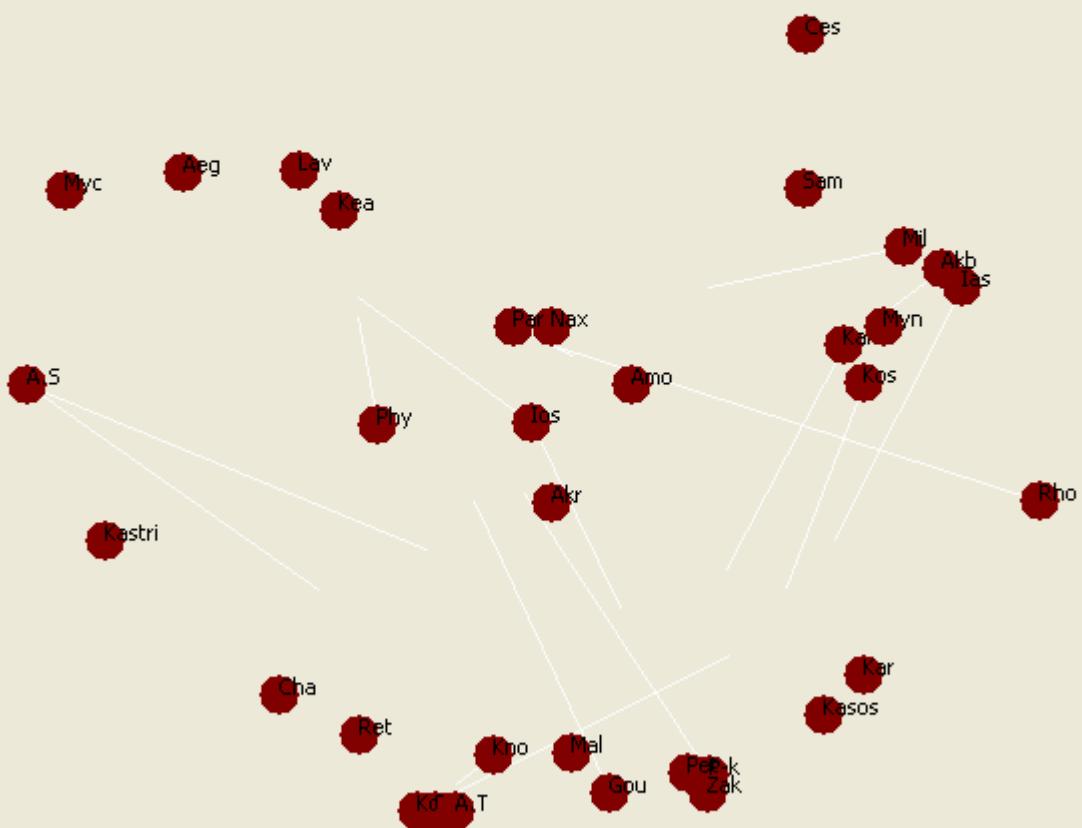
short distance scale 5.0

metric number 5.0

Min. Colour Frac 0.2

Relative Vertex Display

sites by Size



| Quantity/Value | Average | Sigma | Minimum | Maximum |
|---------------------|---------|-------|---------|---------|
| Site Weight | 0.49 | 0.0 | 0.48 | 0.5 |
| Site Out W.Strength | 0.08 | 0.01 | 0.06 | 0.11 |
| Edge Weight | 0.0 | 0.0 | 0.0 | 0.02 |
| Edge Value | 0.0 | 0.0 | 0.0 | 0.03 |

model number 1_3

mu 0.5

b 1.2

beta 524288.0

Absolute Edge Display, Max 1.0

Monte Carlo Update

j 0.0

distance scale 100.0

Zero Colour Frac 0.01

Influence Range 1.0 (prob=0.5)

input file: aegean34

output files: output/aegean34_v1_3e-1.0m0.5j0.0k1.0b1.2s100.0MCr0

Model: Standard Hamiltonian+Gravity (source and target site in trade term)

