Real-time, probabilistic and evolutionary earthquake location for seismic early warning

by **Claudio Satriano (I)**, Anthony Lomax (III) and Aldo Zollo (II)

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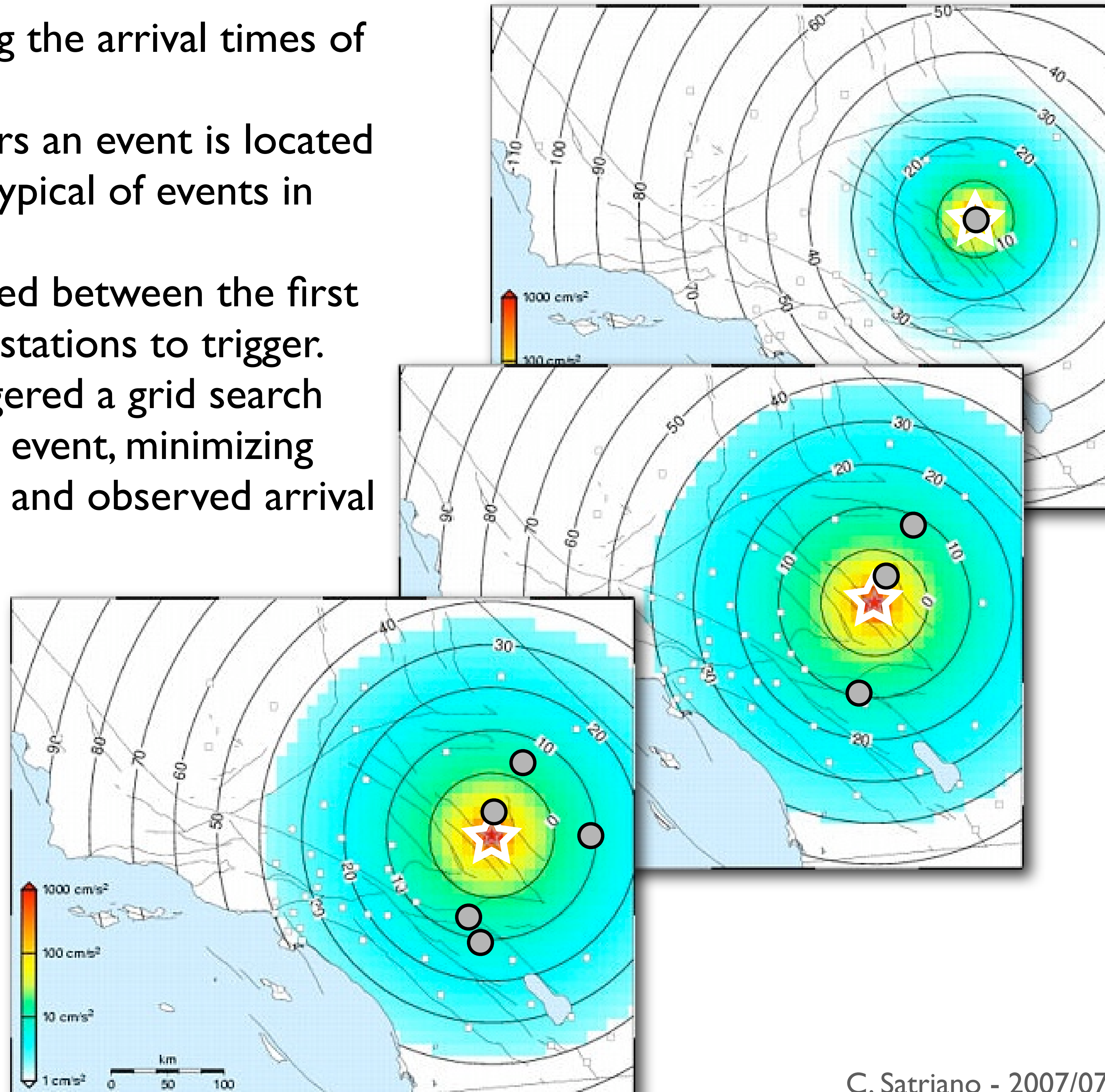
Introduction

- A regional early warning system is based on the ability of a seismic network to provide estimates of the location and size of a potentially destructive earthquake within a few seconds after the event is first detected.
- This information is then used to characterize the earthquake, and to estimate its severity for the selected target in order to take mitigating actions.

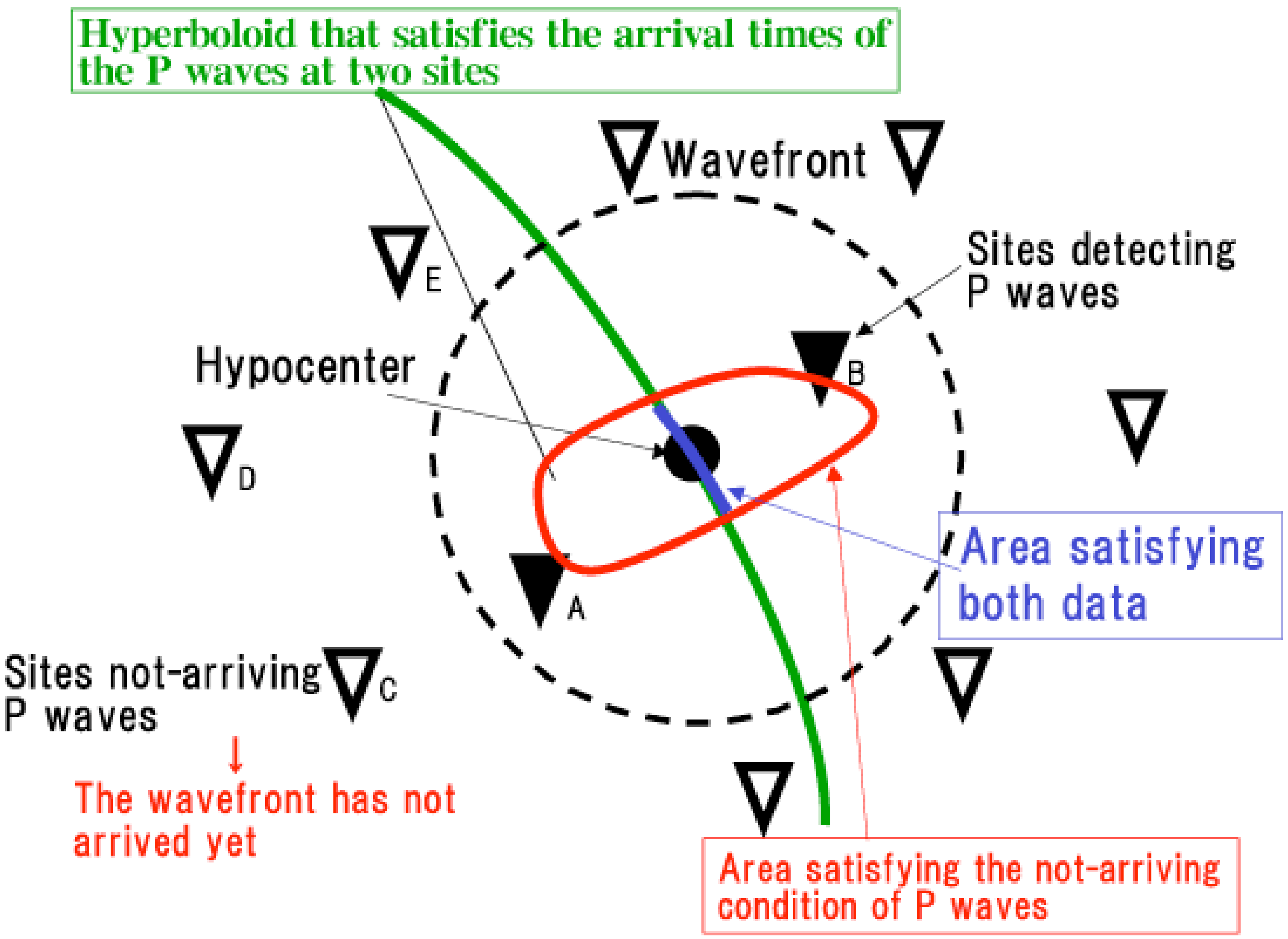
ElarmS

- Earthquakes are located using the arrival times of P-waves.
- When the first station triggers an event is located at that station with a depth typical of events in the region.
- The earthquake is then located between the first two, and then the first three stations to trigger.
- Once four stations have triggered a grid search method is used to locate the event, minimizing the misfit between predicted and observed arrival times.

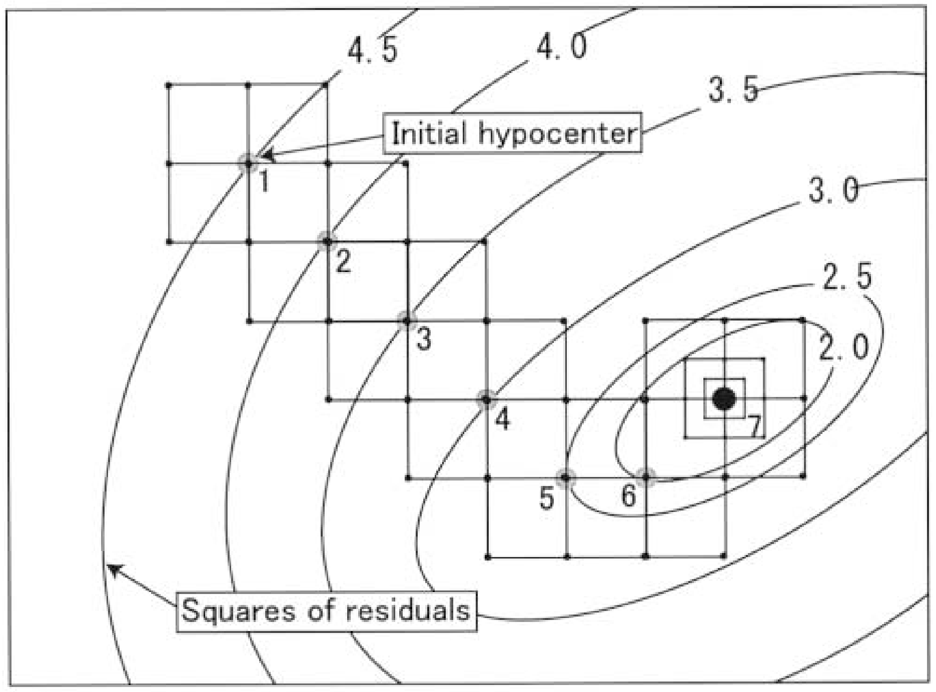


from Allen, 2005 (www.elarms.org)

Real-time location at NIED, Japan



$$T_{now} - T_i(\mathbf{x}, t) < 0$$



from Horiuchi et al., 2005

Real-Time Earthquake Location (RTLoc)

Our methodology is related to that of Horiuchi et al. [2005], which we extend and generalize by:

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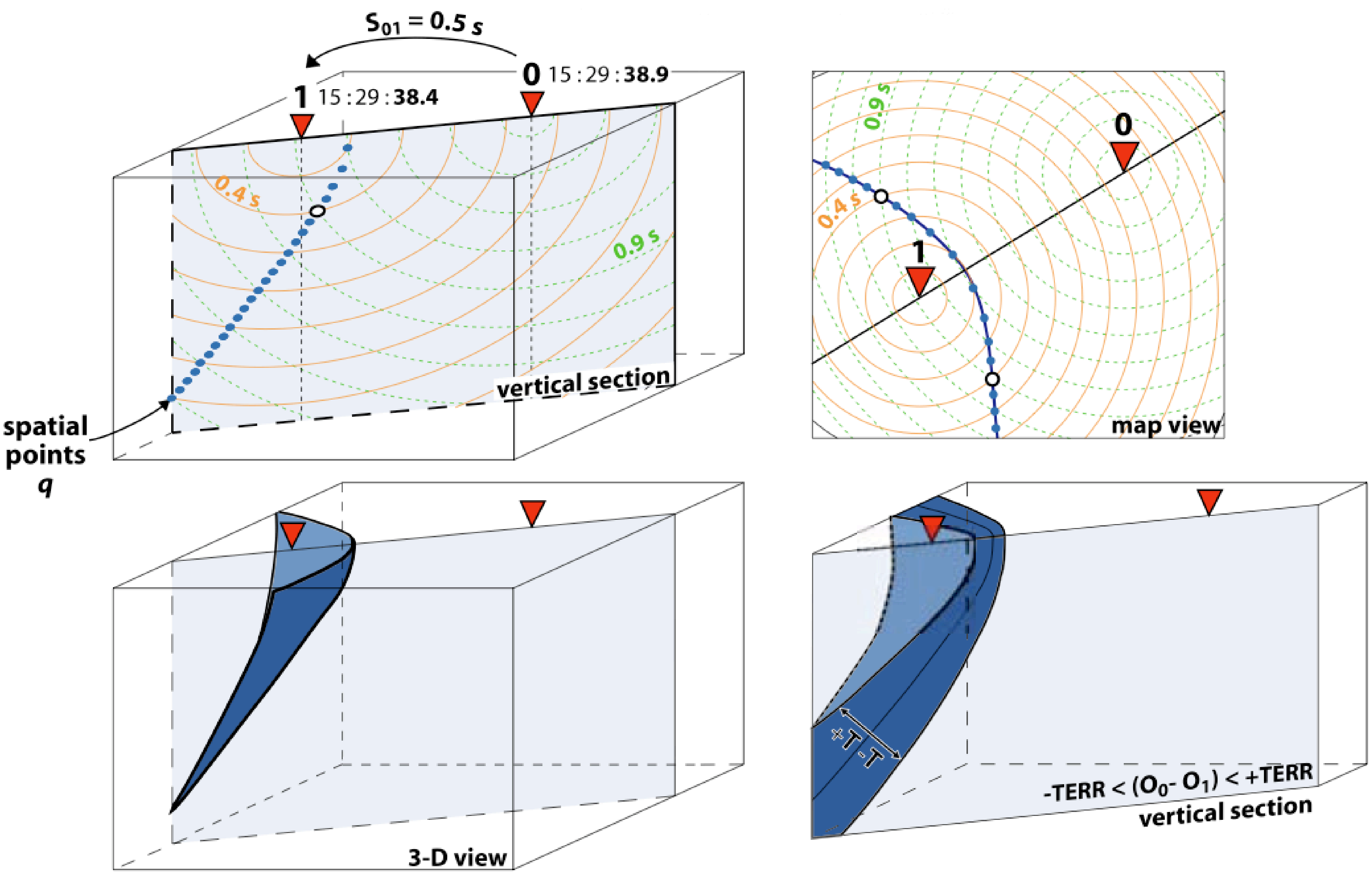
c. estimating the hypocenter probabilistically as a *pdf* instead of as a point

d. applying a full, non-linearized, global-search for each update of the location estimate.

Equal Differential Time (EDT) approach

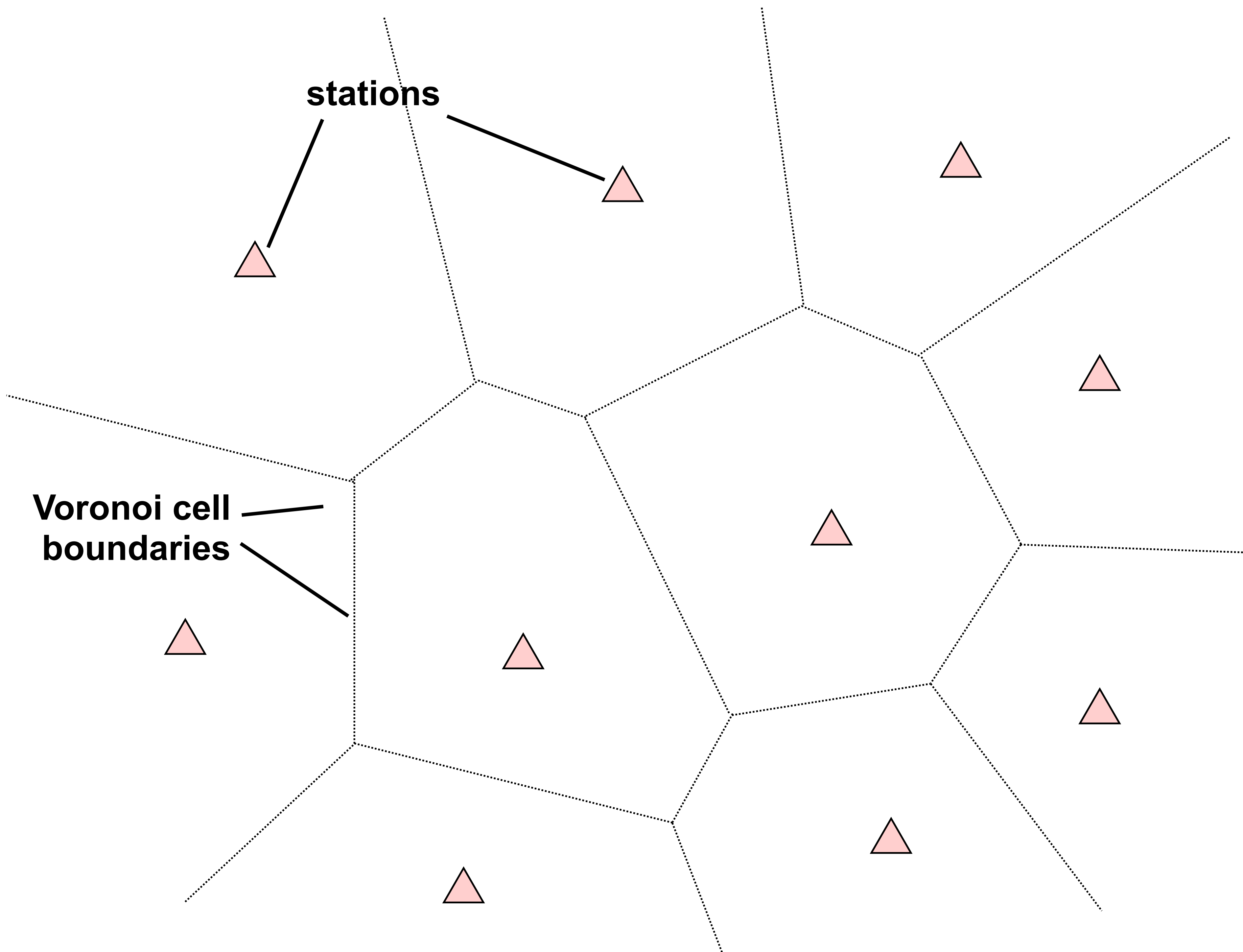


If the hypocenter is exactly determined, the difference between calculated travel times tt_0 and tt_1 from the hypocenter to two stations S_0 and S_1 is equal to the difference between the observed arrival times t_0 and t_1 at the two stations, since the observed arrival times share the common earthquake origin time:

