Prehistoric demography and the spread of the Neolithic: mathematical models based on radiocarbon dates

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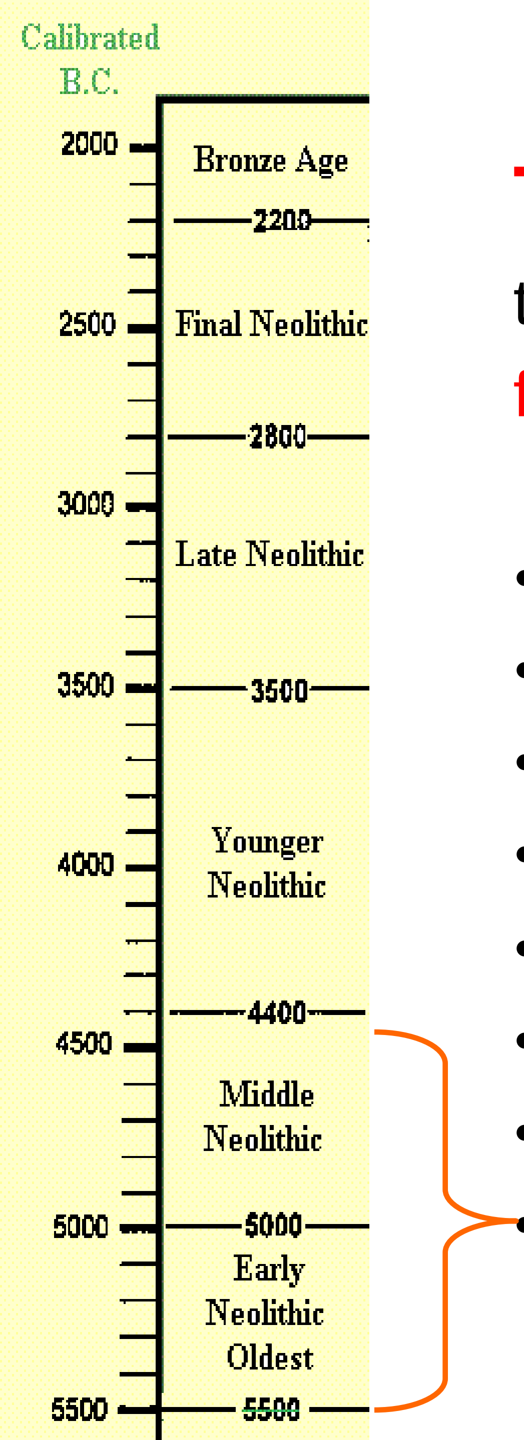
Outline

- **The Neolithic revolution**

- **Radiocarbon dating**

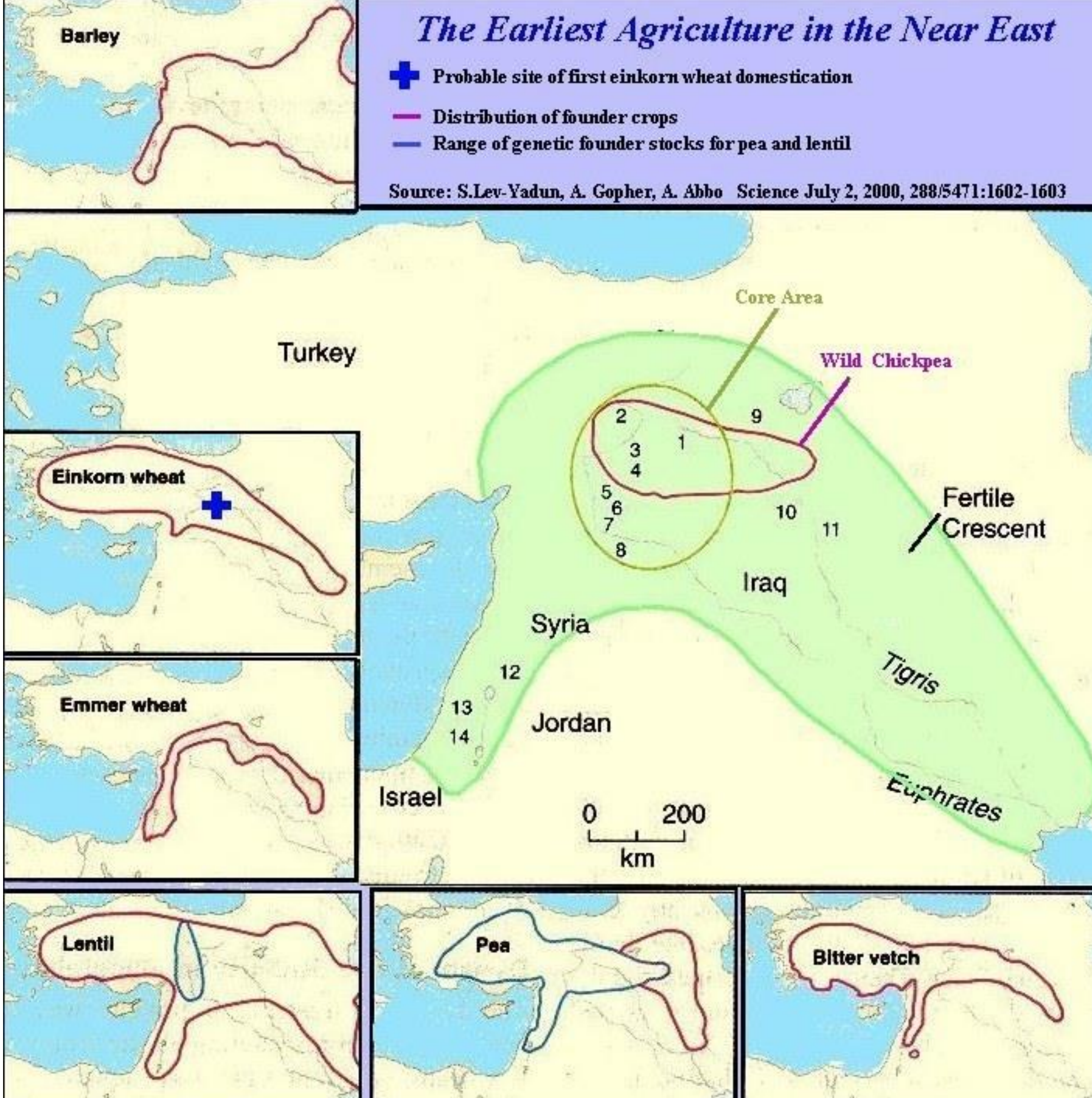
- **Modelling Neolithic population dynamics**
  - Western Europe: spread from the Near East
  - Pan-European model: spread from two centres



The Neolithic:

transition from food gathering to food production

- Origin in the *Fertile Crescent*
- Agro-pastoral farming
- Use of polished stone & bone tools
- Pottery making
- Settled lifestyle
- Rapid population growth
- Spread to Europe and Asia in 7-4 kyr BC
- 5000 BC: world population 5-20 mln

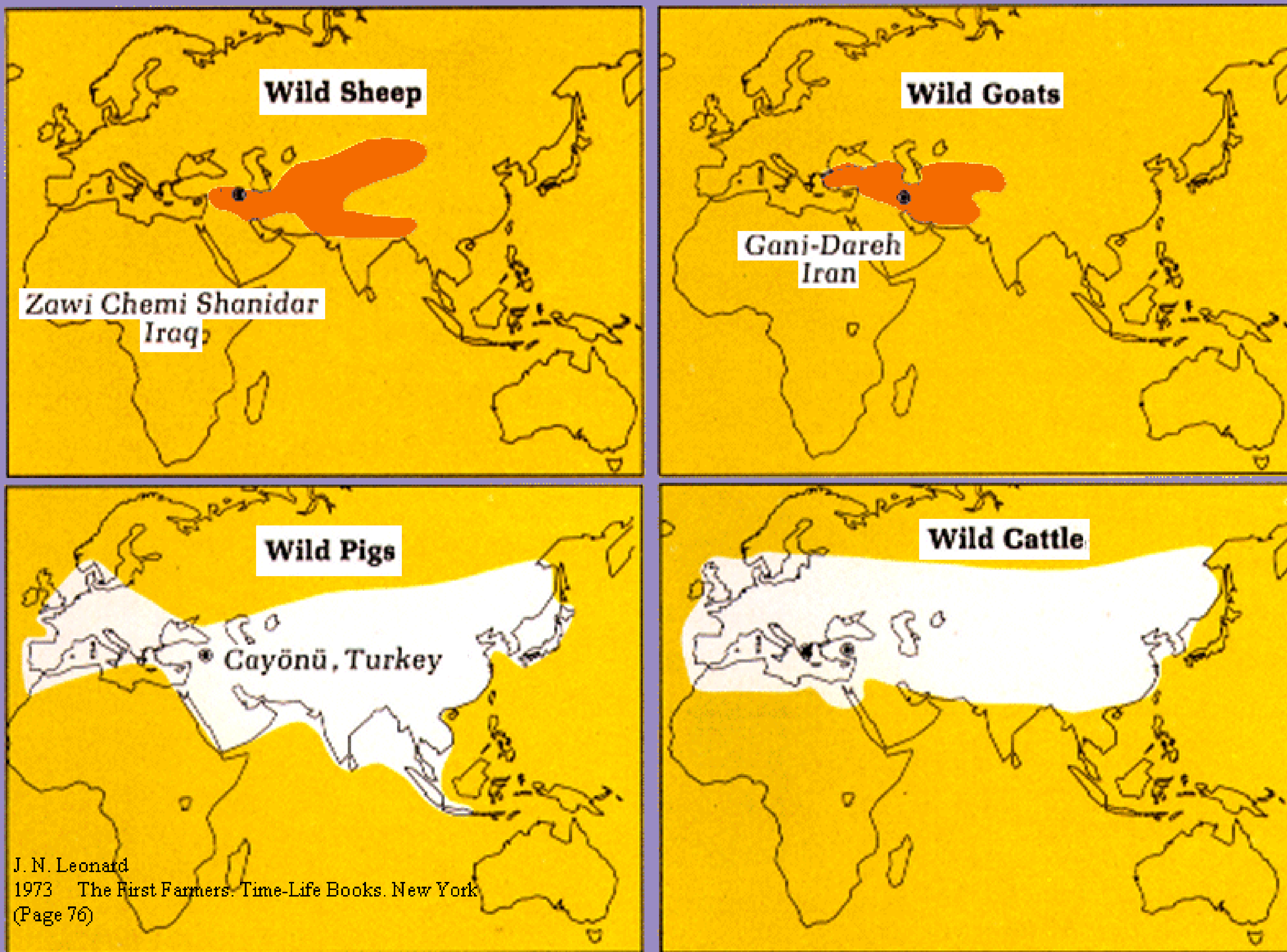


Neolithic Sites in the Fertile Crescent

1. Cayönü
2. Cafer Hüyük
3. Nevali Çori
4. Göbekli Tepe
5. Djade
6. Jerf el-Ahmar
7. Tell Mureybet
8. Tell Abu Hureyra
9. Hallan Çemi Tepesi
10. Qermez Dere
11. Milefaat
12. Tell Aswad
13. Yiftahíel
14. Jericho

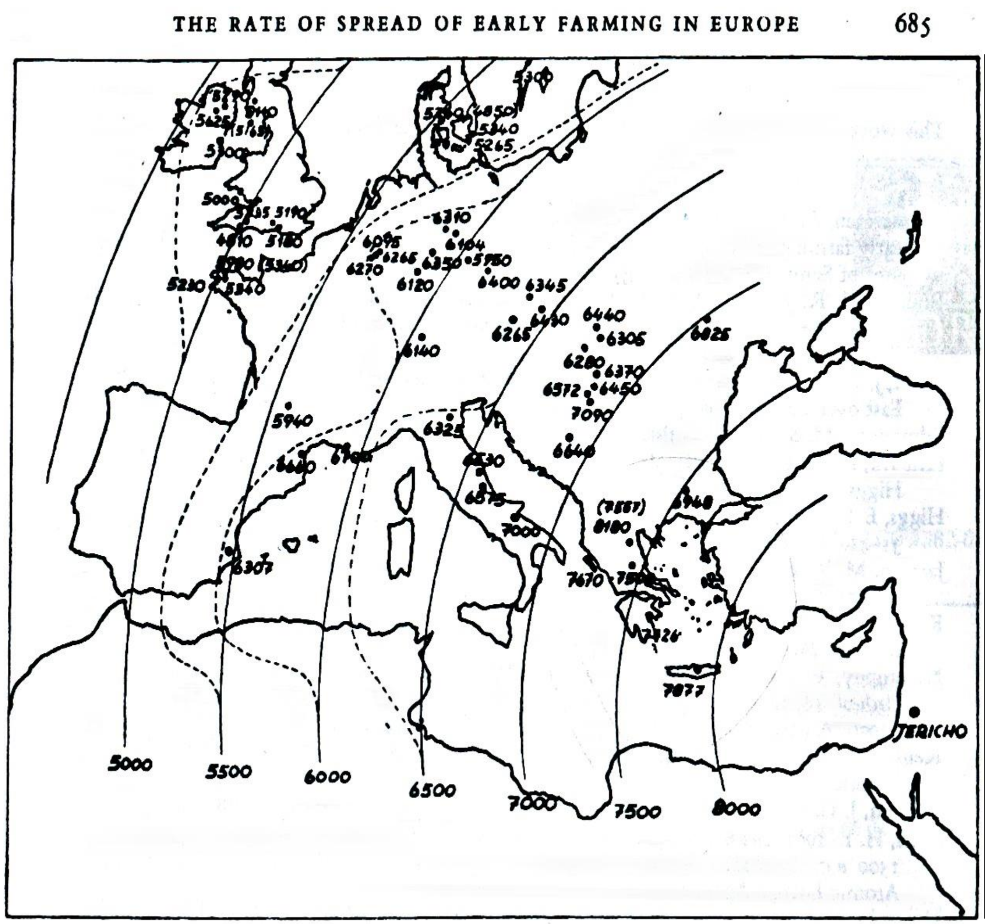
Computer modified Jan. 2001
M. O. Baldia

Distribution of aild animals and the location of sites with evidence of early domestication.

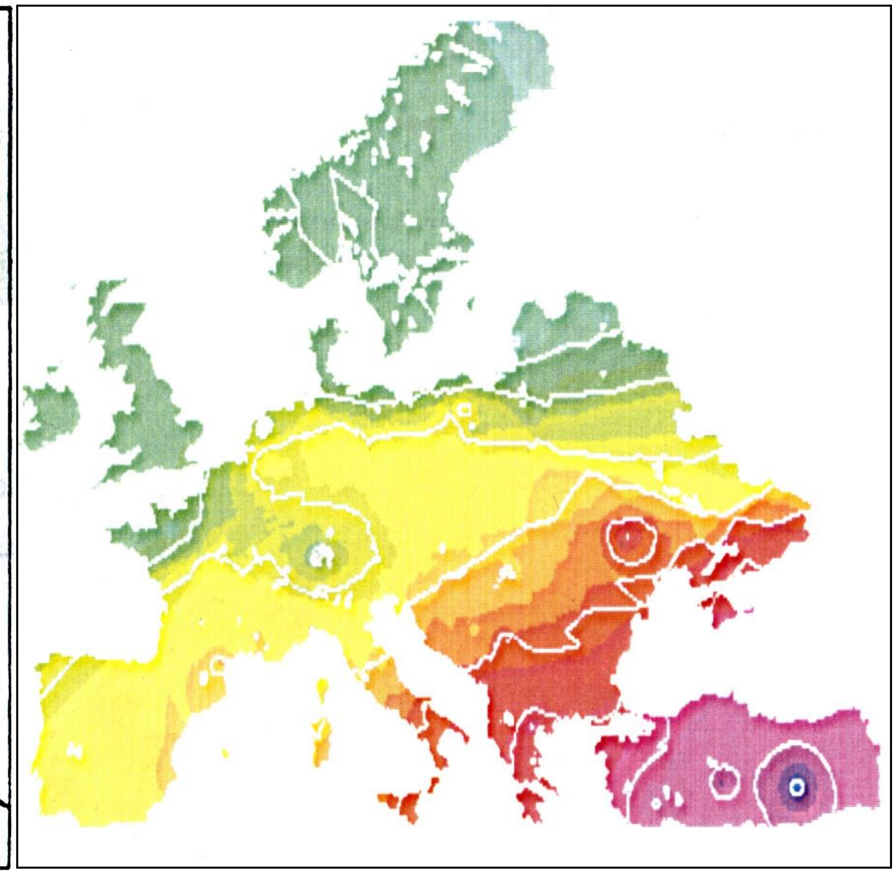


J. N. Leonard
1973 The First Farmers. Time-Life Books. New York
(Page 76)

The spread of farming to Europe:
evidence from radiocarbon dating



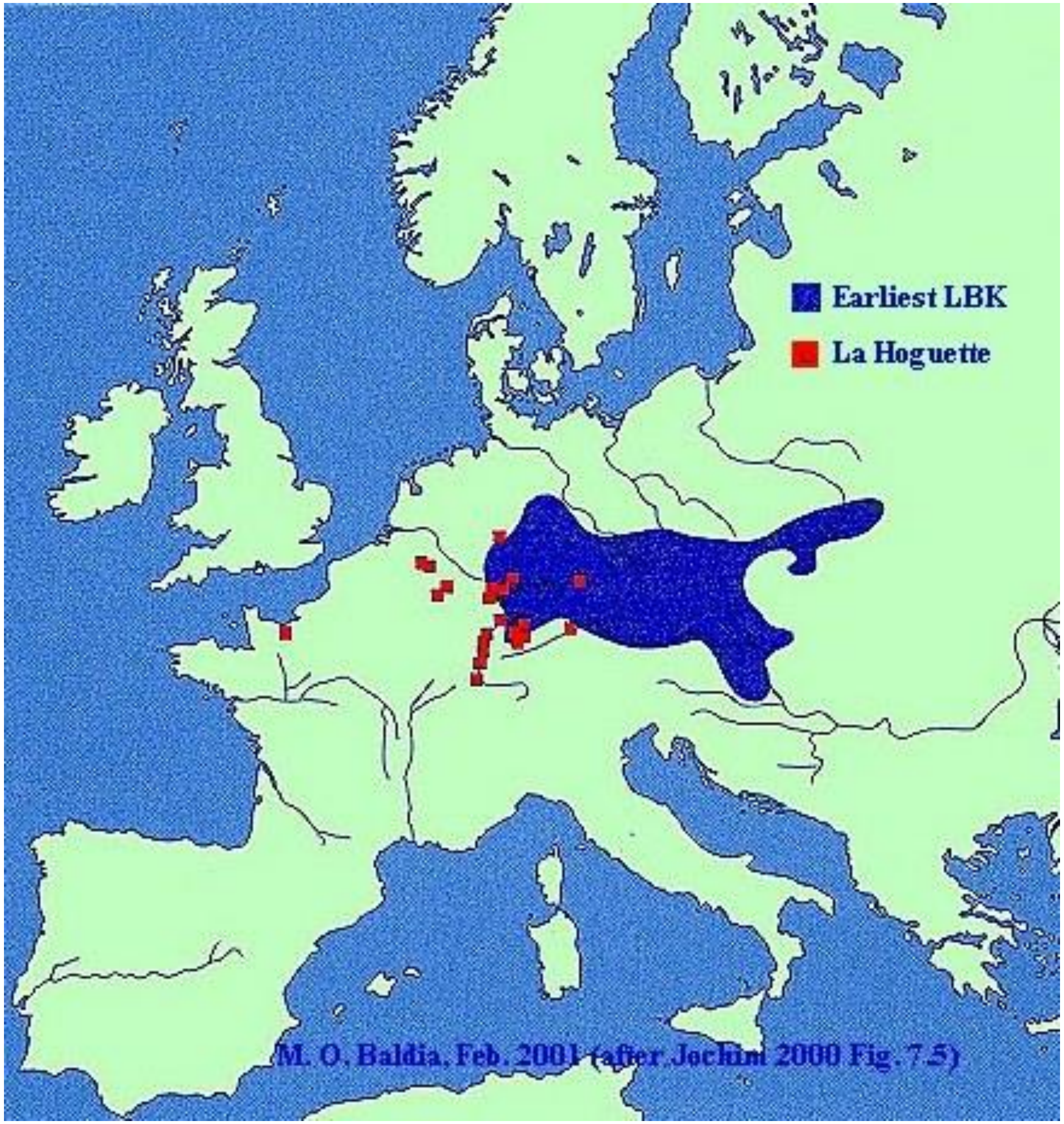
Ammerman & Cavalli-Sforza. *Man* **6**, 674, 1971



Gkiasta et al. *Antiquity*, **77**, 45, 2003

Wave of advance, $\langle\bar{U}\rangle$=1 km/yr; regional variations U=5-10 km/yr

The Linearbandkeramik (LBK) tradition



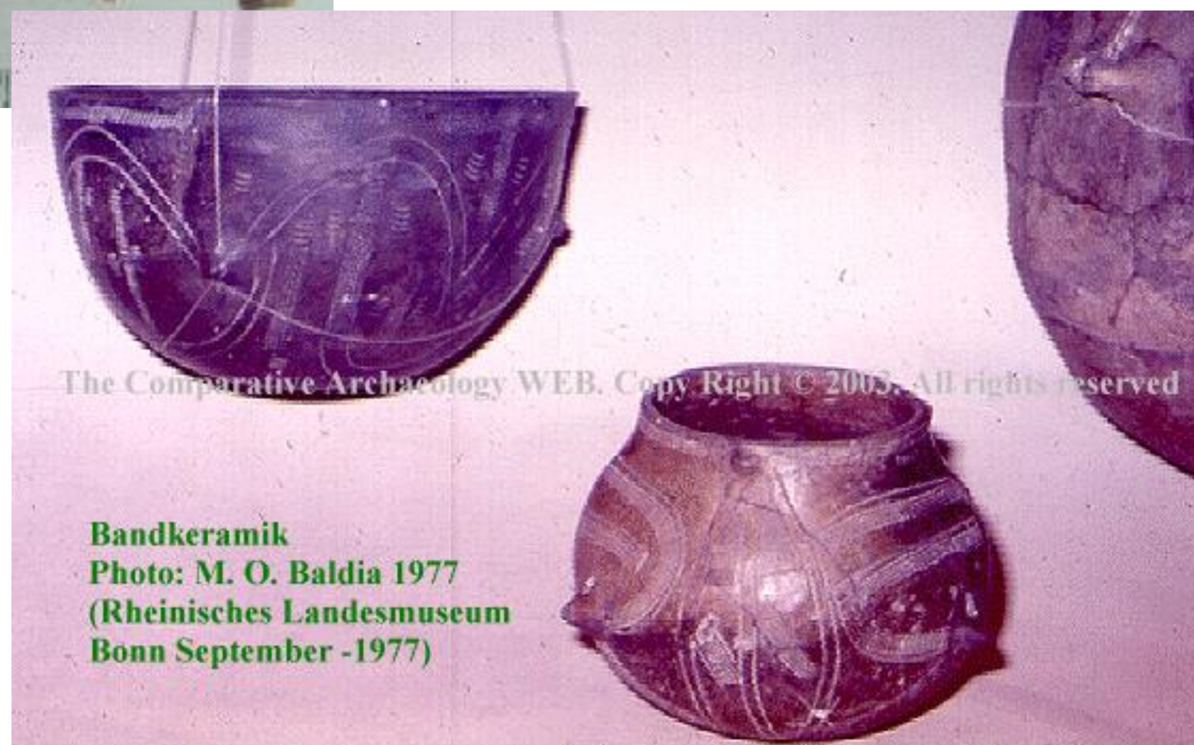
- 5.5-5 kyr BC
- First farmers in Europe
- Rapid spread along the **Danube-Rhine** corridor
- Rate of spread 4-6 km/year