Limits on Out Strength 1.0

max vertex value 5.0

kappa 1.0

lambda 1.0

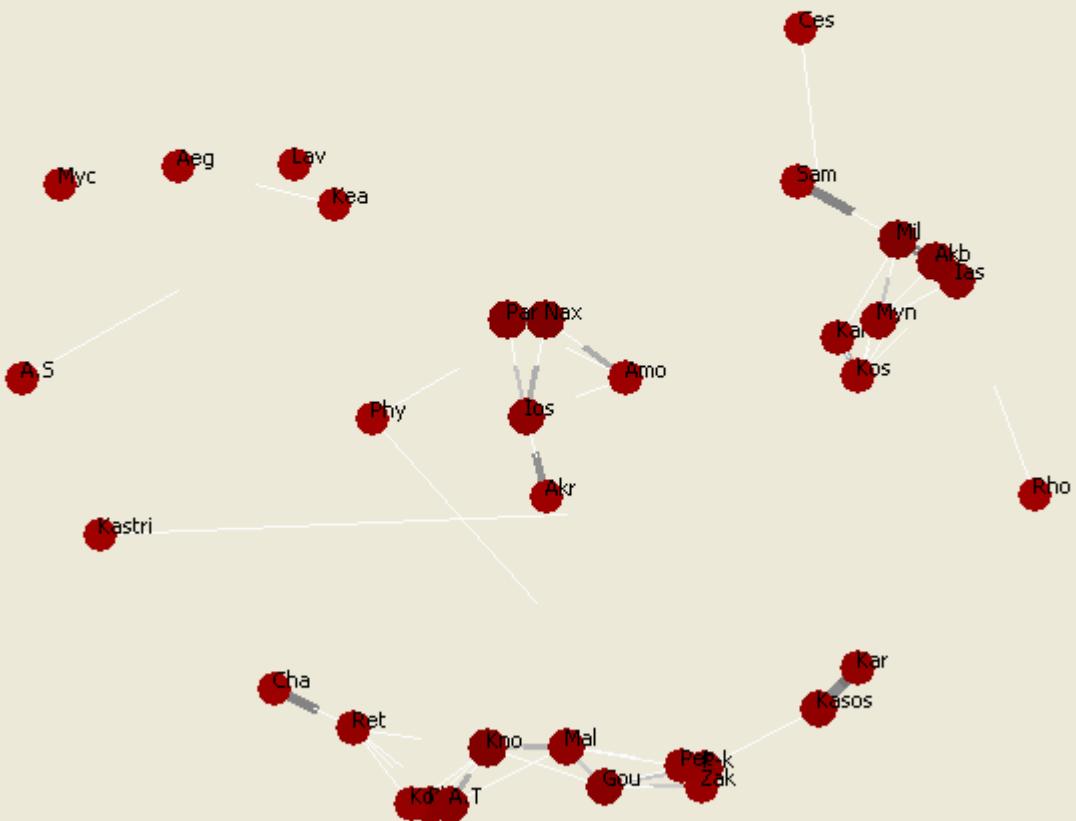
short distance scale 5.0

metric number 5.0

Min. Colour Frac 0.2

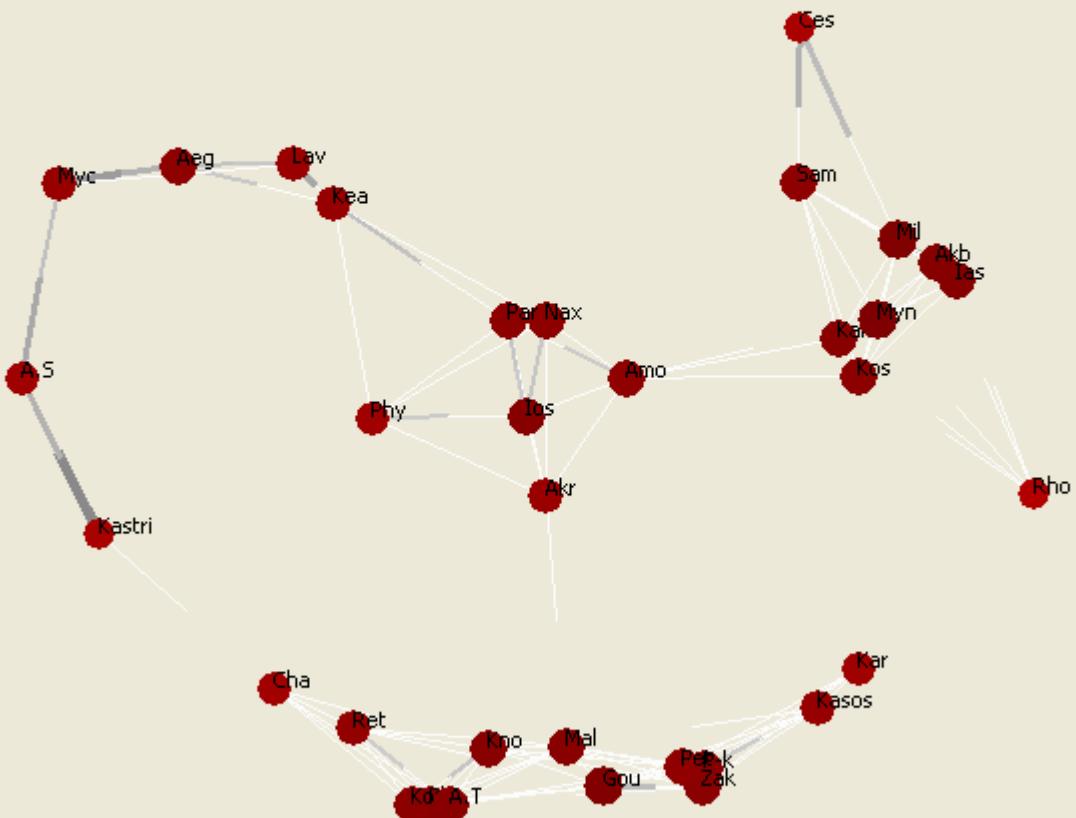
Relative Vertex Display

sites by Size



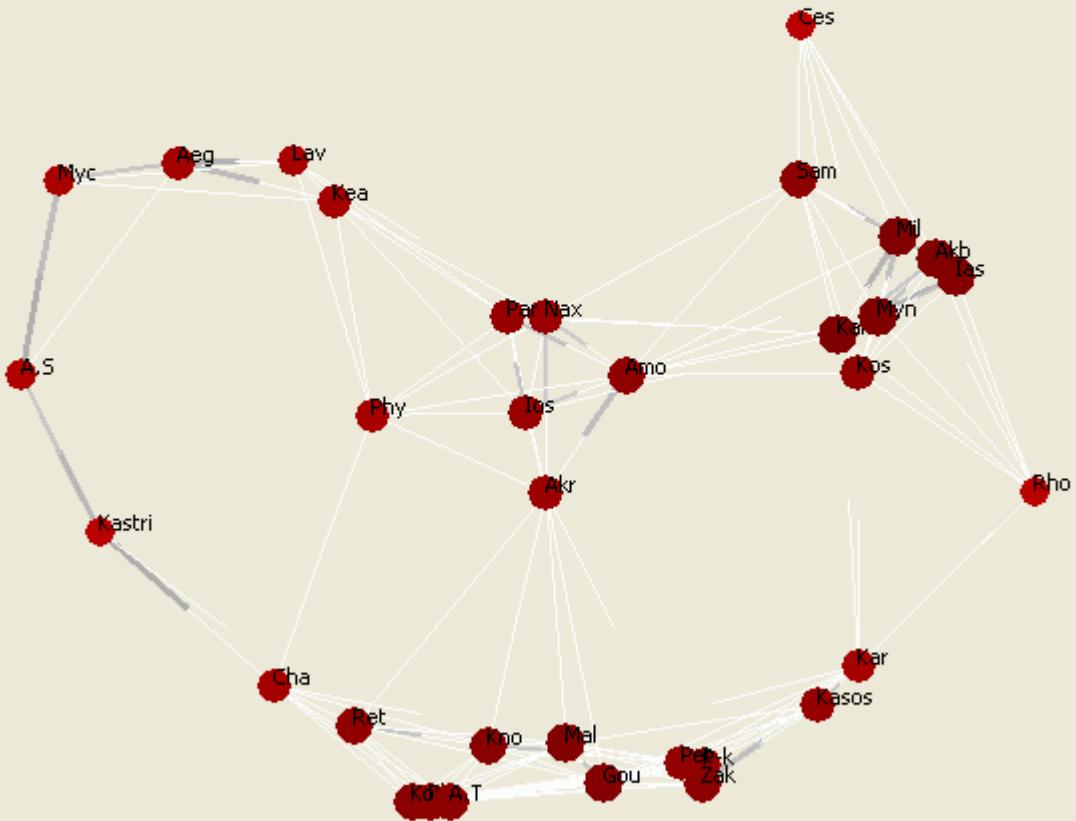
| Quantity/Value | Average | Sigma | Minimum | Maximum |
|---------------------|---------|-------|---------|---------|
| Site Weight | 0.56 | 0.06 | 0.49 | 0.66 |
| Site Out W.Strength | 0.44 | 0.22 | 0.06 | 0.66 |
| Edge Weight | 0.01 | 0.06 | 0.0 | 0.64 |
| Edge Value | 0.02 | 0.1 | 0.0 | 0.96 |

input file: aegean34
 output files: output/aegean34_v1_3e-1.0m0.5j0.0k1.0b1.2s100.0MCr0
 Model: Standard Hamiltonian+Gravity (source and target site in trade term)
 model number 1_3
 mu 0.5
 b 1.2
 beta 524288.0
 Absolute Edge Display, Max 1.0
 Monte Carlo Update
 j 0.0
 distance scale 100.0
 Zero Colour Frac 0.01
 Influence Range 1.0 (prob=0.5)
 Limits on Out Strength 1.0
 kappa 1.0
 short distance scale 5.0
 Min. Colour Frac 0.2
 sites by Size
 max vertex value 5.0
 lambda 2.0
 metric number 5.0
 Relative Vertex Display



| Quantity/Value | Average | Sigma | Minimum | Maximum |
|----------------------|---------|-------|---------|---------|
| Site Weight | 0.74 | 0.08 | 0.53 | 0.87 |
| Site Out W. Strength | 0.74 | 0.09 | 0.52 | 0.87 |
| Edge Weight | 0.02 | 0.06 | 0.0 | 0.46 |
| Edge Value | 0.03 | 0.08 | 0.0 | 0.79 |

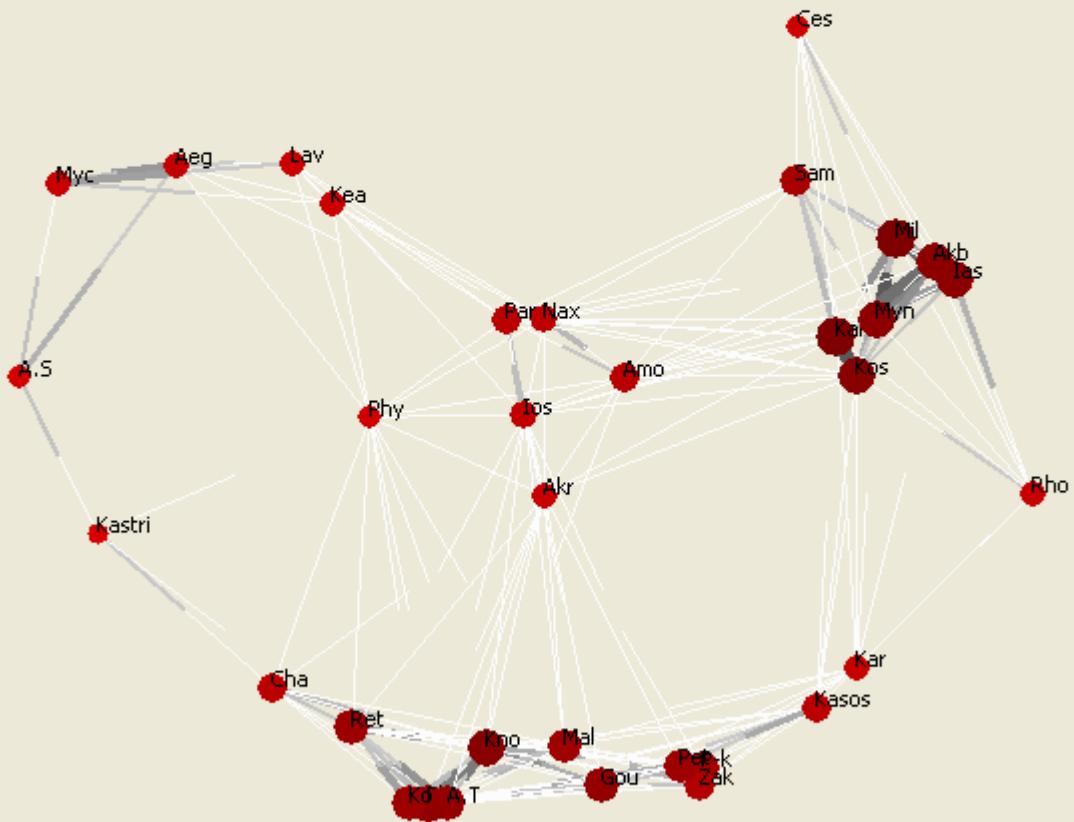
input file: aegean34
 output files: output/aegean34_v1_3e-1.0m0.5j0.0k1.0b1.2s100.0MCr0
 Model: Standard Hamiltonian+Gravity (source and target site in trade term)
 model number 1_3
 mu 0.5
 b 1.2
 beta 524288.0
 Absolute Edge Display, Max 1.0
 Monte Carlo Update
 j 0.0
 distance scale 100.0
 Zero Colour Frac 0.01
 Influence Range 1.0 (prob=0.5)
 Limits on Out Strength 1.0
 kappa 1.0
 short distance scale 5.0
 Min. Colour Frac 0.2
 sites by Size
 max vertex value 5.0
 lambda 3.0
 metric number 5.0
 Relative Vertex Display