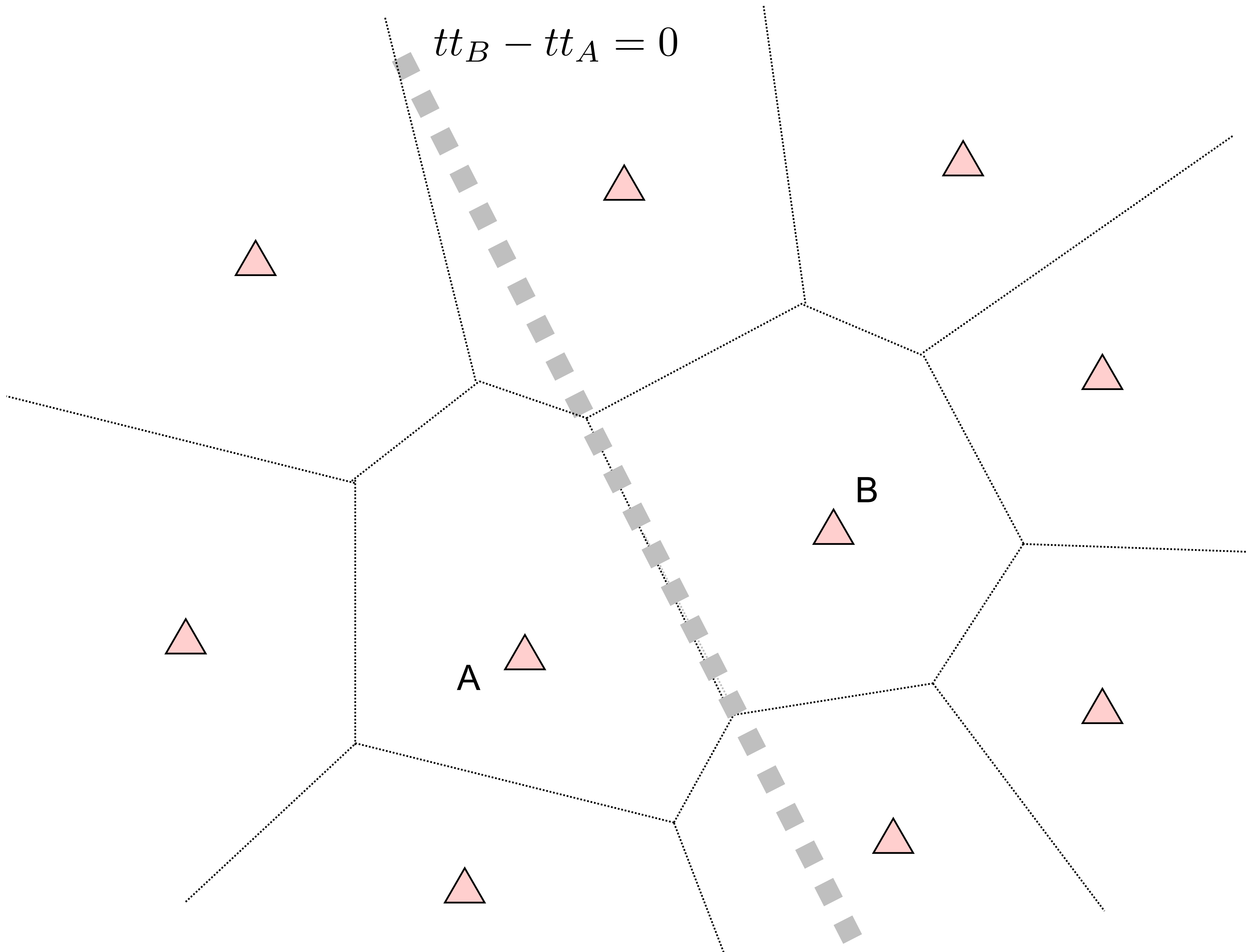
$$tt_1 - tt_0 = t_1 - t_0$$

from Font et al., 2004

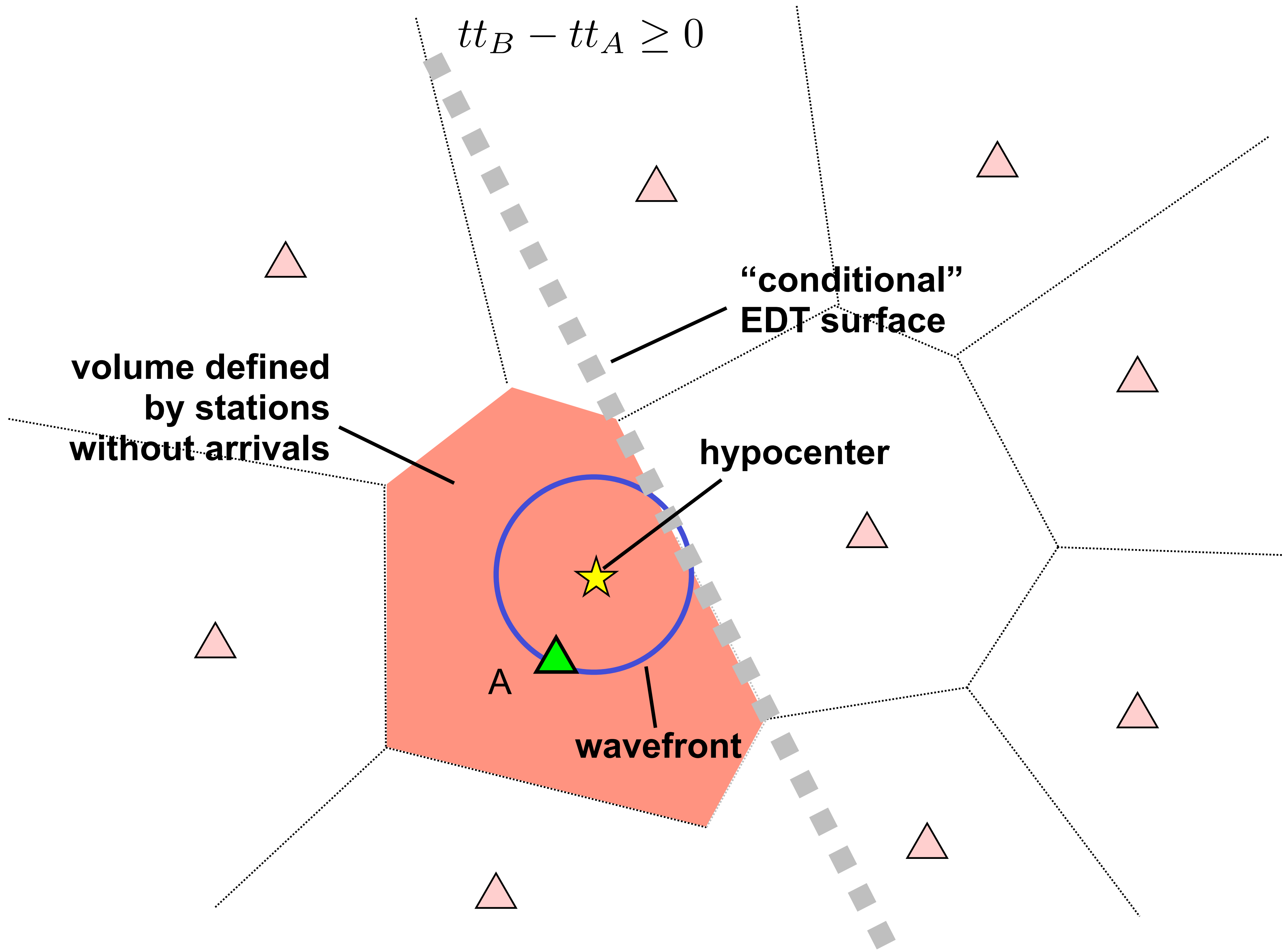
Evolutionary Earthquake Location - 1/7



Evolutionary Earthquake Location - 2/7

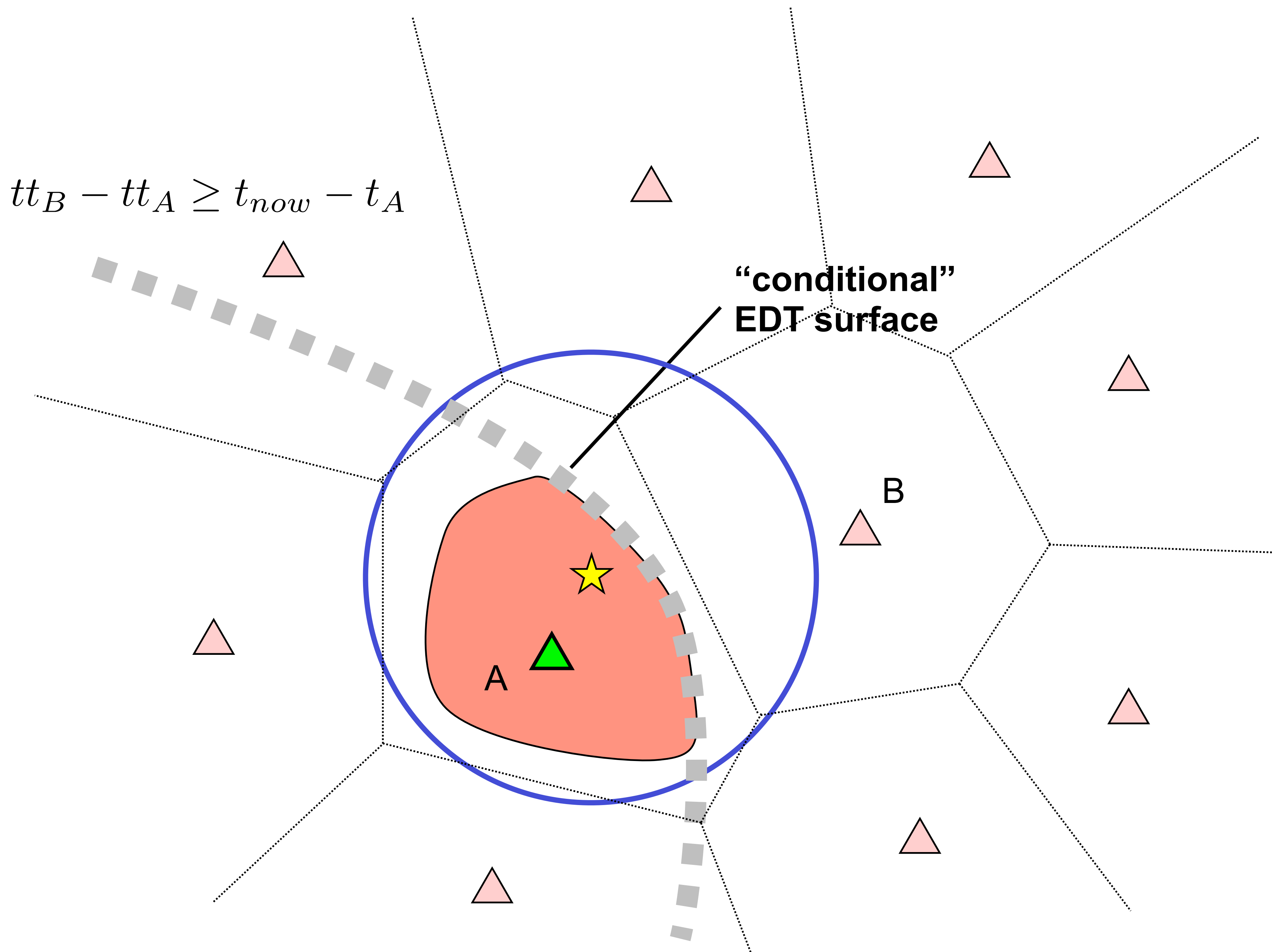


Evolutionary Earthquake Location - 3/7



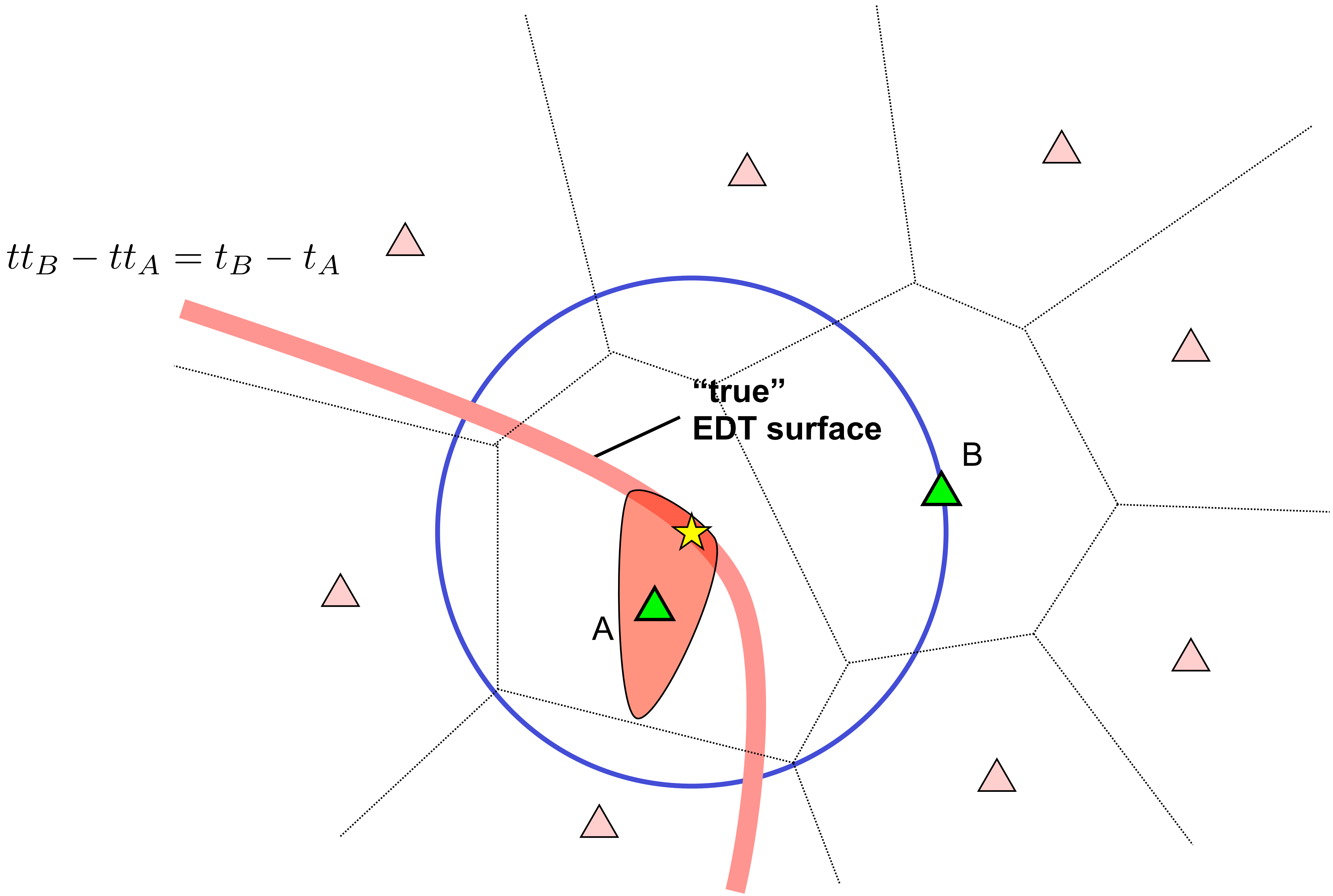
First station detects arrival
constraint is Voronoi cells

Evolutionary Earthquake Location - 4/7



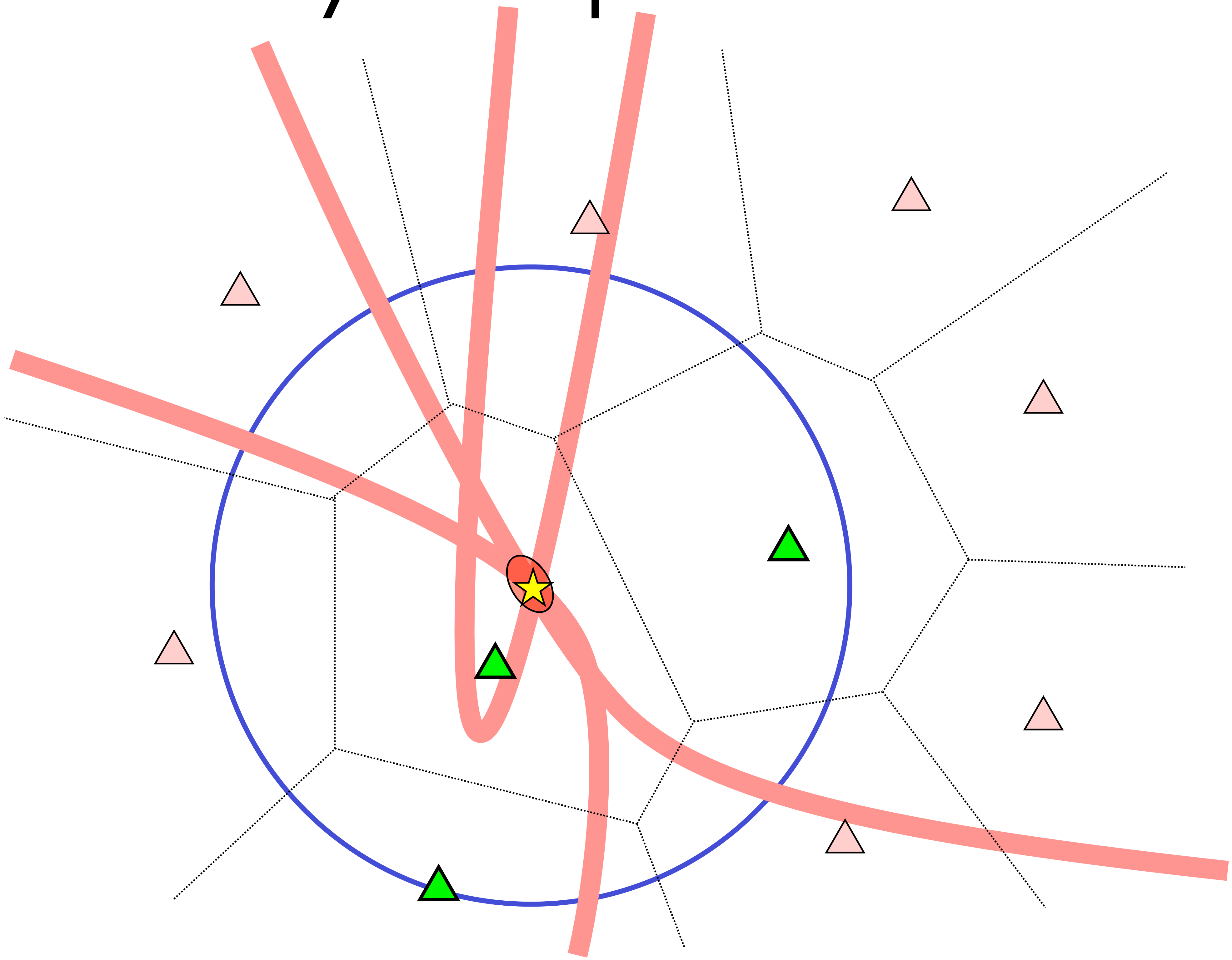
Wavefront expands
EDT surfaces deform, constraint improves

Evolutionary Earthquake Location - 5/7



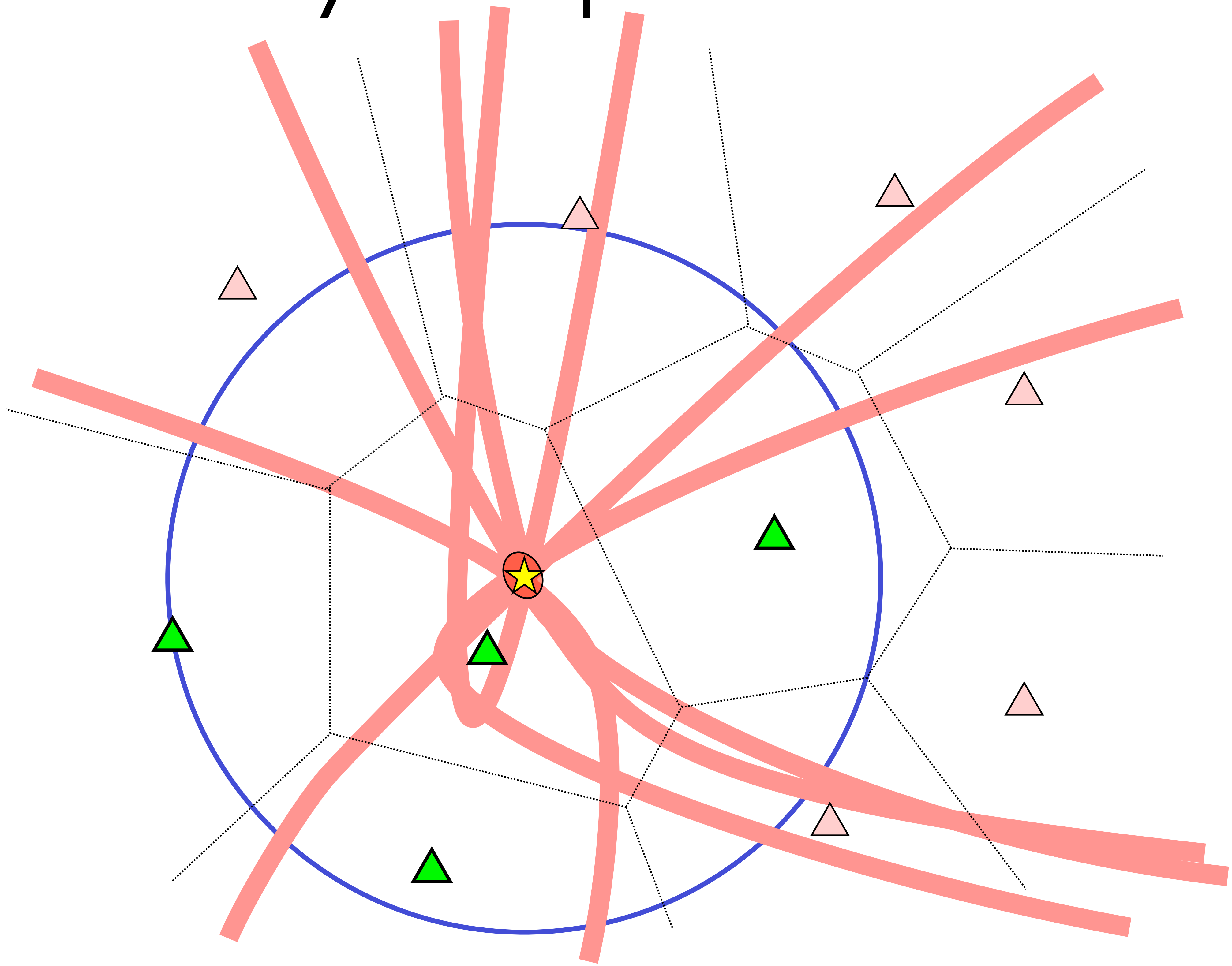
Second station detects arrival
constraint includes EDT surface

Evolutionary Earthquake Location - 6/7



Third station detects arrival
constraint is mainly EDT surfaces

Evolutionary Earthquake Location - 7/7



Fourth station detects arrival
location is well constrained

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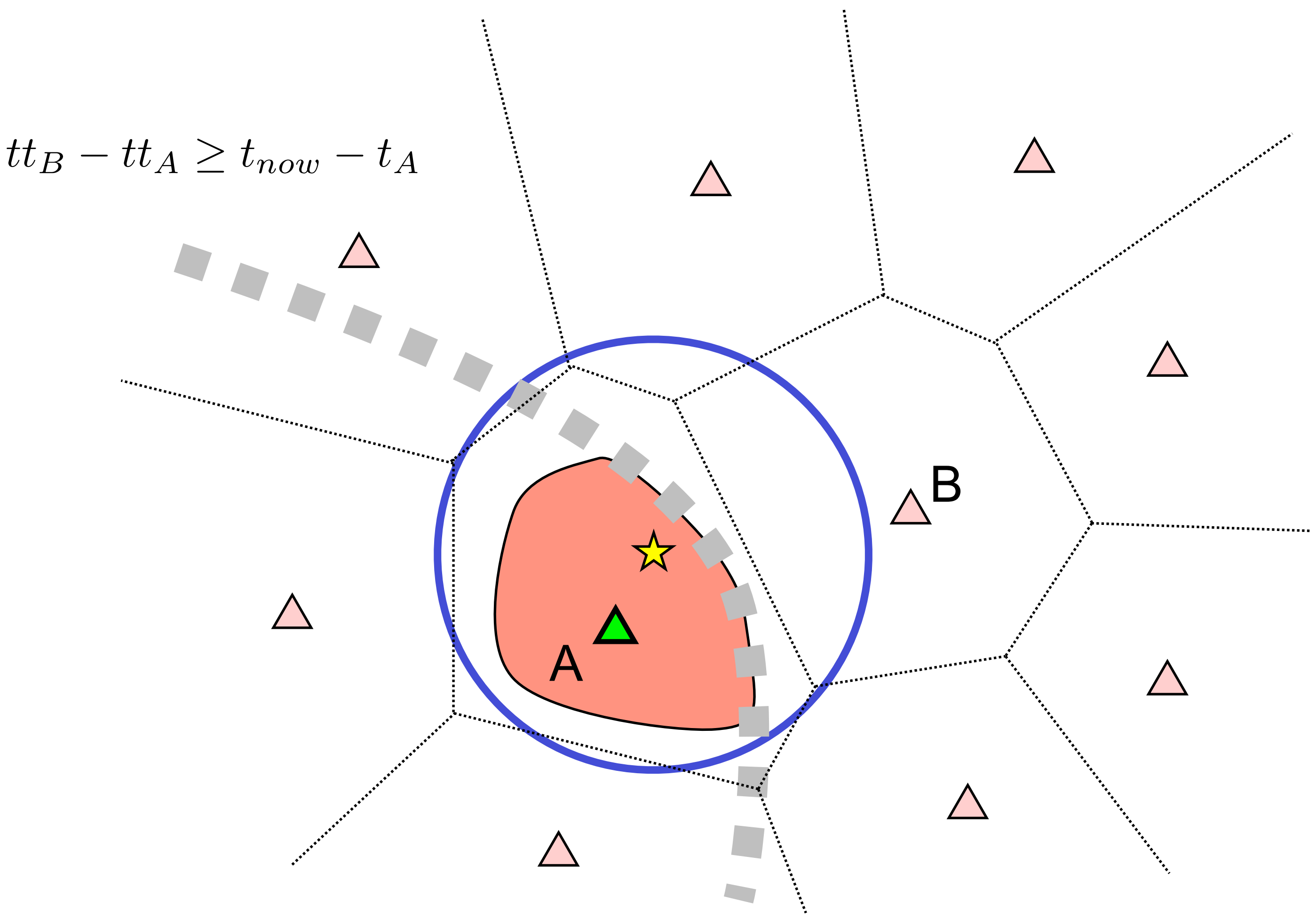
RTLoc: Algorithm (1/2)

We consider N operational stations (S_0, …, S_N), a **gridded search volume** V containing the network and target earthquake source regions, and **pre-computed travel times** from each station to each grid point (i,j,k) in V computed for a given velocity model.

When the first station S_n triggers, we compute for each grid point the quantity:

$$(p_n)_{i,j,k} = \begin{cases} 1 & if \quad (tt_{Sk} - tt_{Sn})_{i,j,k} \geq \delta t_{n,k} \\ 0 & if \quad (tt_{Sk} - tt_{Sn})_{i,j,k} < \delta t_{n,k} \end{cases} \quad ; k \neq n$$

$$\delta t_{n,k} = t_{now} - t_{Sn}$$



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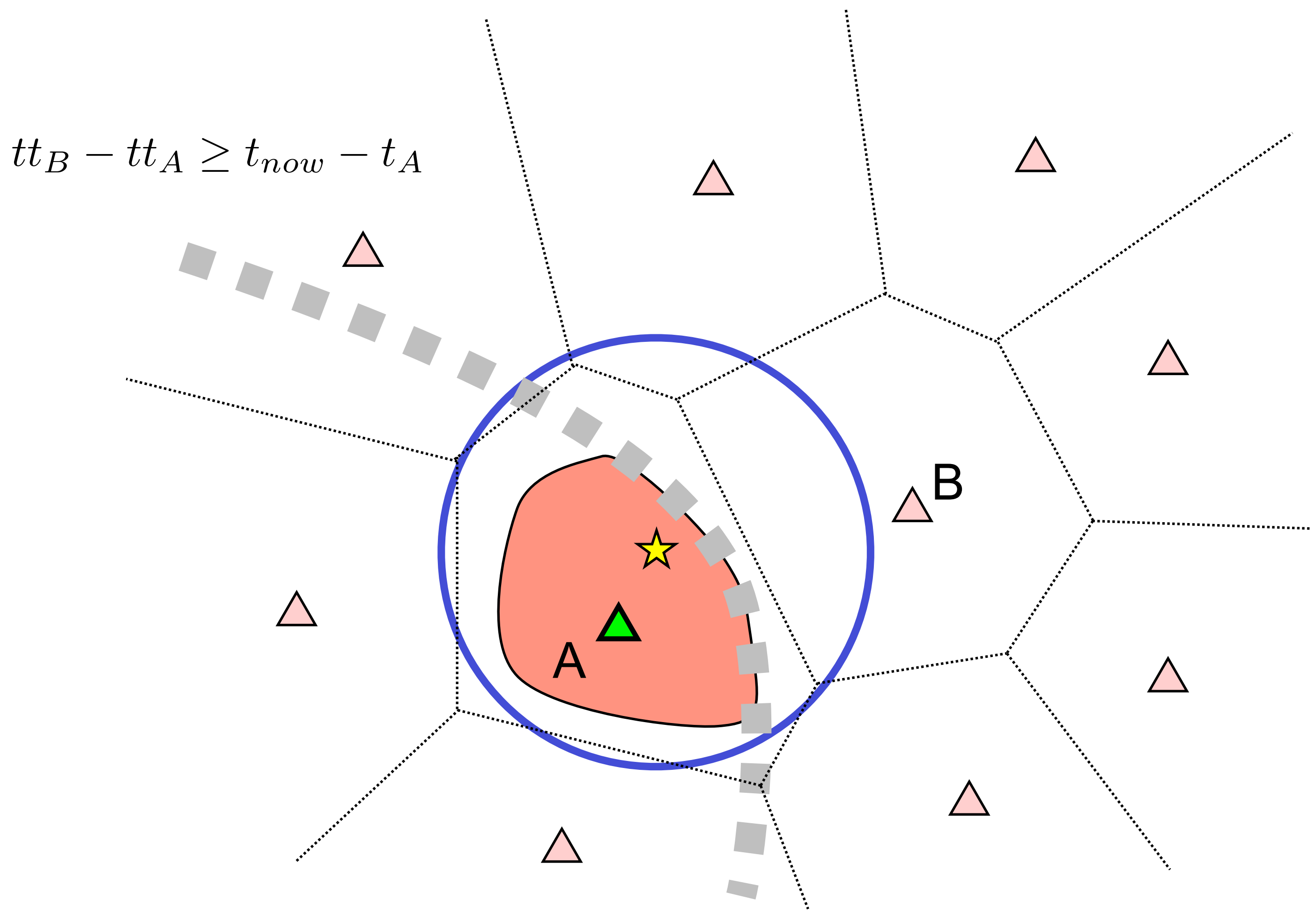
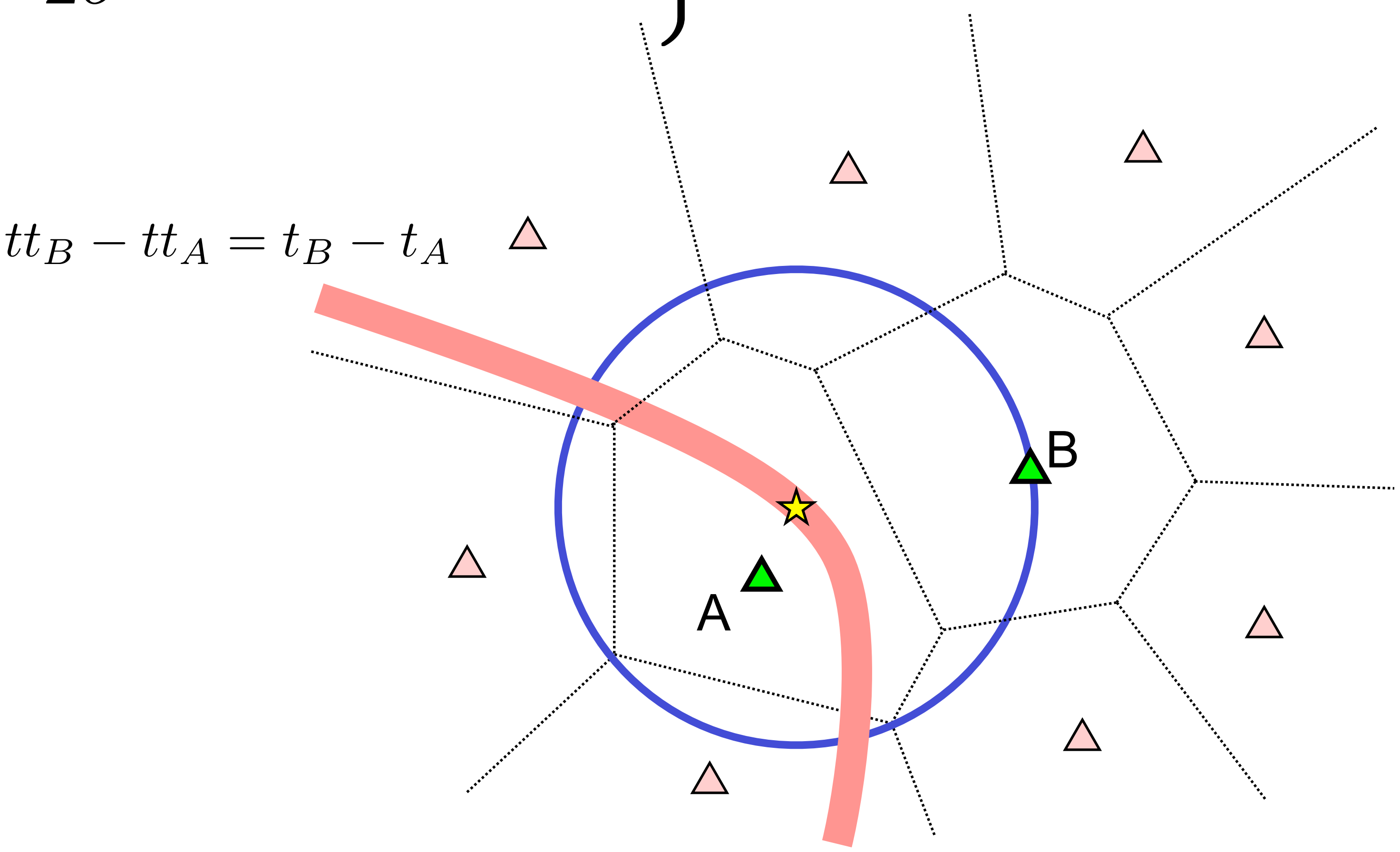


When a new station triggers, we re-evaluate $(p_m)_{i,j,k}$ for all the pairs S_n (triggered) - S_k (not-yet-triggered).