LBK people: the first farmers in Europe

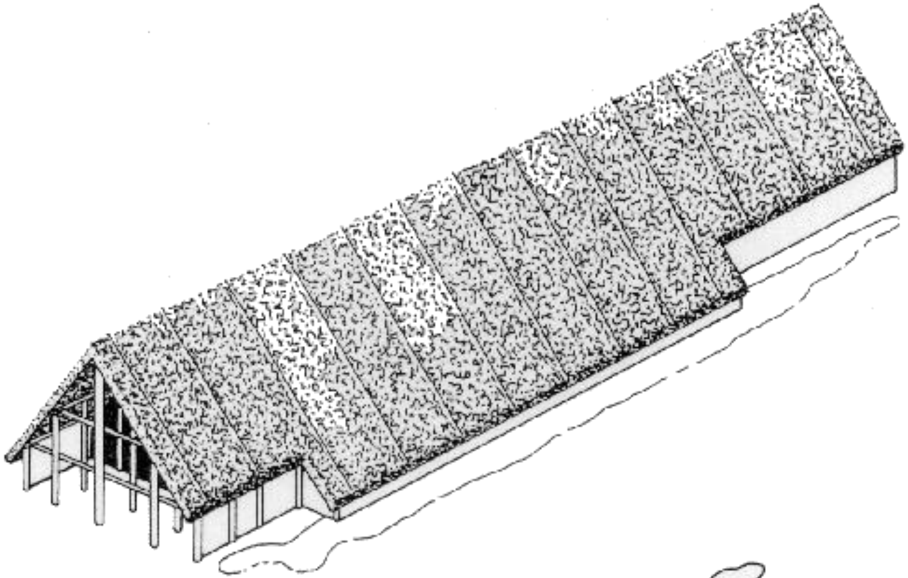
Stone implements and idol figurine from Brunn-am-Gebirge, Austria

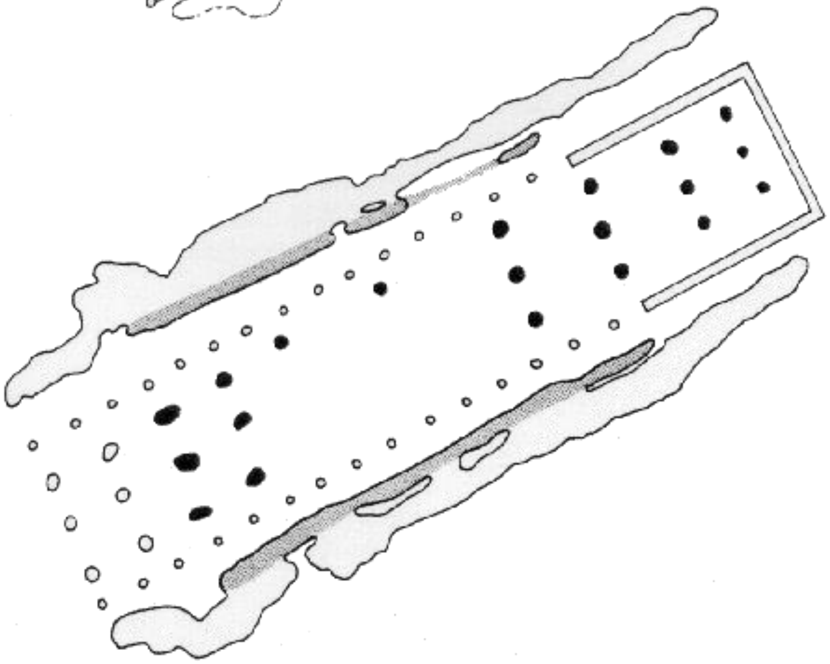
and

pottery from the Rhine



Reconstruction of a house from Brunn-am-Gebirge, Austria





Swidden agriculture (Eero Järnefelt 1863-1937)

Lough Gur,
Co. Limerick

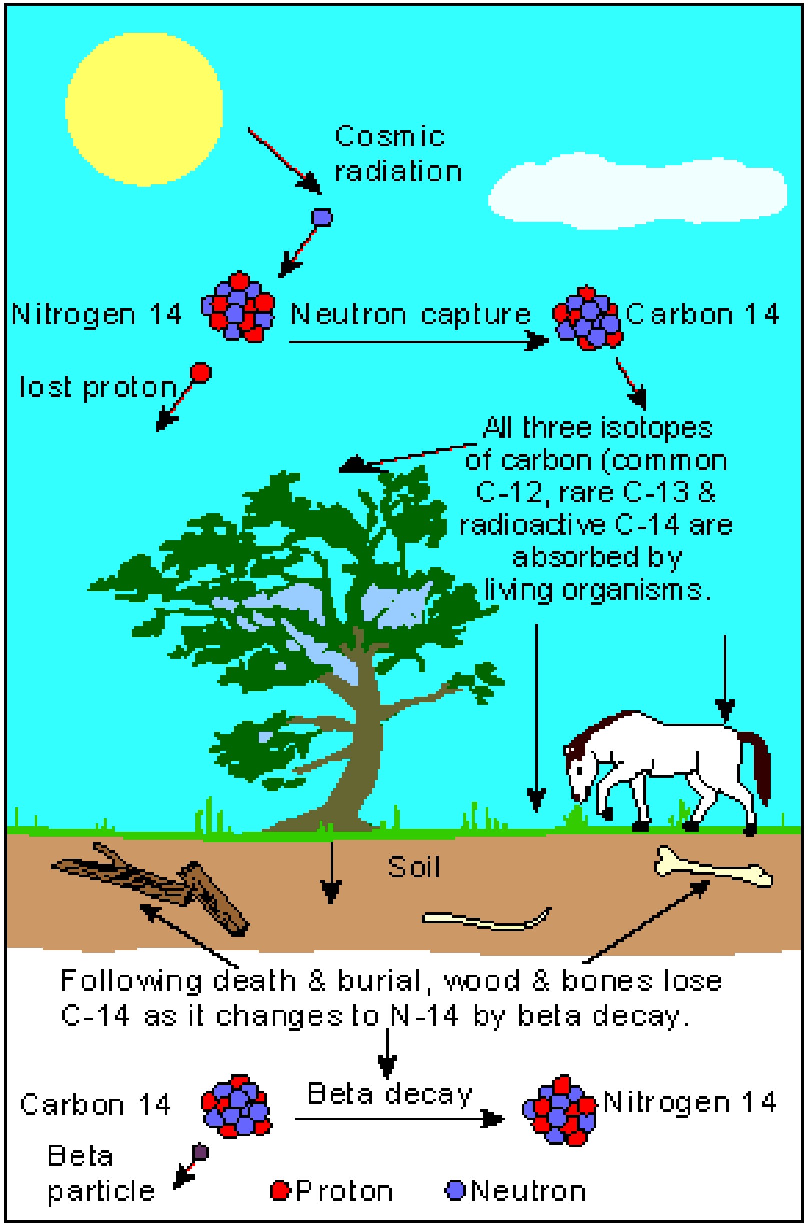
Alabaster statuette, Samarran site (northern Iraq), c.6000 BC. Eyes inlaid with bitumin.

Vase from Dimini, Greece, h25 cm, 5300-4800 BC

Vase from Sesklo, Greece, h35 cm, 5300-3800 BC

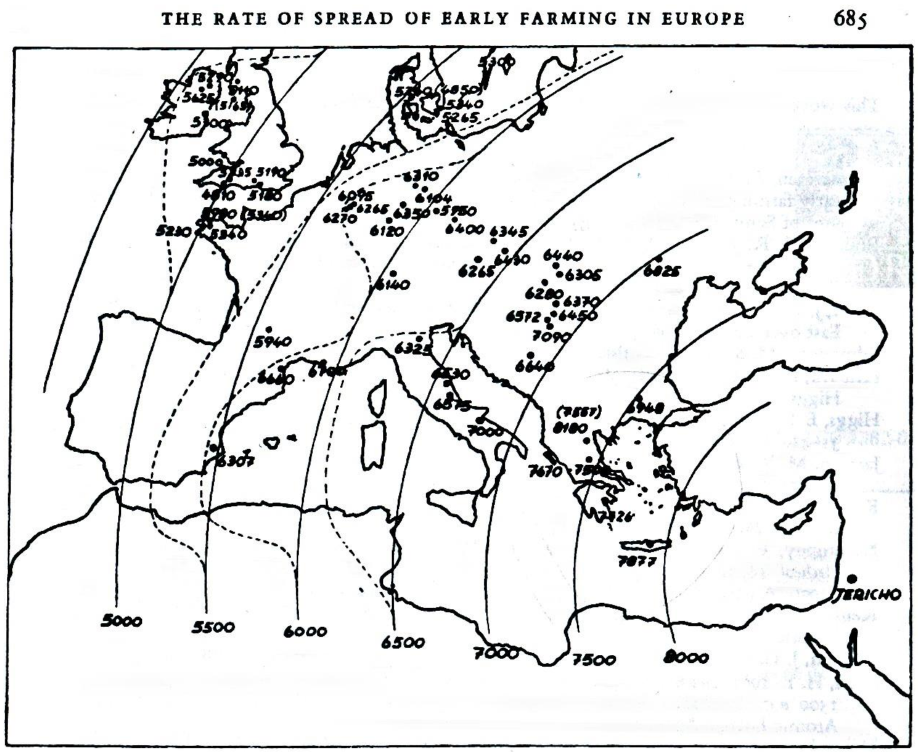
`Ain Ghazal, Jordan, around 6500 B.C.
Plaster and bitumen, H104 & 88 cm
(http://www.asia.si.edu/jordan/html/jor_mm.htm)

Radiocarbon dating

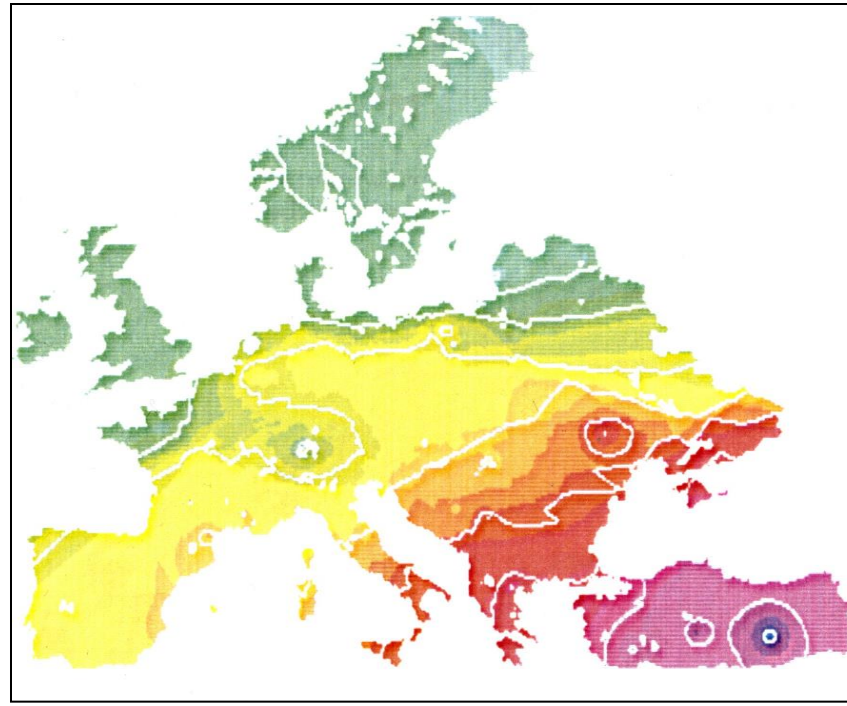


- $n + {}^{14}N \rightarrow {}^{14}C + p^+$
- at 10-15 km altitude
- 10^{-10} of ^{14}C
- $^{14}C \rightarrow {}^{14}N + e^-$
- half-life ≈ 5730 yr
- No exchange with the reservoir ⇒ ^{14}C decays

The spread of the Neolithic in Europe



Ammerman & Cavalli-Sforza, *Man*, **6**, 674, 1971



Gkiasta et al., *Antiquity*, **77**, 45, 2003

Diffusive spread, modelled by the reaction-diffusion equation

Standard population dynamics models

The Fisher-Kolmogorov-Petrovsky-Piskunov (FKPP) equation:

$$\frac{\partial n}{\partial t} = \gamma n \left(1 - \frac{n}{n_0}\right) + \nabla \cdot (\nu \nabla n)$$

(θ, φ) = position

$n(\theta,\varphi,t)$ = population density

$\gamma(\theta,\varphi,t)$ = birth rate

$n_0(\theta,\varphi,t)$ = carrying capacity

$\nu(\theta,\varphi,t)$ = diffusivity

Wave of advance

$$n \propto \exp\,[\gamma t - x^2/(4\nu t)]$$

$$n = \text{const} \quad \Rightarrow \quad x \propto 2(\gamma\nu)^{1/2}\, t$$

The wave front (position where n = const) propagates at a **constant speed**

$$U = 2\sqrt{\gamma\nu}$$

Regional variations

$$U = 2\sqrt{\gamma\nu}$$

- $\bar{U}$ = 1 km/yr on average in Europe
- U_{LBK} = 4-6 km/yr for the LBK
- U_{coast} = 10-20 km/yr in Mediterranean coastal regions

Plausible reasons:

✓ **Local altitude and latitude** ⇨ ν, n_0, γ

✓ **Major rivers and coastlines** ⇨ ν (anisotropy), n_0

× **Biomass and soil fertility** ⇨ n_0, γ

× **Climate variations** ⇨ n_0, ν

Regional variations in the speed of advance

$$U = 2\sqrt{\gamma\nu}$$

U varies by a factor **5-20** ⇒ ν has to vary by a factor **25-400** **(?!)**

⇒ LBK and coastal regions are affected by additional factors

Major water ways ⇒ anisotropic spread ⇒ **advection**

$$\frac{\partial n}{\partial t} + (\vec{\mathbf{V}} \cdot \nabla)n = \gamma n\left(1 - \frac{n}{n_0}\right) + \nabla \cdot (\nu \nabla n)$$

Advection due to anisotropic random walk

$\bar{U}$ = 1 km/yr, γ = 0.02 yr^{-1} ⟹ $\nu = \bar{U}^2/4\gamma \approx$ 13 km^2/yr,

$$\nu = \frac{\bar{U}^2}{4\gamma} = \frac{\ell^2}{4\tau} \Rightarrow \ell = \bar{U}\sqrt{\frac{\tau}{\gamma}} \Rightarrow \ell \approx 27\,\mathrm{km} \text{ for } \tau = 15\,\mathrm{yr}$$

Anisotropic random walk, step length ℓ depending on direction:

$\mu = \Delta\ell/\ell$ ⟹ advection speed $V = \dfrac{\ell\mu}{4\tau}$

$$V = U_{\mathrm{LBK}} \Rightarrow \mu = 4\frac{U_{\mathrm{LBK}}}{\bar{U}}\sqrt{\gamma\tau}$$

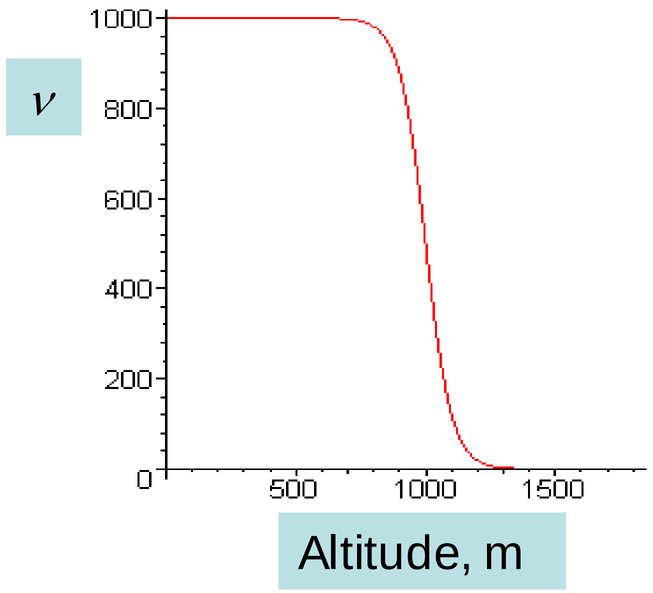
τ = 15 yr, $U_{\mathrm{LBK}}/\bar{U}$ = 4-6 ⟹ $\ell \approx$ 27 km, $\mu \approx$ 8-13

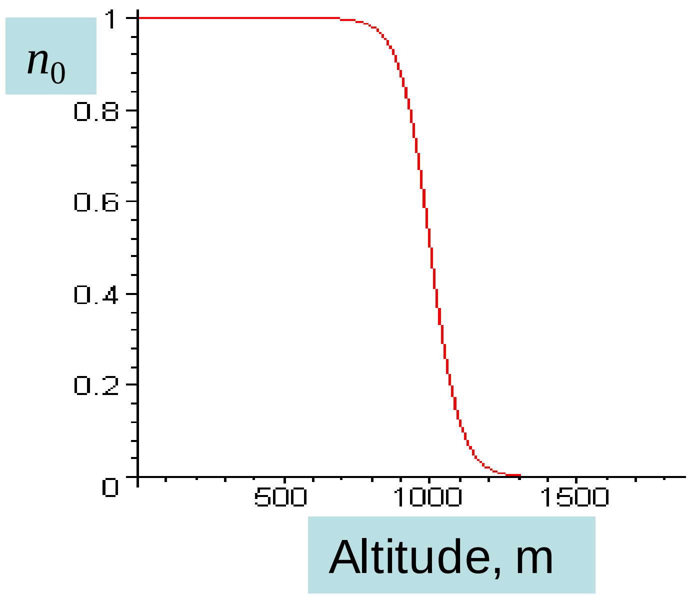
Numerical methods

$$\frac{\partial n}{\partial t} + (\vec{\mathbf{V}} \cdot \nabla) n = \gamma n \left(1 - \frac{n}{n_0}\right) + \nabla \cdot (\nu \nabla n)$$

- Discrete grid on sphere, $\Delta(\varphi,\theta) = 1^o/12$, Δx = 2-9 km
- Explicit Euler time stepping
- Zero flux at the boundaries
- Adaptive time step

n_0, ν, γ: functions of position





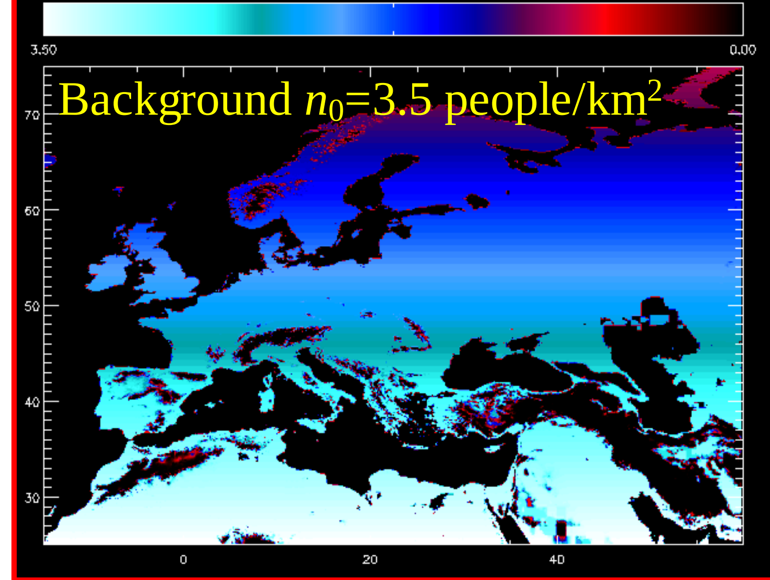
$$\gamma = \begin{cases} \text{const} & \text{on land,} \\ 0 & \text{in sea.} \end{cases}$$

ν, $n_0 \propto \exp(-d/40\ \text{km})$: decrease **offshore**

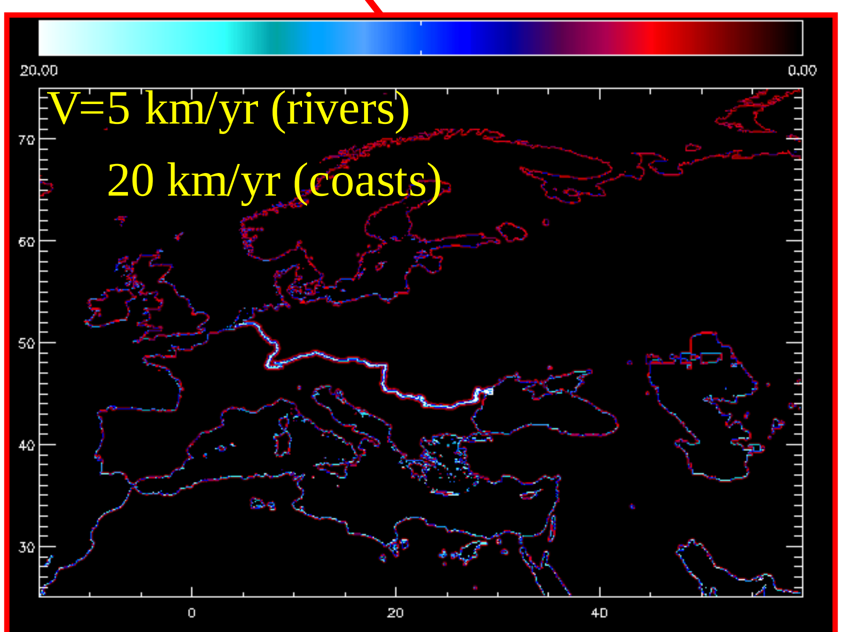
Slower advance beyond 54ºN latitude:

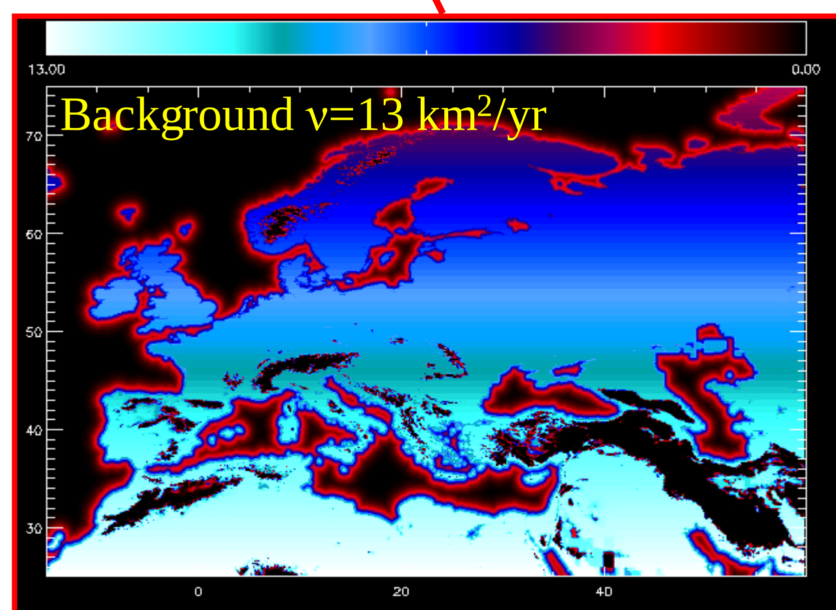
$$n_0,\ \nu \propto 1 - \frac{y}{3750\ \text{km}}$$

$\gamma = 0.02\ \mathrm{yr}^{-1}$
(population doubles in 30 yr)



$$\frac{\partial n}{\partial t} + (\vec{\mathbf{V}} \cdot \nabla) n = \gamma n \left[1 - \frac{n}{n_0} \right] + \nabla \cdot (\nu \nabla n)$$





Rivers and coastlines:

global consequences of local effects

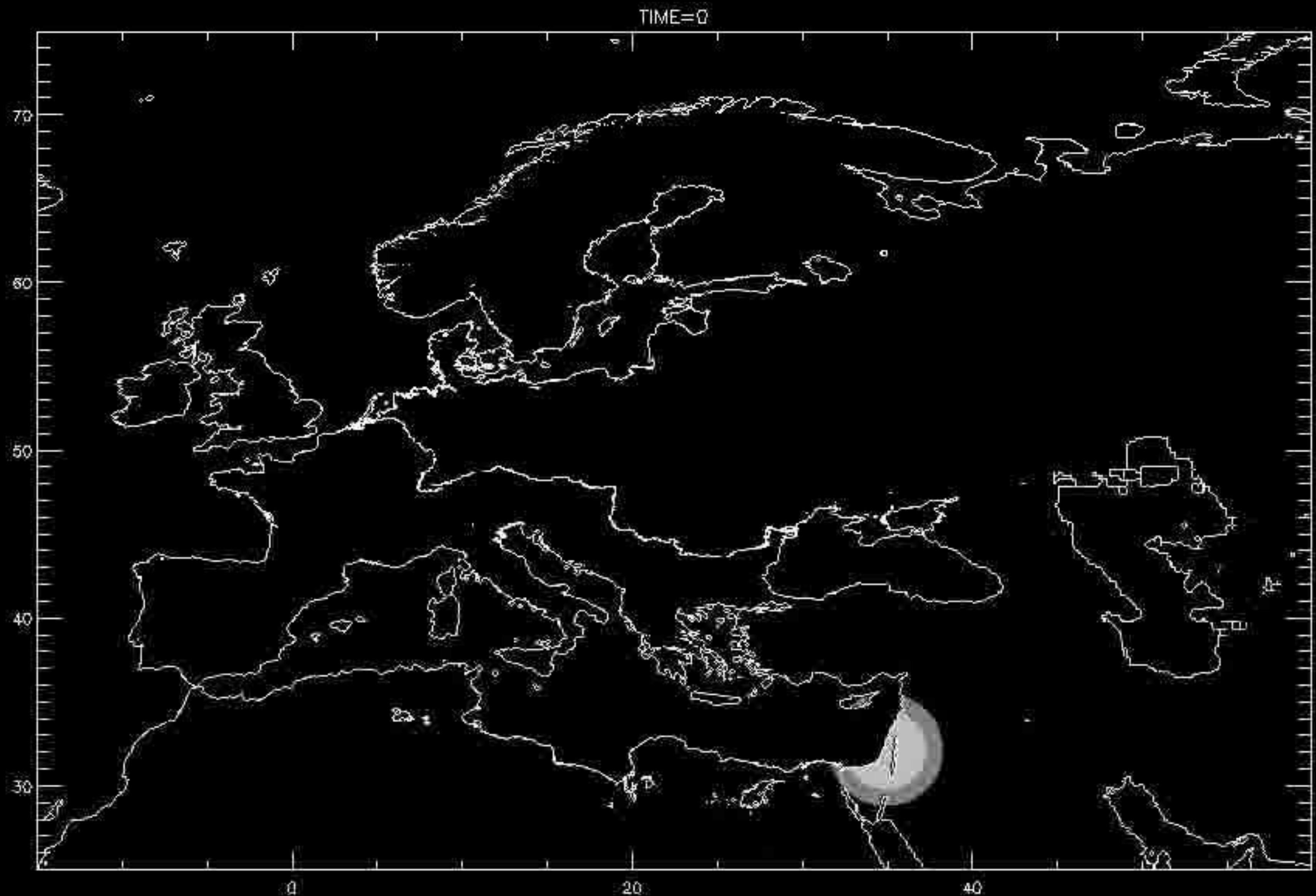
Anisotropic diffusion $\Rightarrow$ faster spread within 15 km of major rivers, 30 km of coastlines

$V = 5$ km/yr for rivers (e.g. A & C-S, 1973)

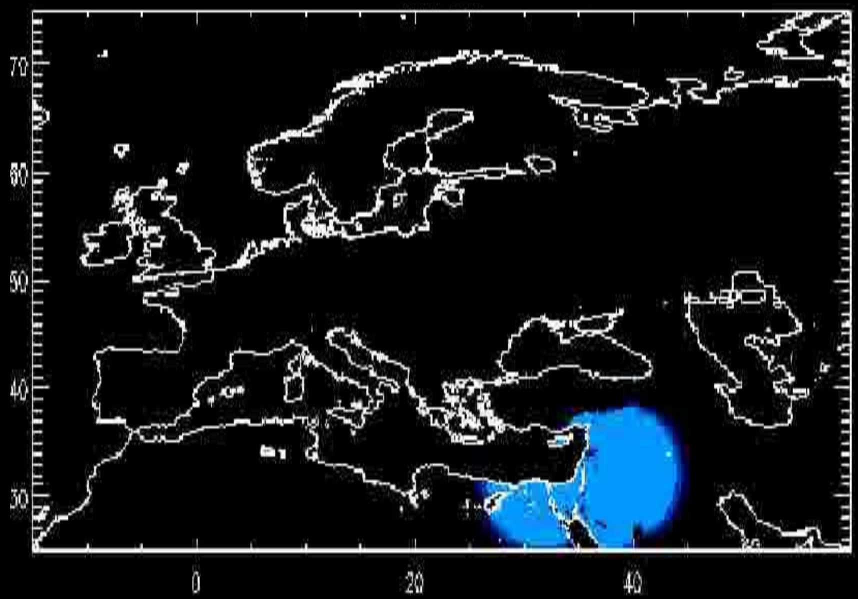
$V = 20$ km/yr in coastal regions (Zilhão, 2003)

$$\frac{\partial n}{\partial t} + (\vec{\mathbf{V}} \cdot \nabla) n = \gamma n \left(1 - \frac{n}{n_0}\right) + \nabla \cdot (\nu \nabla n)$$