| Quantity/Value | Average | Sigma | Minimum | Maximum |
|----------------------|---------|-------|---------|---------|
| Site Weight | 0.97 | 0.16 | 0.65 | 1.2 |
| Site Out W. Strength | 0.97 | 0.16 | 0.65 | 1.2 |
| Edge Weight | 0.03 | 0.06 | 0.0 | 0.32 |
| Edge Value | 0.03 | 0.06 | 0.0 | 0.49 |

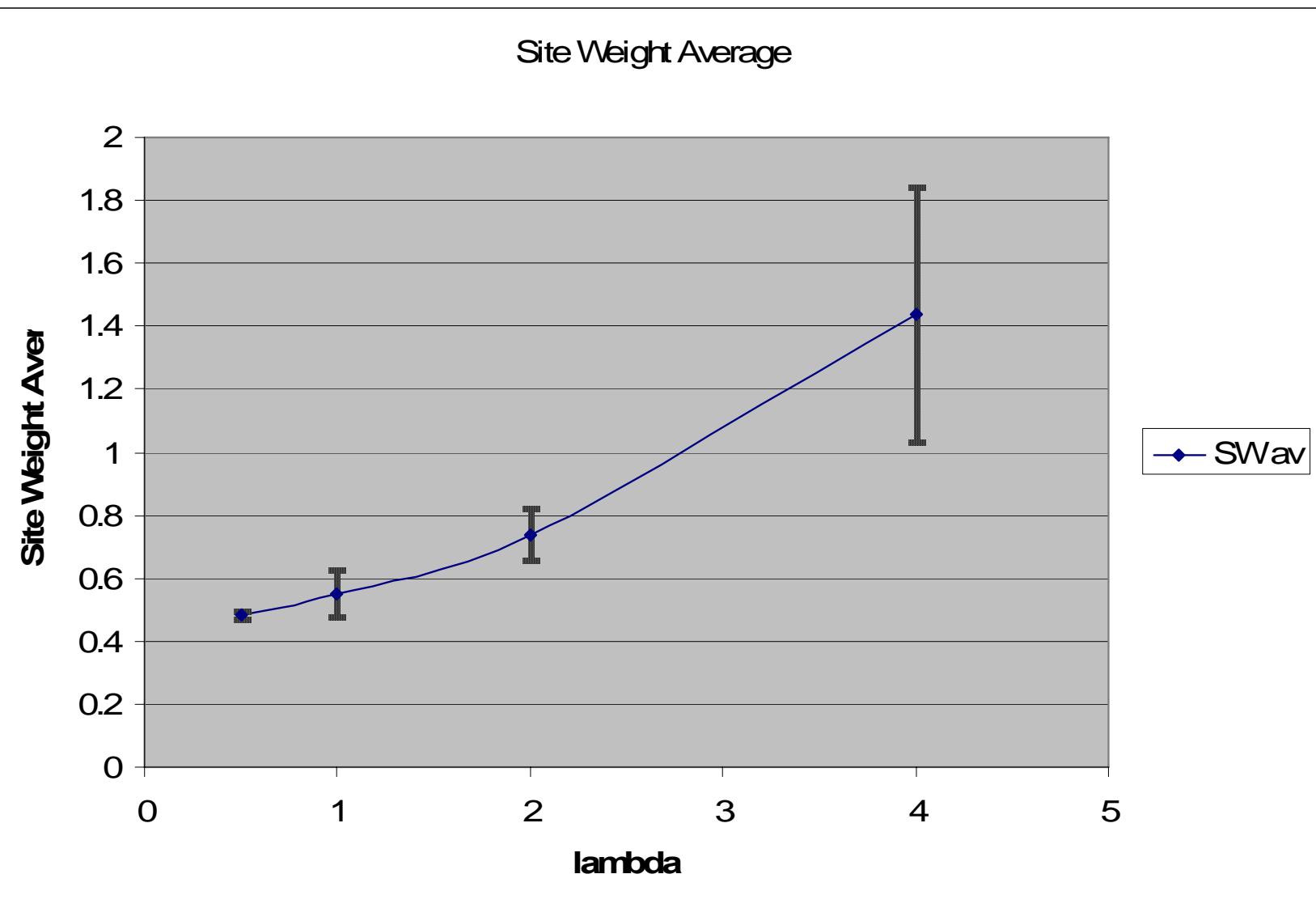
input file: aegean34
 output files: output/aegean34_v1_3e-1.0m0.5j0.0k1.0b1.2s100.0MCr0
 Model: Standard Hamiltonian+Gravity (source and target site in trade term)

| | | | |
|--------------------------------|--------------------------------|----------------------------|-------------------------|
| model number 1_3 | Monte Carlo Update | Limits on Out Strength 1.0 | max vertex value 5.0 |
| mu 0.5 | j 0.0 | kappa 1.0 | lambda 4.0 |
| b 1.2 | distance scale 100.0 | short distance scale 5.0 | metric number 5.0 |
| beta 524288.0 | Zero Colour Frac 0.01 | Min. Colour Frac 0.2 | Relative Vertex Display |
| Absolute Edge Display, Max 1.0 | Influence Range 1.0 (prob=0.5) | sites by Size | |



| Quantity/Value | Average | Sigma | Minimum | Maximum |
|----------------------|---------|-------|---------|---------|
| Site Weight | 1.52 | 0.51 | 0.73 | 2.39 |
| Site Out W. Strength | 1.51 | 0.51 | 0.73 | 2.39 |
| Edge Weight | 0.04 | 0.09 | 0.0 | 0.65 |
| Edge Value | 0.03 | 0.06 | 0.0 | 0.38 |