RTLoc: Algorithm (2/2)

For each pair S_n, S_m of triggered stations, we compute at each grid point (i, j, k), the quantity:

$$(q_m)_{i,j,k} = exp\left\{-\frac{[(tt_{Sm} - tt_{Sn}) - (t_{Sm} - t_{Sn})]^2_{i,j,k}}{2\sigma^2}\right\}; m \neq n$$



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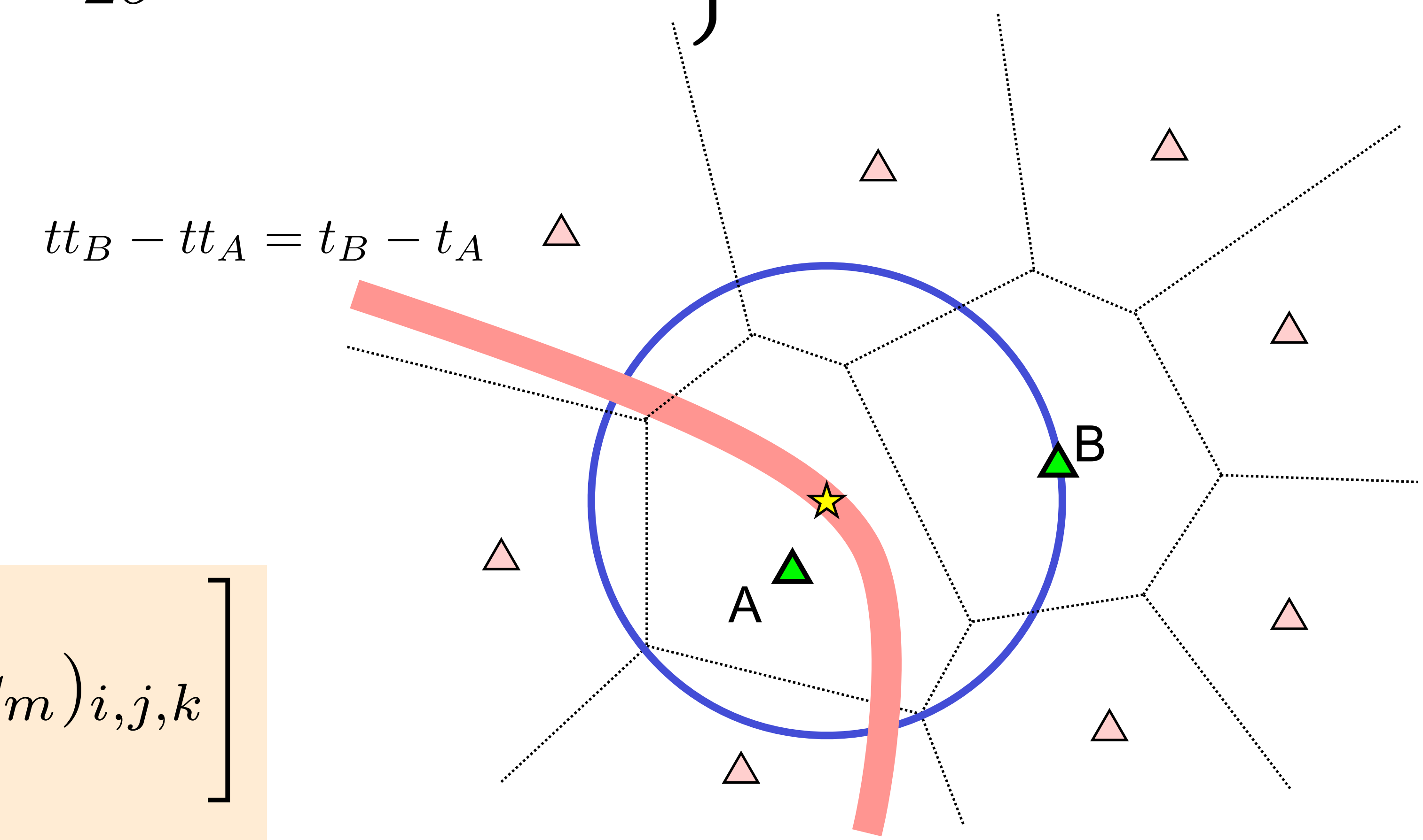
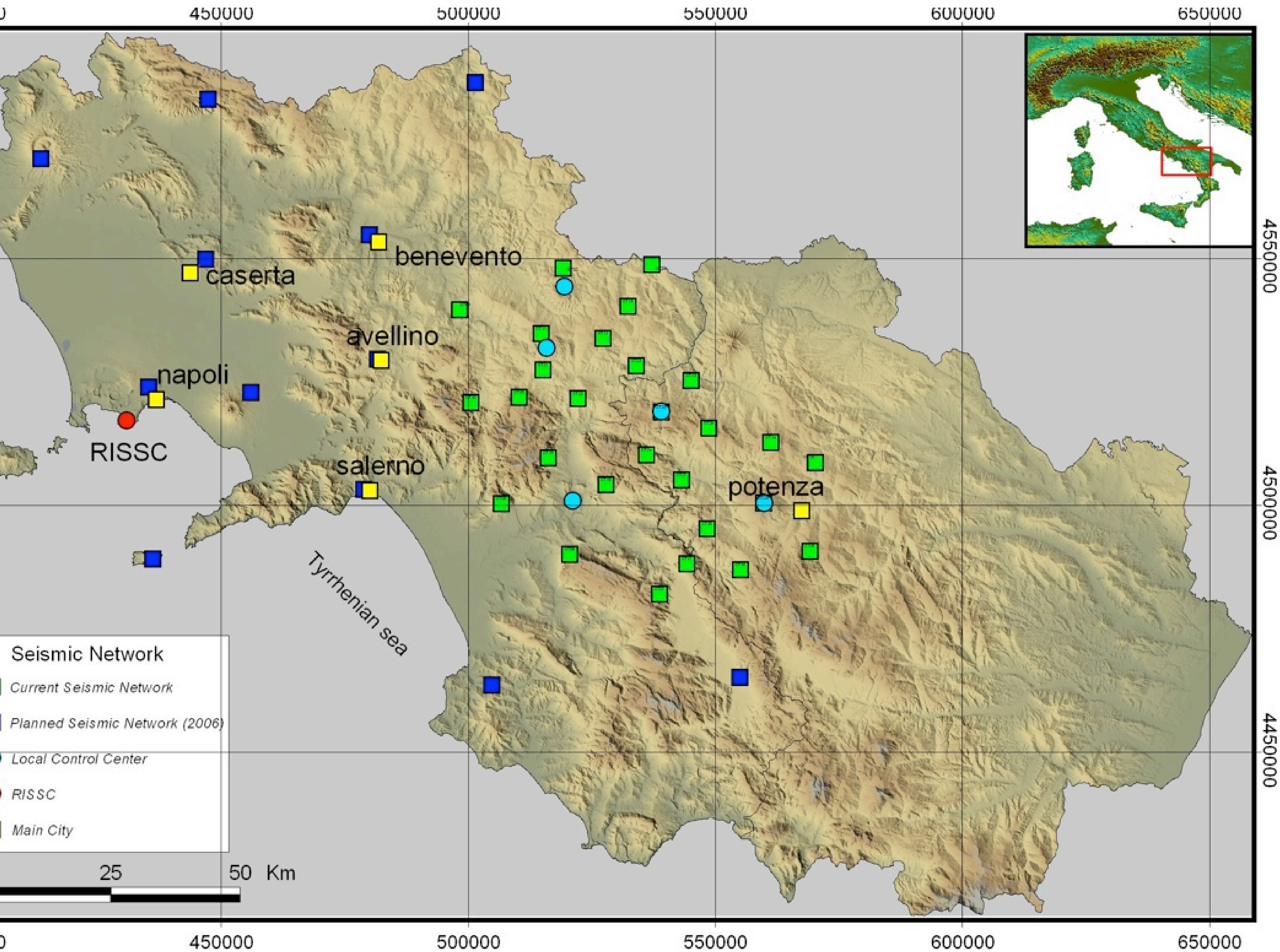


Eventually, for each grid point we define:

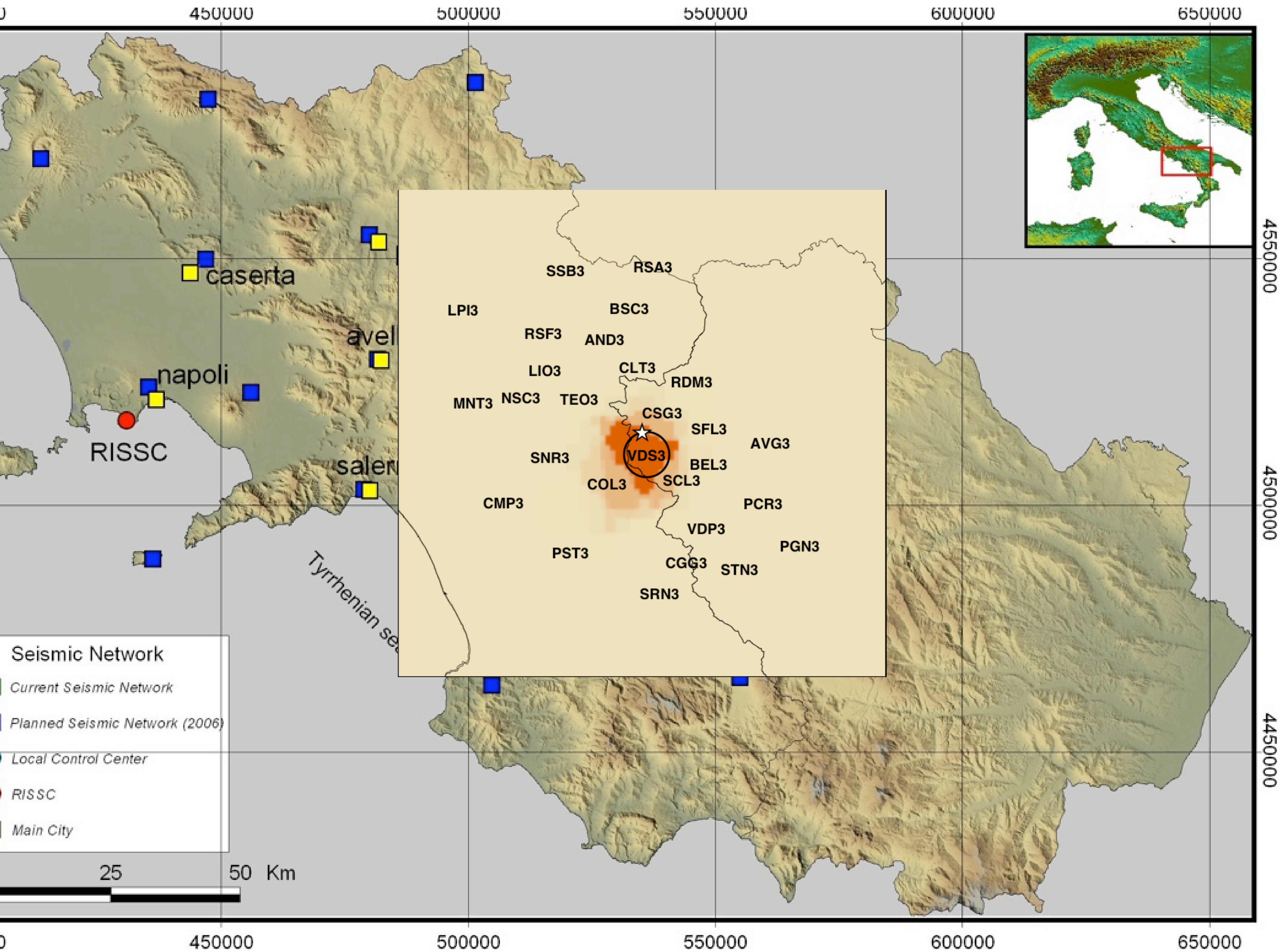
$$P_{i,j,k} = \frac{1}{M}\left[\sum_n (p_n)_{i,j,k} + \sum_m (q_m)_{i,j,k}\right]$$

$$Q_{i,j,k} = (P_{i,j,k})^N$$

where M is the number of equations.
The quantity $Q_{i,j,k}$ forms a relative probability density function (with values between 0 and 1) for the hypocenter location within the grid cell (i, j, k).

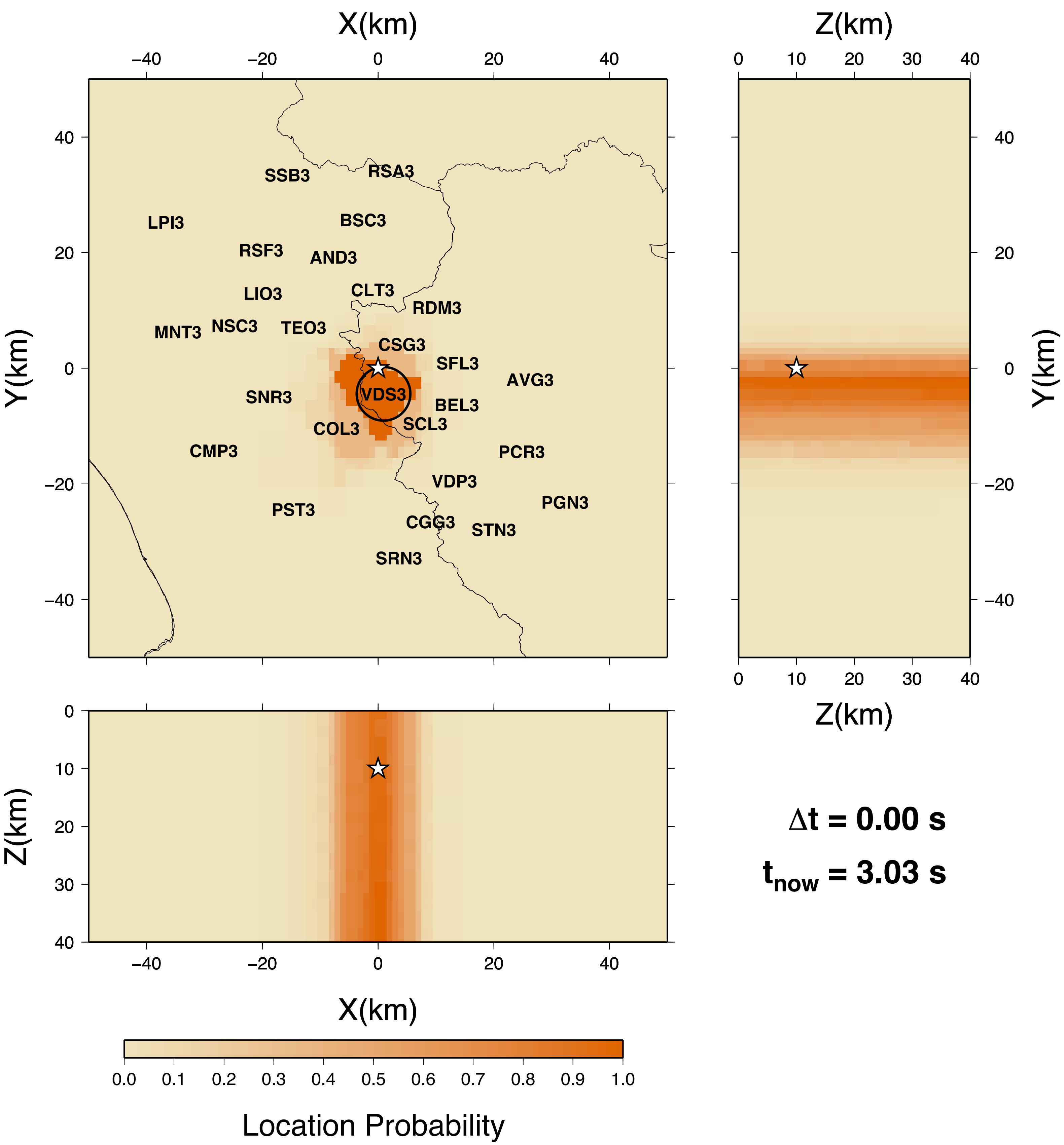


The Irpinia Seismic Network (ISNet)



The Irpinia Seismic Network (ISNet)

RTLoc test at the ISNet



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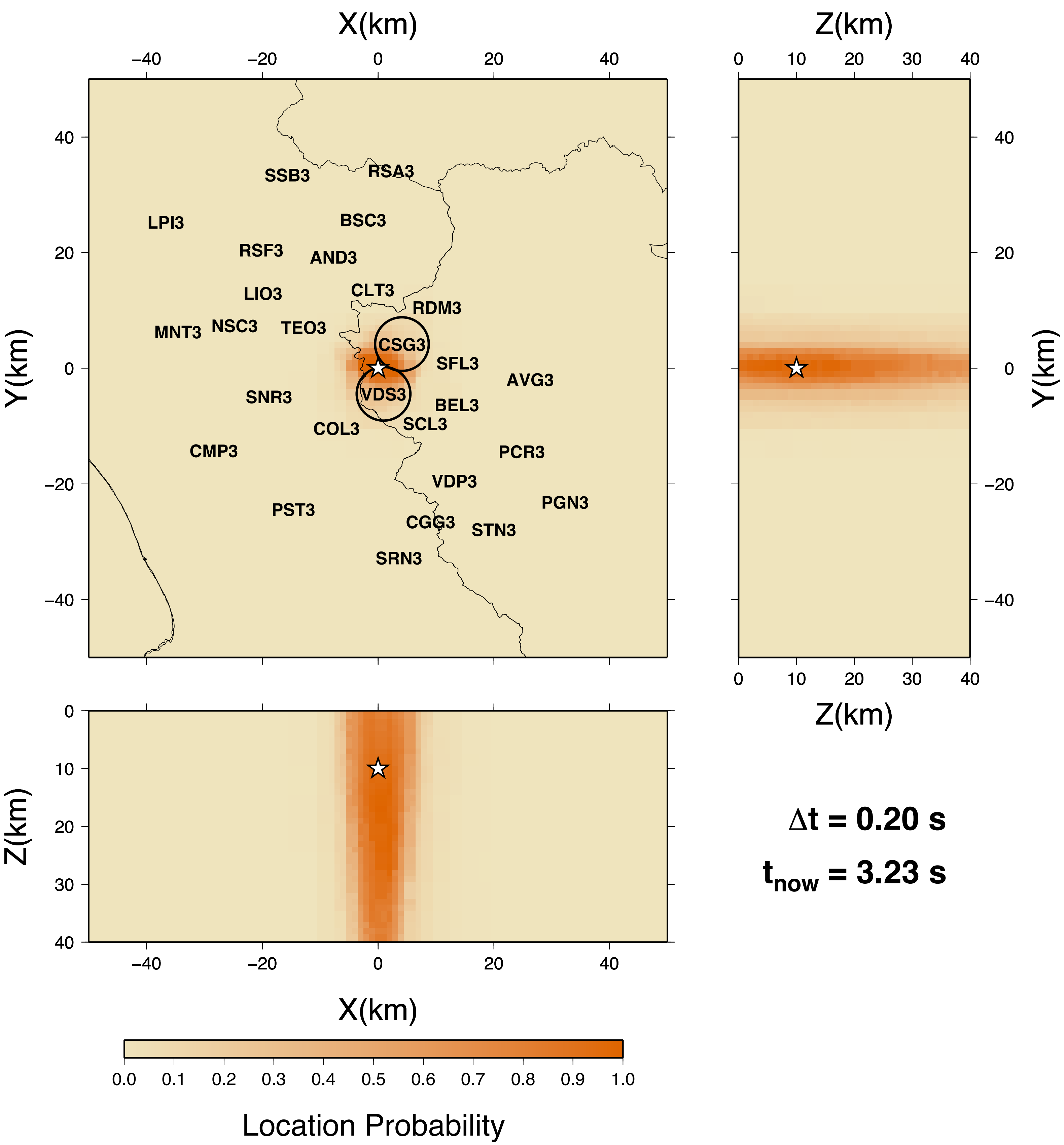

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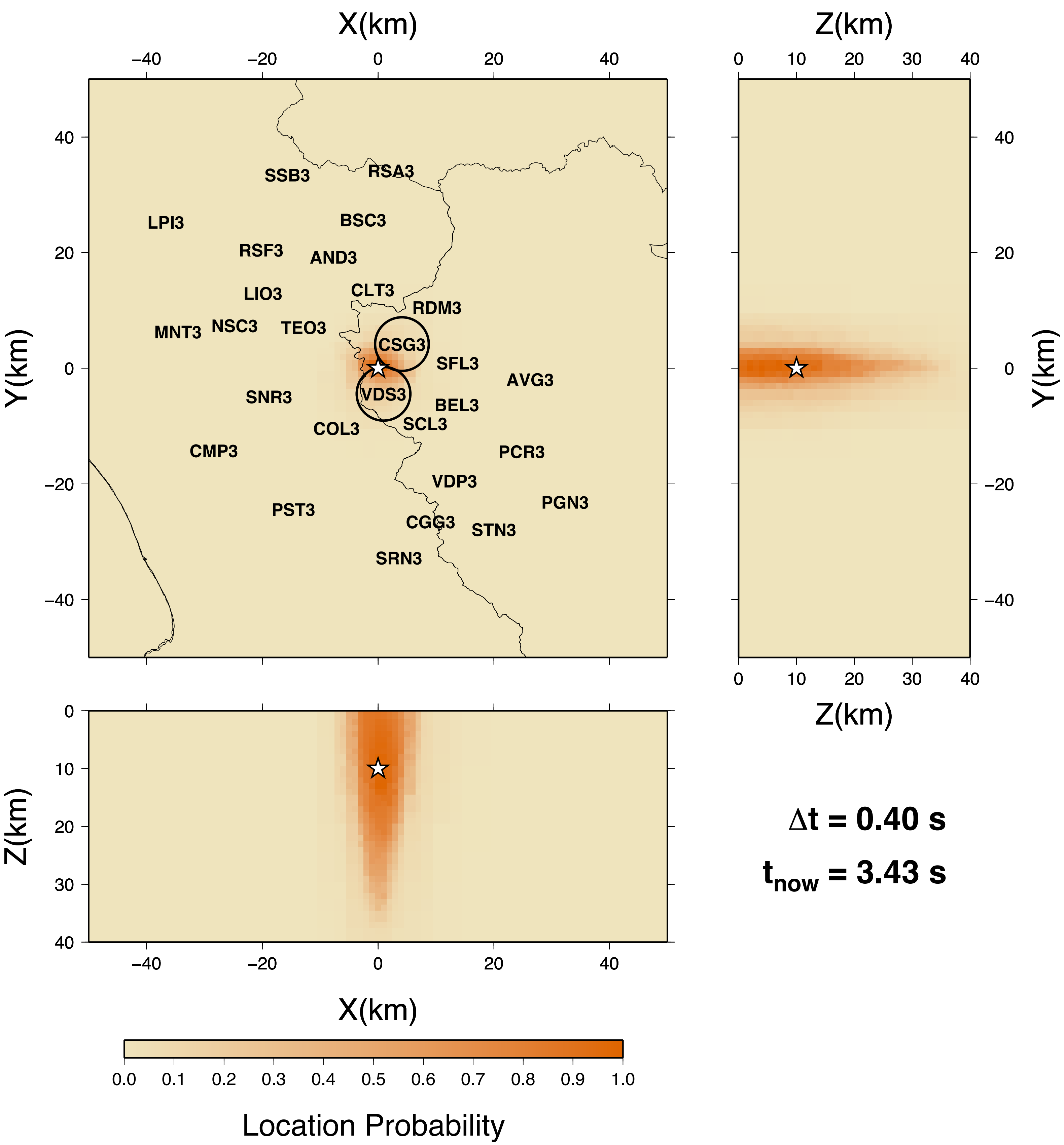

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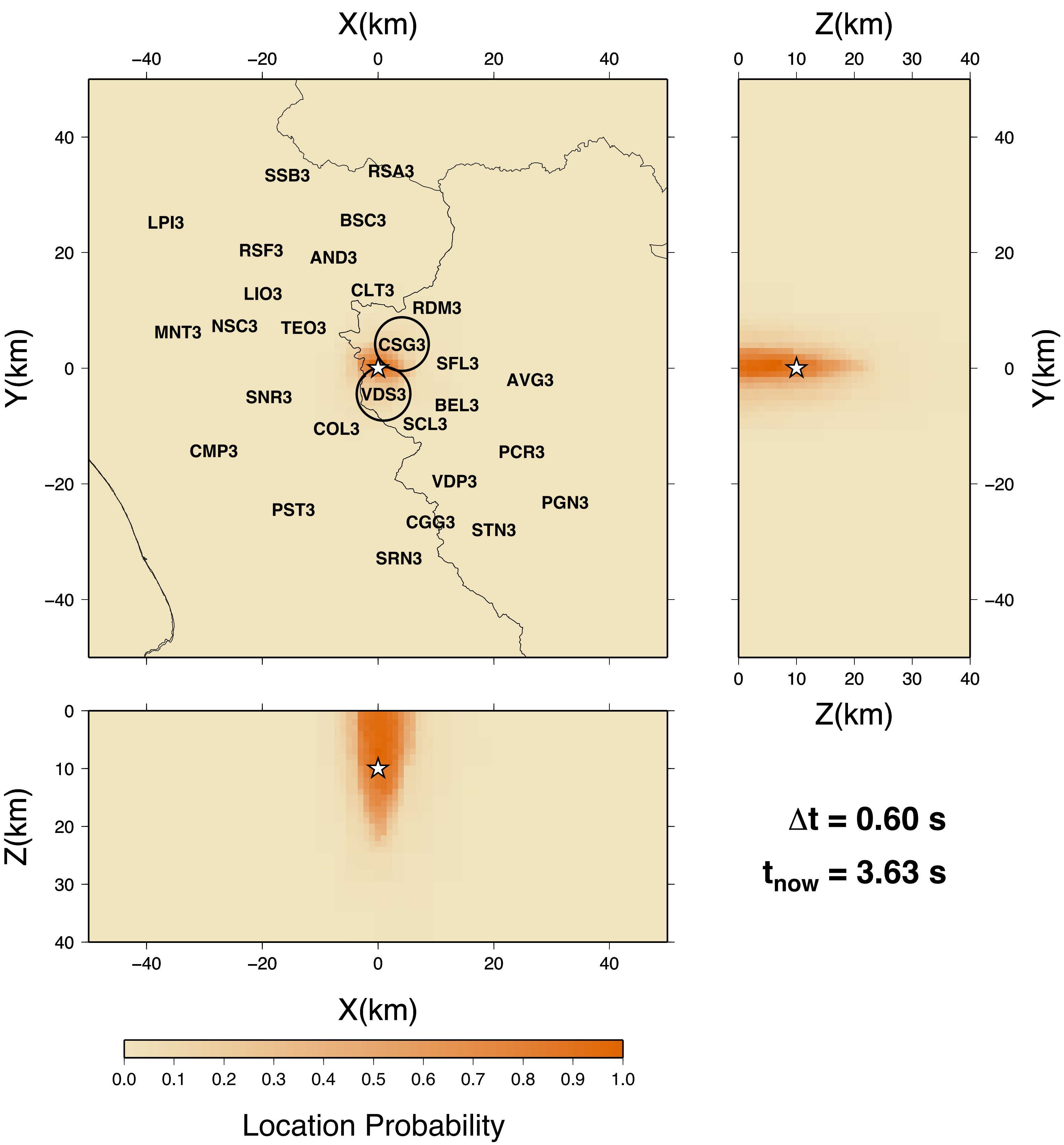