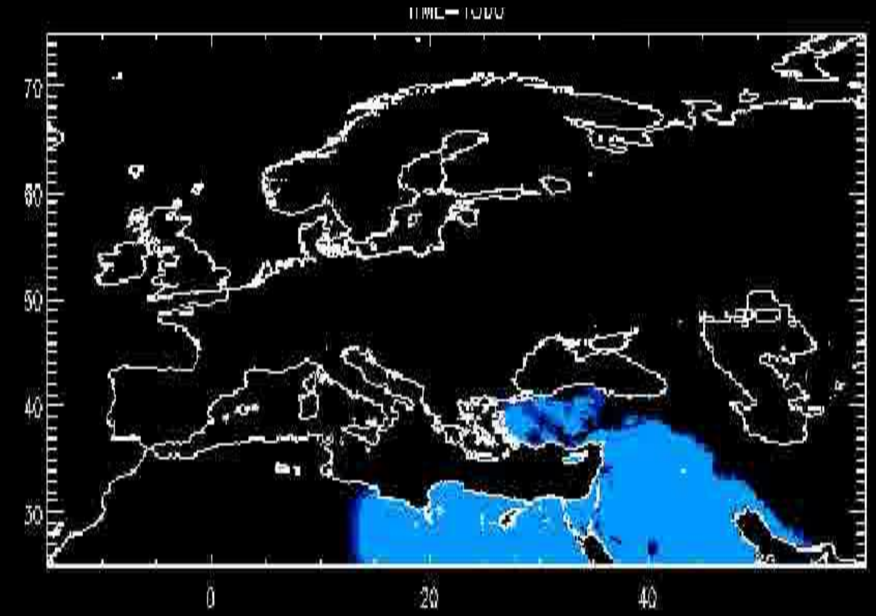
Spread from Jericho



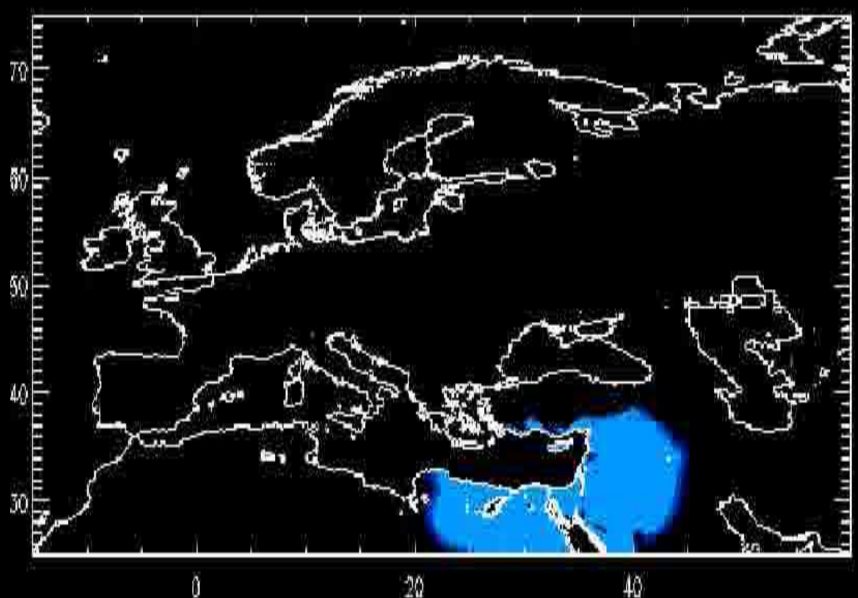
Without advection Time = 500 yrs



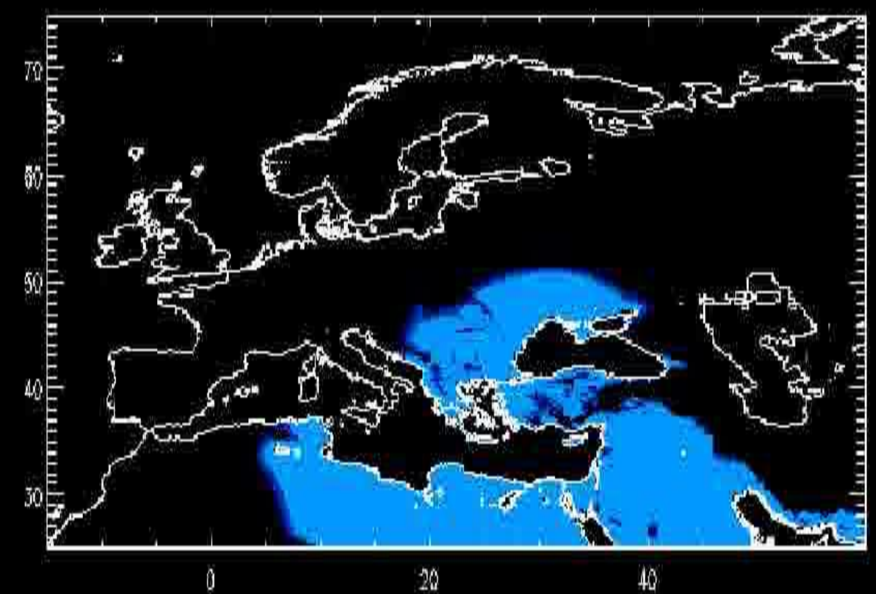
Without advection Time = 1500 yrs



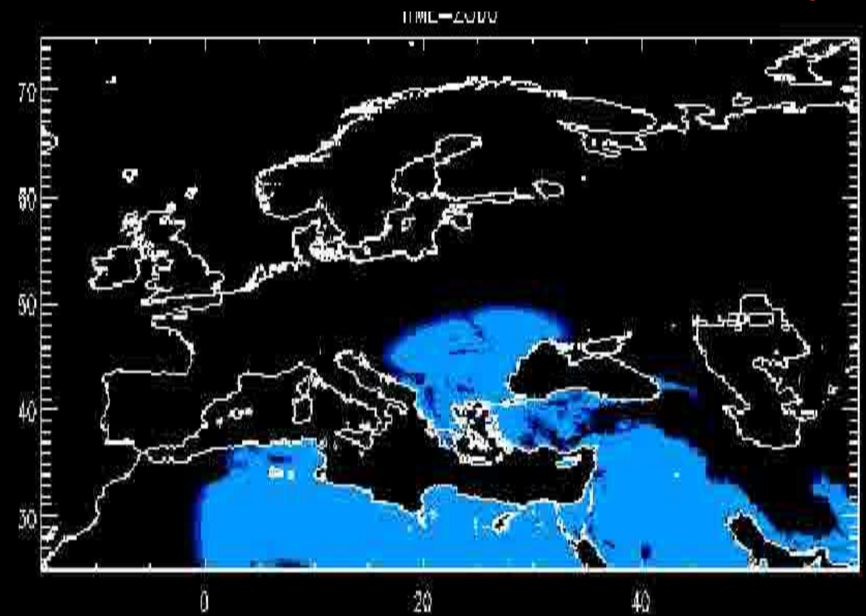
With advection Time = 500 yrs



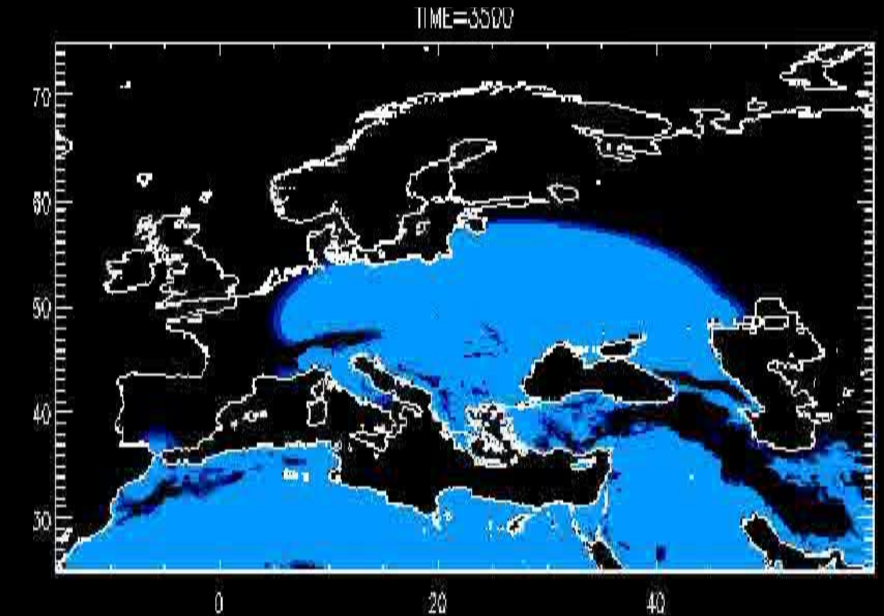
With advection Time = 1500 yrs



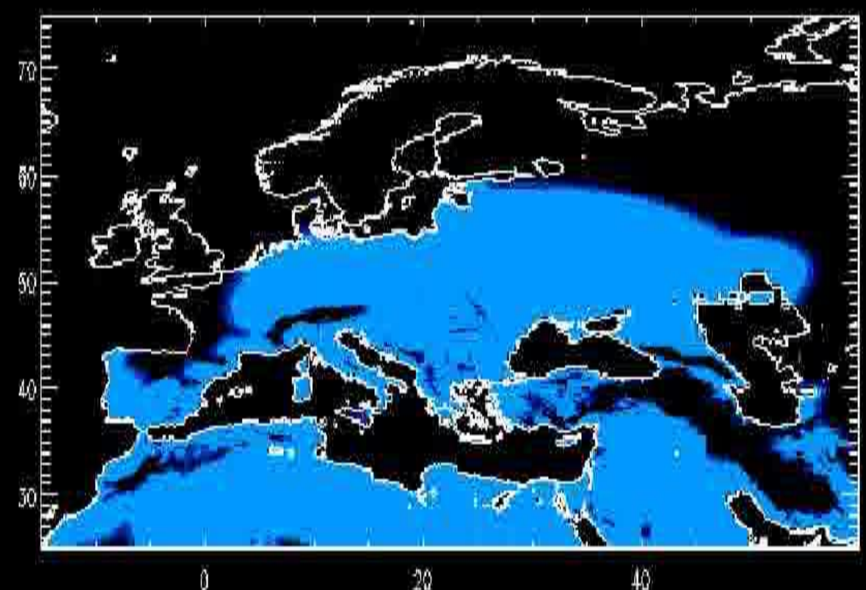
Without advection Time = 2500 yrs



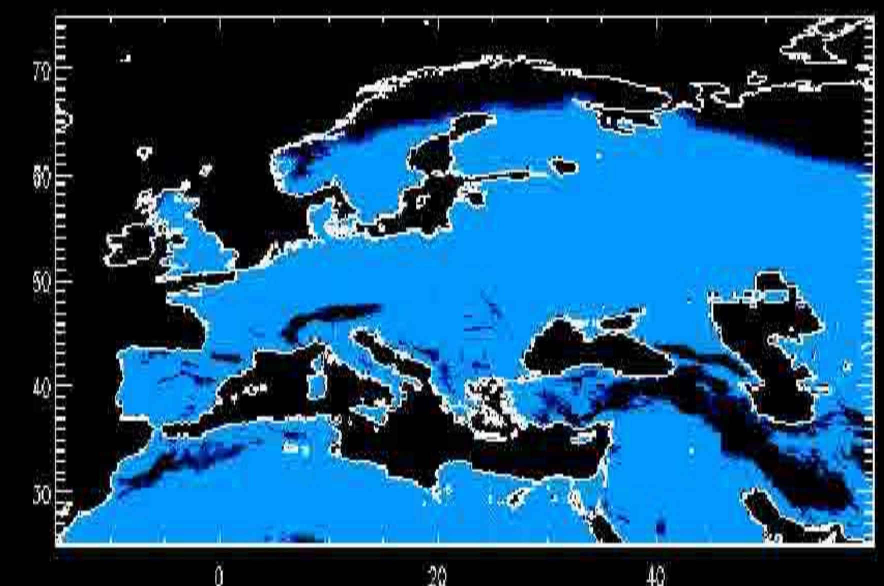
Without advection Time = 3500 yrs



With advection Time = 2500 yrs

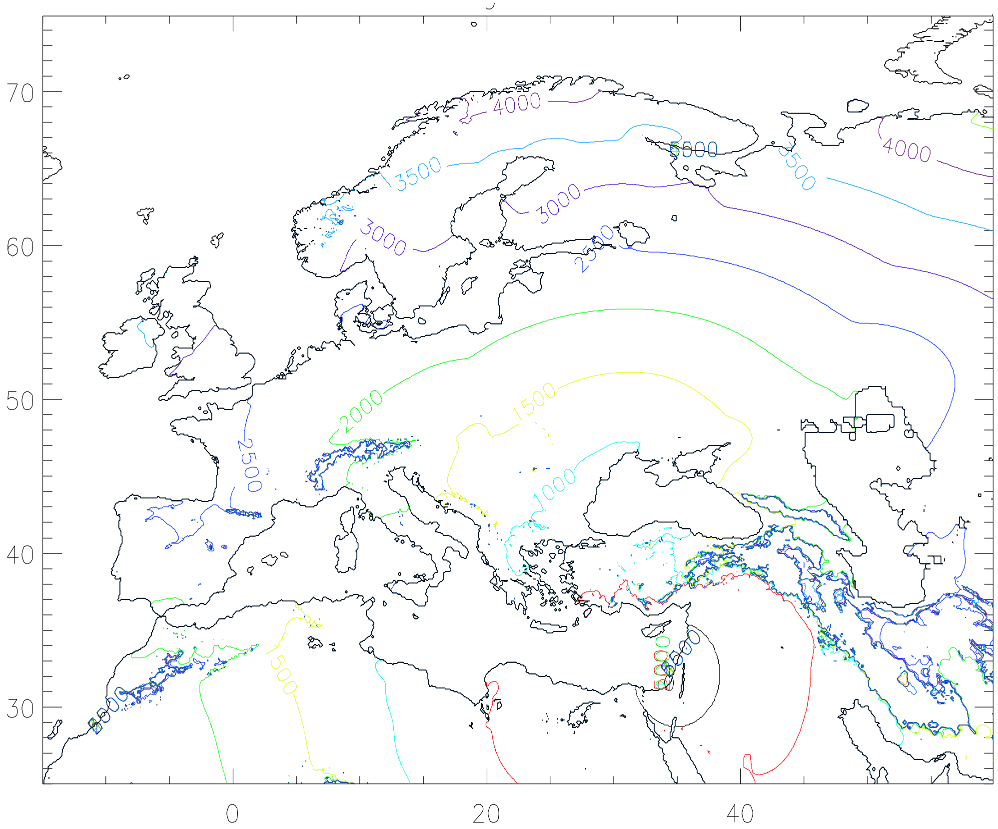


With advection Time = 3500 yrs

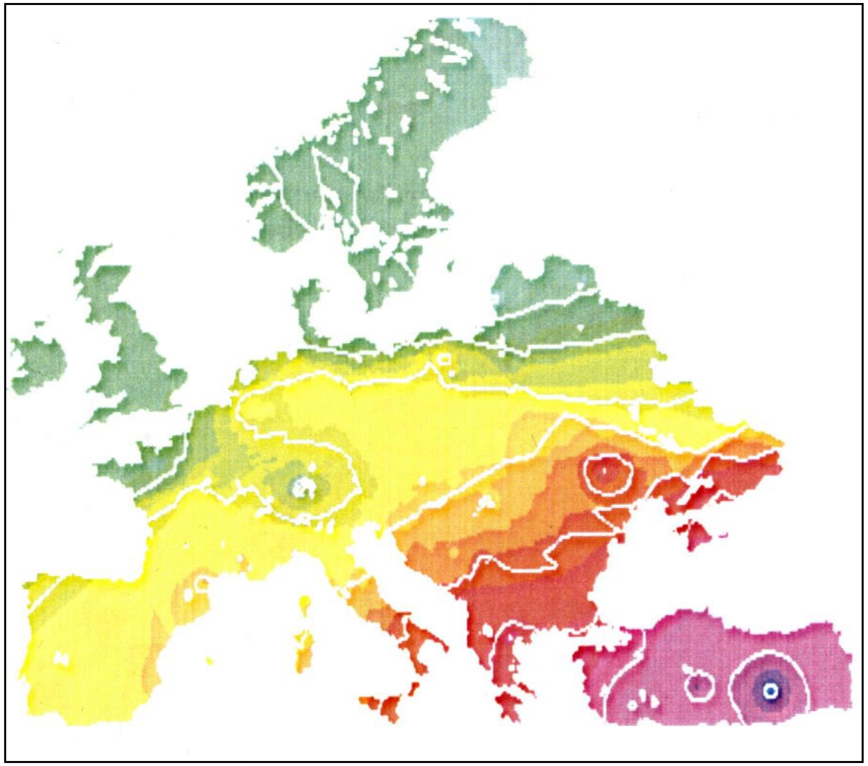


Isochrones

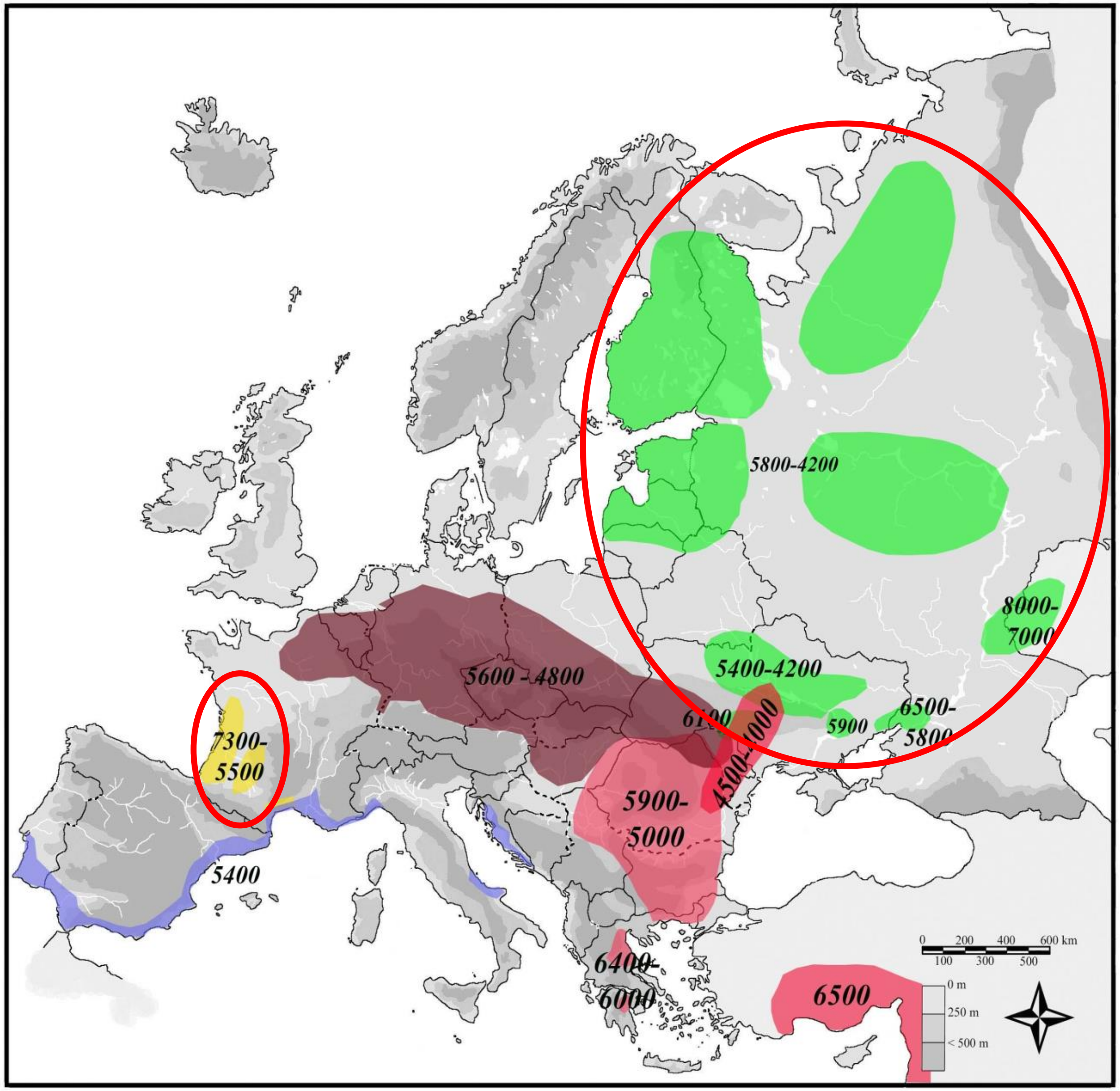
This model



Gkiasta et al., 2003



Pan-European model



East:

Limited evidence of farming

Well-developed pottery making

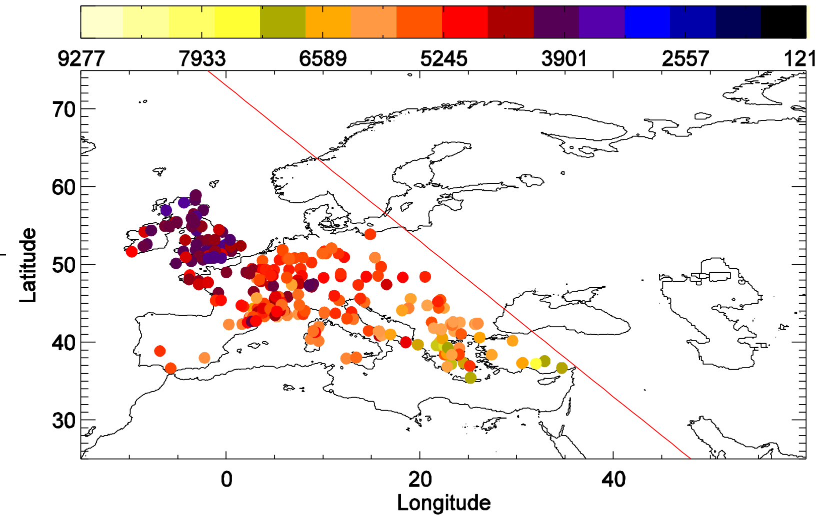
West:

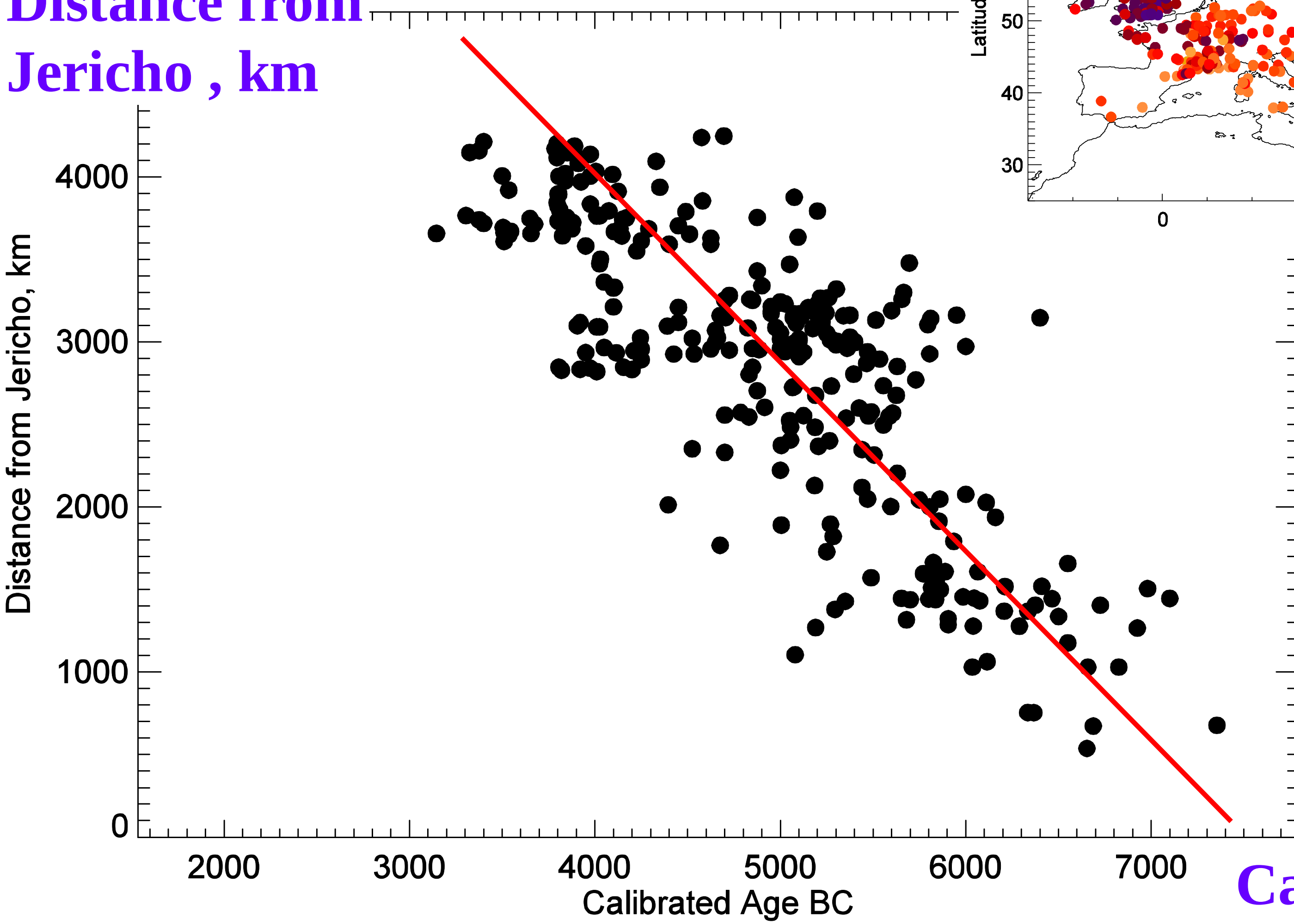
Pre-farming ceramic cultures

(La Hoguette & Roucadour)

Spread from the Near East

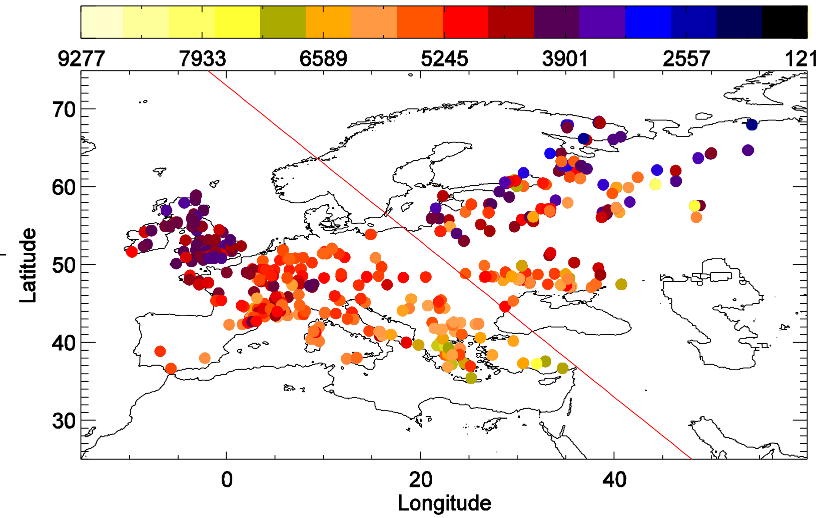
Distance from Jericho , km



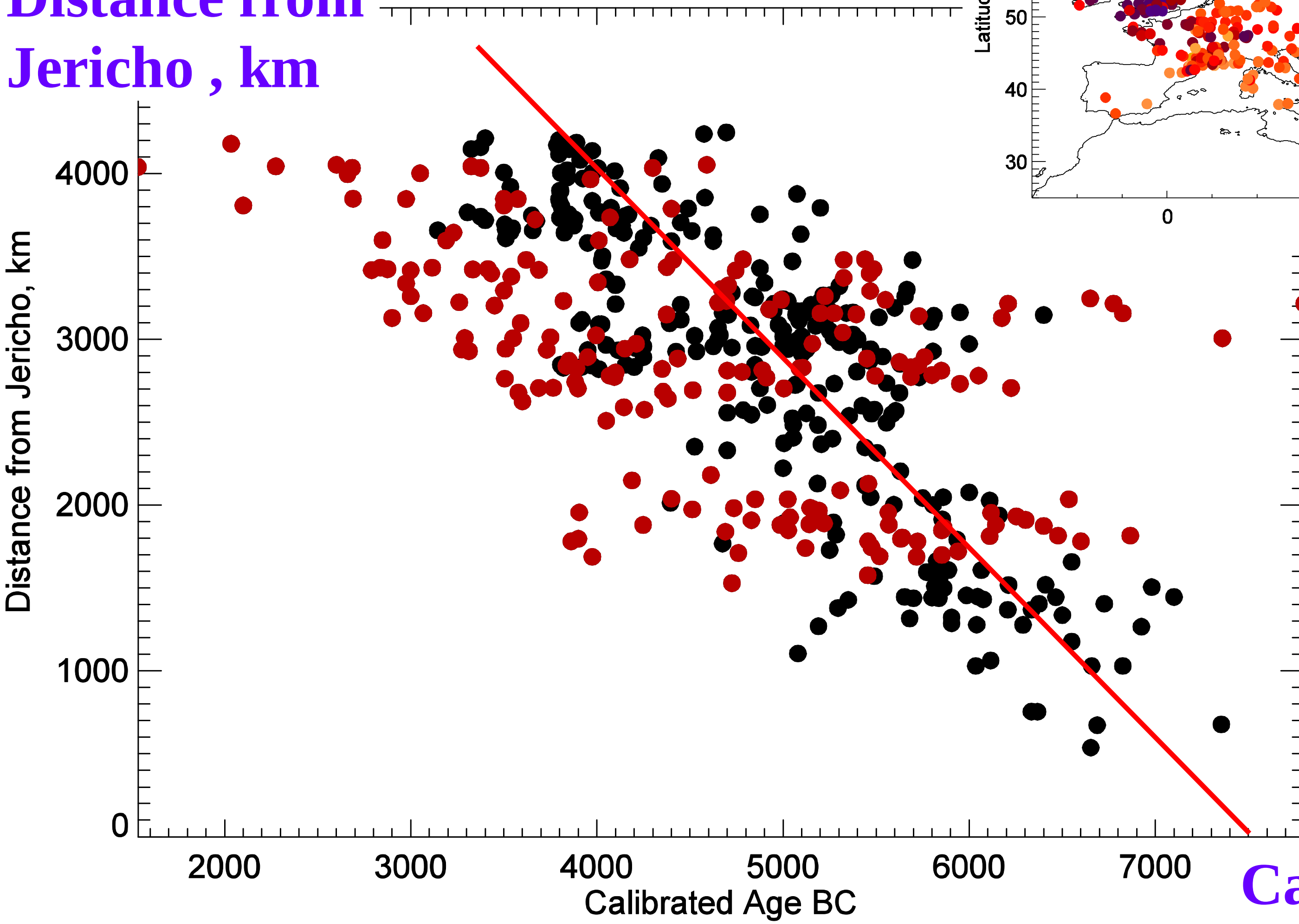


Calibrated Age BC

cannot explain the Eastern Neolithic

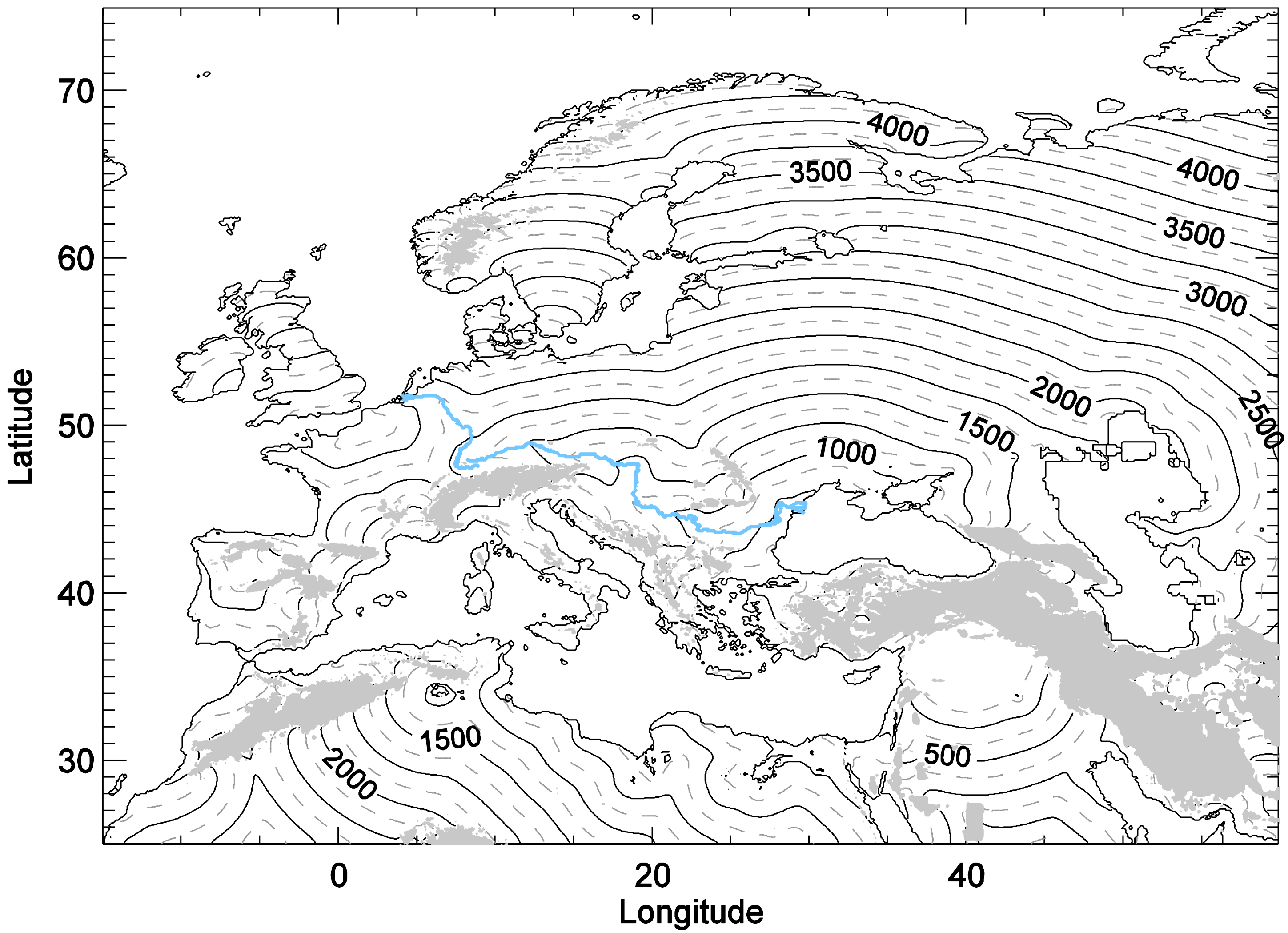


Distance from Jericho , km

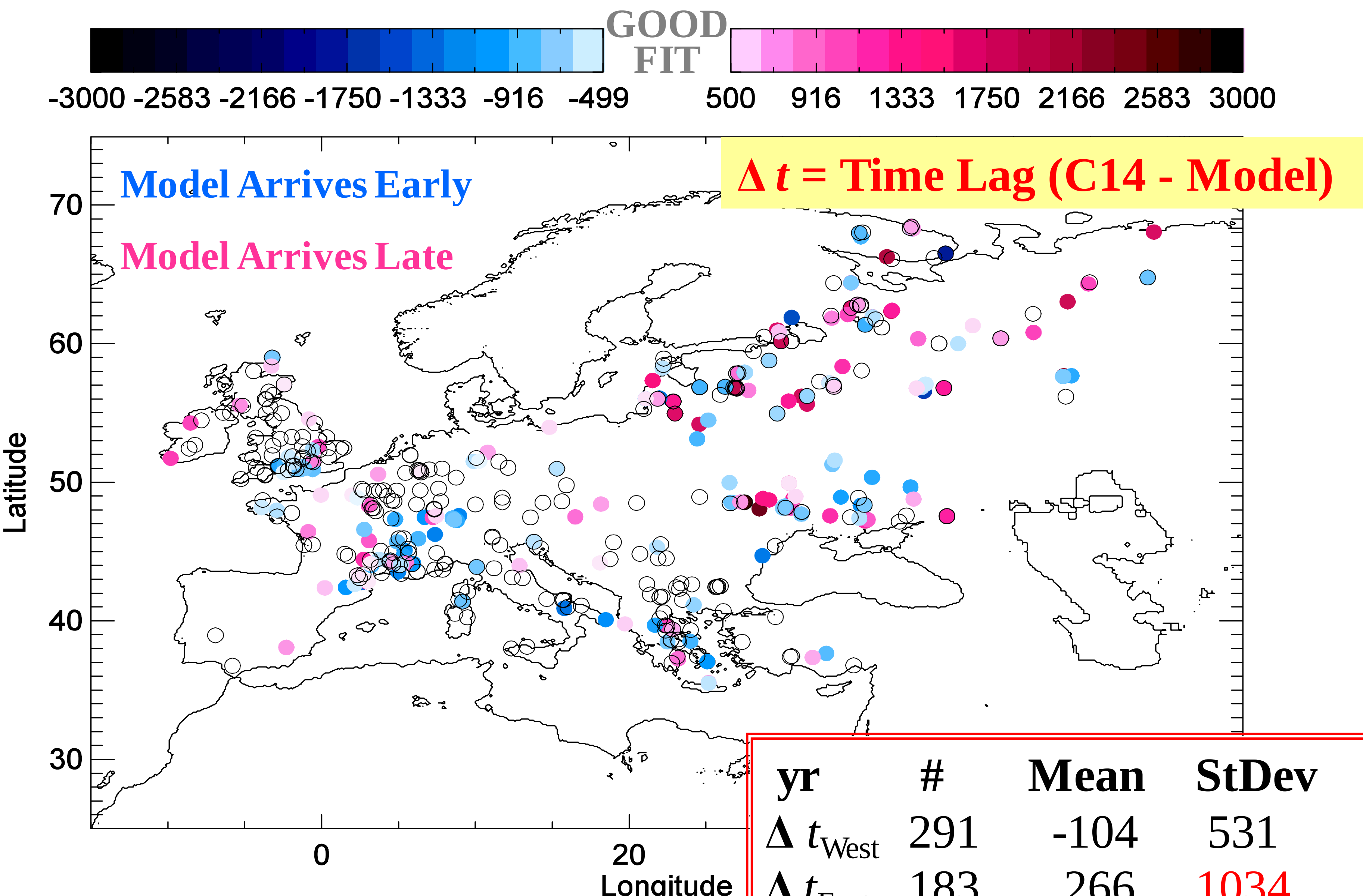


Calibrated Age BC

Single source in Jericho:
isochrones (n = const)