End of increasing λ sequence



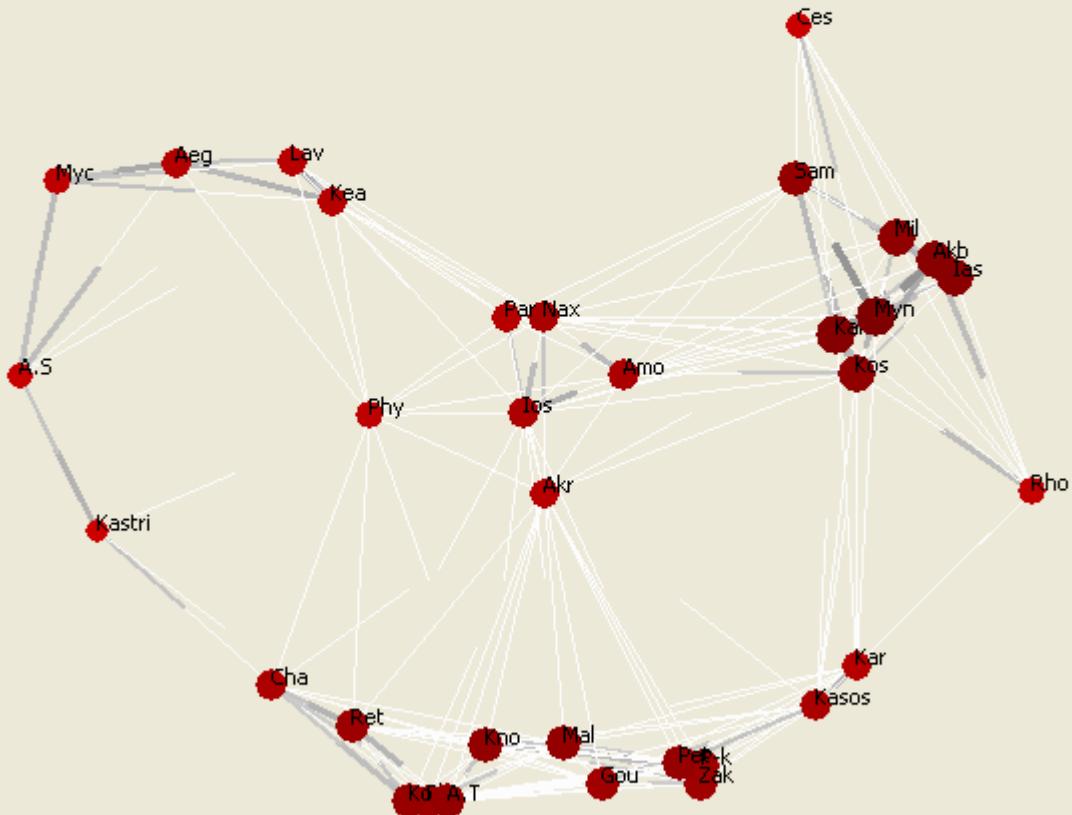
Statistical Variation Constant Values

- The variables are held constant so simple statistical variations are evident
- These are resonable, strengths of individual components vary by reasonable amounts, the details remain similar.

model number 1_3
 mu 0.5
 b 1.2
 beta 524288.0
 Absolute Edge Display, Max 1.0

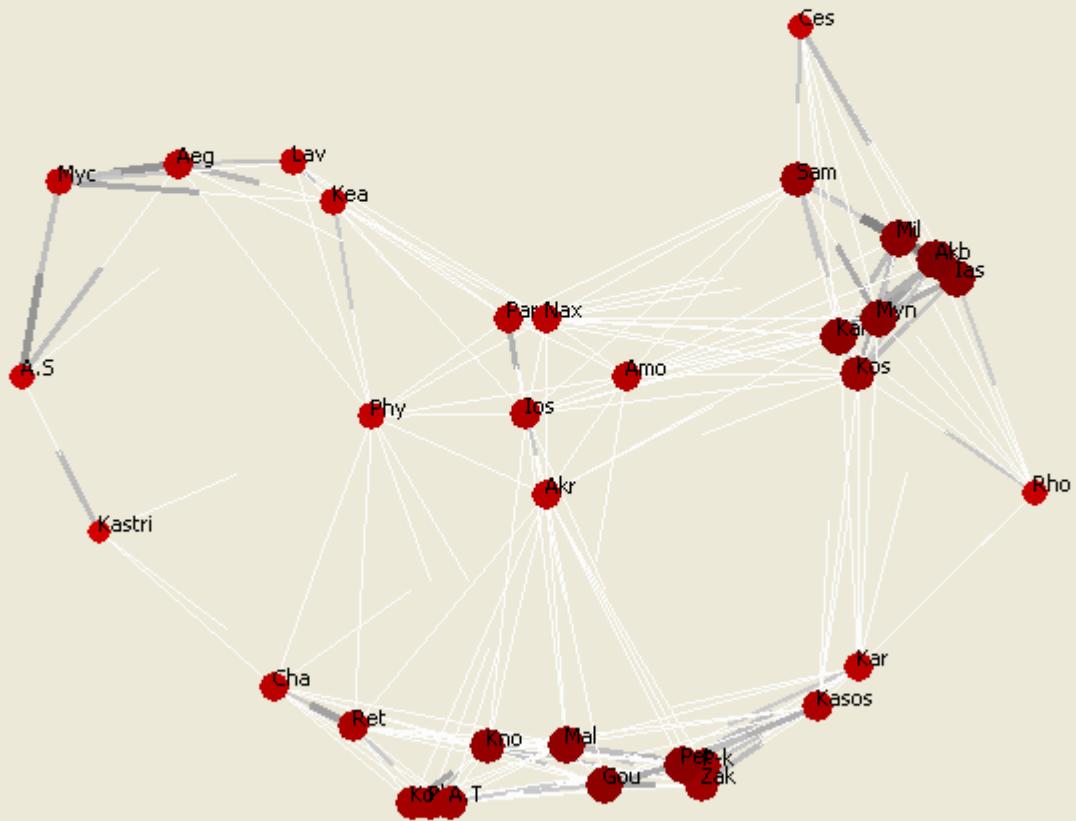
Monte Carlo Update
 j 0.0
 distance scale 100.0
 Zero Colour Frac 0.01
 Influence Range 1.0 (prob=0.5)

input file: aegean34
 output files: output/aegean34_v1_3e-1.0m0.5j0.0k1.0b1.2s100.0MCr0
 Model: Standard Hamiltonian+Gravity (source and target site in trade term)
 Limits on Out Strength 1.0
 max vertex value 5.0
 kappa 1.0
 short distance scale 5.0
 Min. Colour Frac 0.2
 Relative Vertex Display
 sites by Size



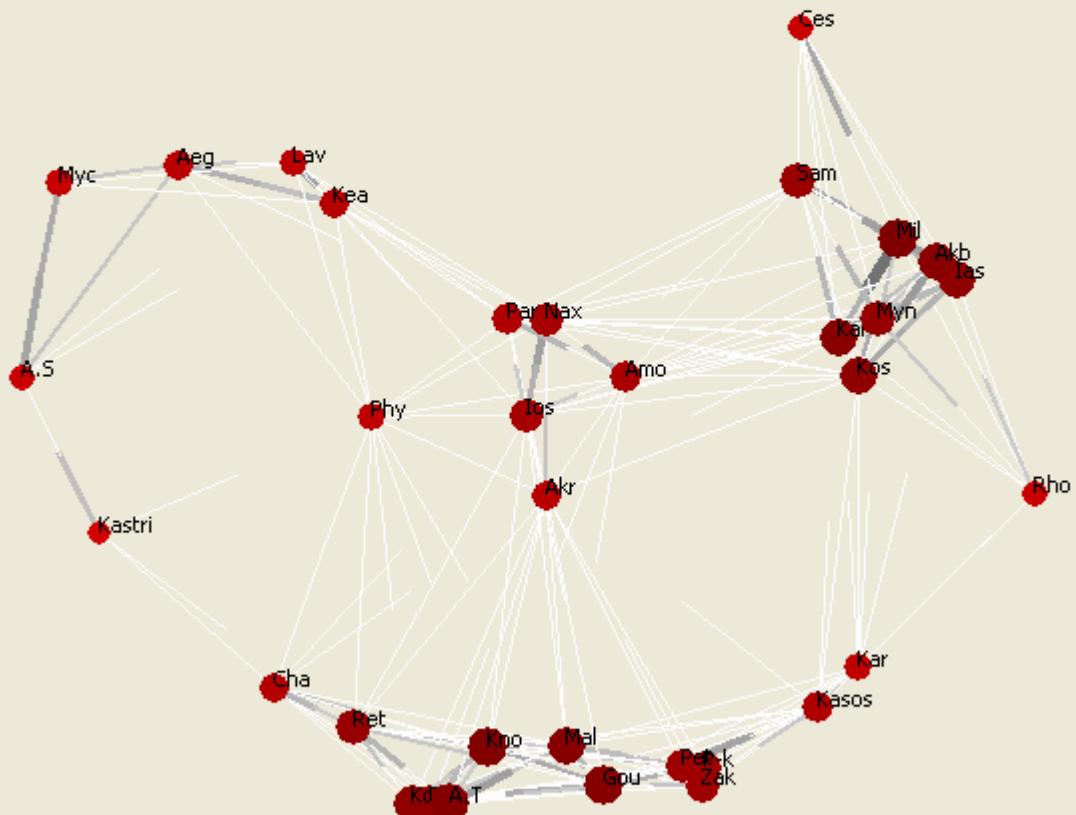
| Quantity/Value | Average | Sigma | Minimum | Maximum |
|----------------------|---------|-------|---------|---------|
| Site Weight | 1.38 | 0.33 | 0.77 | 1.99 |
| Site Out W. Strength | 1.38 | 0.33 | 0.77 | 1.99 |
| Edge Weight | 0.04 | 0.08 | 0.0 | 0.42 |
| Edge Value | 0.03 | 0.06 | 0.0 | 0.38 |