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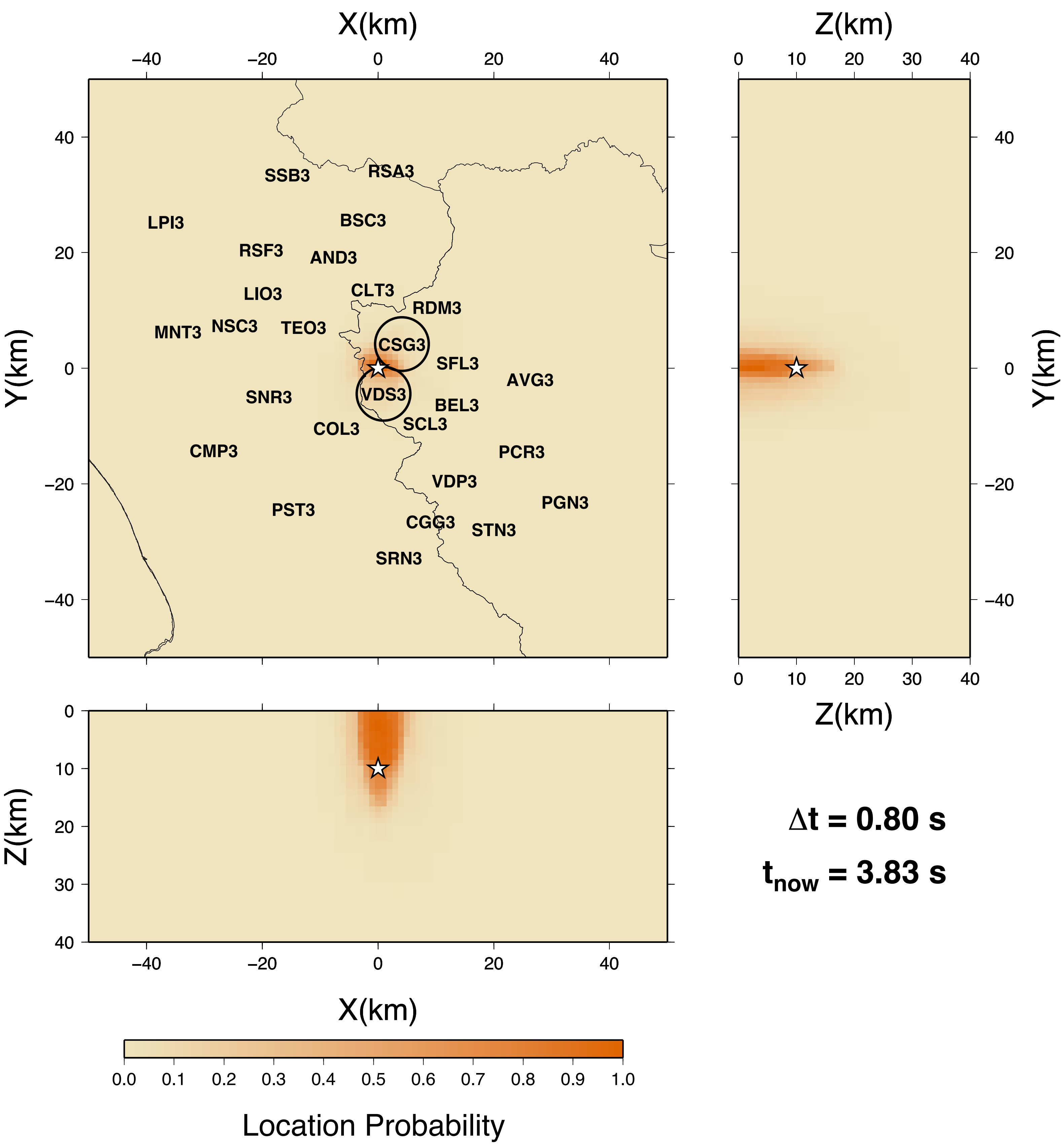

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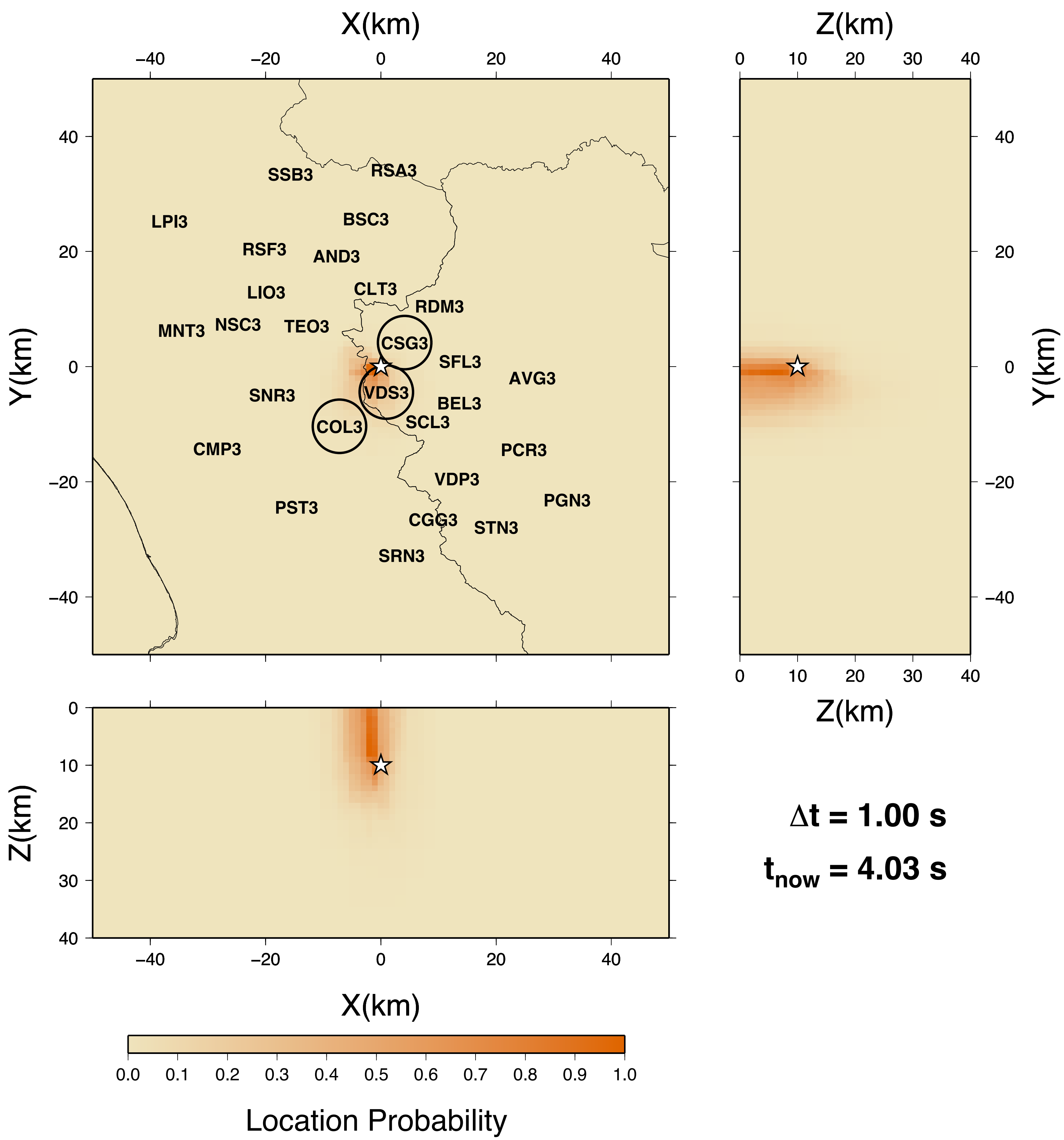

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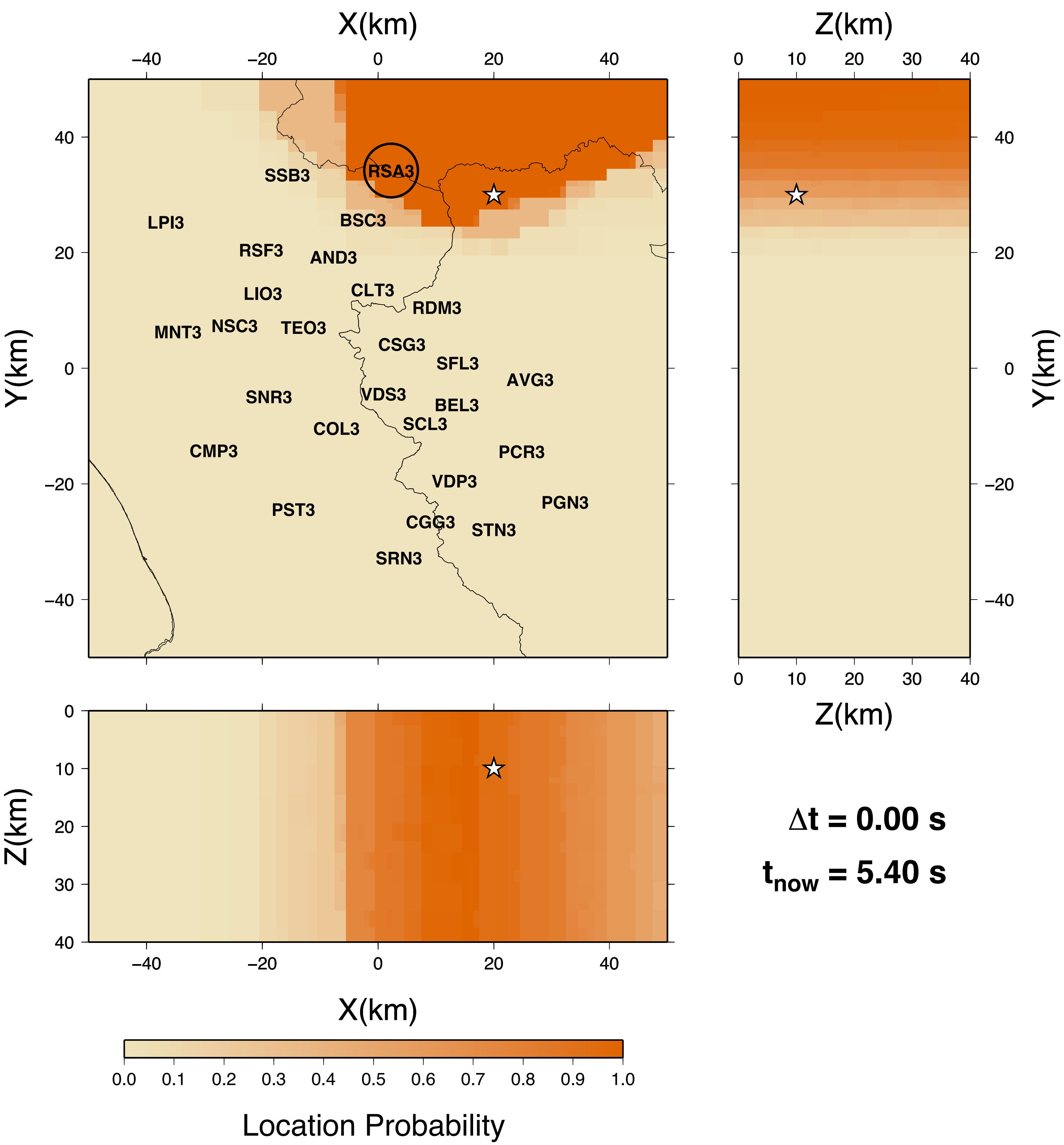

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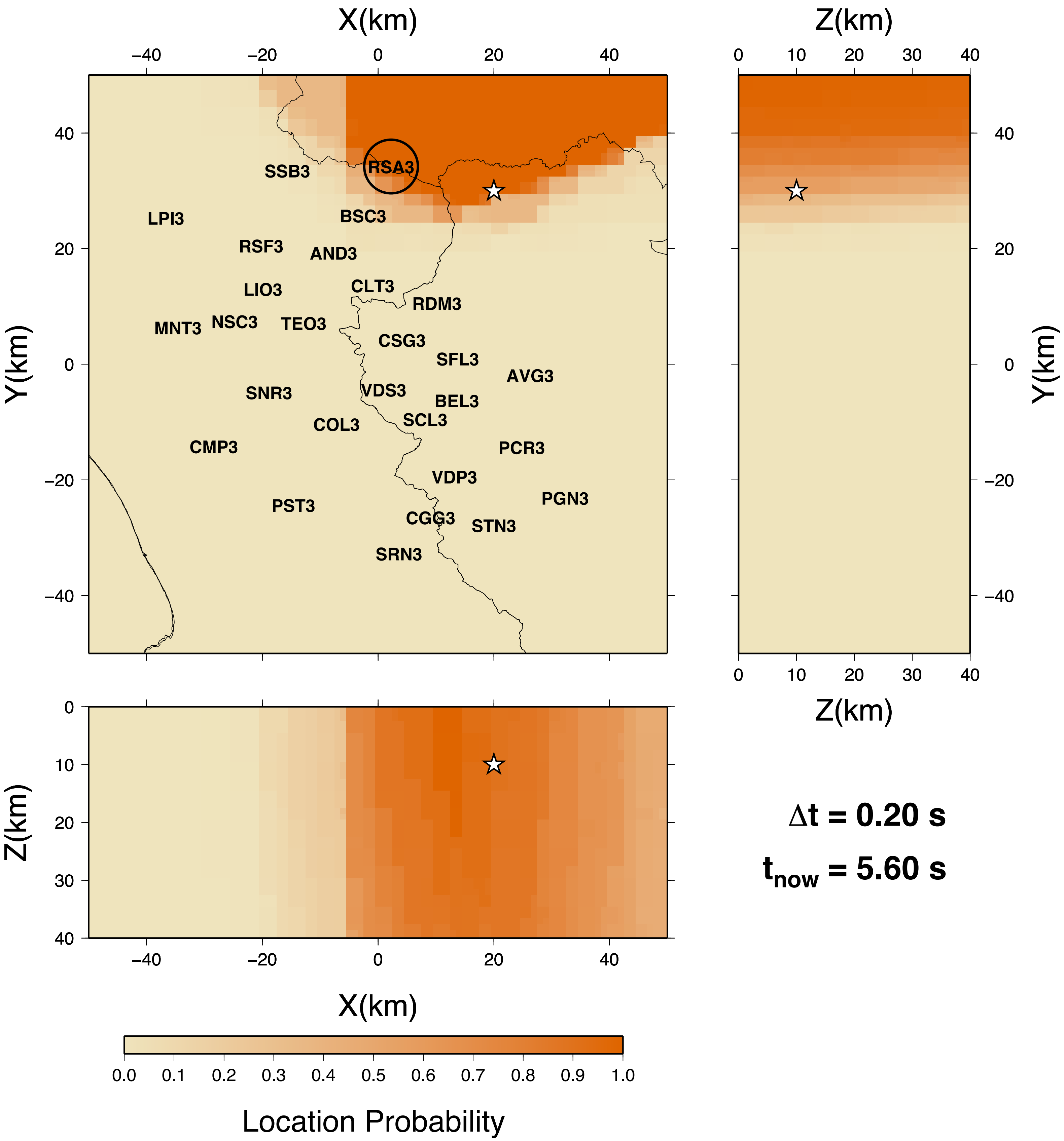

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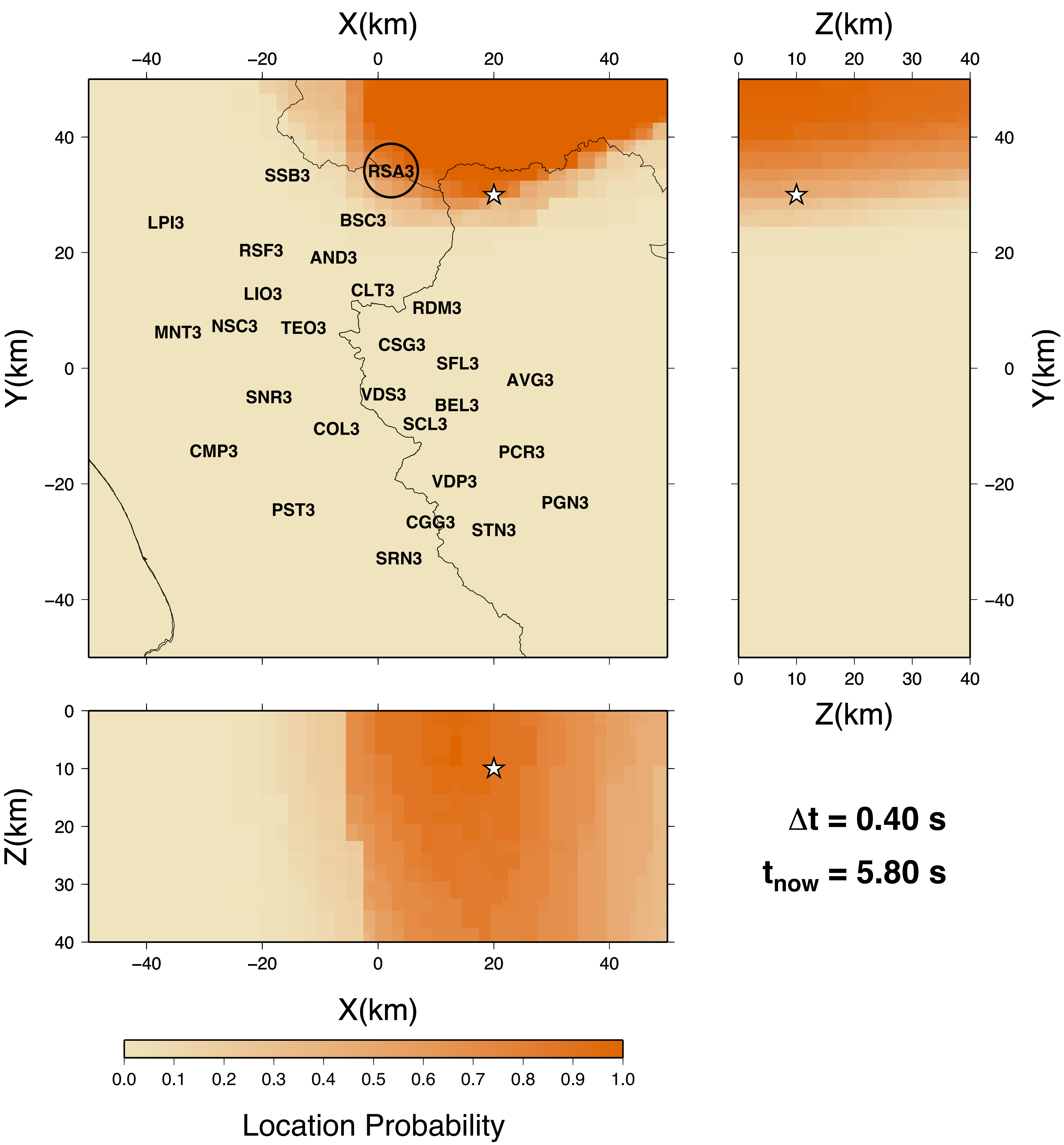

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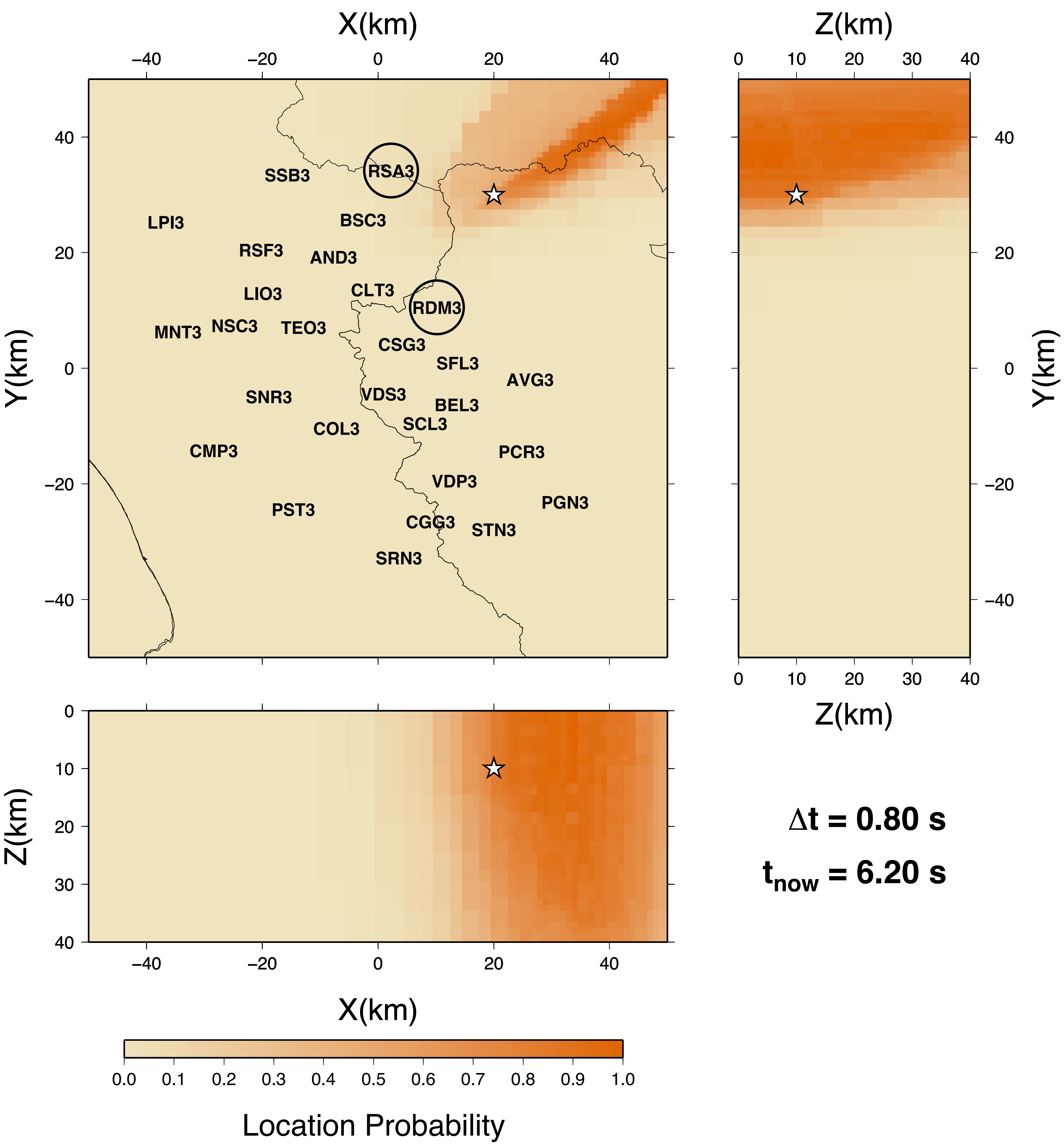

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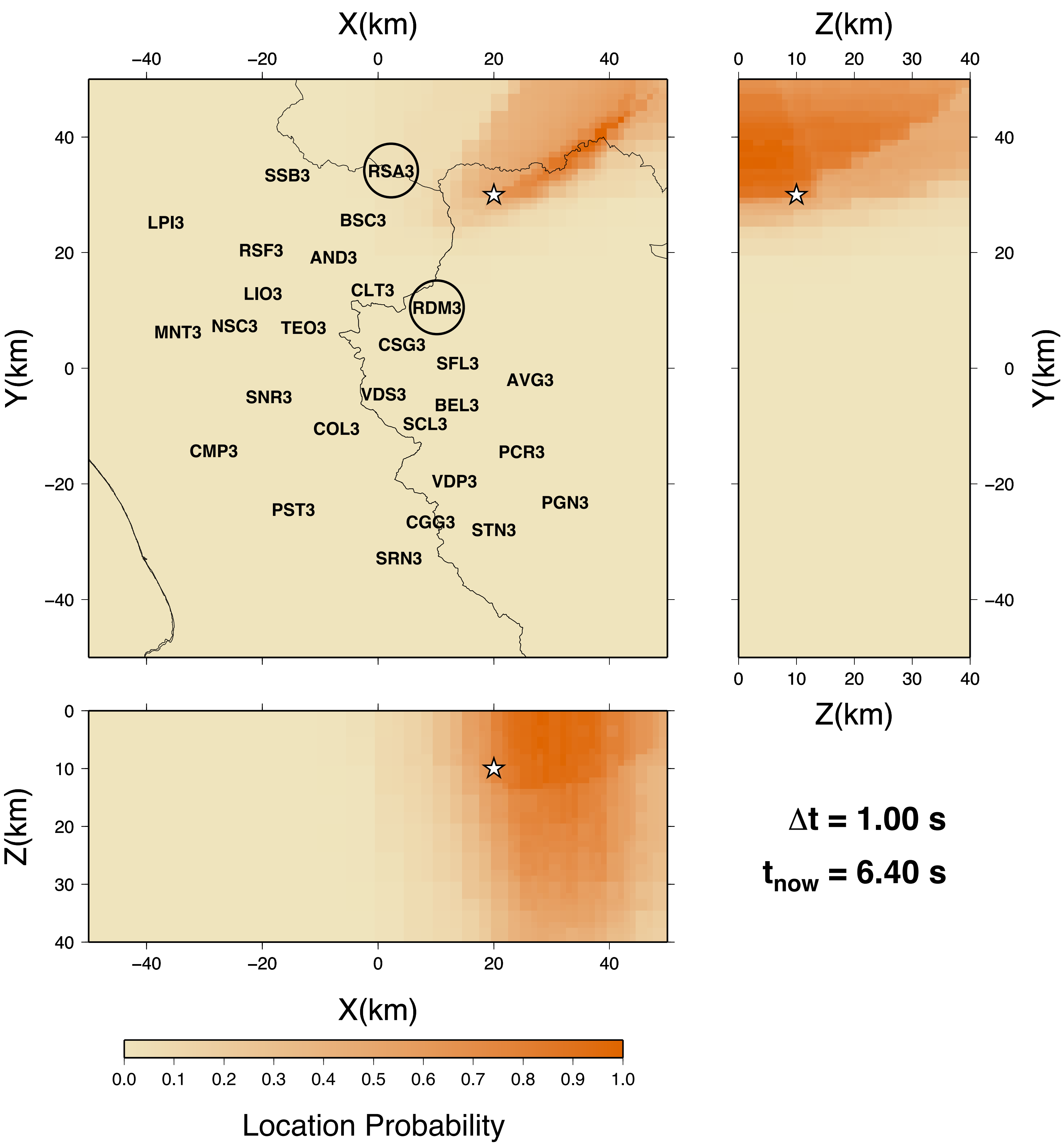