Single-source model vs ^{14}C data



yr	#	Mean	StDev
Δt_{West}	291	-104	531
Δt_{East}	183	266	1034

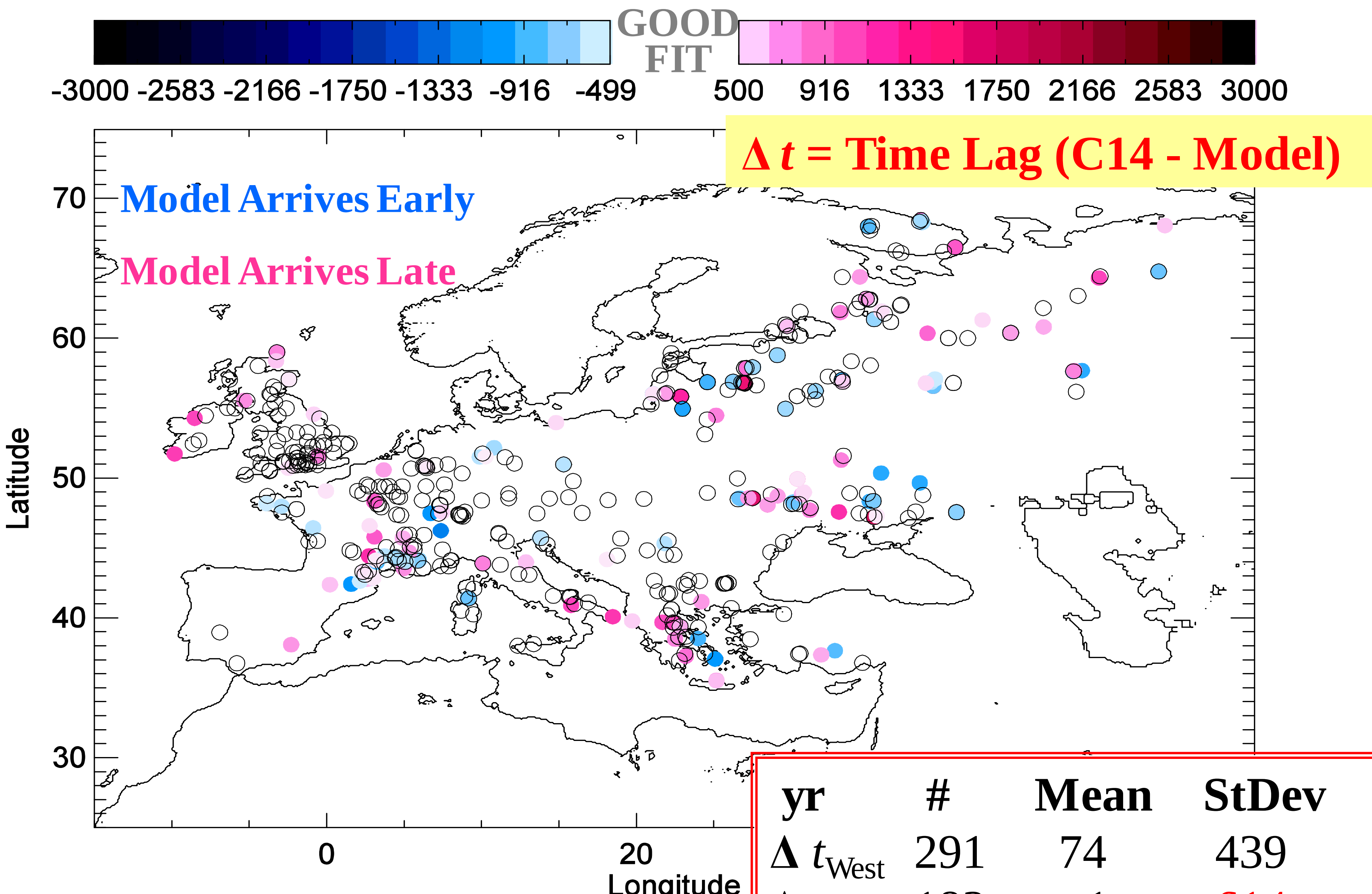
Two sources of the European Neolithic

- ^{14}C dates in Eastern Europe do not all belong to the source in the Near East

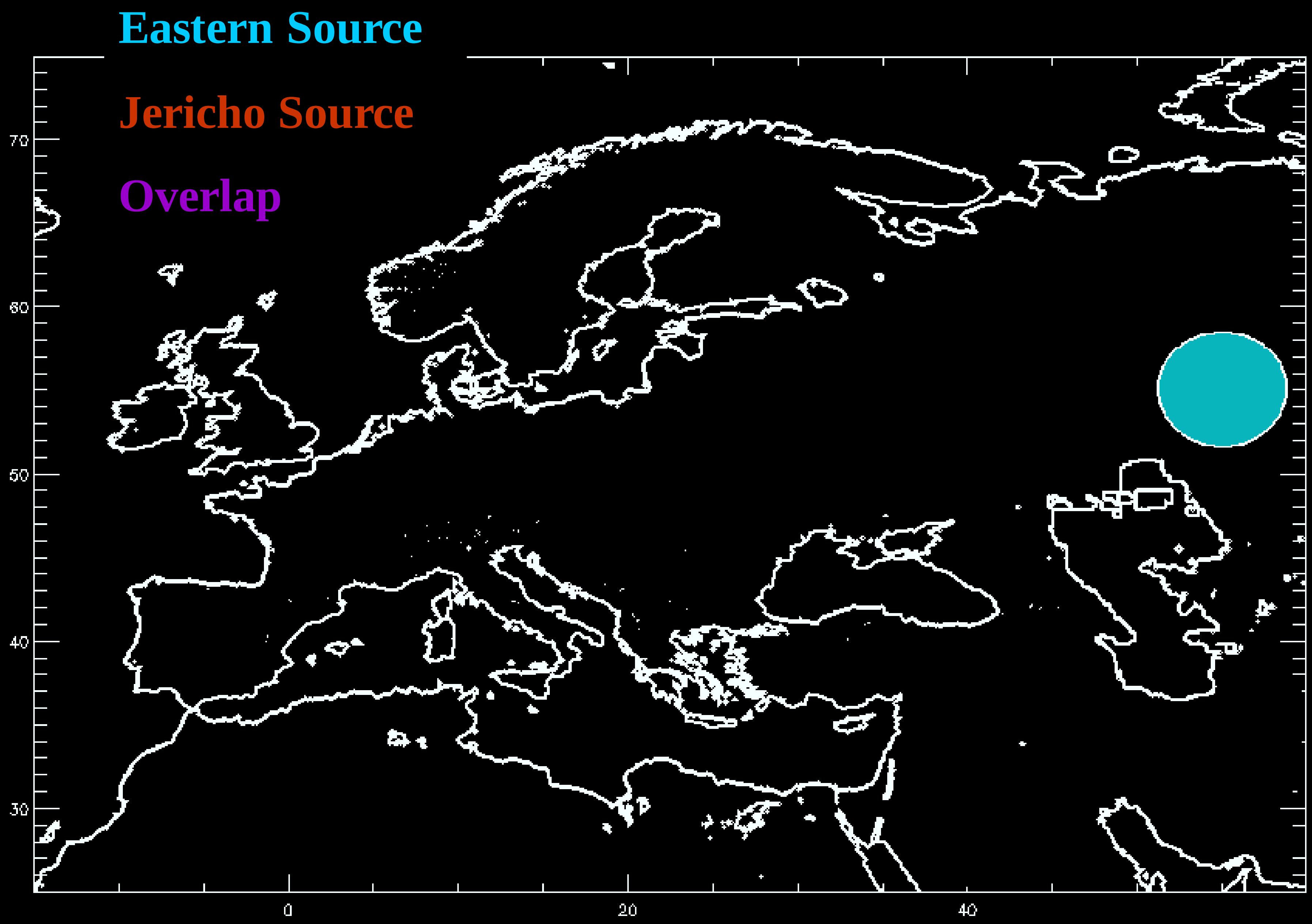
- Additional source in Eastern Europe at 71^{o}N, 56^{o}E

- Hunter-gatherers: γ = 0.007 yr^{-1};
  ν = 90 km^2/yr (λ = 75 km, τ = 15 yr);
  U = 0.8 km/yr; n_0 = 7 people per 100 km^2

Two sources



yr	#	Mean	StDev
Δt_{West}	291	74	439
Δt_{East}	183	-1	614


Eastern Source
Jericho Source
Overlap
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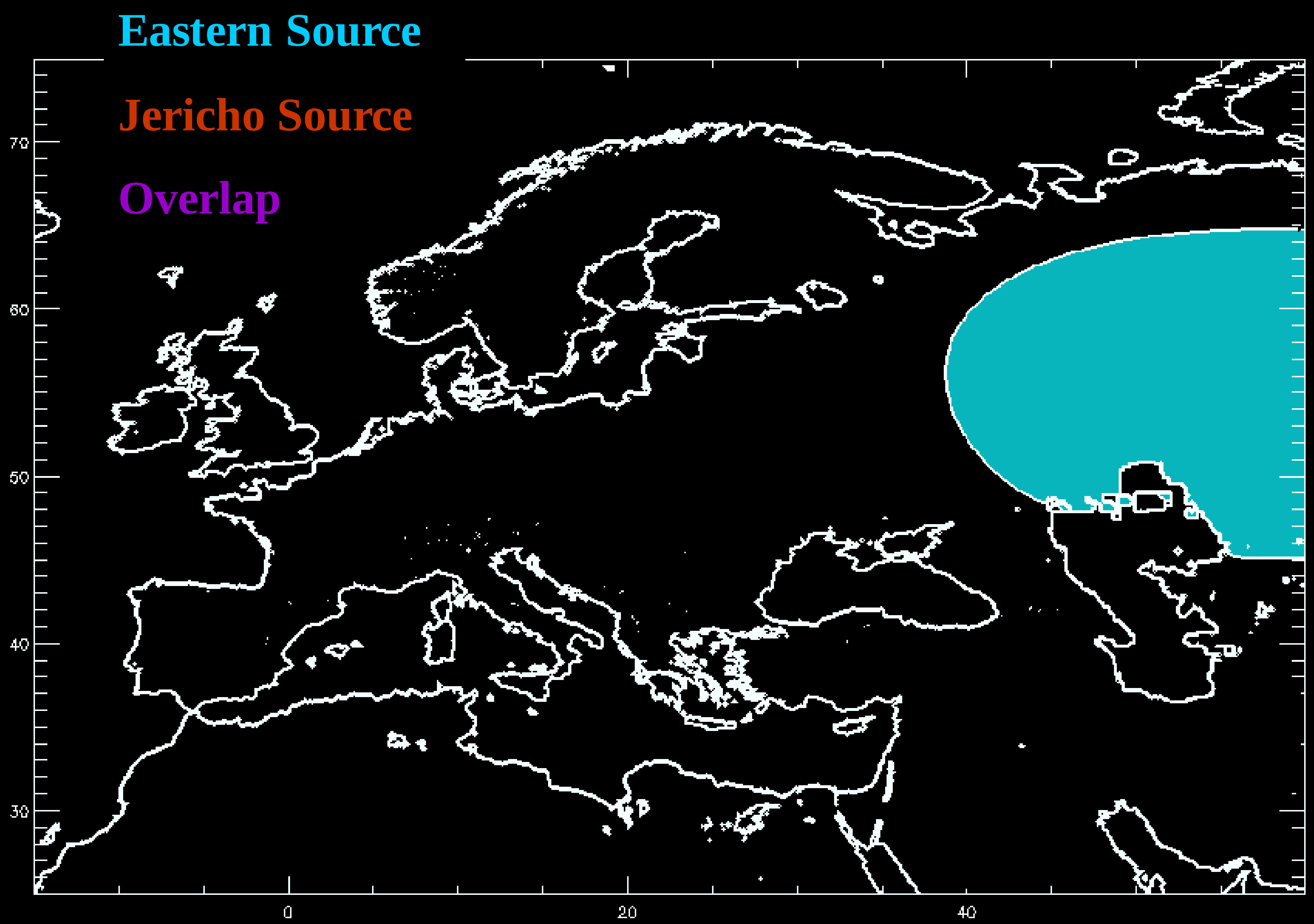

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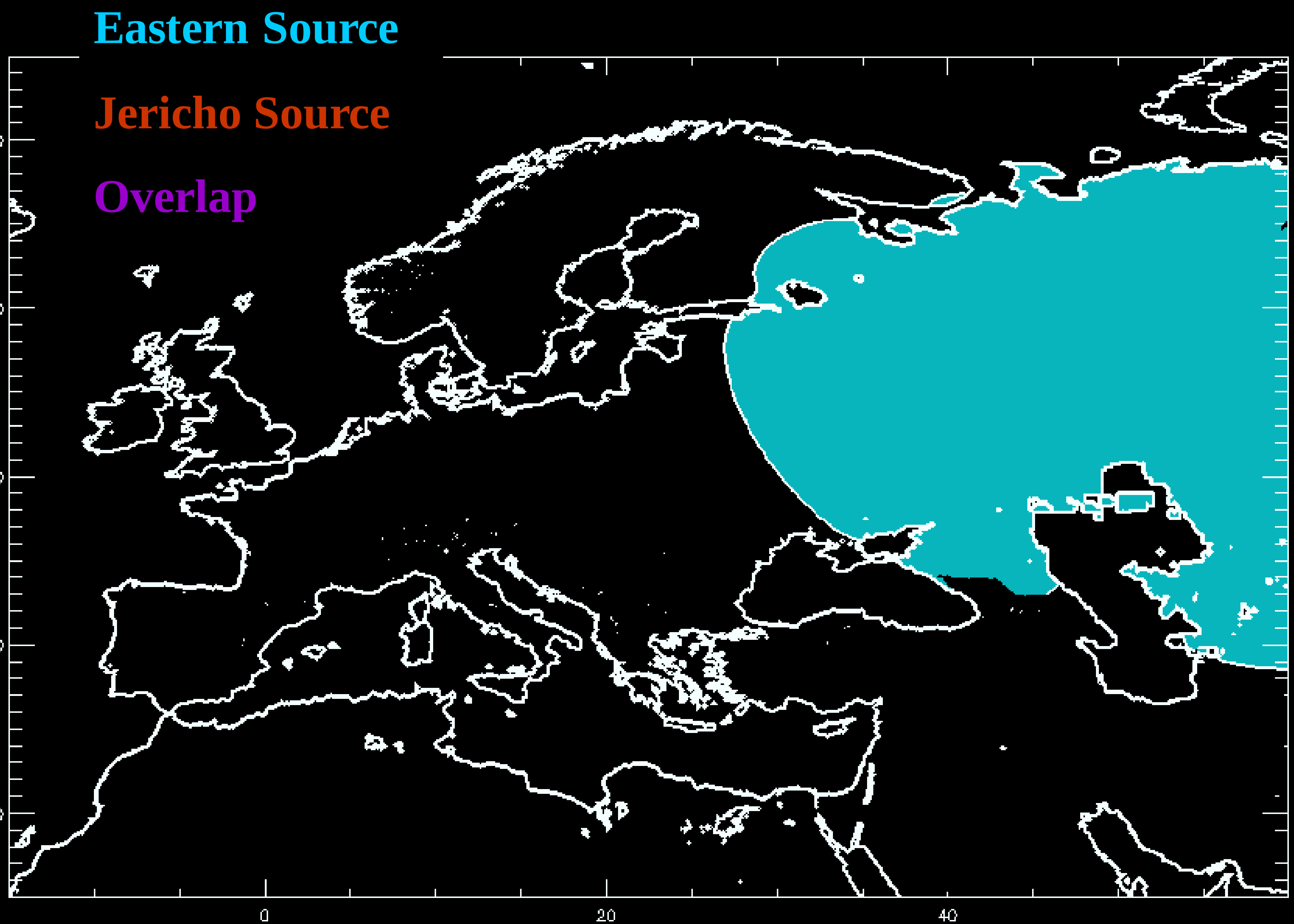
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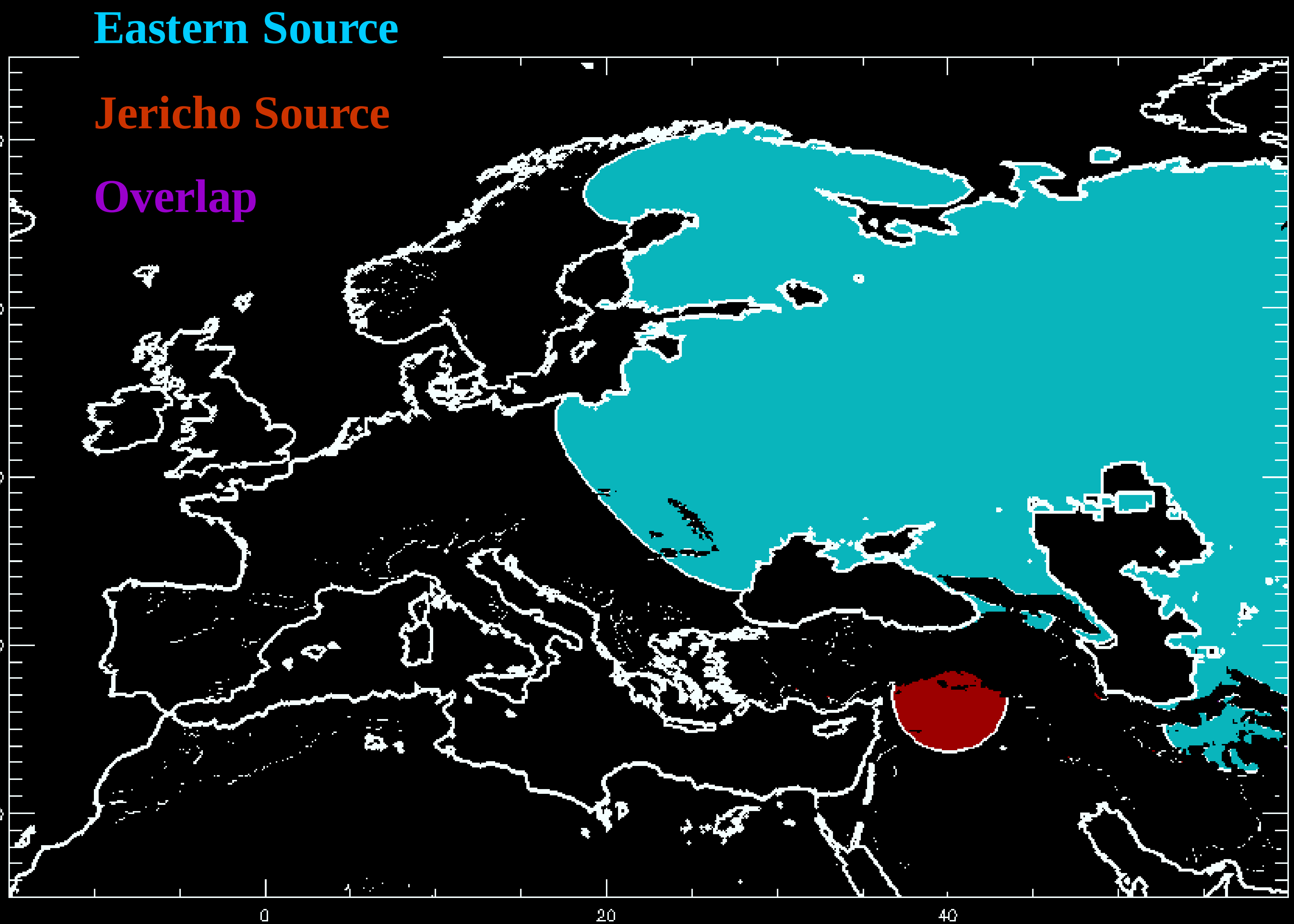