input file: aegean34
 output files: output/aegean34_v1_3e-1.0m0.5j0.0k1.0b1.2s100.0MCr1
 Model: Standard Hamiltonian+Gravity (source and target site in trade term)
 model number 1_3
 mu 0.5
 b 1.2
 beta 524288.0
 Absolute Edge Display, Max 1.0
 Monte Carlo Update
 j 0.0
 distance scale 100.0
 Zero Colour Frac 0.01
 Influence Range 1.0 (prob=0.5)
 Limits on Out Strength 1.0
 kappa 1.0
 short distance scale 5.0
 Min. Colour Frac 0.2
 sites by Size
 max vertex value 5.0
 lambda 4.0
 metric number 5.0
 Relative Vertex Display



| Quantity/Value | Average | Sigma | Minimum | Maximum |
|---------------------|---------|-------|---------|---------|
| Site Weight | 1.42 | 0.38 | 0.72 | 2.12 |
| Site Out W.Strength | 1.42 | 0.38 | 0.72 | 2.12 |
| Edge Weight | 0.04 | 0.08 | 0.0 | 0.49 |
| Edge Value | 0.03 | 0.06 | 0.0 | 0.48 |

input file: aegean34
 output files: output/aegean34_v1_3e-1.0m0.5j0.0k1.0b1.2s100.0MCr2
 Model: Standard Hamiltonian+Gravity (source and target site in trade term)
 model number 1_3
 mu 0.5
 b 1.2
 beta 524288.0
 Absolute Edge Display, Max 1.0
 Monte Carlo Update
 j 0.0
 distance scale 100.0
 Zero Colour Frac 0.01
 Influence Range 1.0 (prob=0.5)
 Limits on Out Strength 1.0
 kappa 1.0
 short distance scale 5.0
 Min. Colour Frac 0.2
 sites by Size
 max vertex value 5.0
 lambda 4.0
 metric number 5.0
 Relative Vertex Display



| Quantity/Value | Average | Sigma | Minimum | Maximum |
|----------------------|---------|-------|---------|---------|
| Site Weight | 1.45 | 0.39 | 0.72 | 2.05 |
| Site Out W. Strength | 1.45 | 0.39 | 0.72 | 2.05 |
| Edge Weight | 0.04 | 0.08 | 0.0 | 0.55 |
| Edge Value | 0.03 | 0.06 | 0.0 | 0.4 |

model number 1_3

mu 0.5

b 1.2

beta 524288.0

Absolute Edge Display, Max 1.0

Monte Carlo Update

j 0.0

distance scale 100.0

Zero Colour Frac 0.01

Influence Range 1.0 (prob=0.5)

input file: aegean34

output files: output/aegean34_v1_3e-1.0m0.5j0.0k1.0b1.2s100.0MCr3

Model: Standard Hamiltonian+Gravity (source and target site in trade term)