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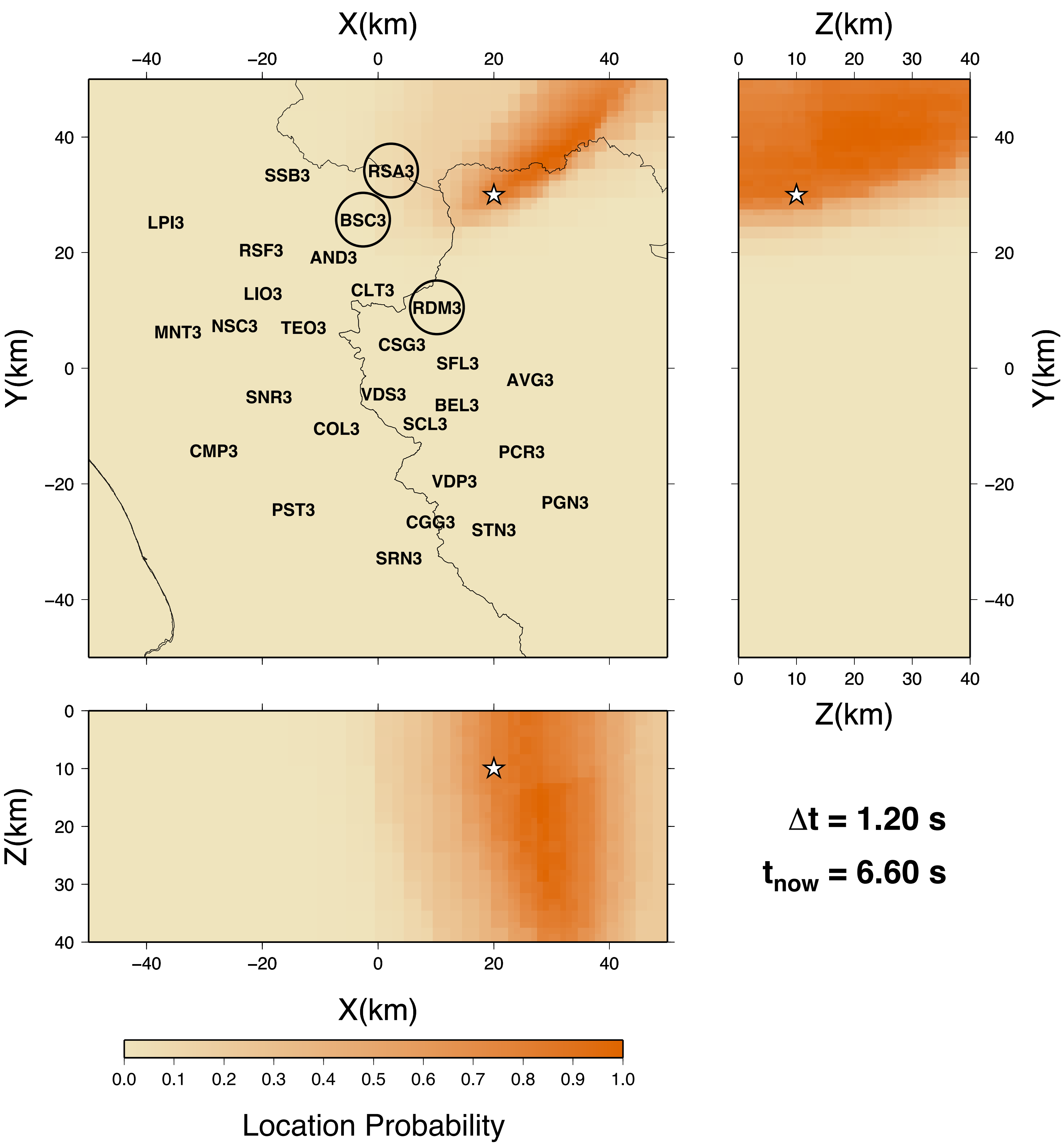

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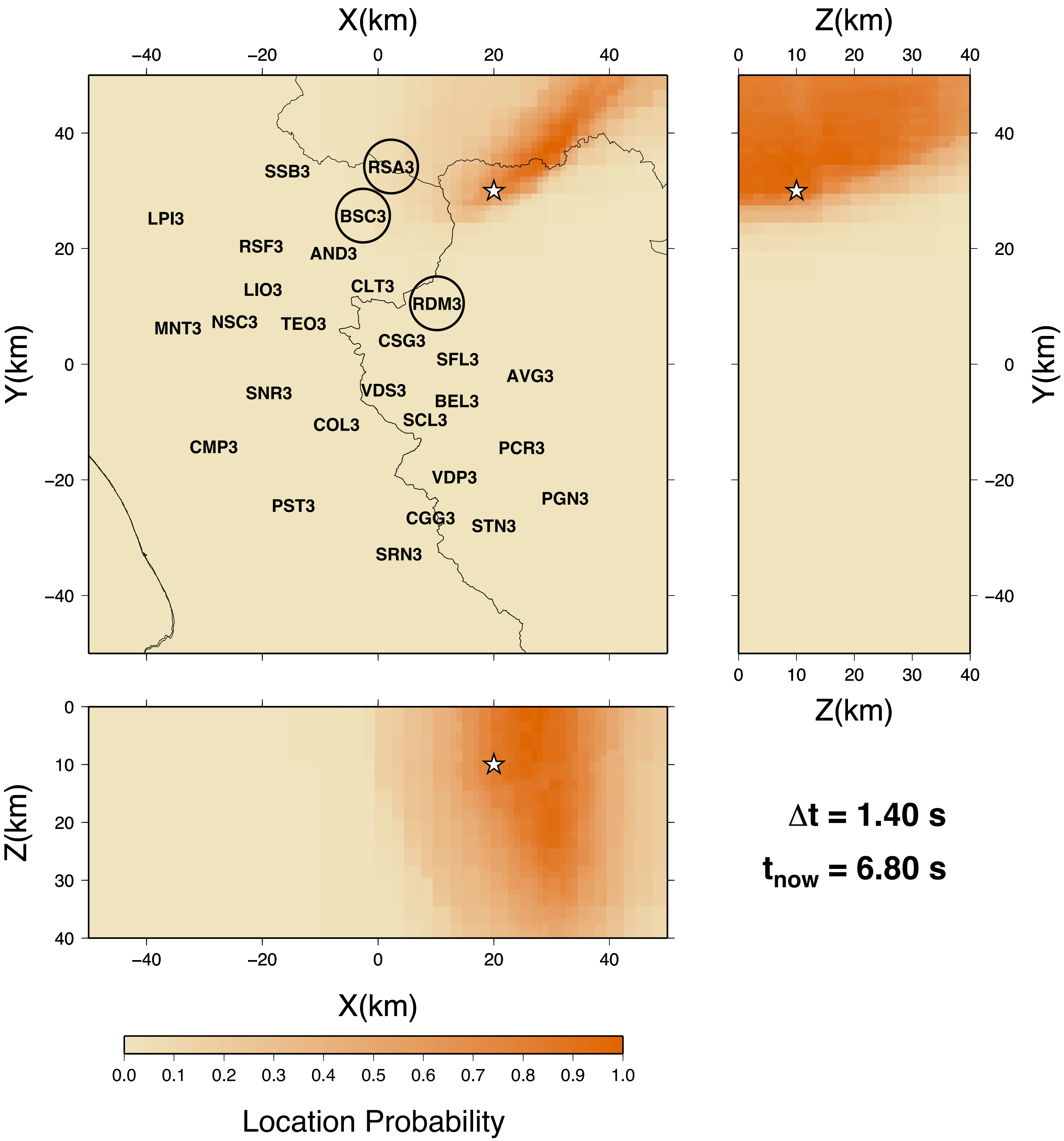

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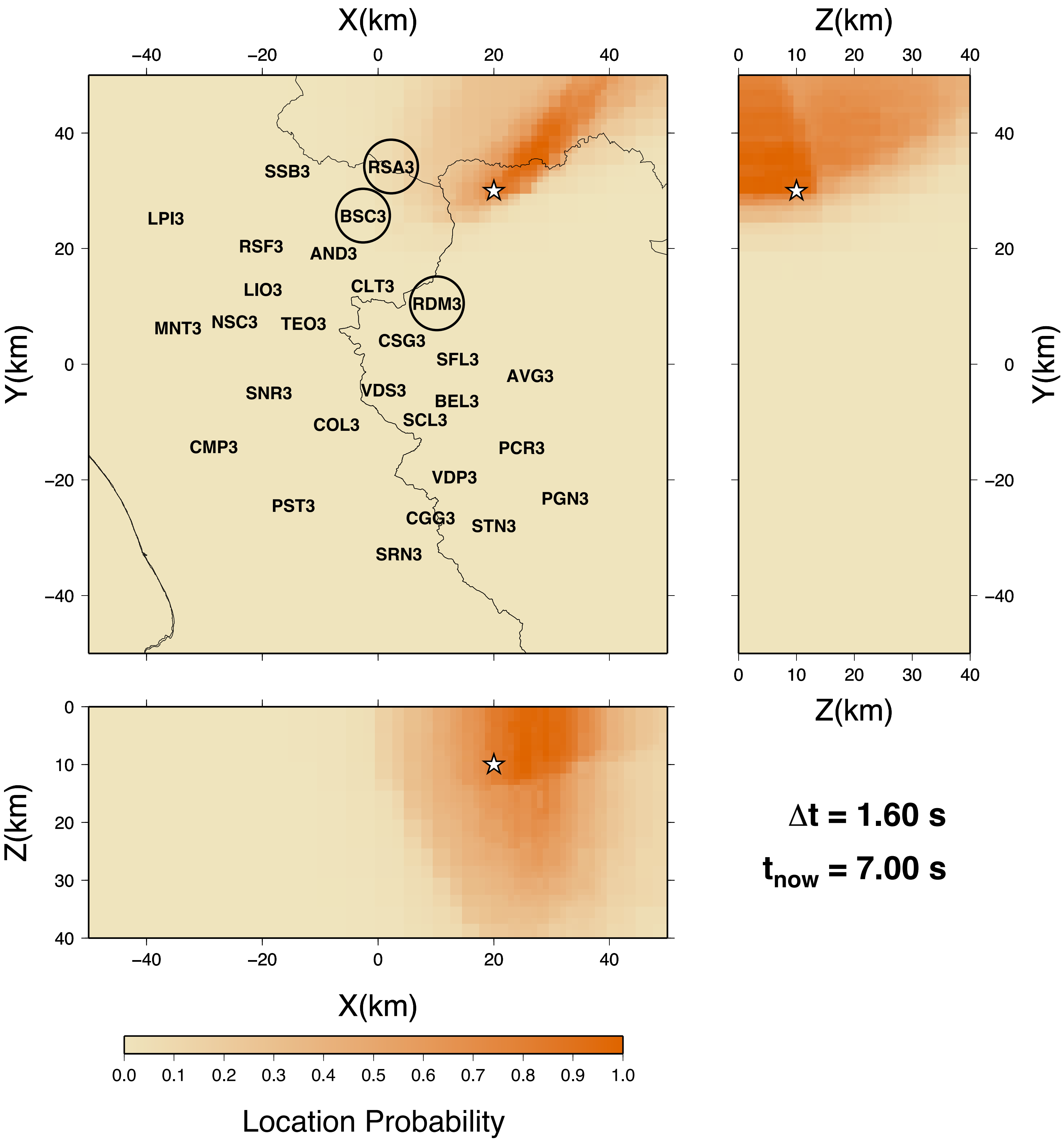

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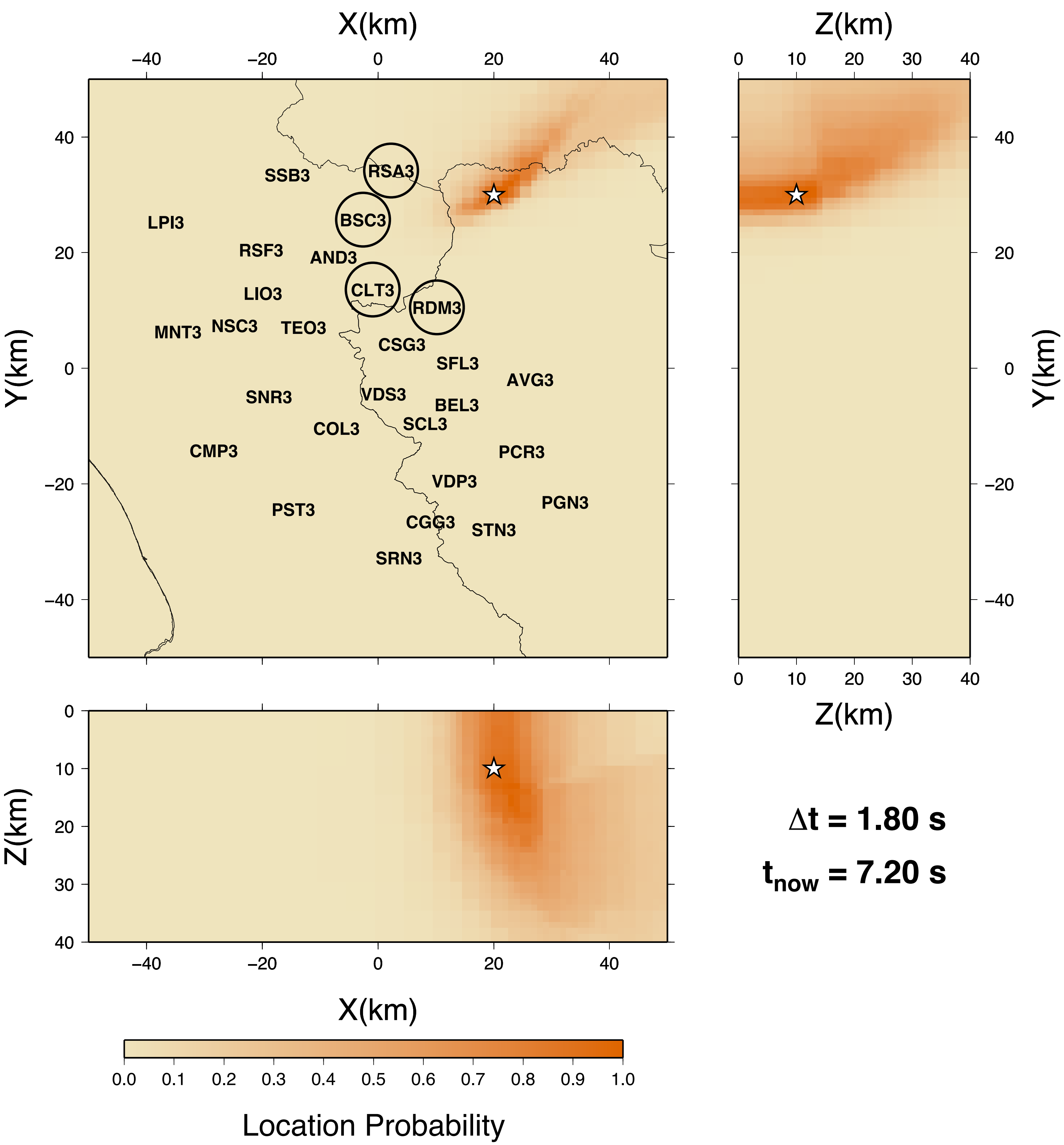

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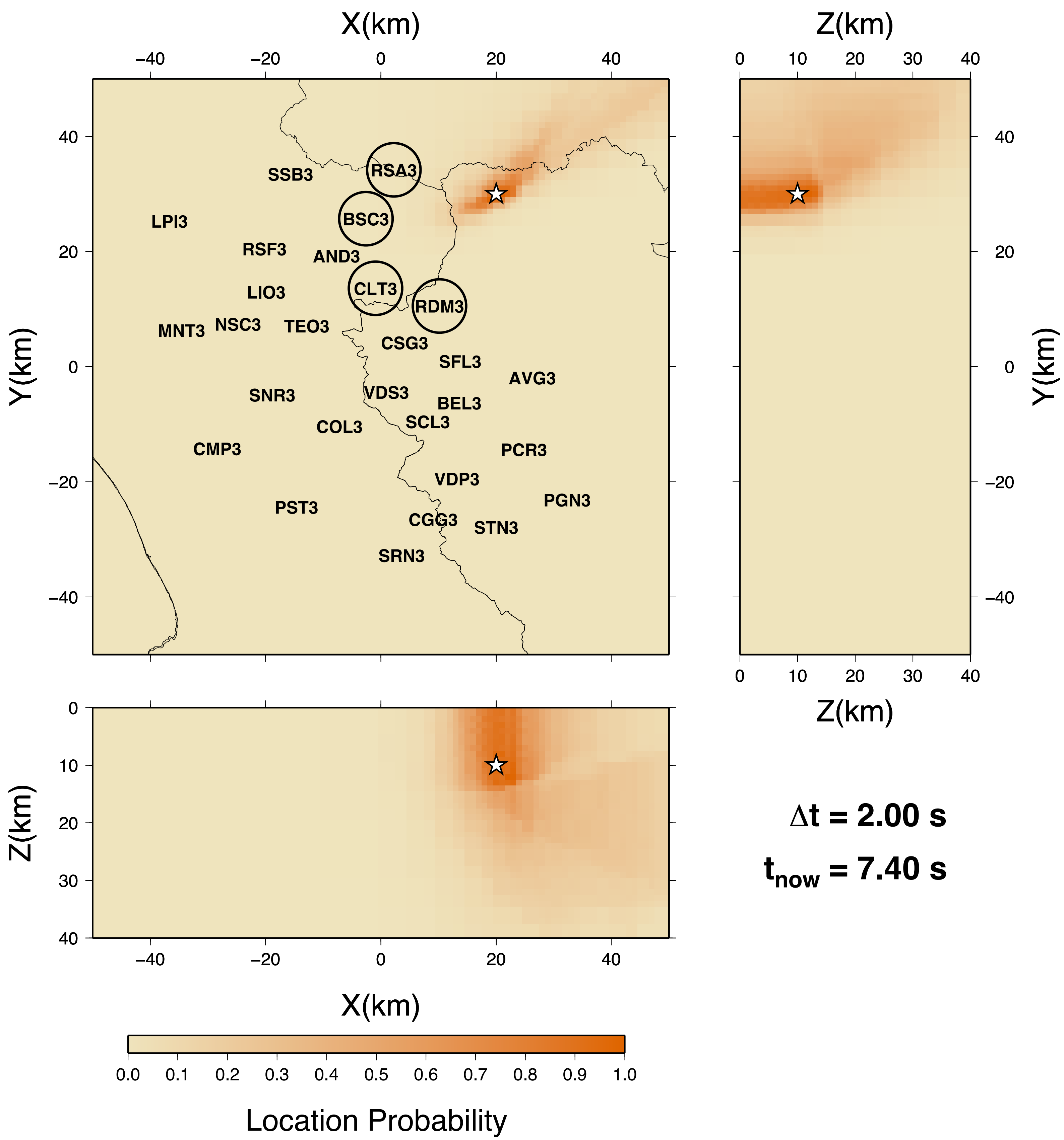

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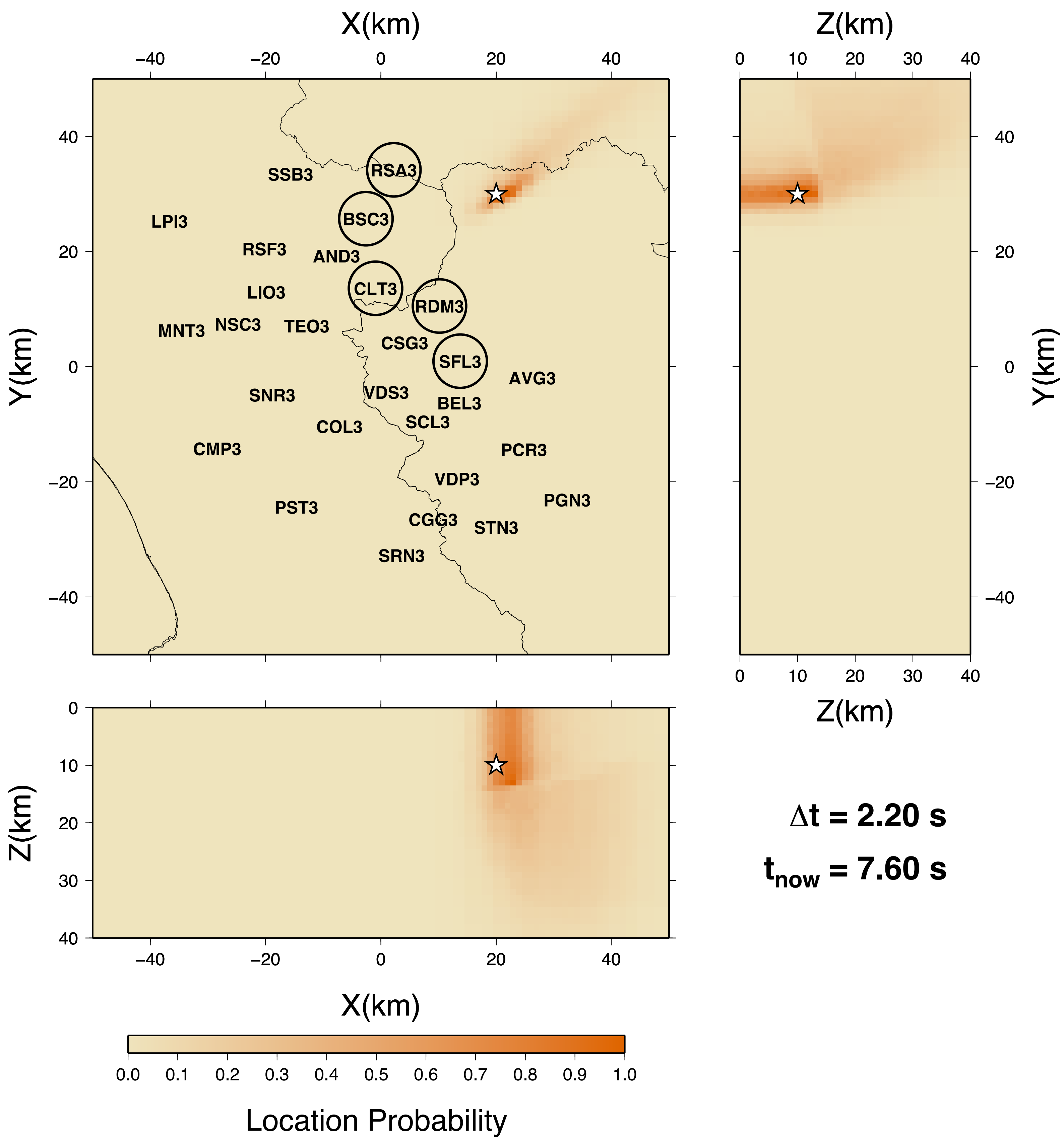

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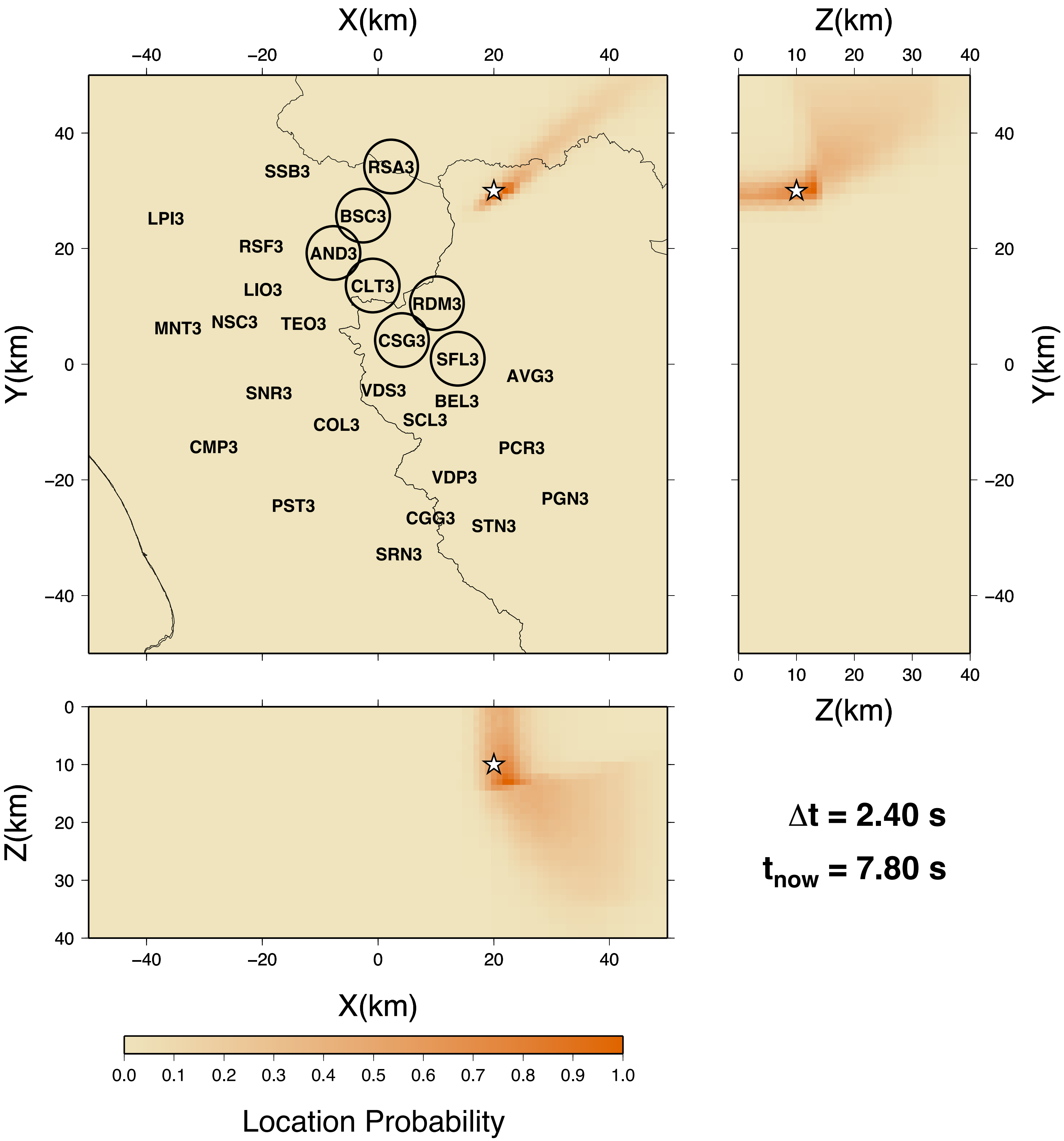