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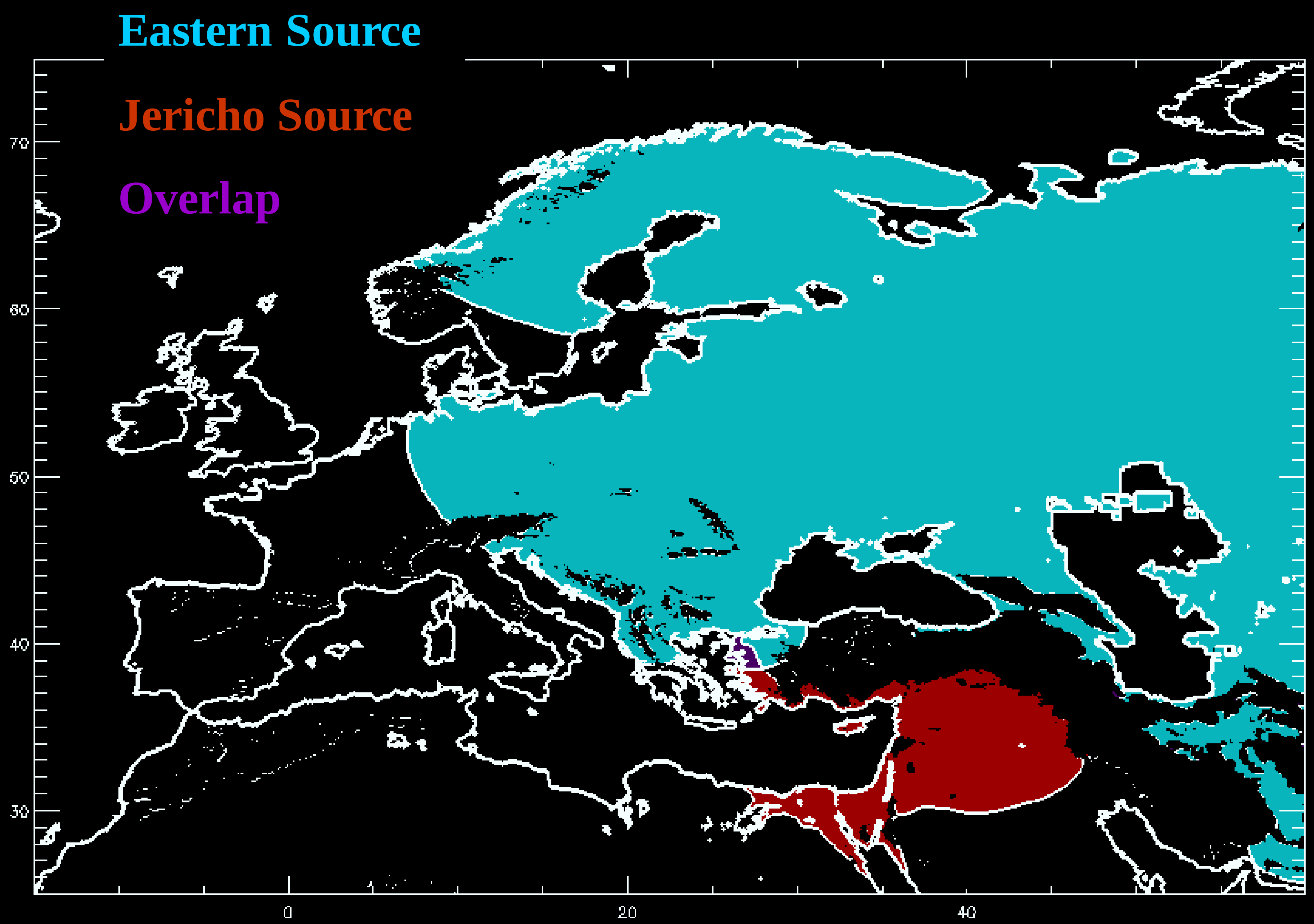
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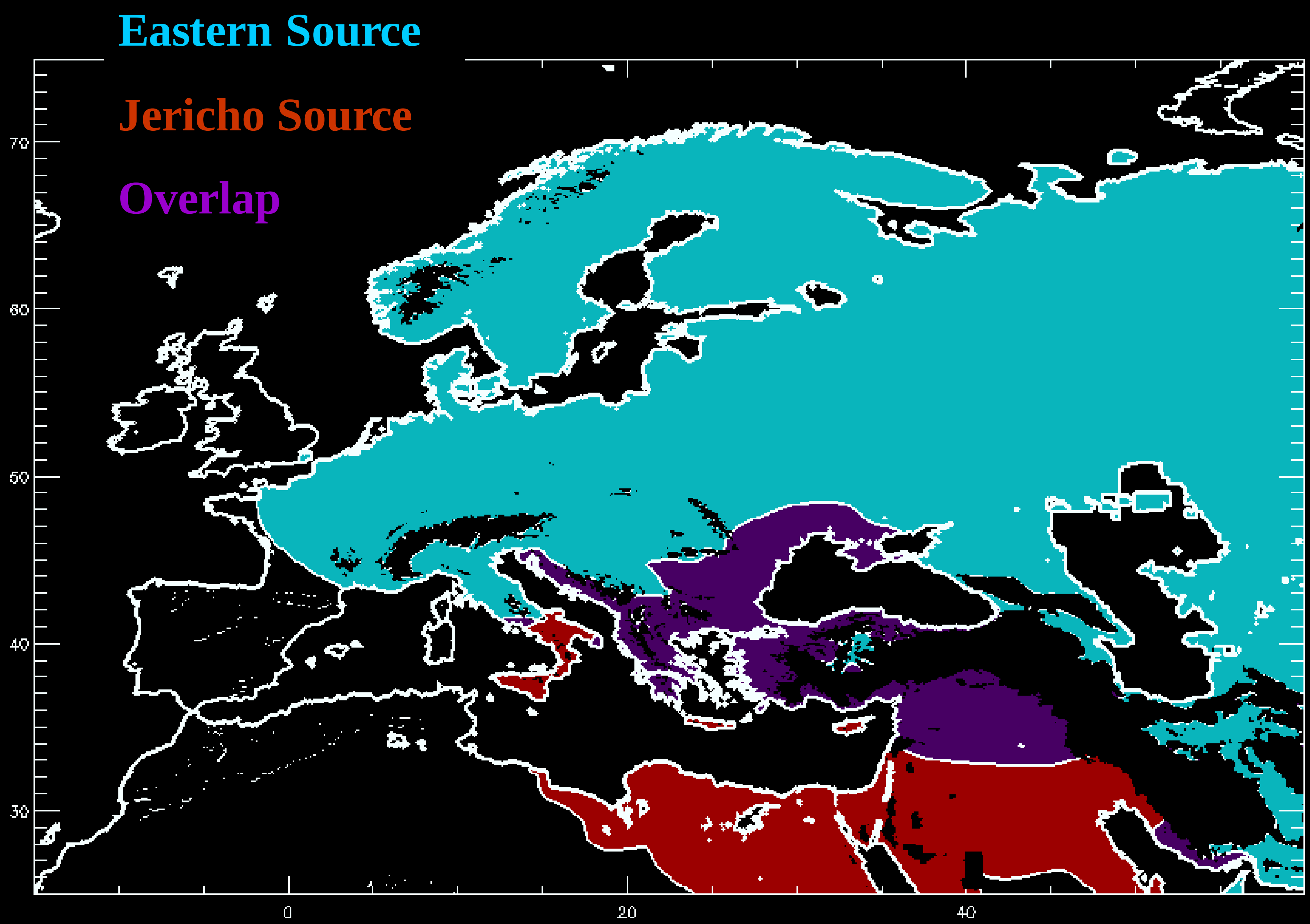

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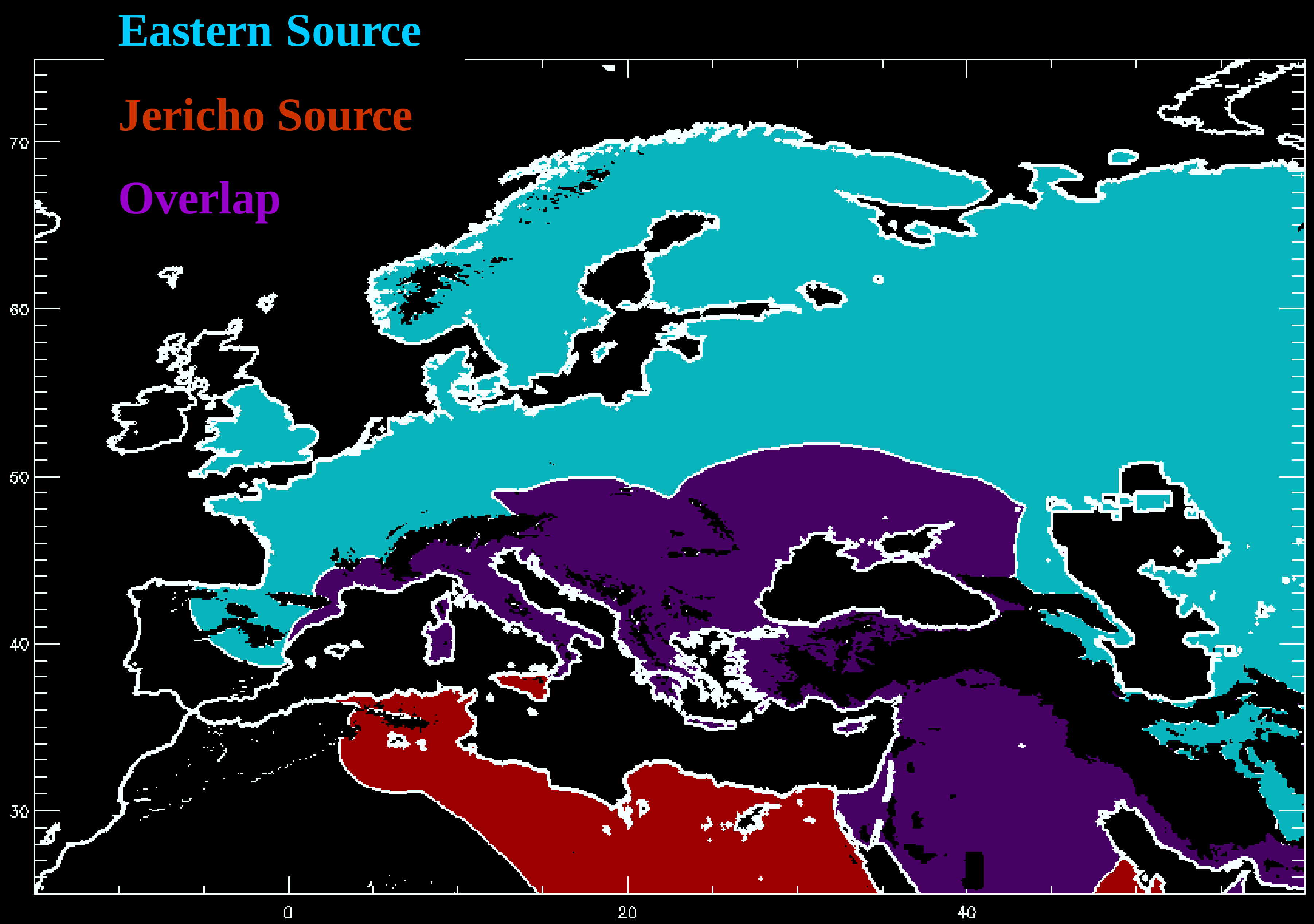

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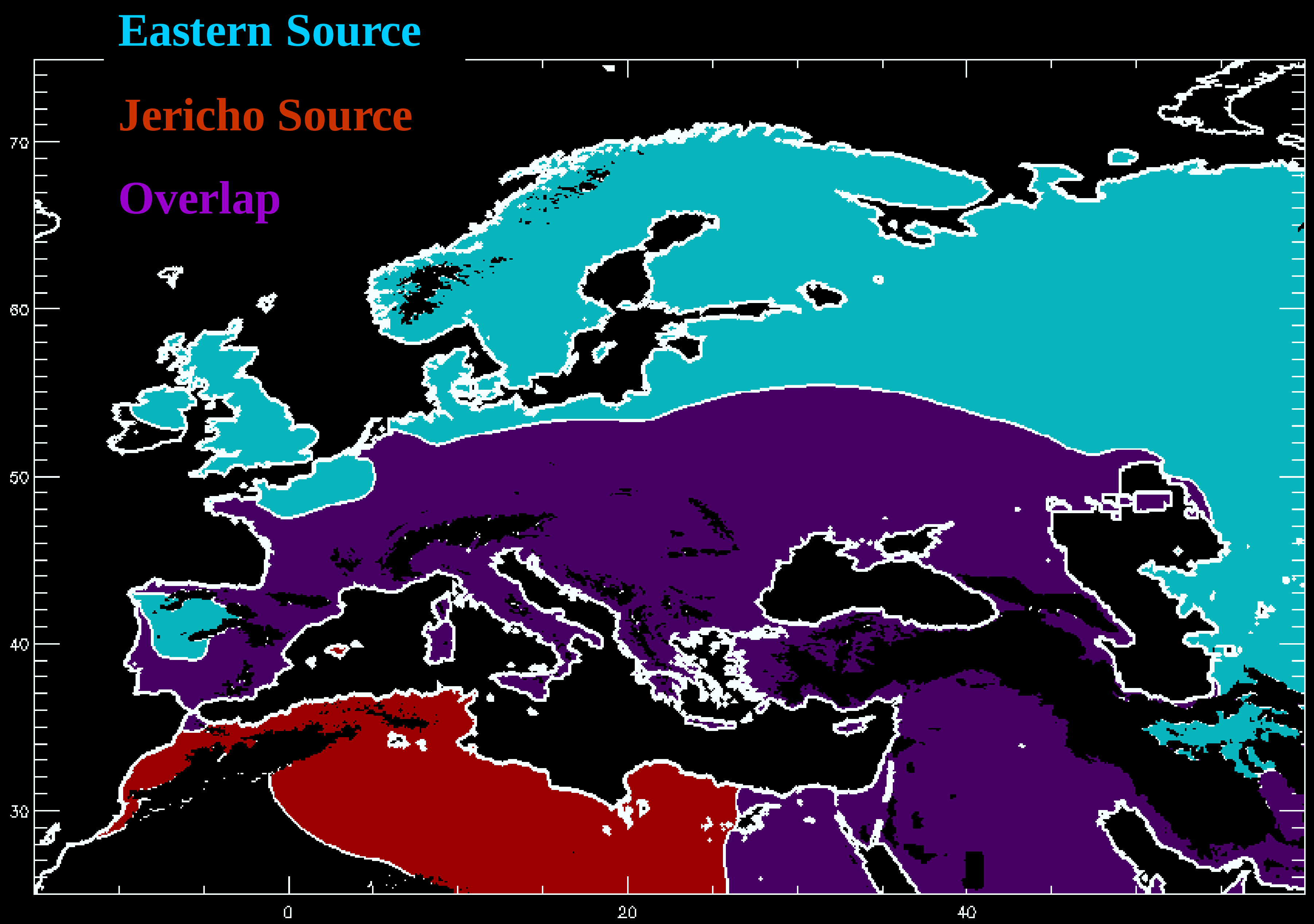

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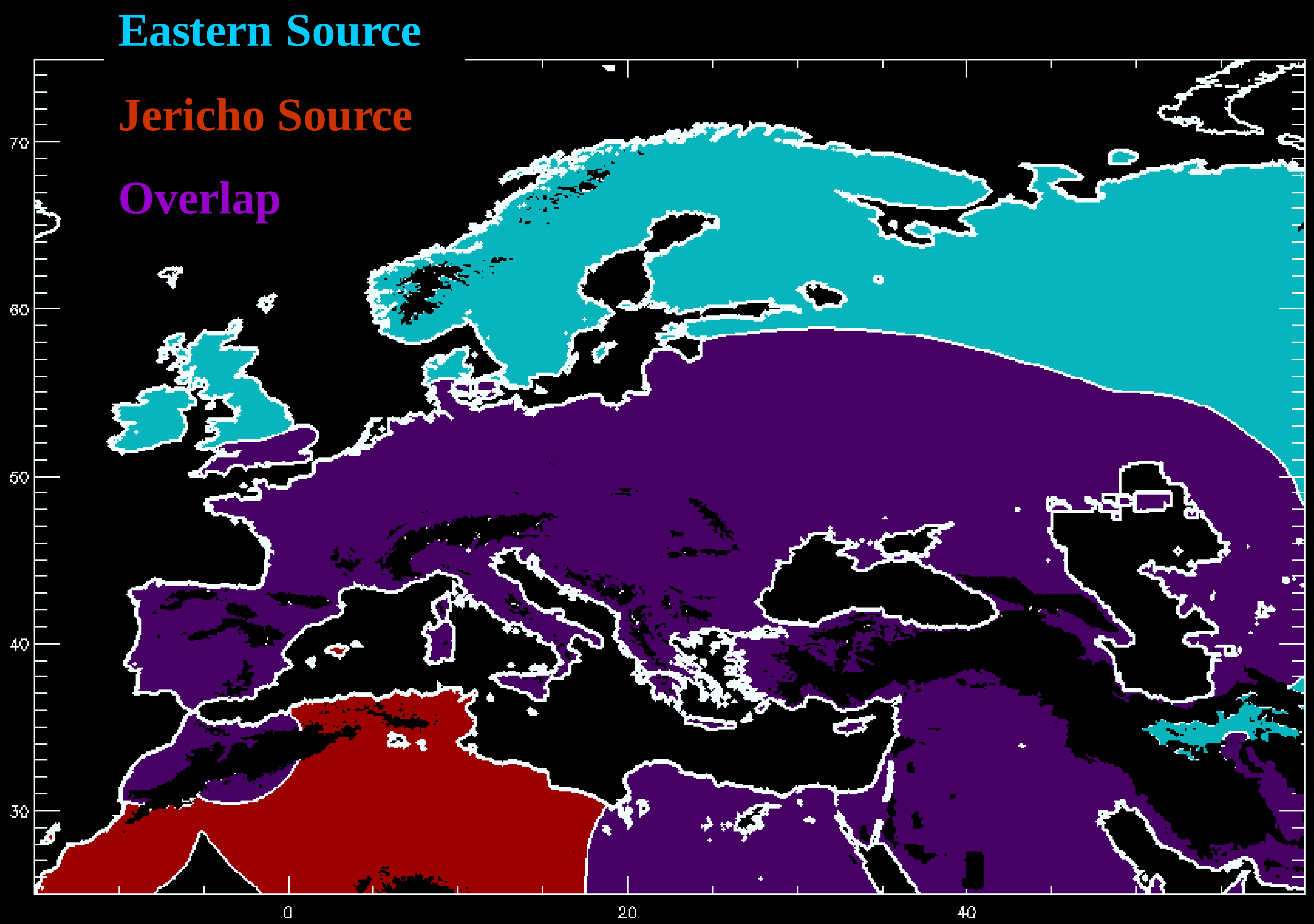