Limits on Out Strength 1.0

max vertex value 5.0

kappa 1.0

lambda 4.0

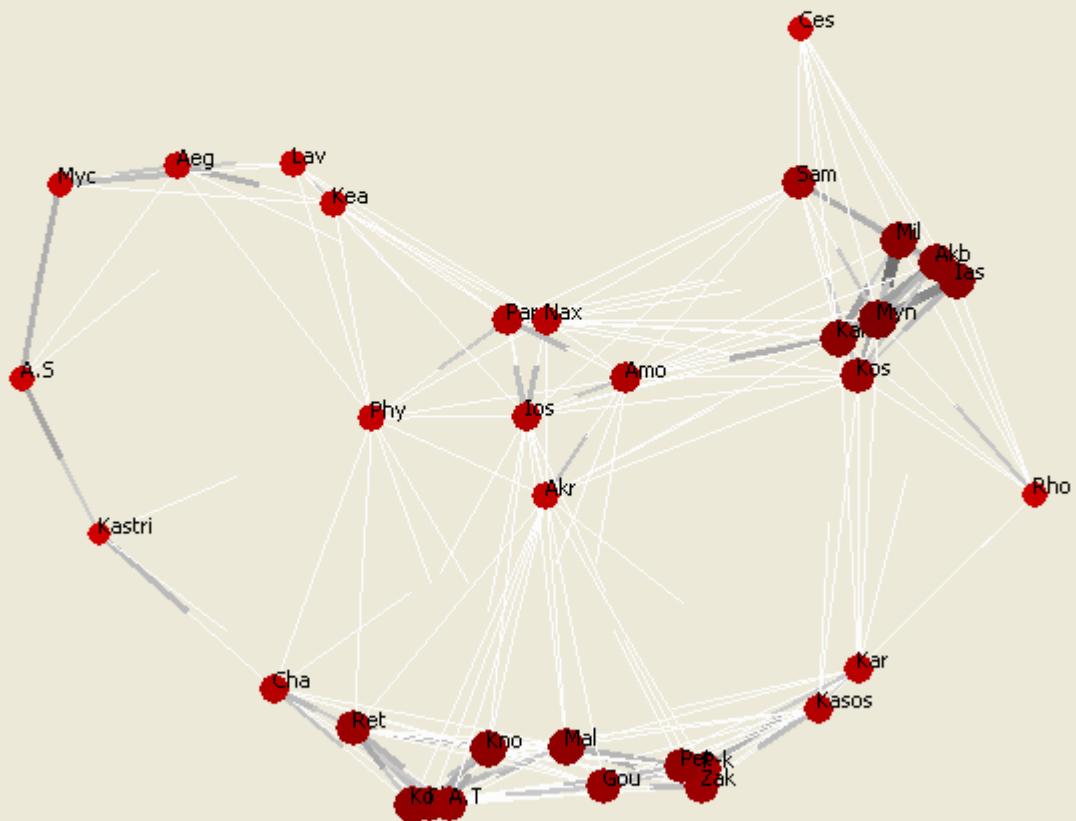
short distance scale 5.0

metric number 5.0

Min. Colour Frac 0.2

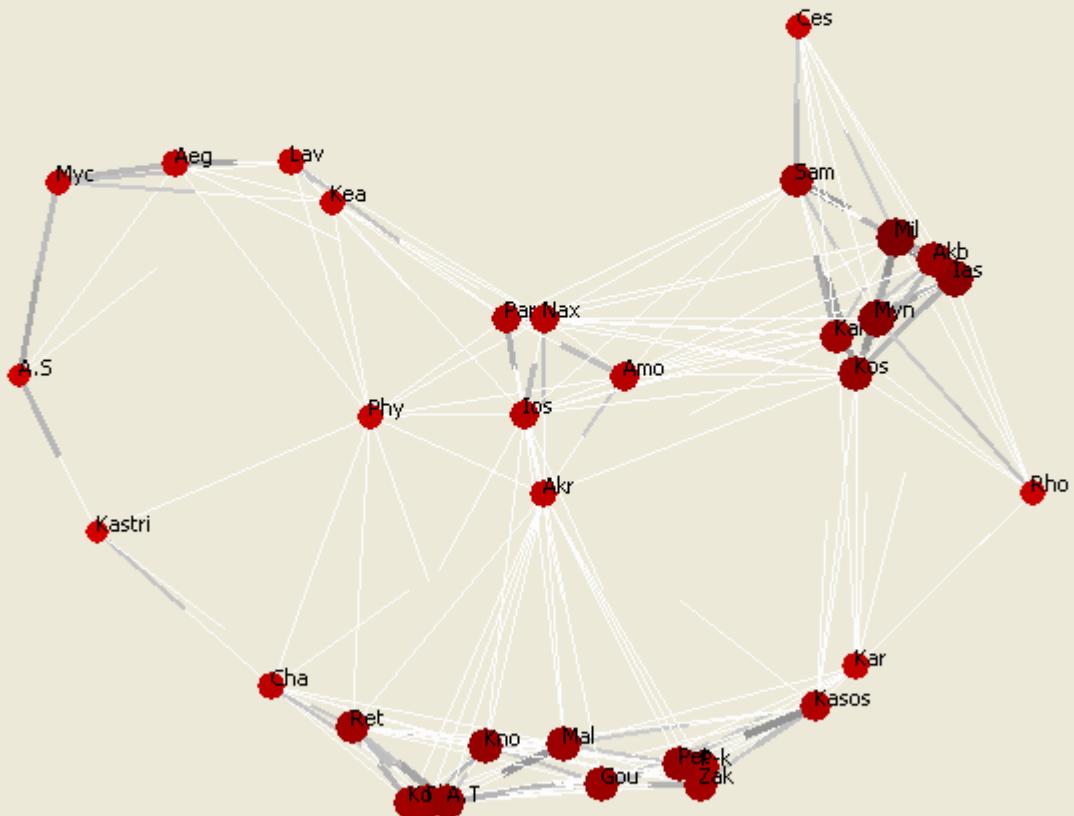
Relative Vertex Display

sites by Size



| Quantity/Value | Average | Sigma | Minimum | Maximum |
|---------------------|---------|-------|---------|---------|
| Site Weight | 1.44 | 0.4 | 0.79 | 2.15 |
| Site Out W.Strength | 1.44 | 0.41 | 0.79 | 2.15 |
| Edge Weight | 0.04 | 0.08 | 0.0 | 0.56 |
| Edge Value | 0.03 | 0.06 | 0.0 | 0.41 |

input file: aegean34
 output files: output/aegean34_v1_3e-1.0m0.5j0.0k1.0b1.2s100.0MCr4
 Model: Standard Hamiltonian+Gravity (source and target site in trade term)
 model number 1_3
 mu 0.5
 b 1.2
 beta 524288.0
 Absolute Edge Display, Max 1.0
 Monte Carlo Update
 j 0.0
 distance scale 100.0
 Zero Colour Frac 0.01
 Influence Range 1.0 (prob=0.5)
 Limits on Out Strength 1.0
 kappa 1.0
 short distance scale 5.0
 Min. Colour Frac 0.2
 sites by Size
 max vertex value 5.0
 lambda 4.0
 metric number 5.0
 Relative Vertex Display

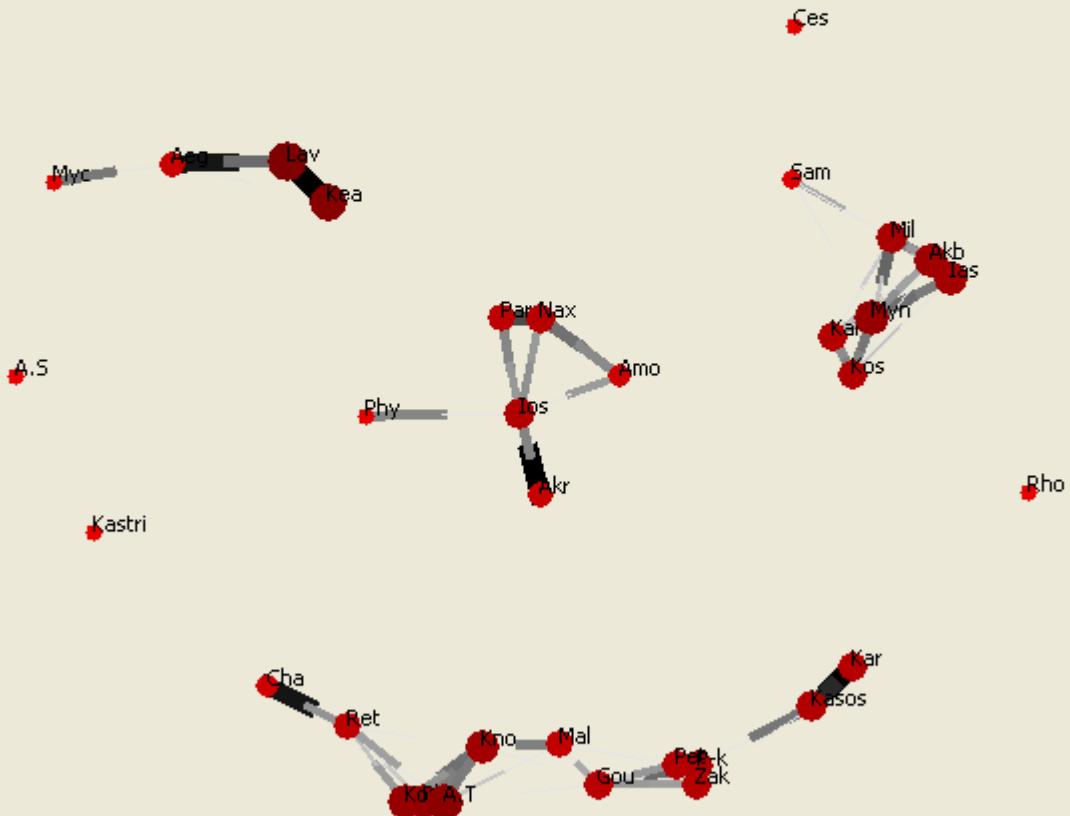


| Quantity/Value | Average | Sigma | Minimum | Maximum |
|----------------------|---------|-------|---------|---------|
| Site Weight | 1.44 | 0.39 | 0.75 | 2.24 |
| Site Out W. Strength | 1.44 | 0.39 | 0.74 | 2.24 |
| Edge Weight | 0.04 | 0.08 | 0.0 | 0.6 |
| Edge Value | 0.03 | 0.06 | 0.0 | 0.4 |

Range of Distance Scales (d)

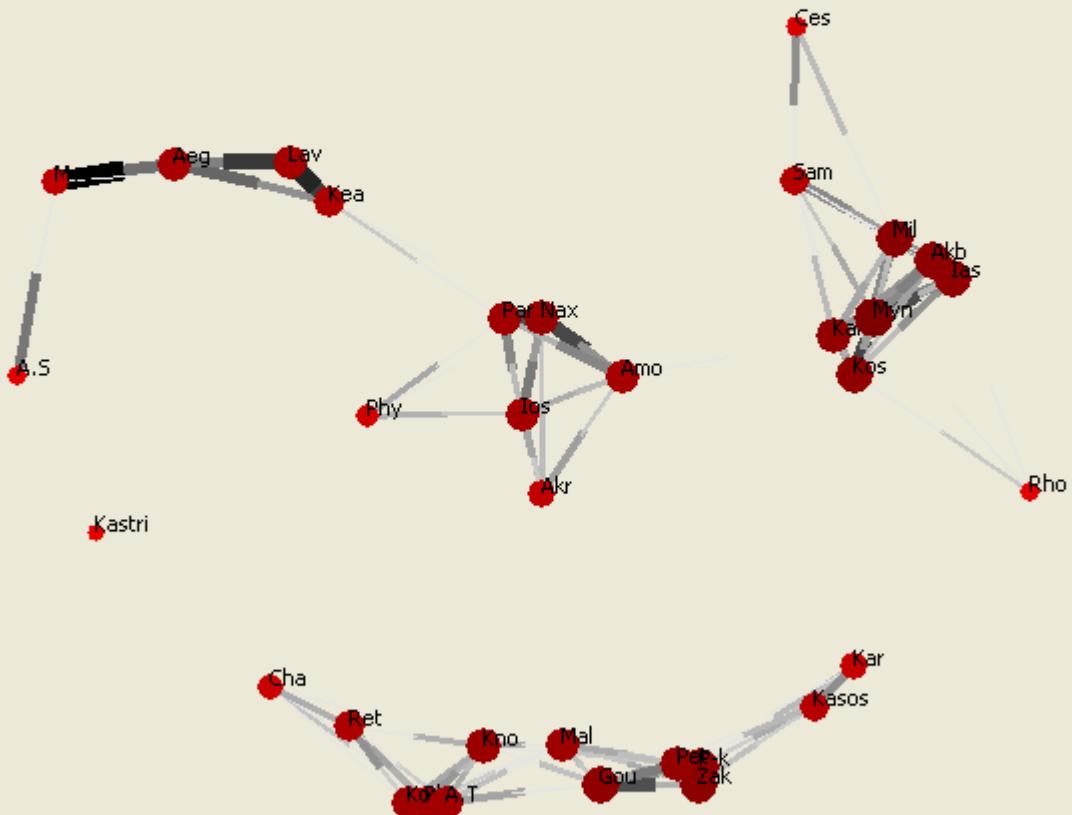
- Next 4 slides

input file: aegean34
 output files: output/aegean34_v1_3e-1.0m1.0j0.0k1.0b1.2s50.0MCr0
 Model: Standard Hamiltonian+Gravity (source and target site in trade term)
 model number 1_3
 mu 1.0
 b 1.2
 beta 524288.0
 Absolute Edge Display, Max 1.0
 Monte Carlo Update
 j 0.0
 distance scale 50.0
 Zero Colour Frac 0.1
 Influence Range 1.0 (prob=0.5)
 Limits on Out Strength 1.0
 kappa 1.0
 short distance scale 5.0
 Min. Colour Frac 0.2
 sites by Size
 max vertex value 5.0
 lambda 4.0
 metric number 5.0
 Relative Vertex Display