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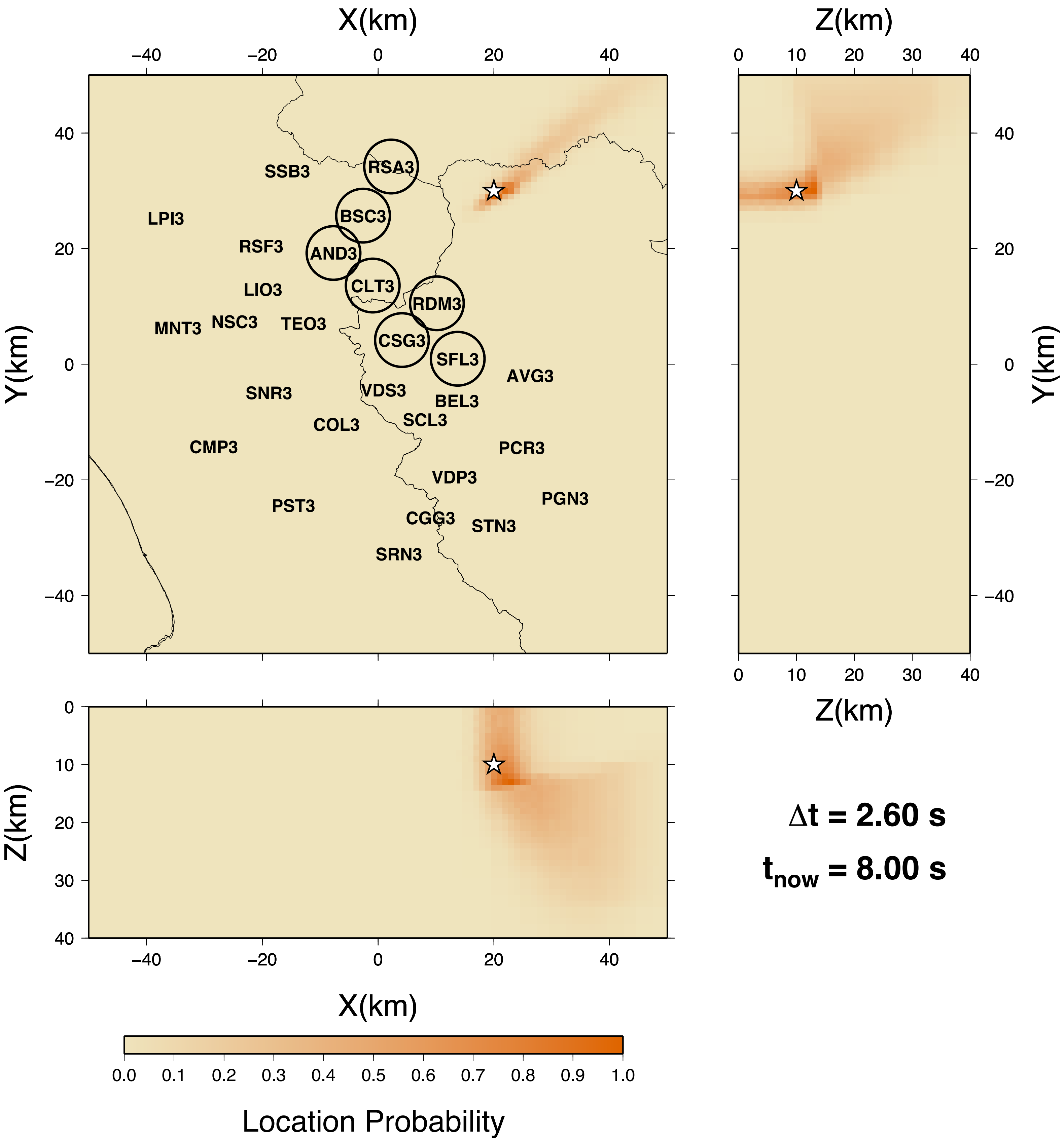

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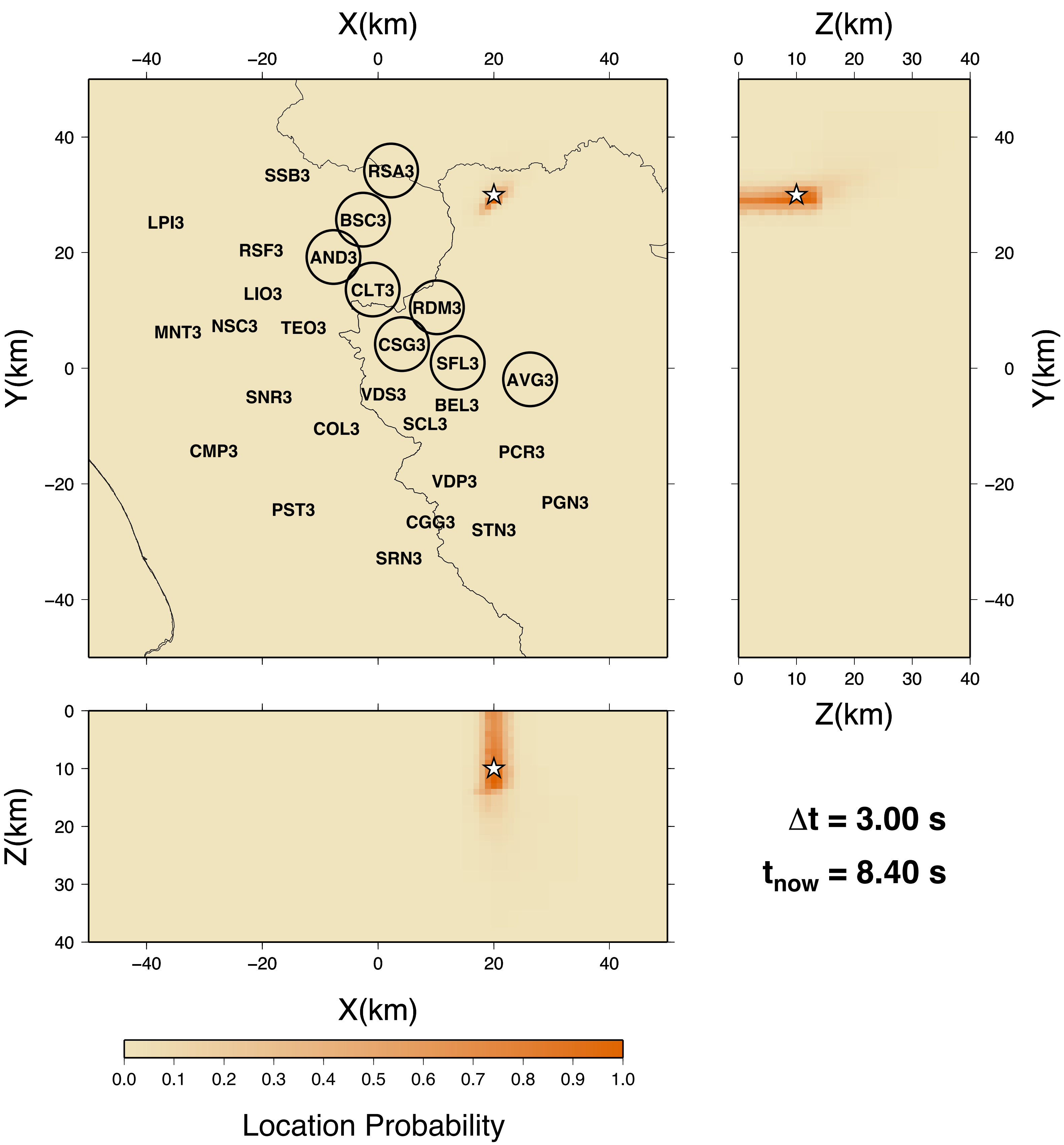

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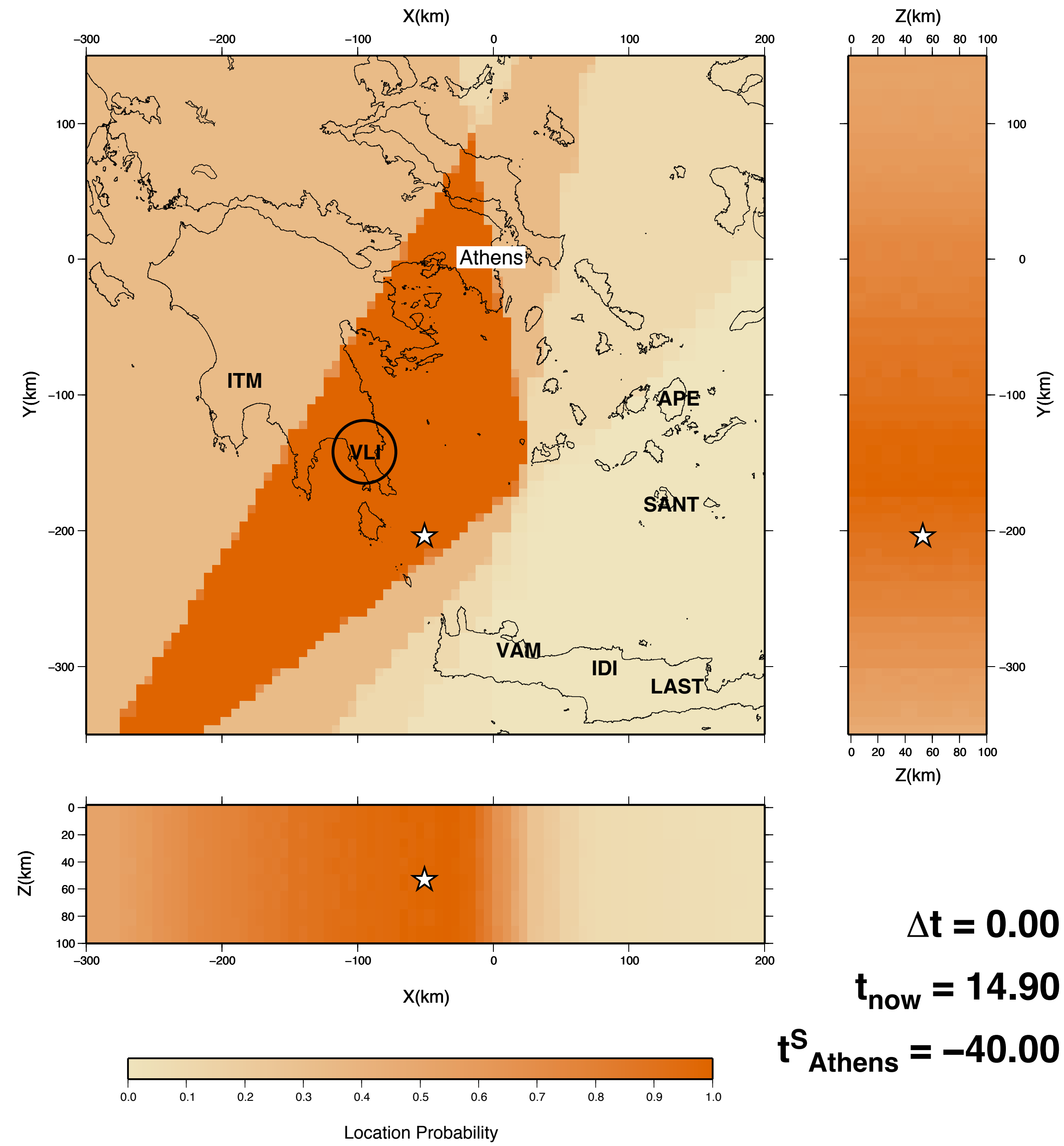
Magnitude 6.8 - SOUTHERN GREECE, 2006 January 8 11:34:55 UTC



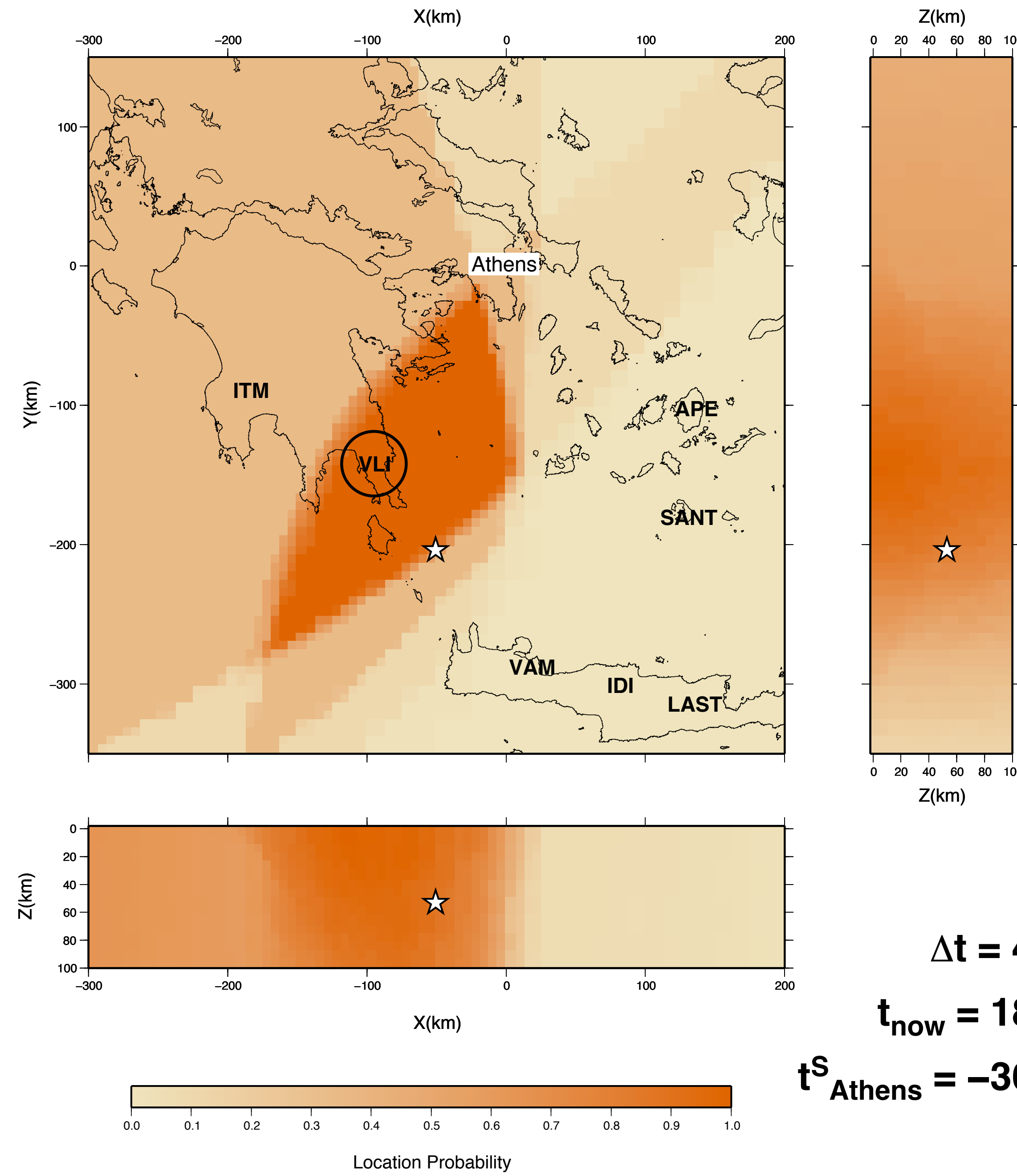
Δt = 0.00 s

t_{now} = 14.90 s

t^{S}_{Athens} = –40.00 s

RTLoc

Magnitude 6.8 - SOUTHERN GREECE, 2006 January 8 11:34:55 UTC



Δt = 4.00 s

t_{now} = 18.90 s

t^{S}_{Athens} = –36.00 s

RTLoc

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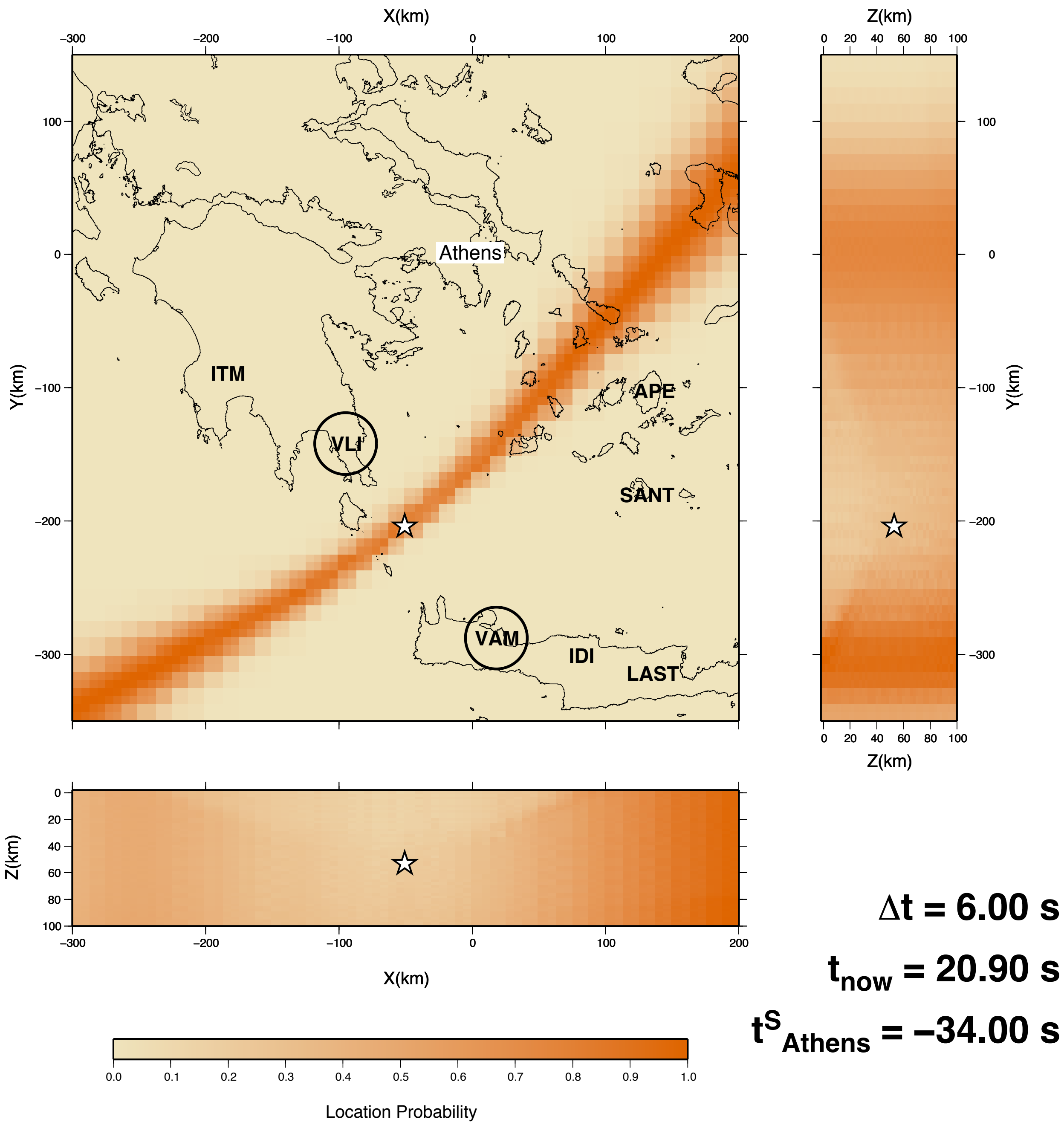
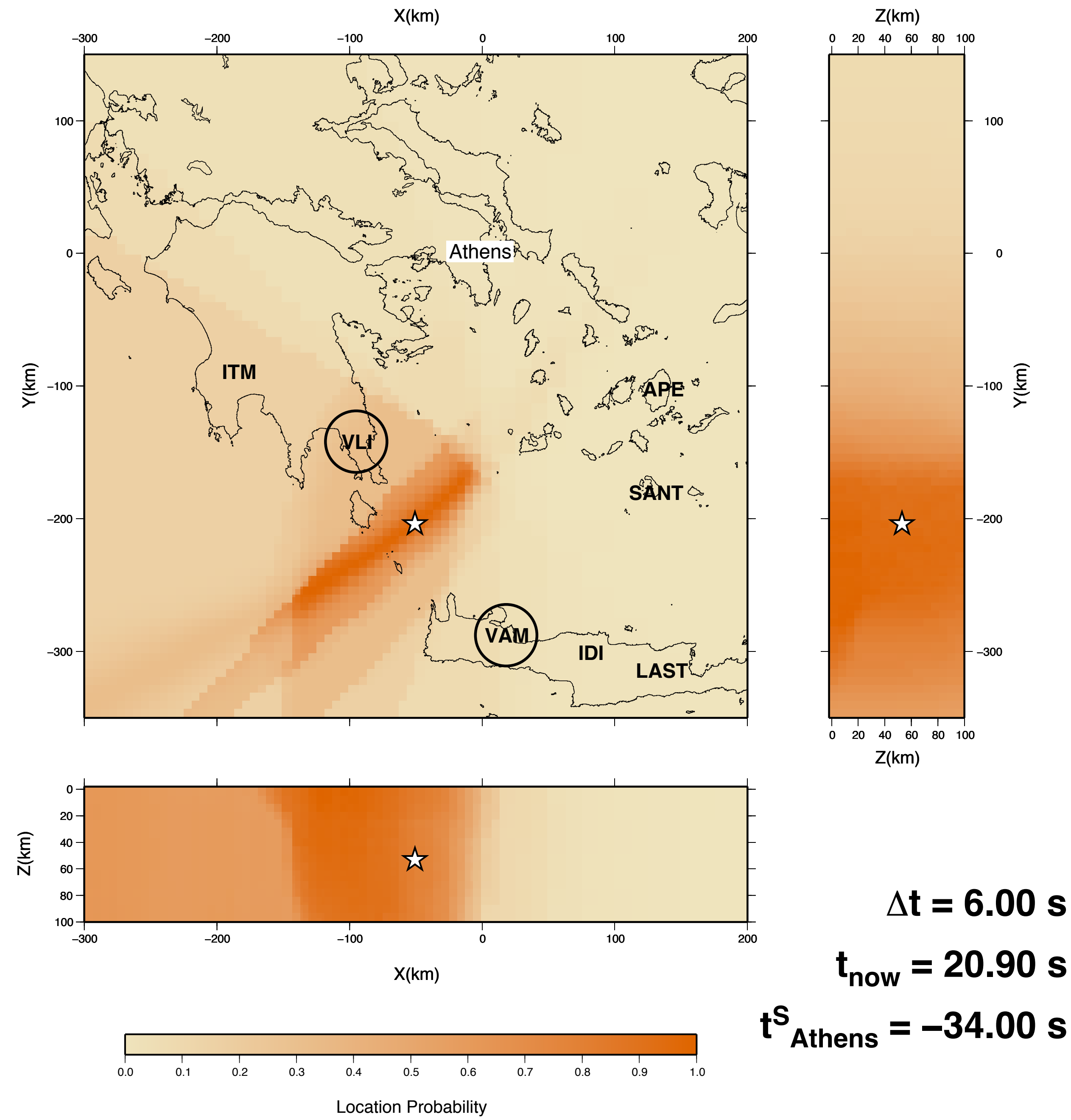


NLLoc

Lomax, et al., 2000



RTLoc

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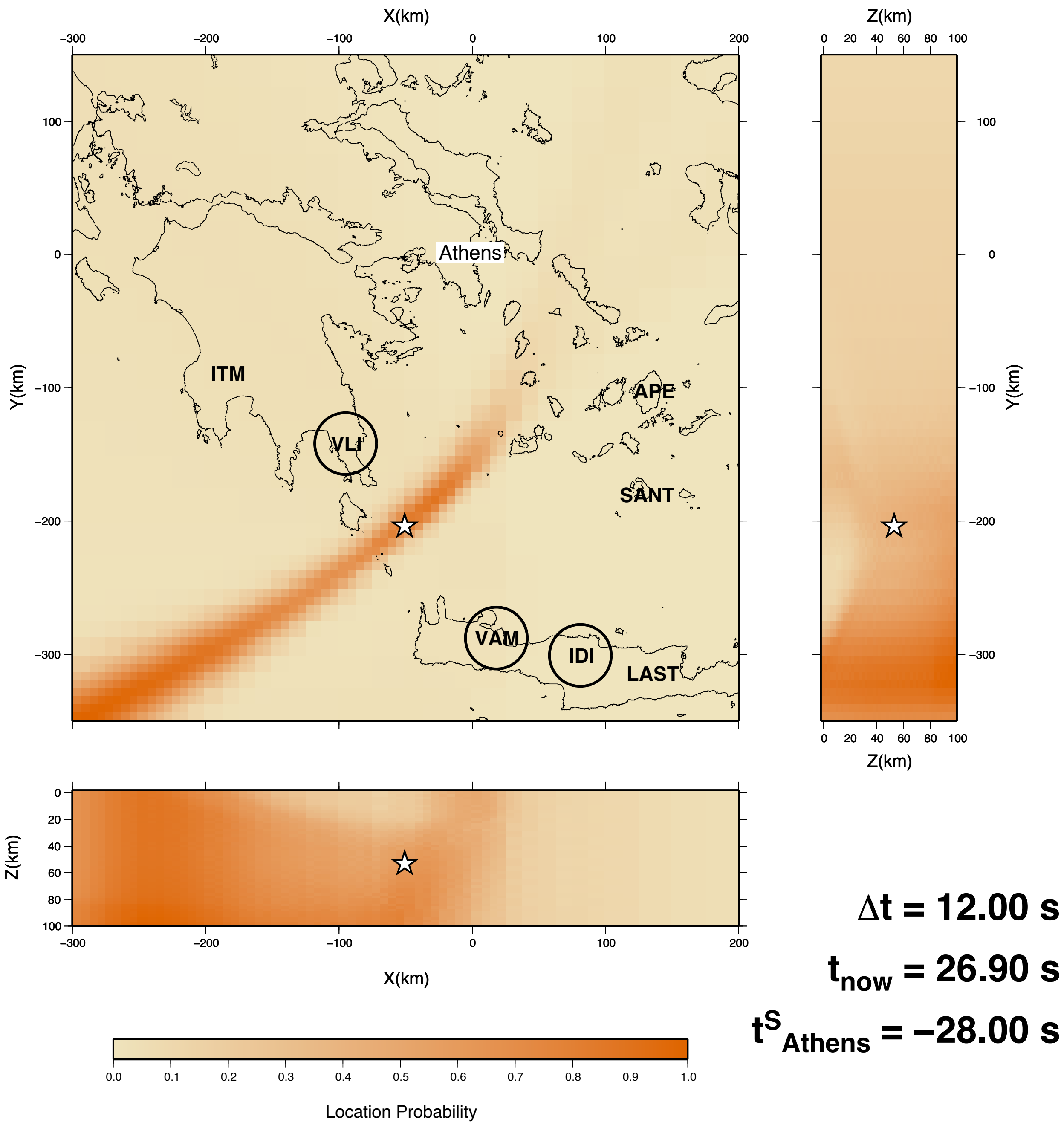