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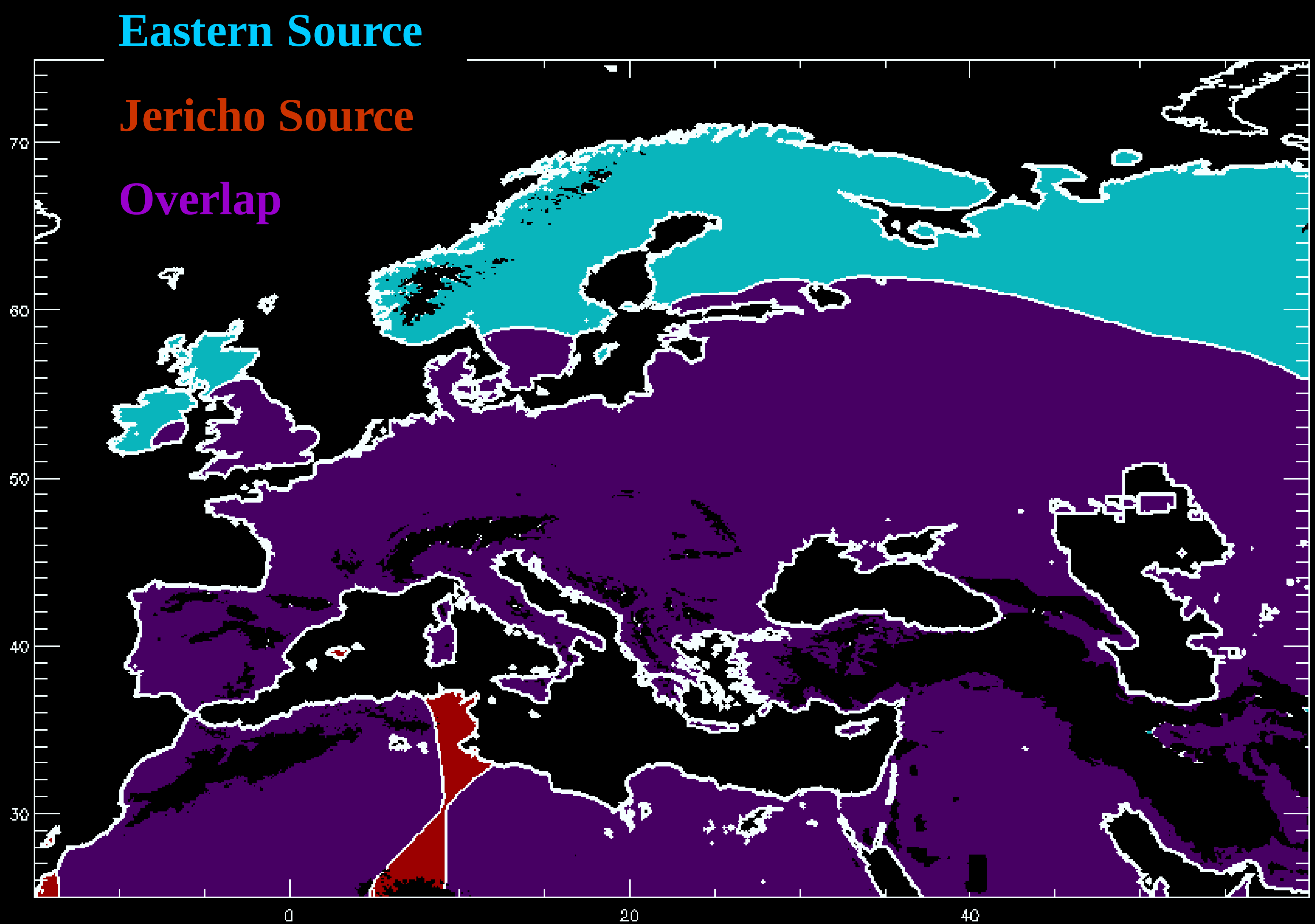
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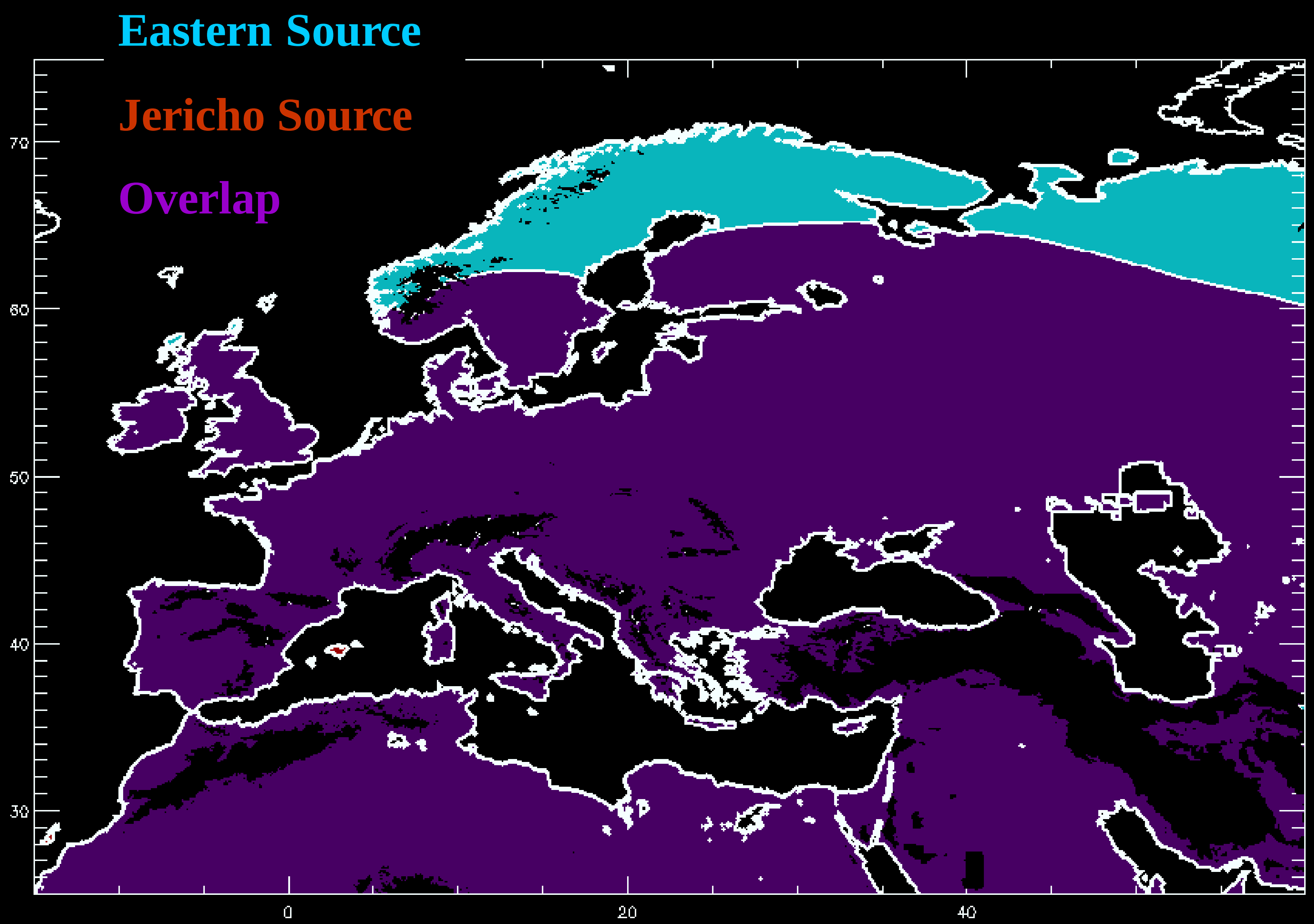
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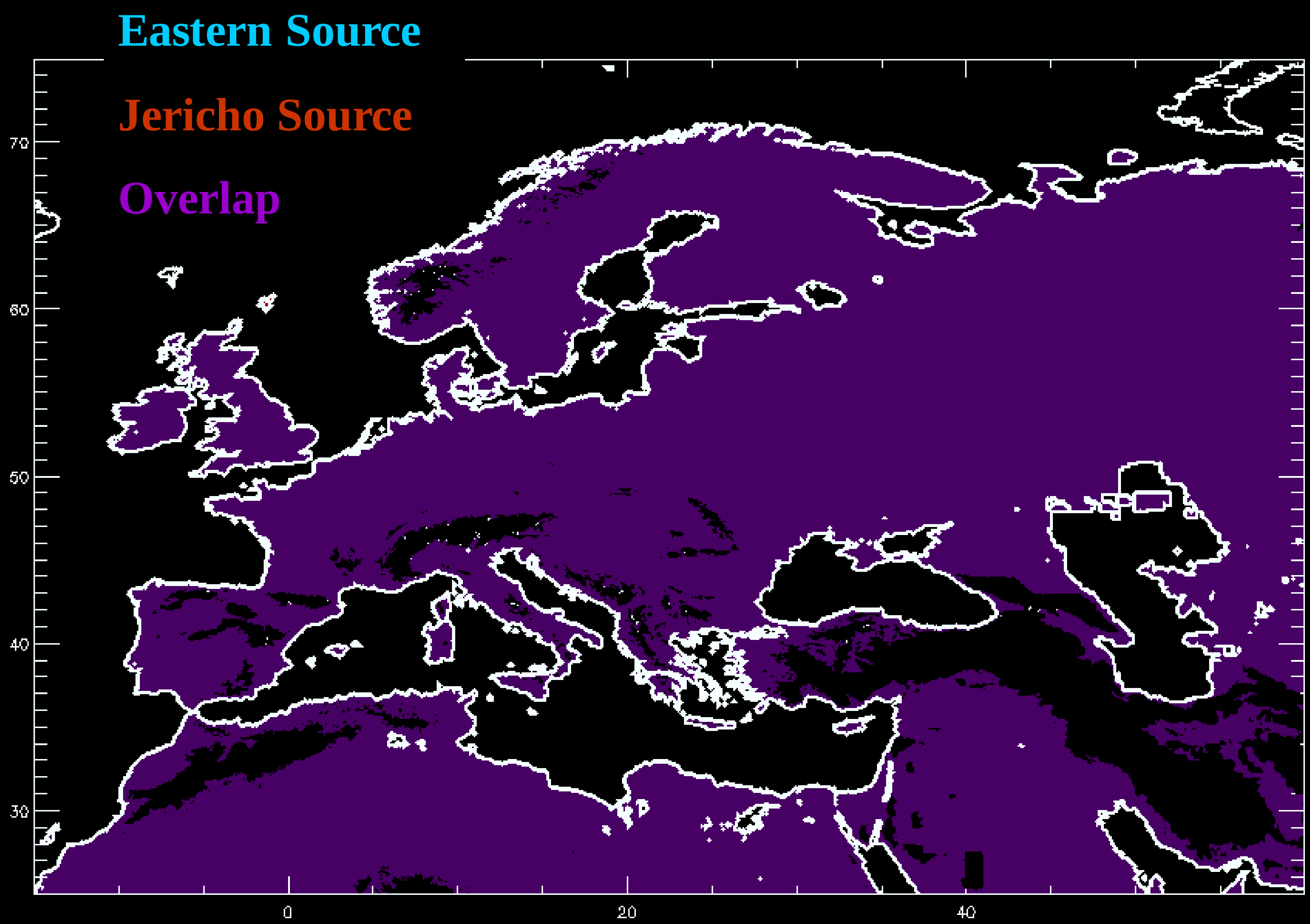
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Jericho Source
Overlap
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30
0
20
40

Better fit with two sources, $\Delta t = T_{C14} - T_{model}$ [yr]

Single source (Jericho)

Region	**#**	**Mean**	**St. Dev.**
W & E	474	39	786
W	291	-104	531
E	183	**260**	**1034**

Two sources (Jericho + Eastern Europe)

Region	**#**	**Mean**	**St. Dev.**
W & E	474	45	514
W	291	74	439
E	183	**-1**	**614**

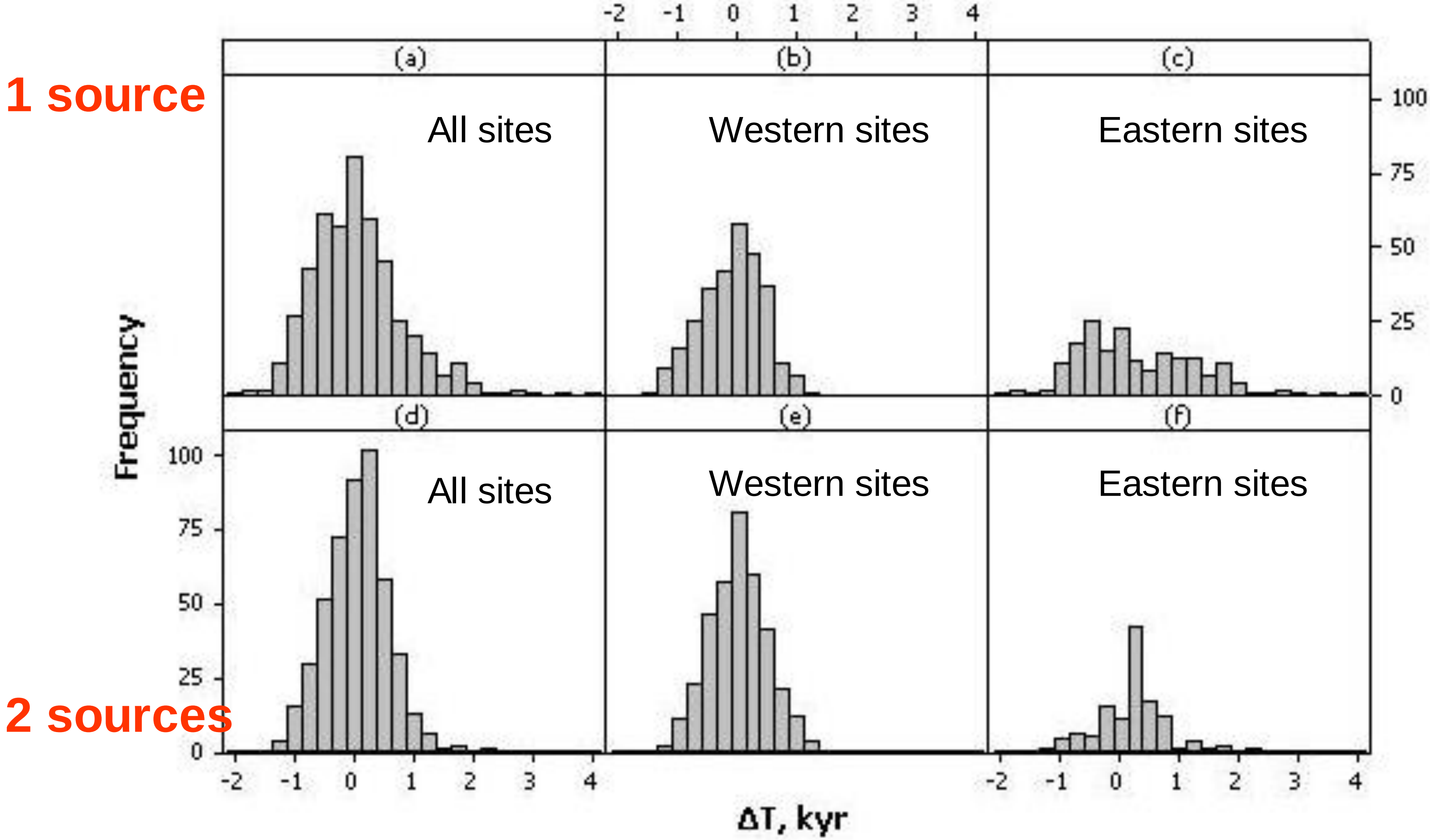
Is the improvement significant?

95% confidence intervals for the standard deviation of Δt do not overlap:

- Single source, $740 < \sigma_1 < 840$ years
- Two sources, $480 < \sigma_2 < 550$ years

F-test: $\sigma_1 = \sigma_2$ rejected at 95% level

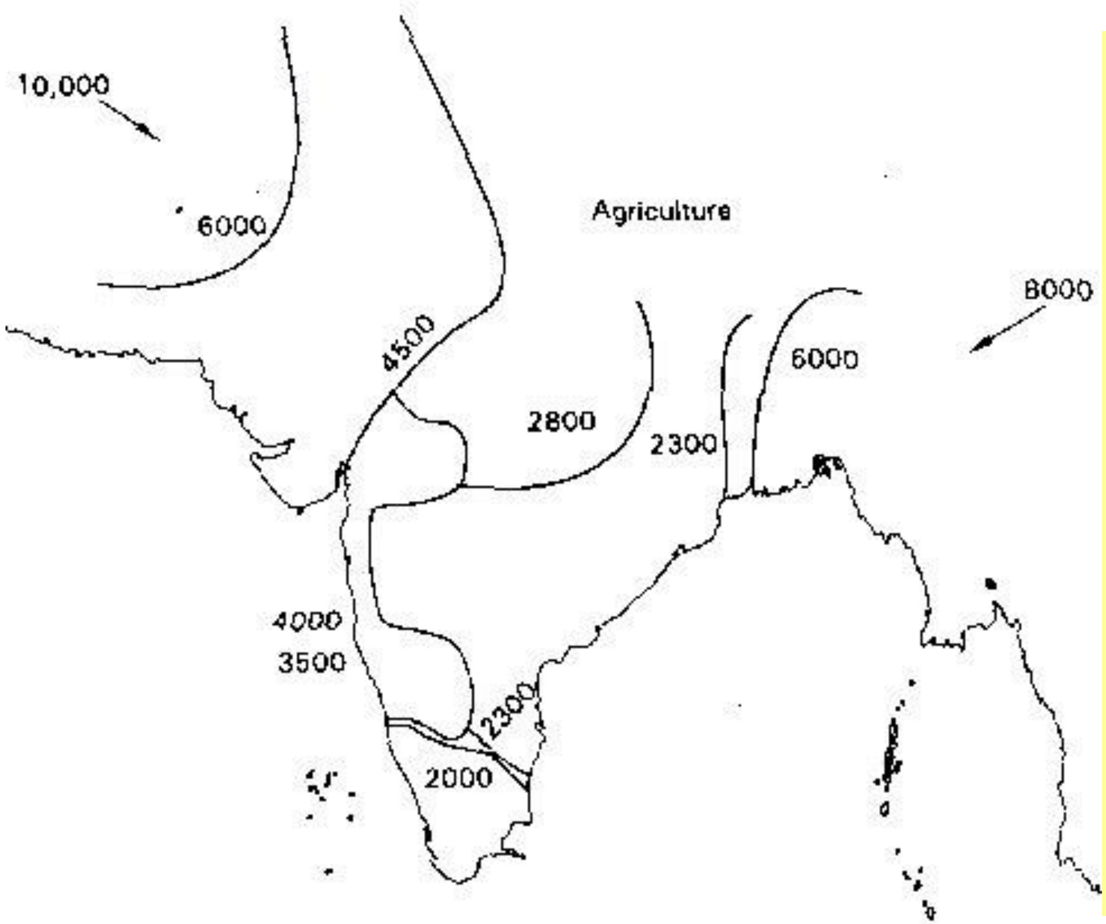
Histograms of Δt



Conclusions

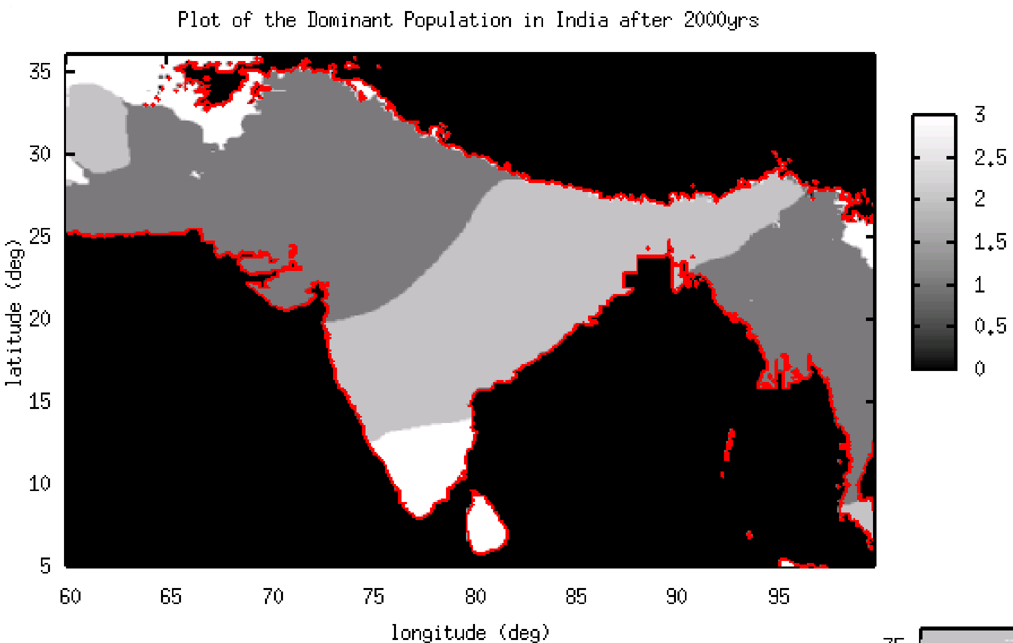
- Mathematical modelling of prehistory is feasible
- Anisotropic diffusion near major waterways affects the global pattern of the spread of farming
- Evidence for a second source of the Neolithic in the East
- Sites in the East are 50% of Eastern origin and 50% of Near-Eastern origin
- Sea-faring capabilities: 40 km offshore
- Mobility of hunter-gatherers:
  $U = 0.8$ km/yr ➔ $\nu = 90$ km^2/yr
  ($\lambda = 75$ km, $\tau = 15$ yr)

Incipient agriculture in India:
interaction of 3 populations



- Advance from two centres
- Isolated groups of hunter-gatherers
- Multi-population model:
  1. invading farmers
  2. retreating foragers
  3. foragers converted into farming

Dominant population types



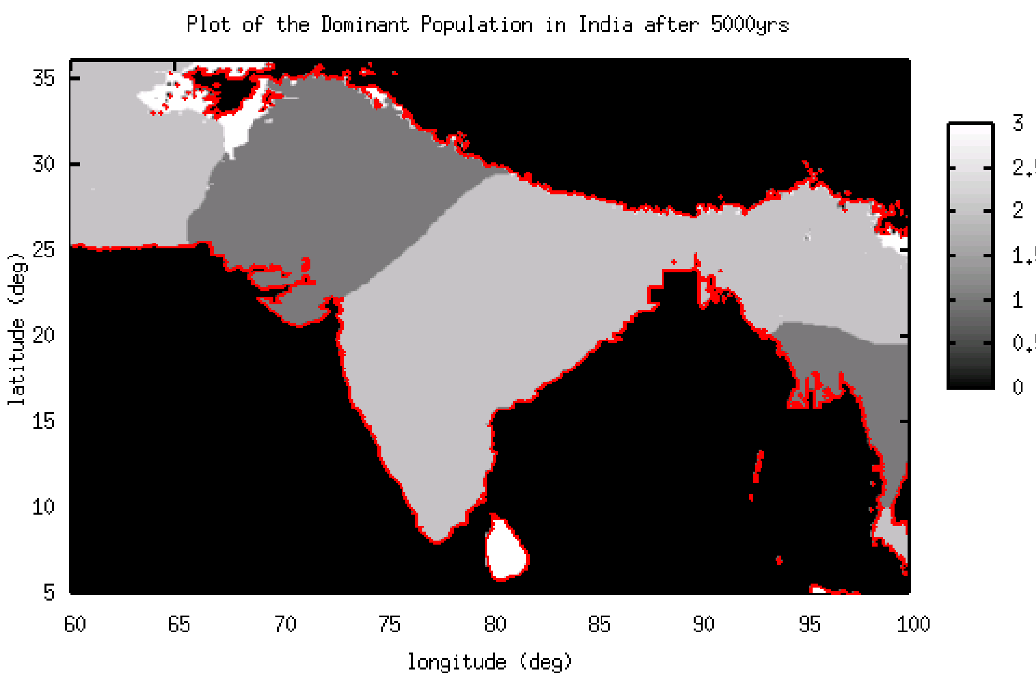
⇐ after 2000 yrs

⇓ after 5000 yrs

Invading farmers

Converted farmers

Hunter-gatherers

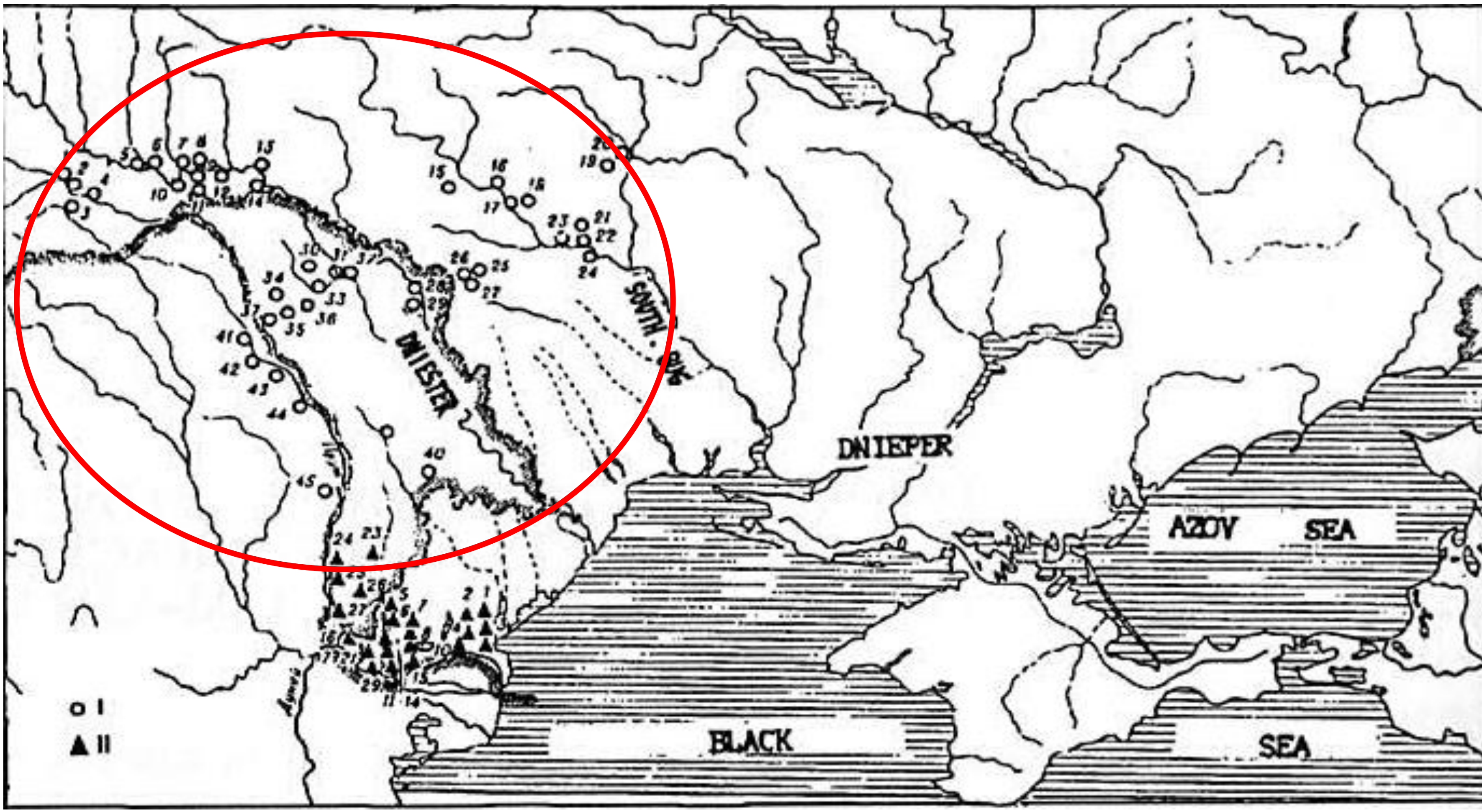


Settled life: the Cucuteni-Tripolye culture

Cultural Stage		Time Span
In Ukraine	In Romania	kyr BC
Tripolye A	Precucuteni	5.4/5.3–4.7/4.6
Tripolye B-I	Cucuteni A	4.5–4.2
Tripolye B-I/II	Cucuteni A-B	4.2–4.0
Tripolye B-II + C-I	Cucuteni B	4.0–3.5
Tripolye C-II		3.2–2.75/2.65