| Quantity/Value | Average | Sigma | Minimum | Maximum |
|----------------------|---------|-------|---------|---------|
| Site Weight | 1.38 | 0.57 | 0.48 | 2.52 |
| Site Out W. Strength | 1.32 | 0.65 | 0.07 | 2.5 |
| Edge Weight | 0.04 | 0.16 | 0.0 | 2.29 |
| Edge Value | 0.03 | 0.1 | 0.0 | 0.97 |

input file: aegean34
 output files: output/aegean34_v1_3e-1.0m1.0j0.0k1.0b1.2s75.0MCr0
 Model: Standard Hamiltonian+Gravity (source and target site in trade term)
 model number 1_3
 mu 1.0 Monte Carlo Update
 b 1.2 j 0.0
 beta 524288.0 distance scale 75.0
 Absolute Edge Display, Max 1.0 Zero Colour Frac 0.1
 Monte Carlo Update
 Influence Range 1.0 (prob=0.5) sites by Size
 Limits on Out Strength 1.0
 kappa 1.0 max vertex value 5.0
 short distance scale 5.0 lambda 4.0
 Min. Colour Frac 0.2 metric number 5.0
 Relative Vertex Display



| Quantity/Value | Average | Sigma | Minimum | Maximum |
|----------------------|---------|-------|---------|---------|
| Site Weight | 1.6 | 0.52 | 0.48 | 2.42 |
| Site Out W. Strength | 1.58 | 0.54 | 0.08 | 2.42 |
| Edge Weight | 0.05 | 0.13 | 0.0 | 1.03 |
| Edge Value | 0.03 | 0.08 | 0.0 | 0.96 |

model number 1_3

mu 1.0

b 1.2

beta 524288.0

Absolute Edge Display, Max 1.0

Monte Carlo Update

j 0.0

distance scale 100.0

Zero Colour Frac 0.1

Influence Range 1.0 (prob=0.5)

input file: aegean34

output files: output/aegean34_v1_3e-1.0m1.0j0.0k1.0b1.2s100.0MCr0

Model: Standard Hamiltonian+Gravity (source and target site in trade term)

Limits on Out Strength 1.0

max vertex value 5.0

kappa 1.0

lambda 4.0

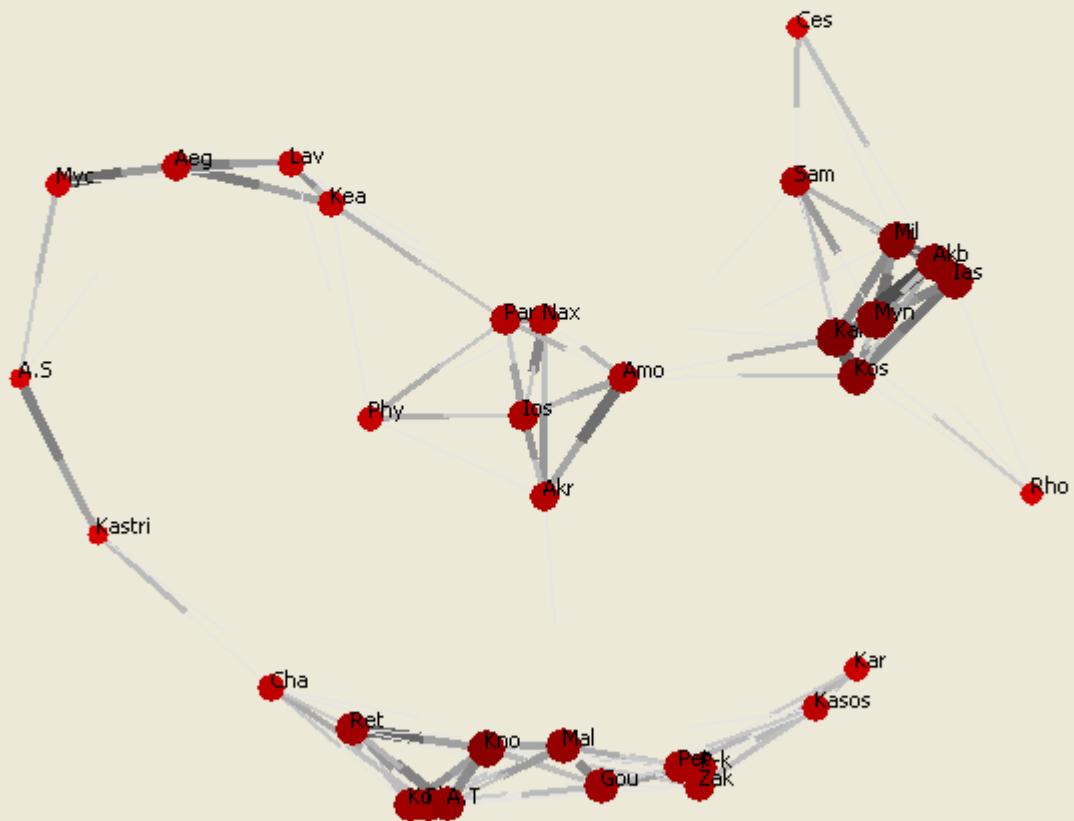
short distance scale 5.0

metric number 5.0

Min. Colour Frac 0.2

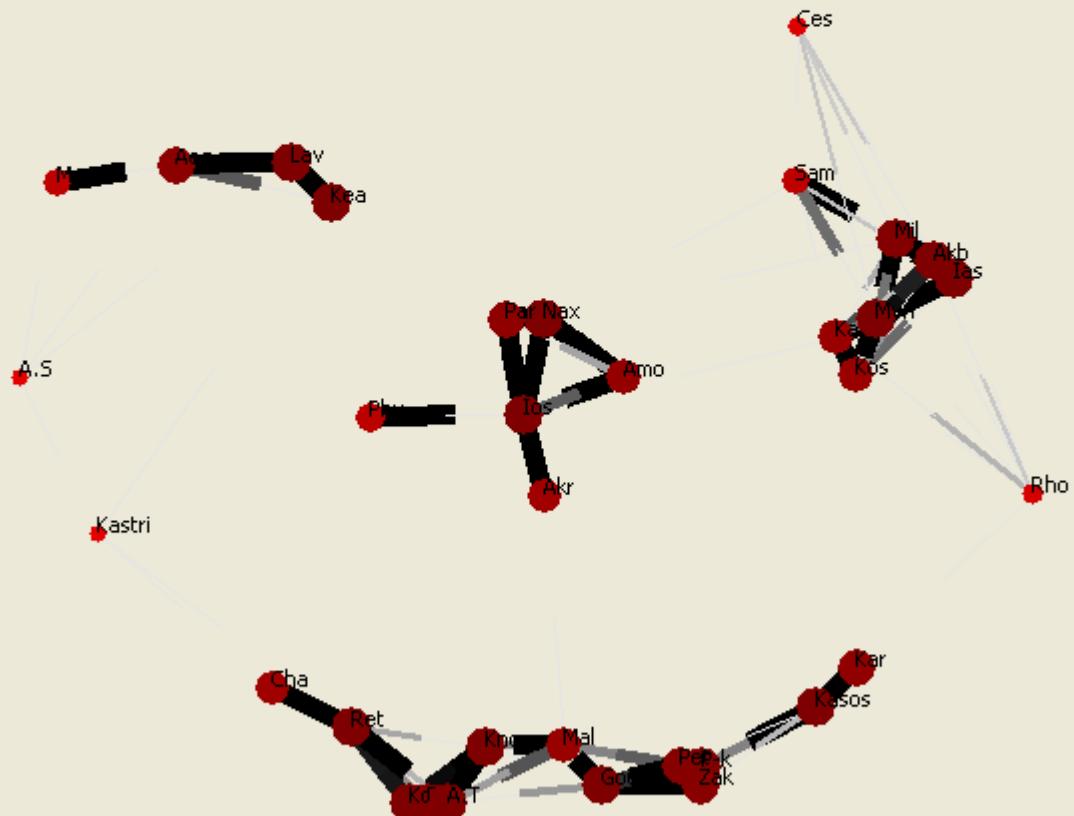
Relative Vertex Display

sites by Size



| Quantity/Value | Average | Sigma | Minimum | Maximum |
|---------------------|---------|-------|---------|---------|
| Site Weight | 1.78 | 0.56 | 0.82 | 2.74 |
| Site Out W.Strength | 1.78 | 0.56 | 0.82 | 2.74 |
| Edge Weight | 0.05 | 0.12 | 0.0 | 0.69 |
| Edge Value | 0.03 | 0.07 | 0.0 | 0.57 |