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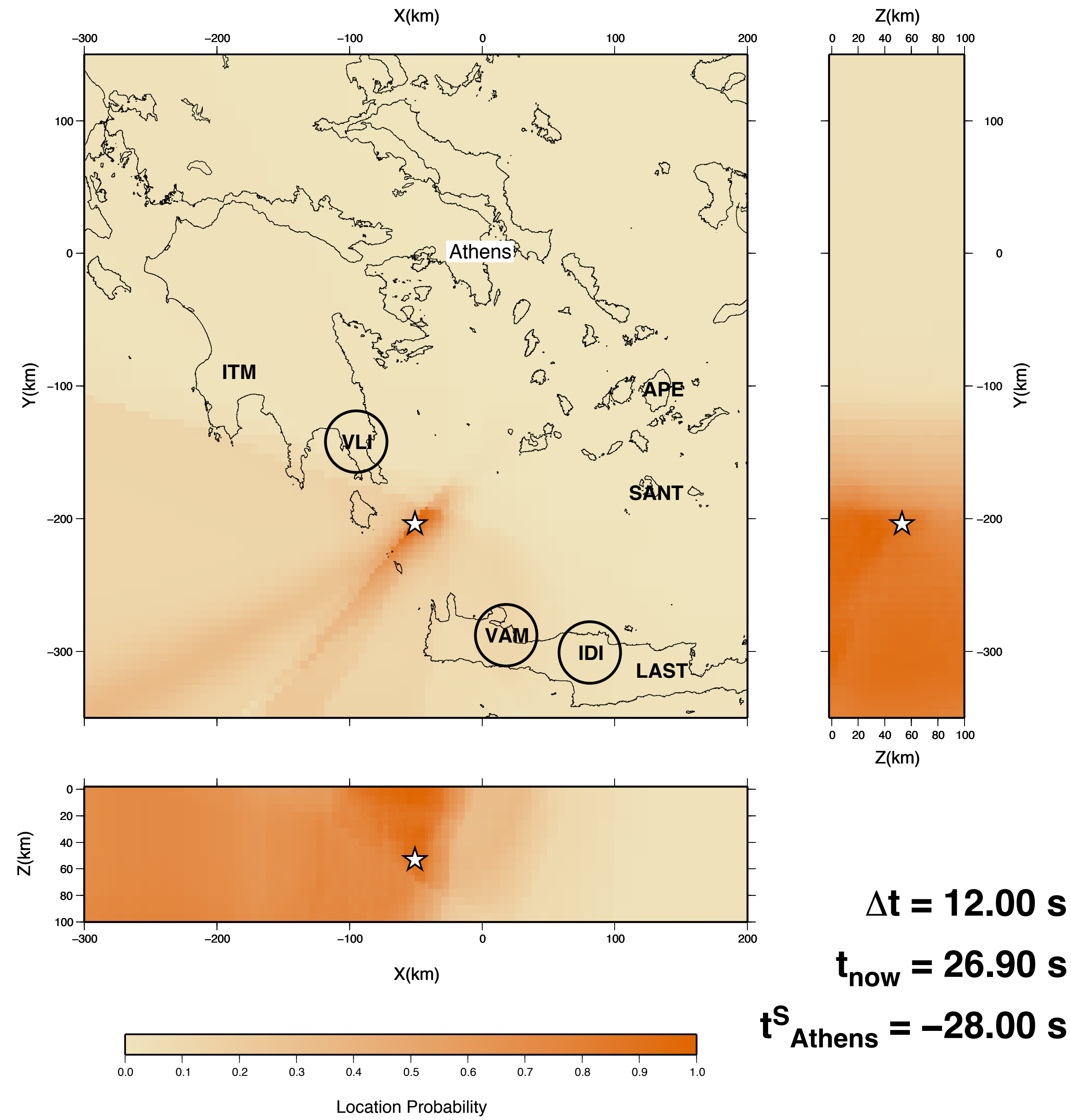

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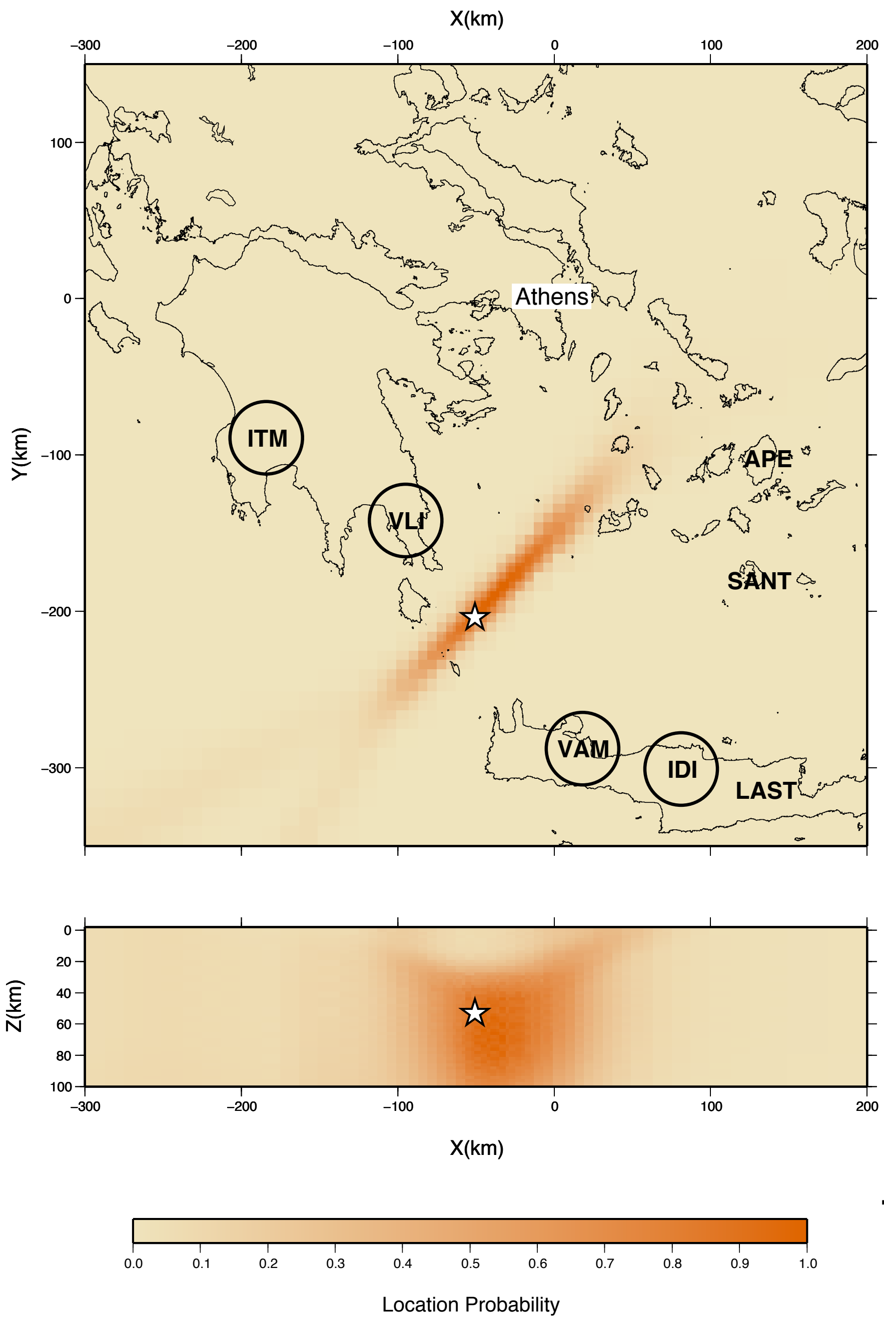
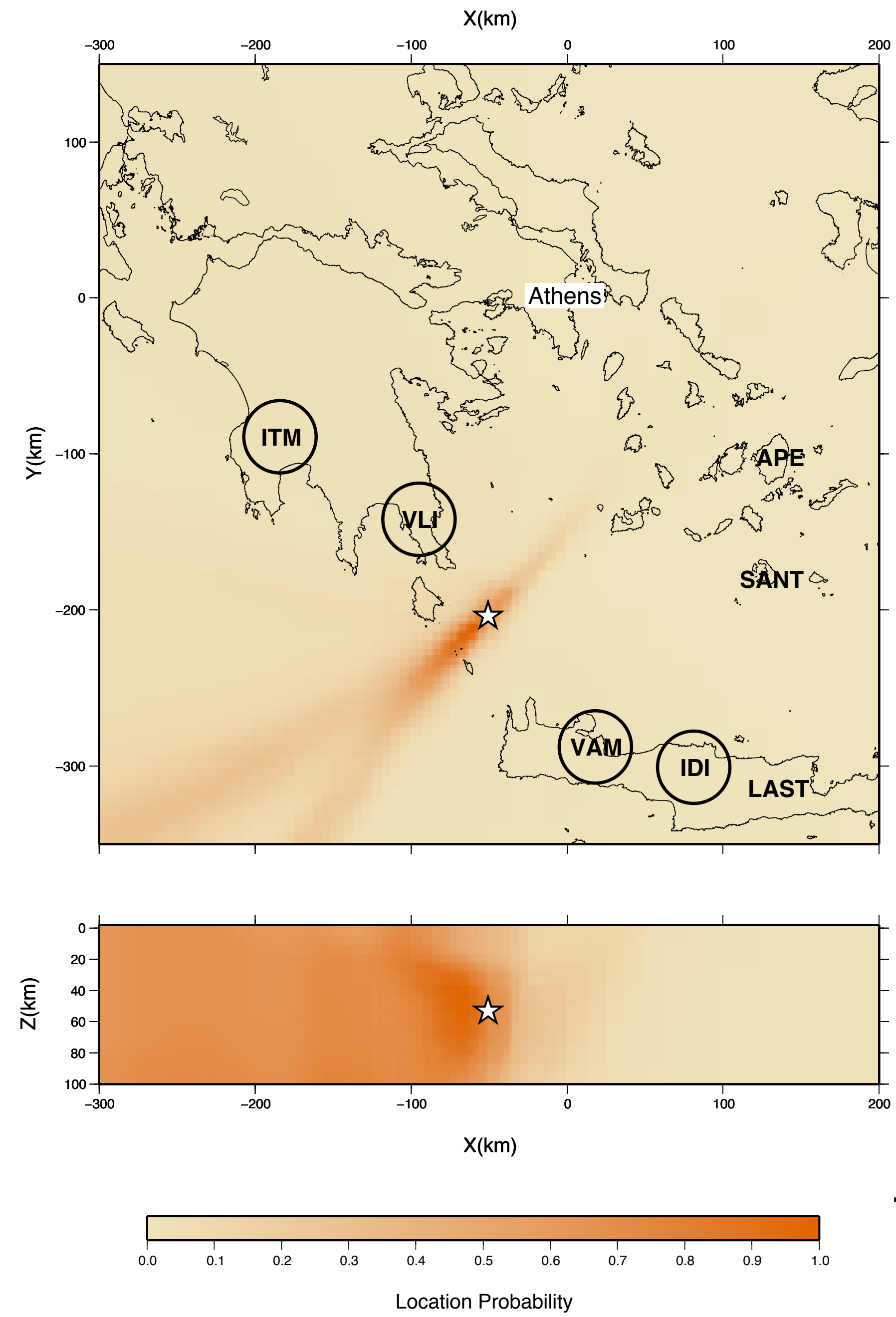


$\Delta t = 14.00$ s

$t_{now} = 28.90$ s

$t^{S}_{Athens} = -26.00$ s

NLLoc



$\Delta t = 14.00$ s

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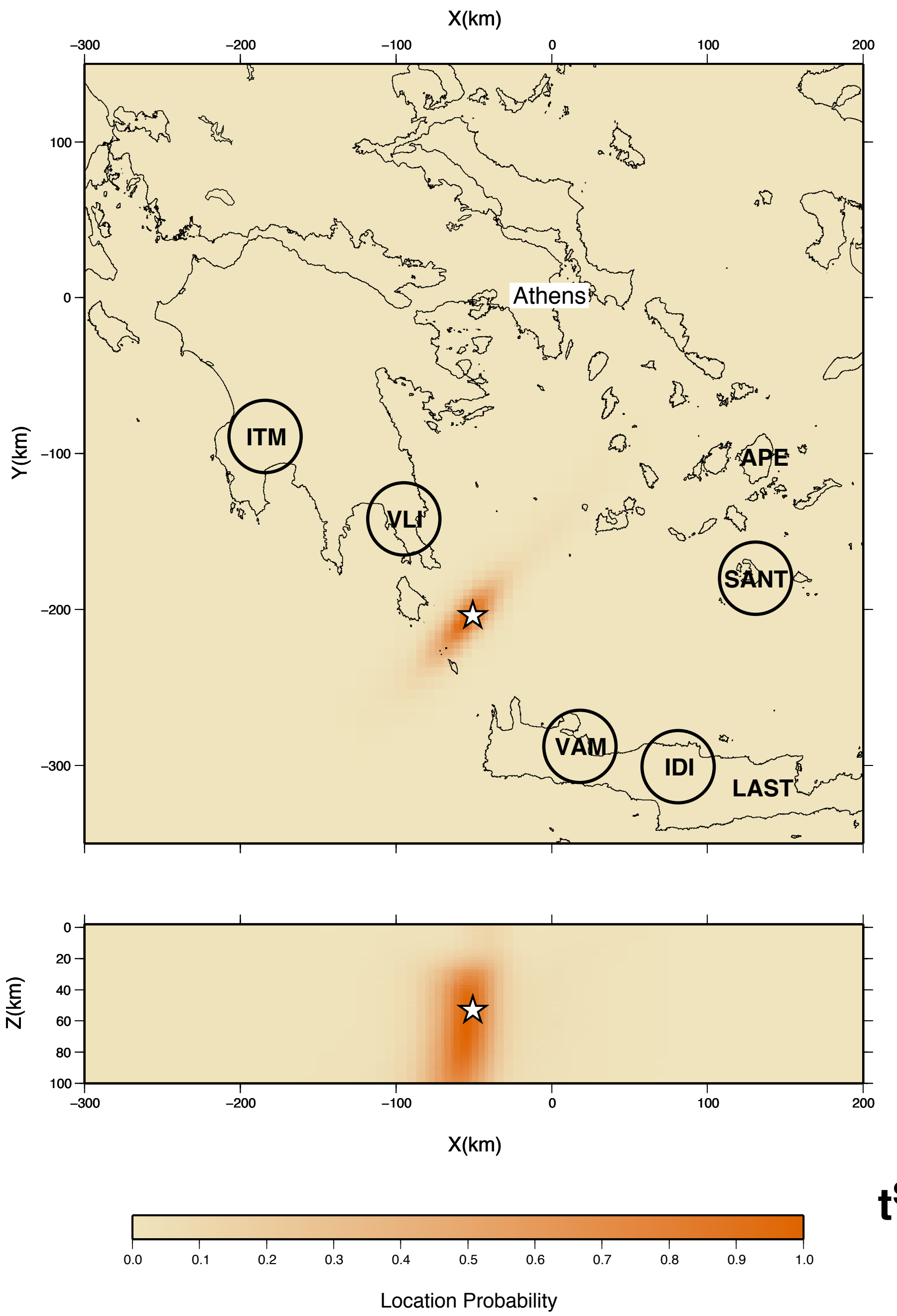
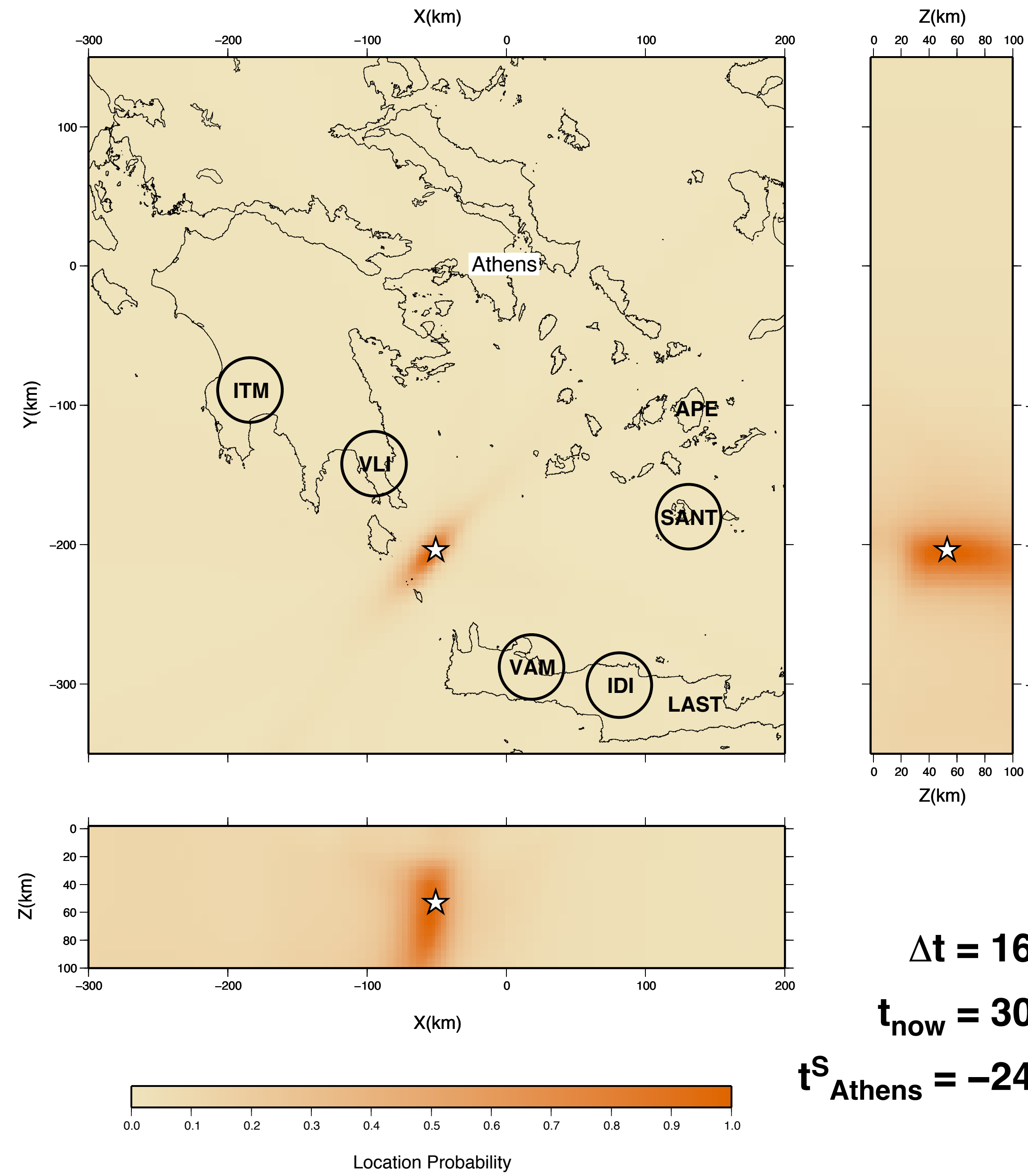


Δt = 16.00 s

t_{now} = 30.90 s

t^{S}_{Athens} = –24.00 s

NLLoc



Δt = 16.00 s

t_{now} = 30.90 s

t^{S}_{Athens} = –24.00 s

RTLoc

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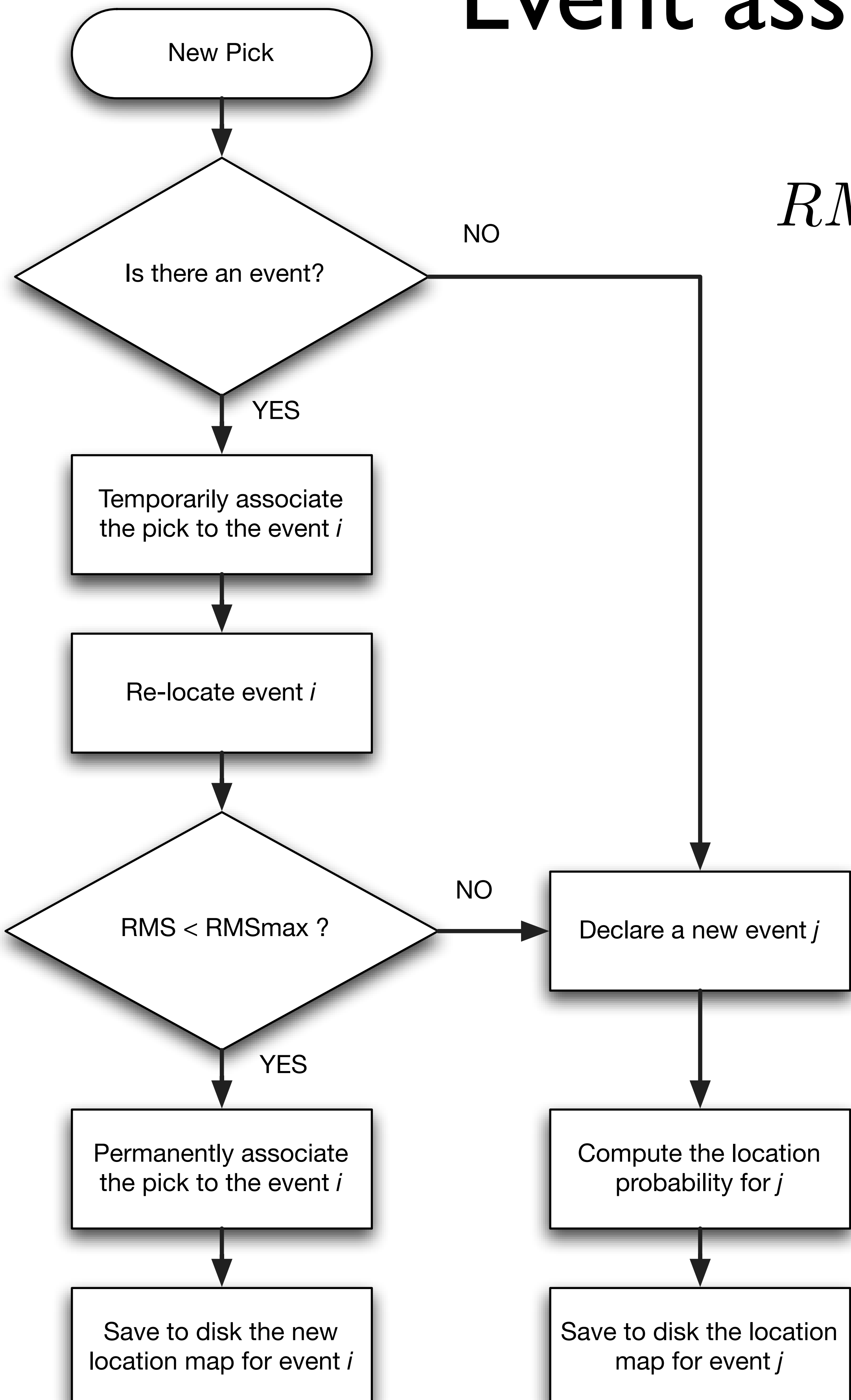
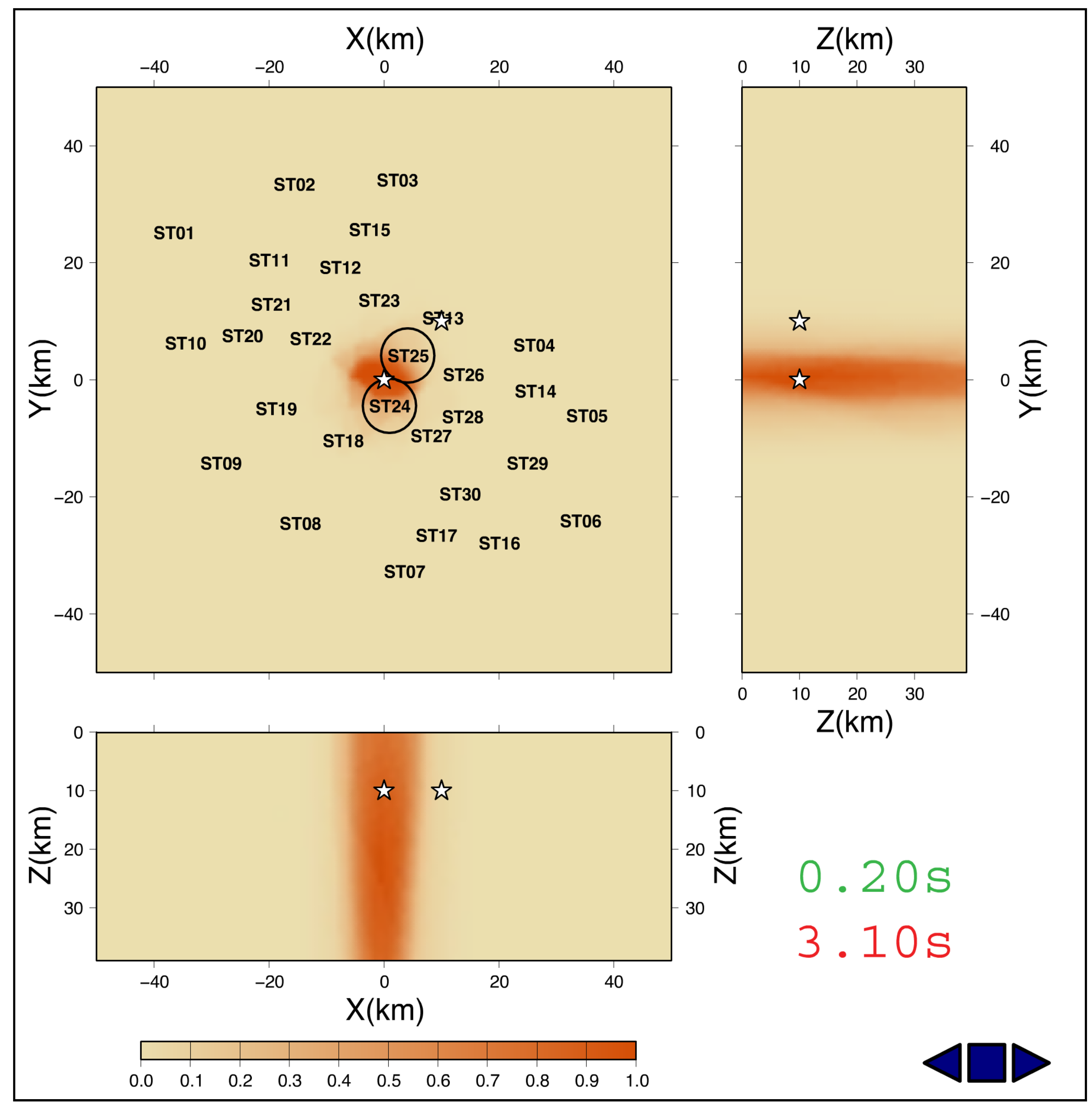
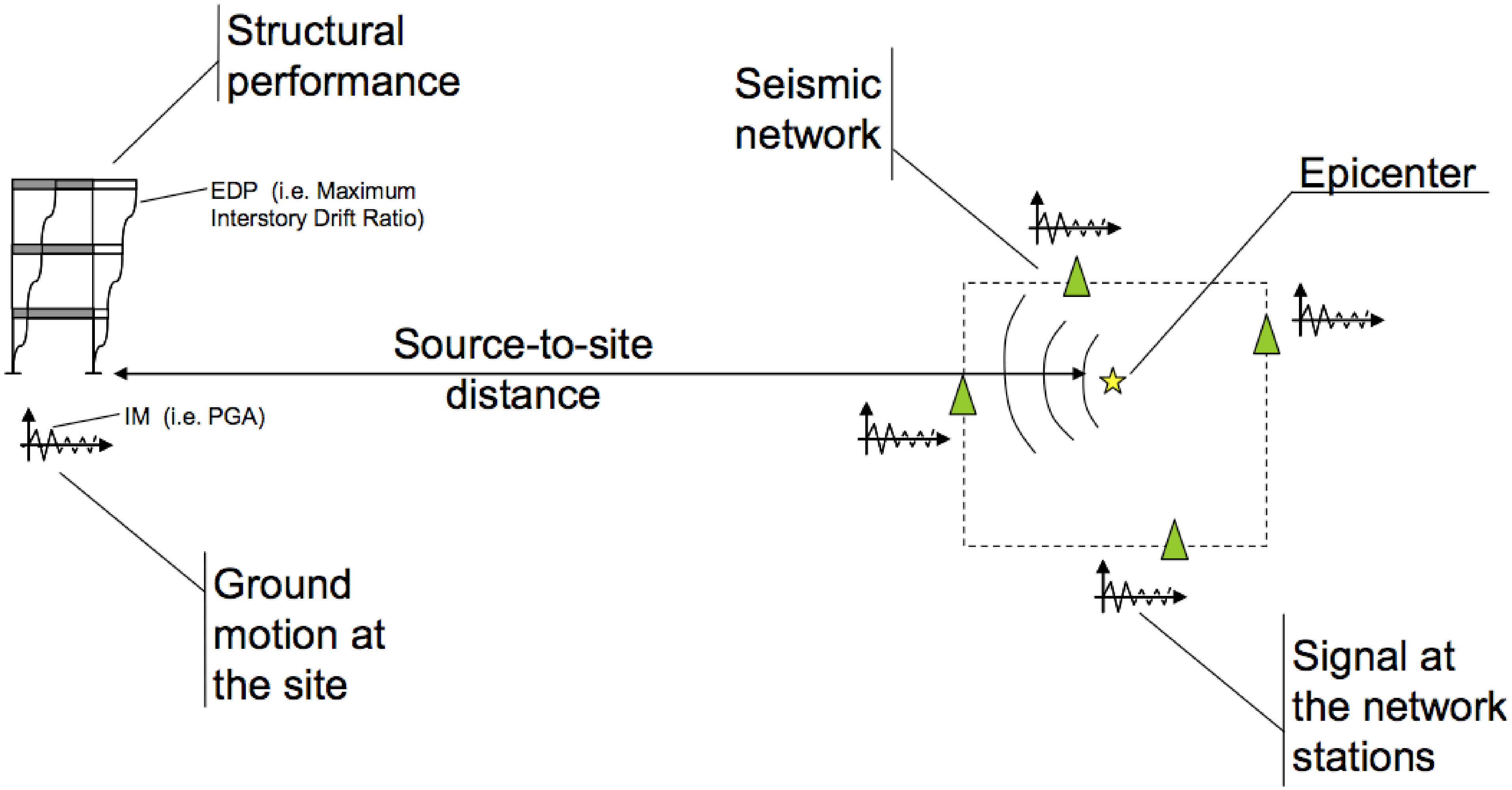
Event association (binding)