Cucuteni-Tripolye
Phase A

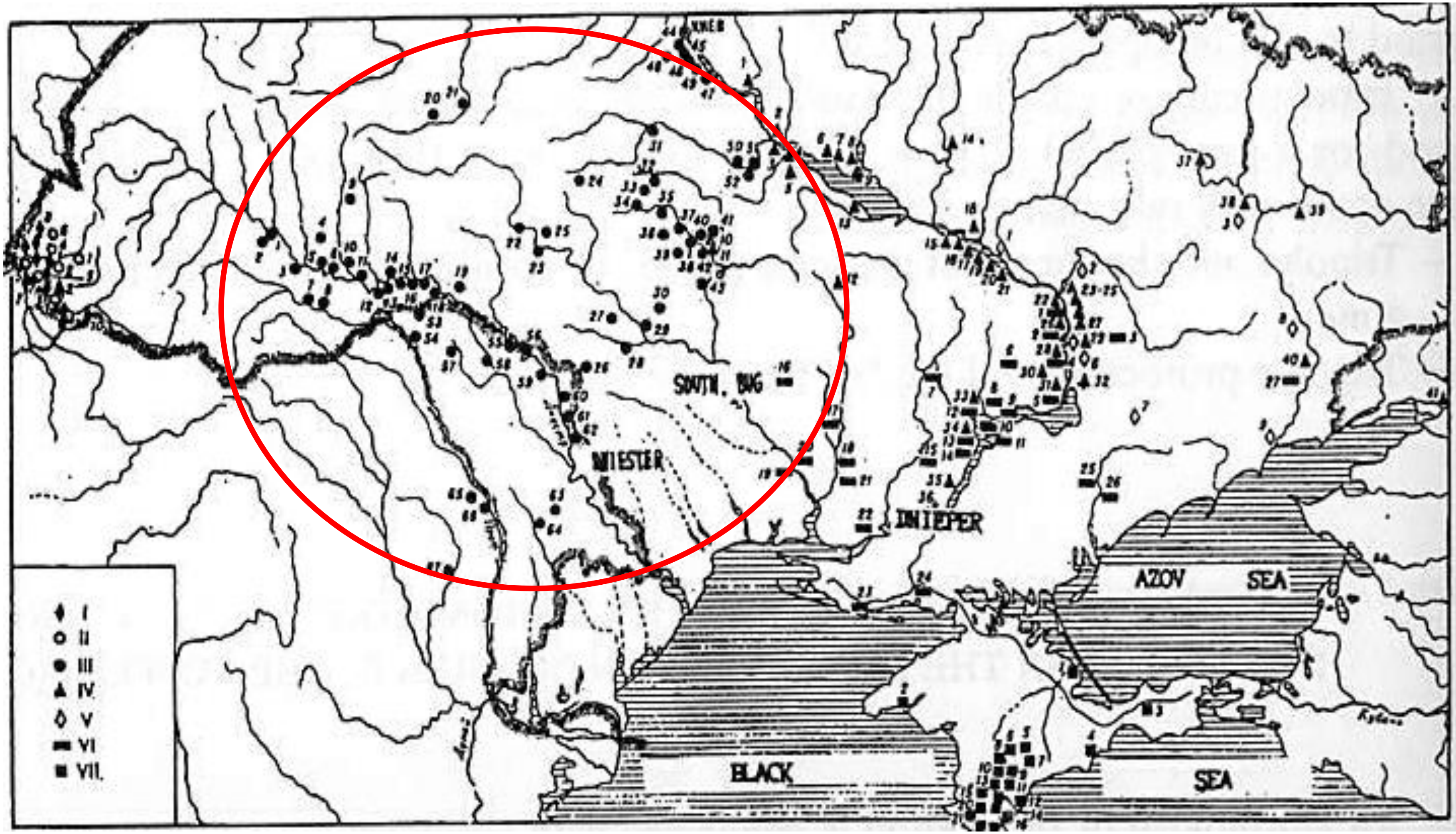
O = Tripolye A



Kadrow, Videiko et al, 1994

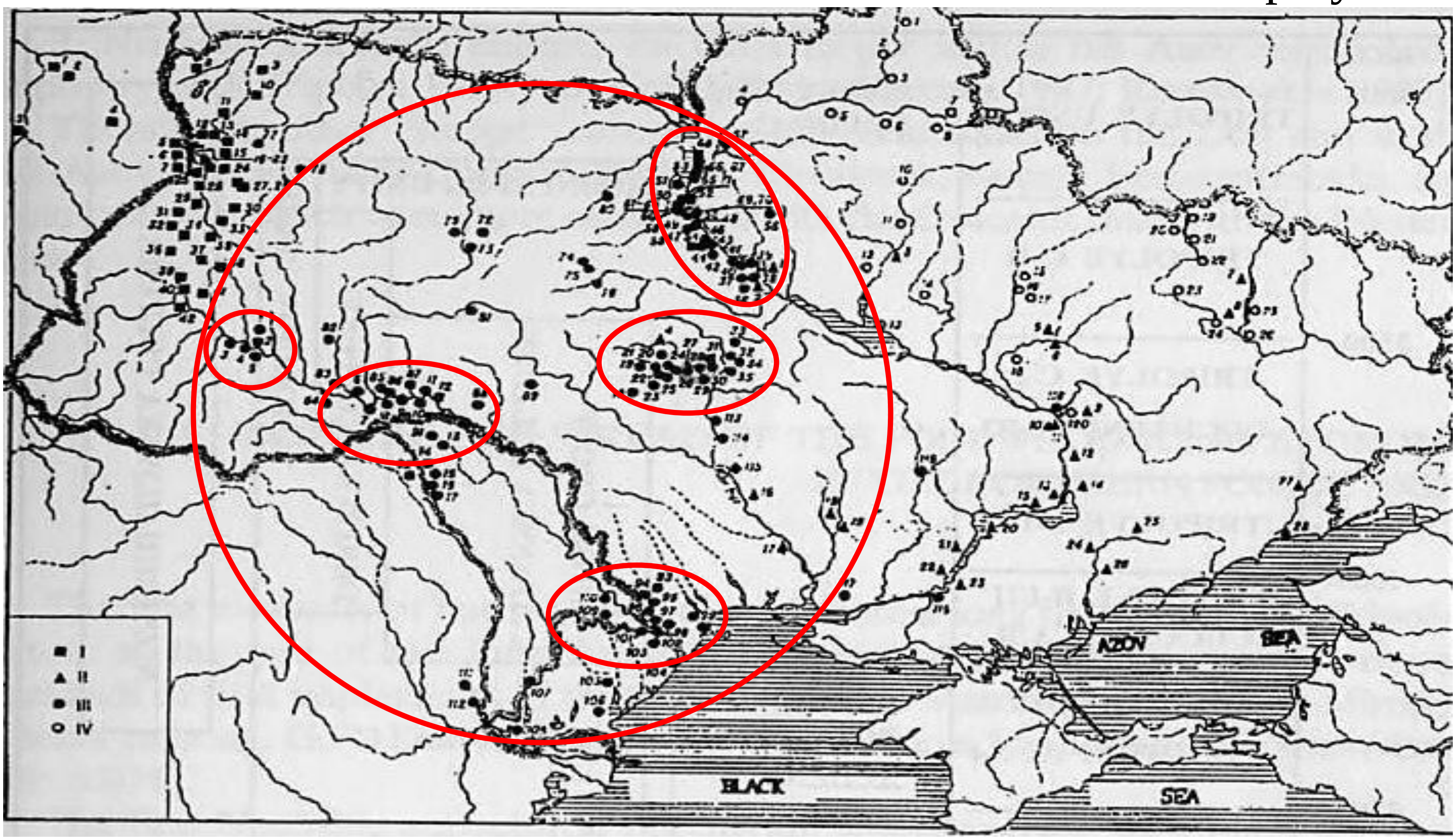
Cucuteni-Tripolye Phase B

• = Tripolye B

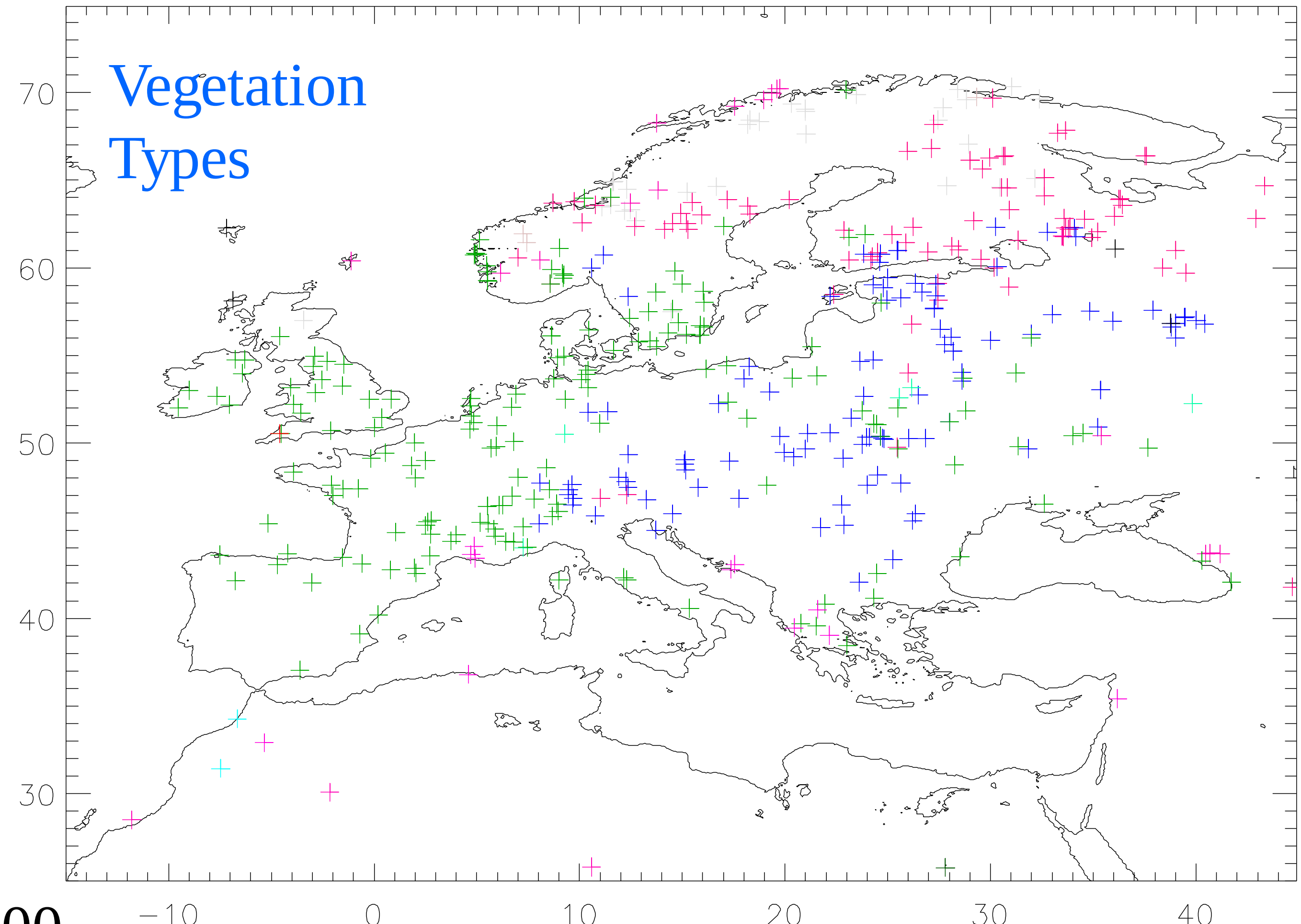


Cucuteni-Tripolye Phase C

• = Tripolye C



Further work: vegetation, soil type, nonlocal effects, …



Biomes 6000

Conclusion

Mathematical modelling of prehistory is feasible,

- but detailed models need to be developed,

- dominant environmental factors need to be identified
- and quantified,

- and methods need to be developed to compare the results with archaeological and radiometric data.

Statistical screening of ^{14}C dates

- **Multiple ^{14}C dates:** *need to isolate the most probable age*

- **Intrinsic statistical scatter in individual dates:** *need to obtain an accurate age estimate*

- **Multiple evolution phases at a given site:** *need to isolate and date individual phases*

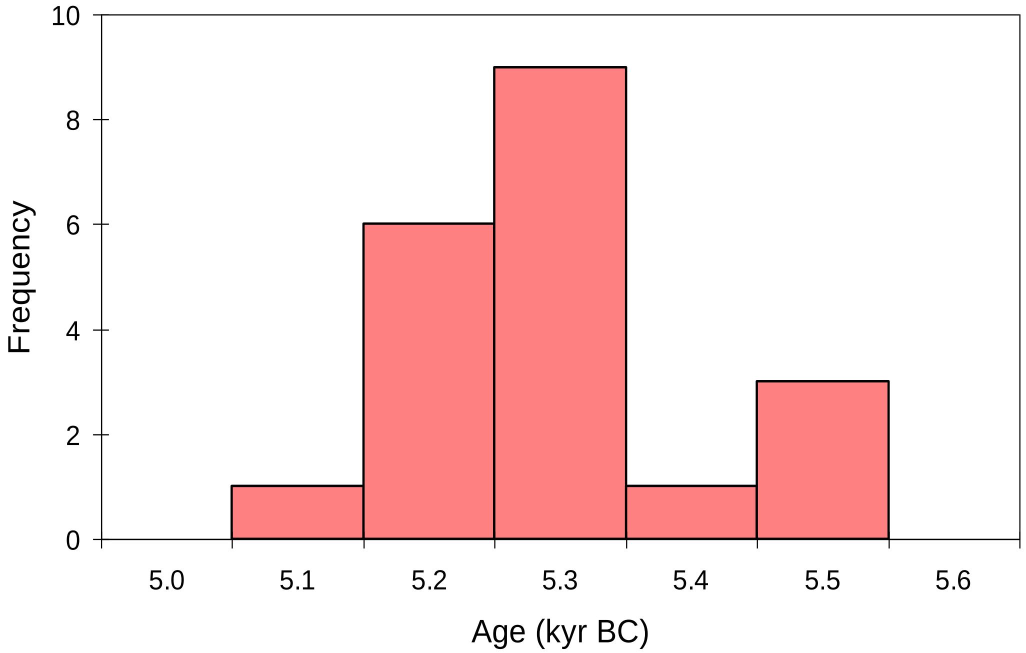
Multiple ^{14}C dates for well-explored sites

(RADON Database, http://www.jungsteinzeit.de/radon/radon.htm)

ID Daten	KULTUR	FUNDORT	GEMEINDE	LABNR	BP	STD
182	LBK	Strzelce		GrN-5087	6260	60
183	LBK	Stúrovo		Bln-557	5565	120
184	LBK	Stúrovo		Bln-558	6170	100
185	LBK	Stúrovo		Bln-559	6260	100
186	LBK	Tomaszow		GrN-7050	5895	40
187	LBK	Ulm-Eggingen	Ulm	Hv-12982	5960	90
188	LBK	Ulm-Eggingen	Ulm	Hv-13594	5740	195
189	LBK	Ulm-Eggingen	Ulm	Hv-13595	5855	80
190	LBK	Ulm-Eggingen	Ulm	Hv-13596	6245	120
191	LBK	Ulm-Eggingen	Ulm	Hv-13597	5840	145
192	LBK	Ulm-Eggingen	Ulm	Hv-13598	5810	80
193	LBK	Ulm-Eggingen	Ulm	Hv-13599	5960	60
194	LBK	Ulm-Eggingen	Ulm	Hv-13600	6205	60
195	LBK	Ulm-Eggingen	Ulm	Hv-13601	5995	60
196	LBK	Ulm-Eggingen	Ulm	Hv-14721	5590	160

Example: Brunn am Gebirge, Austria

Compact cluster of 20 dates, interpreted as a single date contaminated by noise

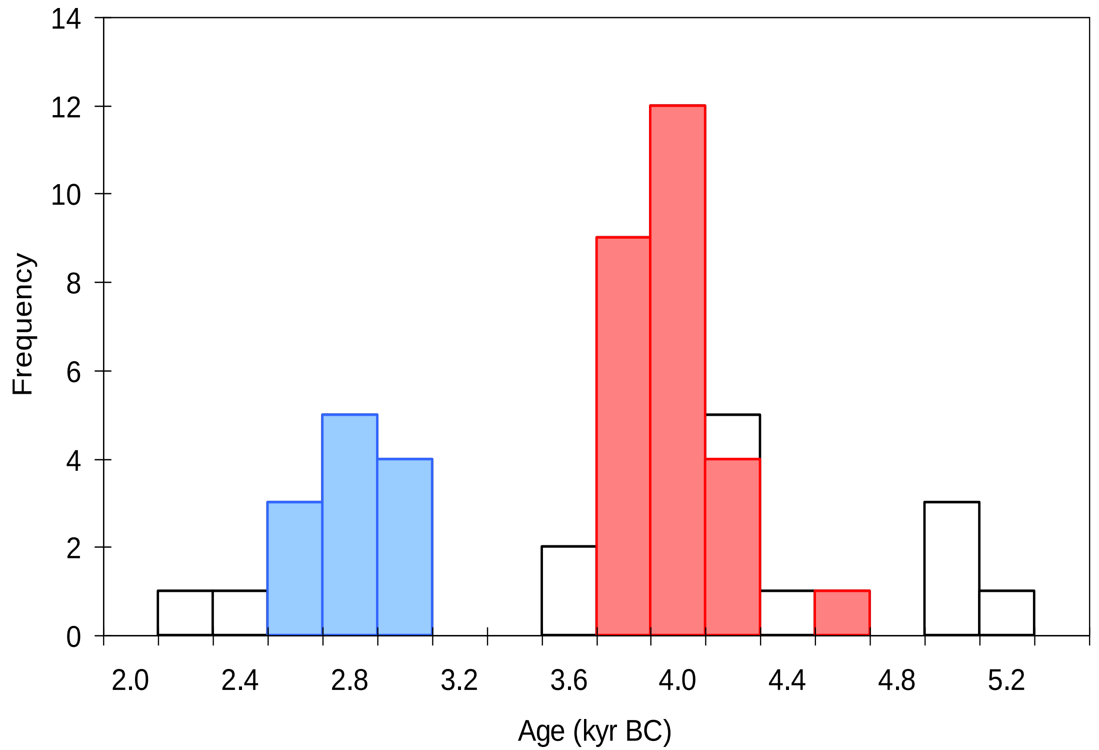


- Most probable age: $T_0 = 5252 \pm 99$ BC
- $\sigma = 100$ years adopted as the minimum error for LBK sites
- Fine temporal structure implied by archaeological evidence is not visible in ^{14}C dates due to insufficient accuracy

Example: Zedmar, Kaliningrad, Russia

48 dates in two clusters, interpreted as two dates

(using the χ^2 test)



$T_0 = 3870 \pm 38$ BC, $\sigma = 192$ years (26 dates)

$T_0 = 2770 \pm 76$ BC, $\sigma = 179$ years (12 dates)

(minimum error 127 years suggested by similar sites)