input file: aegean34
 output files: output/aegean34_v1_3e-1.0m1.0j0.0k1.0b1.2s125.0MCr0
 Model: Standard Hamiltonian+Gravity (source and target site in trade term)
 model number 1_3
 mu 1.0 Monte Carlo Update
 b 1.2 j 0.0
 beta 524288.0 distance scale 125.0
 Absolute Edge Display, Max 1.0 Zero Colour Frac 0.1
 Influence Range 1.0 (prob=0.5) sites by Size
 Limits on Out Strength 1.0
 kappa 1.0 max vertex value 5.0
 short distance scale 5.0 lambda 4.0
 Min. Colour Frac 0.2 metric number 5.0
 Relative Vertex Display



| Quantity/Value | Average | Sigma | Minimum | Maximum |
|---------------------|---------|-------|---------|---------|
| Site Weight | 4.07 | 1.26 | 1.0 | 5.0 |
| Site Out W.Strength | 4.07 | 1.26 | 1.0 | 5.0 |
| Edge Weight | 0.12 | 0.43 | 0.0 | 4.82 |
| Edge Value | 0.03 | 0.1 | 0.0 | 0.96 |

Network Description

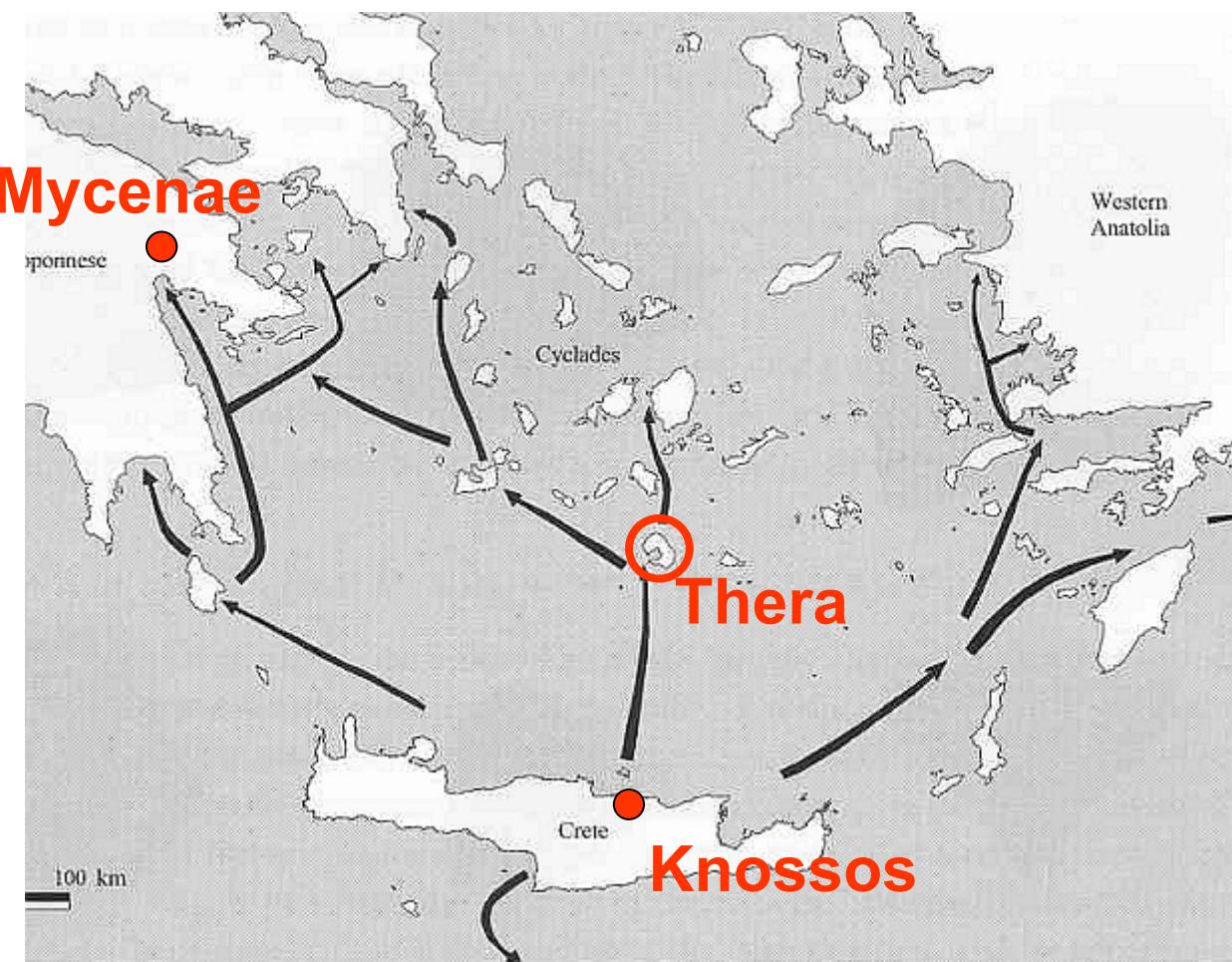


- d_{ij} Fixed distance between sites identified from the archaeological record
may be physical but may include penalties for prevailing winds, currents, land travel, ...
- S_i Fixed site size = maximum local resources
- v_i Variable site occupation fraction
so if $v_i > 1$ then site needs external resources
 - » Site **Weight** ($S_i v_i$) = Site `population'
- e_{ij} Fractional Edge values $0 \leq \sum_j e_{ij} \leq 1$
 - » Edge **Weights** ($S_i v_i e_{ij}$)
= 'Trade' (interaction) going from site i to site j

Robustness

- Are we finding a model that gives us the results we want?
 - Select on the basis of some pre-determined notion of reasonable results.
 - Do comparisons, do not use absolute results
- Do results depend on fine details of model?
 - Topological Congruence, Universality Classes
- Do results depend on how we encode the input data?
 - Scaling behaviour - when is an archaeological site a vertex?

Middle Bronze Age Aegean (2000-1500 BC)



Palaces on Crete

‘Minoanisation’ begins

Theran eruption 1600 BC

‘Collapse’ – 1500 BC

DIFFERENT TO EBA
of Broodbank (2000)

Ø Scale of networks

Ø Uneven site size

Ø Length of links

Ø Directionality

Brief Chronology of the Aegean

| Neolithic | 7000 BC | •Initial colonisation – introduction of farming |
|-----------|---------|---|
| E | 4000 BC | •Secondary colonisation of small islands |
| B | 2500BC | •Nucleation and hierarchy in 3 rd millennium BC |
| A | 2200 BC | •Partial collapse? |
| M | 1900BC | •Emergence of Minoan civilisation in 2 nd mill BC on Crete, sail technology appears |
| B | 1500BC | •Collapse |
| L | 1450 BC | •Mycenaean mainlanders emerging power |
| B | 1200 BC | •Bronze Age collapse |
| A | 1100 BC | •‘Dark Ages’ |

Efficiency?

- Need not be space filling in any sense.
- Need not be lowest number of links needed to connect all sites **(Minimal Spanning Tree)**.
- ‘Deliberate Waste’ -
may well favour redundancy to reduce path lengths, to increase possible interactions, to increase resilience to change.

Site Strength