$$RMS_{Si} = \frac{1}{M}\sum_{j=1}^{M}\left[(tt_{Si} - tt_{Sj}) - (t_{Si} - t_{Sj})\right]^2$$



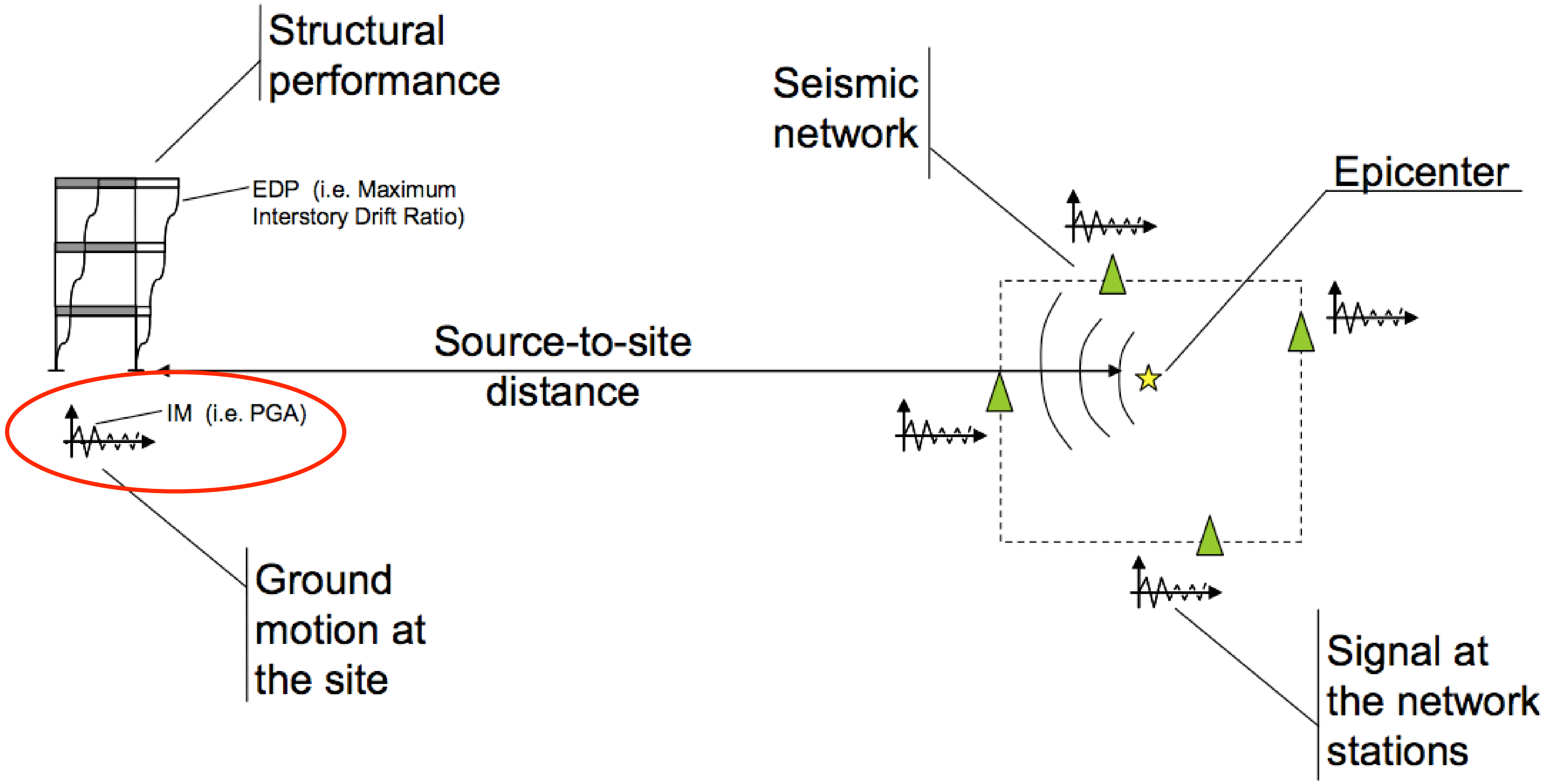
Real-Time Hazard Evaluation/Mitigation



$$\hat{f}_{PGA}(pga) = \int_M \int_R f_{PGA|M,R}(pga|m,r)\hat{f}_M(m)\hat{f}_R(r)dmdr$$

from Iervolino et al., 2006

Real-Time Hazard Evaluation/Mitigation



$$\hat{f}_{PGA}(pga) = \int_M \int_R f_{PGA|M,R}(pga|m,r)\hat{f}_M(m)\hat{f}_R(r)dmdr$$

from Iervolino et al., 2006

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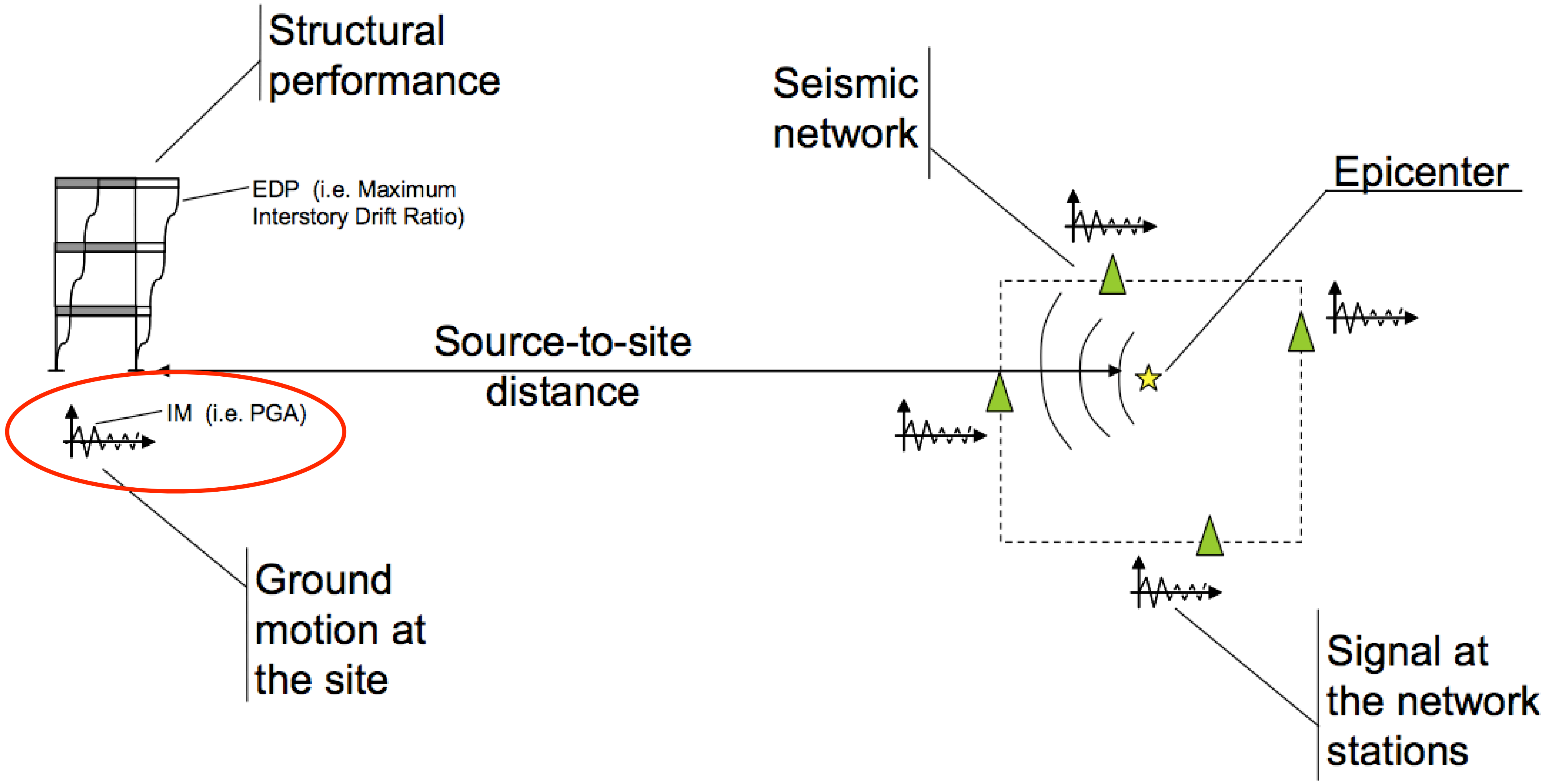

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EEW
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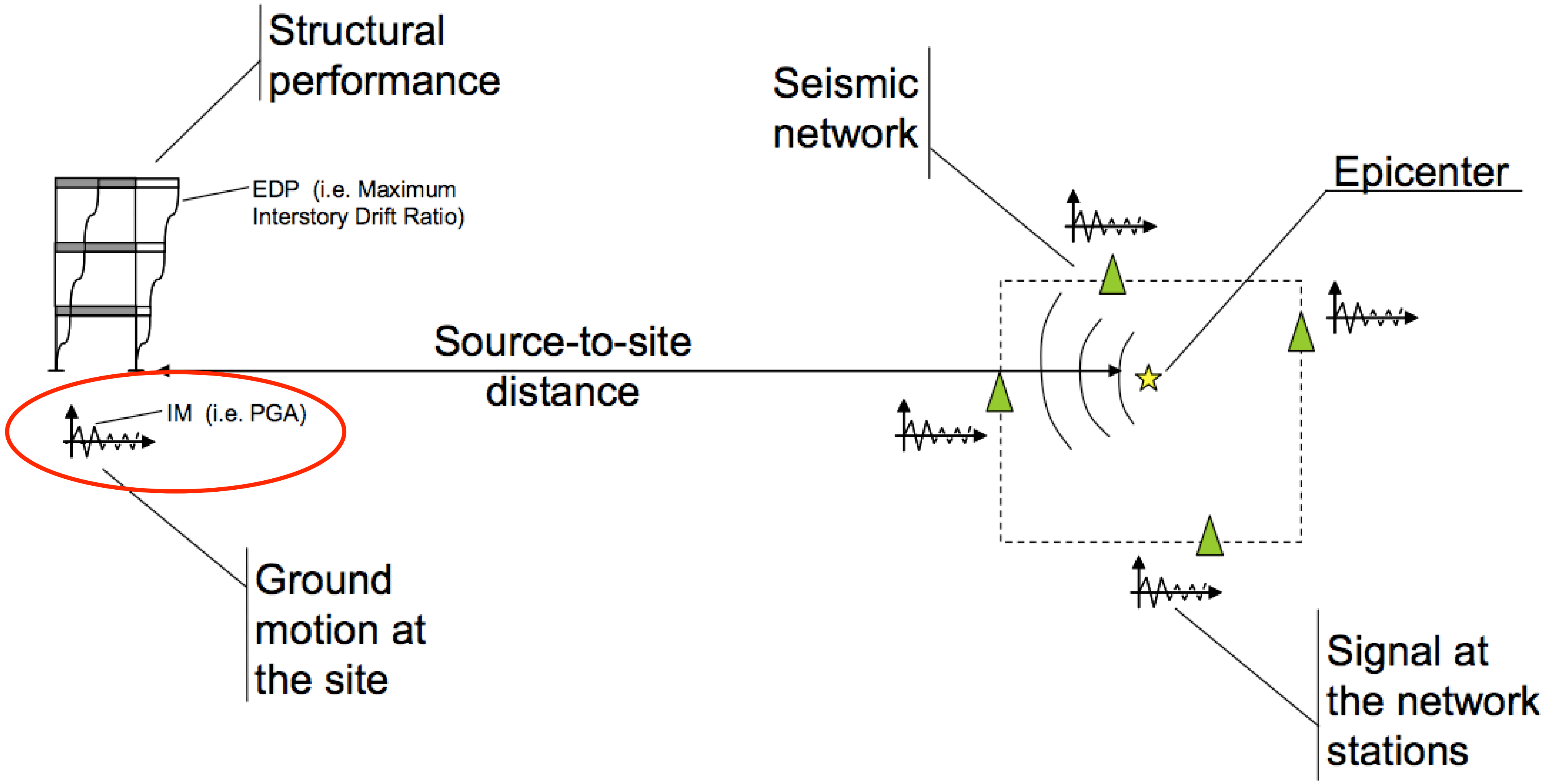

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Attenuation Law

EEW
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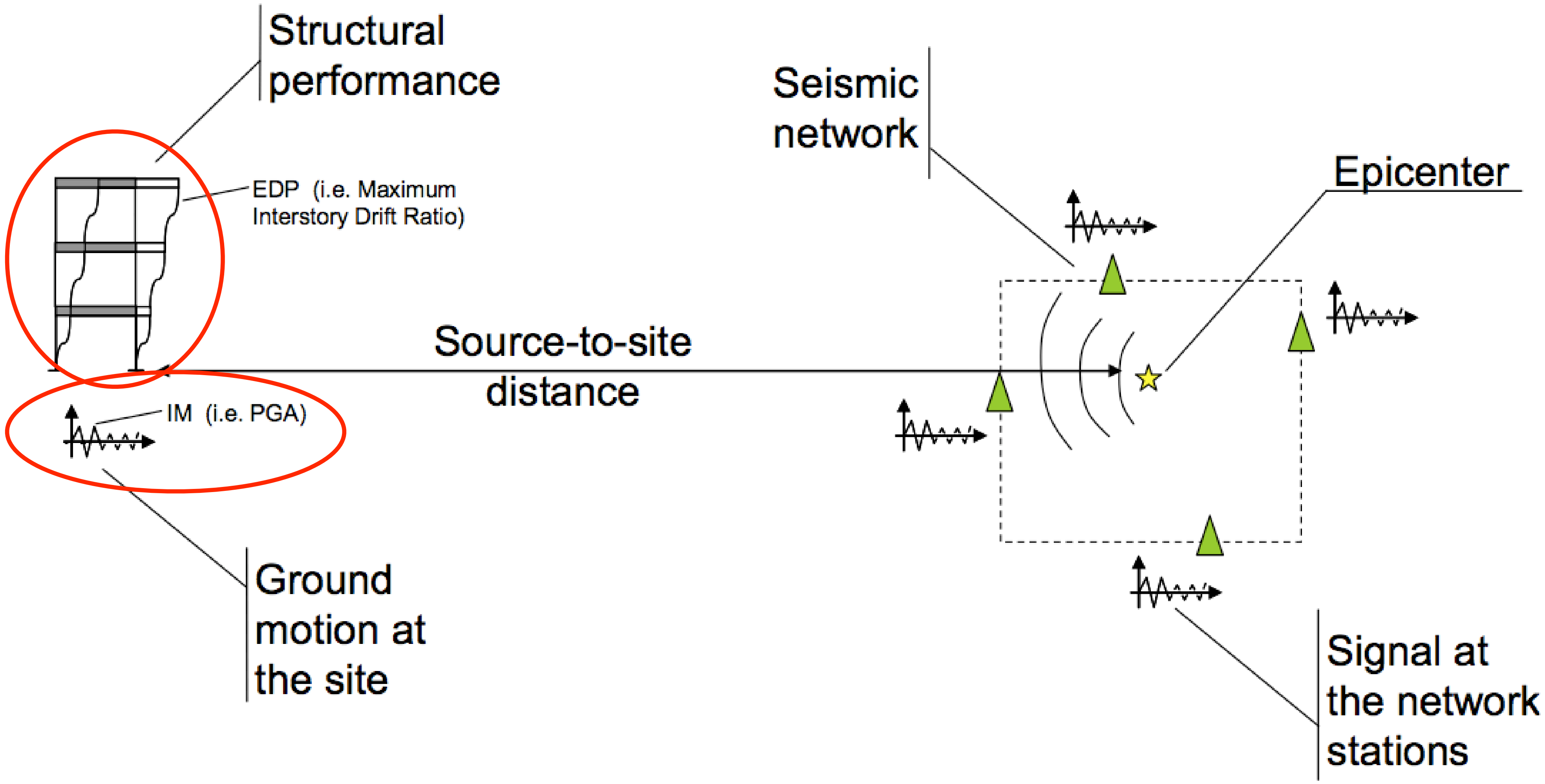

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Attenuation Law: $f_{PGA|M,R}(pga|m,r)$

EEW (function of time): $\hat{f}_M(m)\hat{f}_R(r)$

from Iervolino et al., 2006

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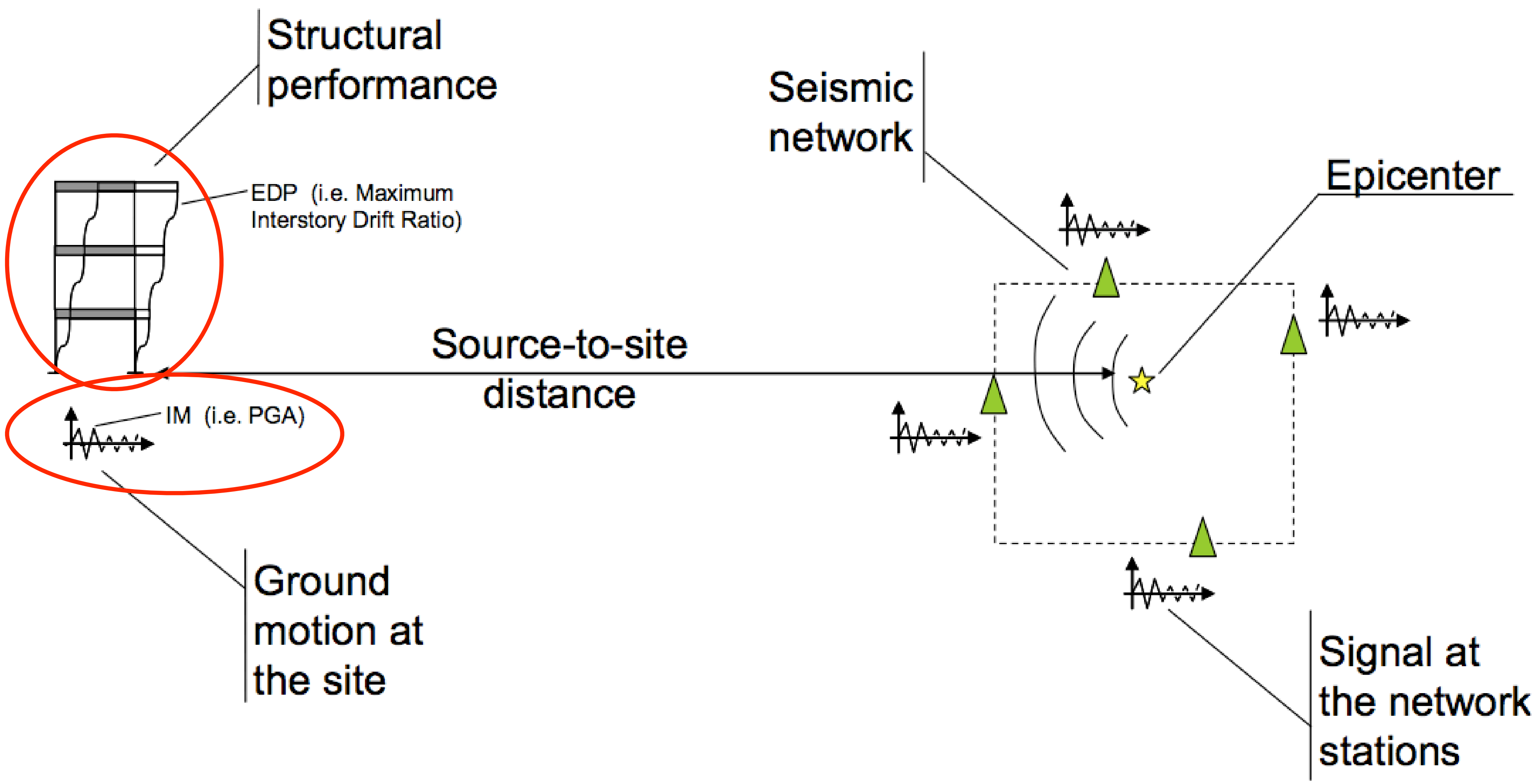

$$\hat{f}_{PGA}(pga) = \int_M \int_R f_{PGA|M,R}(pga|m,r) \hat{f}_M(m) \hat{f}_R(r) dmdr$$

Attenuation Law

EEW (function of time)

Estimation of Engineering Demand Parameters (EDP):

$$\hat{f}_{EDP}(edp) = \int_{IM} f_{EDP|PGA}(edp|pga) \hat{f}_{PGA}(pga) dpga$$

from Iervolino et al., 2006

Discussion

- We have developed a probabilistic, real-time evolutionary location technique (RTLoc) based on the equal differential-time (EDT) formulation.
  - At each time step, this algorithm makes use of both the information from triggered arrivals and not-yet-triggered stations.
  - Constraint on the hypocenter location is obtained as soon as the first station has triggered and is updated at fixed time intervals or when a new station triggers.

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- The hypocenter location is estimated as a probability density function defined within a pre-defined search volume.
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- Both synthetic and real data show that useful locations can be obtained within 1-2 seconds for a local earthquake and 6-10 seconds at a regional scale