Supplementary Material 2 – G.L.I.D.E. preliminary results

In order to quantify the contribution of erosion/exhumation rates in the western Northern Apennines at a more regional scale, we used numerical methods which calculate exhumation rates from spatially distributed low temperature thermochronological data. After having seen (§ 7) the results produced by Pecube throughout small- and medium-scale portions of the study area, we now present the preliminary results obtained through the use of G.L.I.D.E., a finite element code developed by Fox et al. (in press). Since the work is still in progress, the preliminary results have not been integrated with those presented in the previous chapters.

G.L.I.D.E., acronym for Gaussian Linear Inversion of Data to Exhumation, inverts linearly thermochronological data through Gaussian procedures and it is based on these few concepts:

a) the depth of the "closure isotherm" (sensu Dodson, 1973) can be described as the time integral of the exhumation rate, from the cooling age to the present day;

b) exhumation rate is assumed to vary smoothly in space, and so it can be described through a spatial correlation function;

The exhumation rates history is then discretized over a set of time steps, but at the same time it is spatially correlated over each time step. This method implies the use of an "*a priori*" estimate of various model parameters, and, at the end of the procedure, the results are accompanied by an estimate of the resolving power of the data, obtained by computing "*a posteriori*" variance values, and comparing them directly to the "*a priori*" variance.

The input parameters of the model are the following:

- DTM of the analyzed area;
- thermochronological data (for each datum: latitude, longitude, elevation, age, error relative to the age, reference thermochronologic system);
- location of control points on which the code specifically prints output information about their exhumation history;
- *a priori* estimate of the average exhumation rate and uncertainty characterizing the investigated area (in km/My);
- parameters for the spatial correlation of the exhumation rate values;
- length of the time steps;

- starting time for the model;
- thermal parameters of the crust (considered thermal thickness, temperature at surface, temperature at the base of the model, thermal diffusivity, radiogenic heat production)

At first, the code calculates the geothermal gradient at the beginning and at the end of the model. These two values are indirectly controlled by the chosen temperature at the base of the model and the *a priori* exhumation rate. This fact implies the need to obtain information about the tectonic and geodynamic framework and above all about the crustal thermal state (i.e., the geothermal gradient spatial distribution) of the investigated area from external sources.

The geothermal gradient characterizing the period just before the beginning of the tectonic activity inside an orogenic belt can be reasonably approximated to the present-day geothermal gradient in tectonically inactive areas located in proximity of the studied mountain belt (e.g., Braun et al., 2006). In the case of the Northern Apennines this value (17-20 °C/km) has been obtained by present-day measurements of temperature and heat flow in deep boreholes in zones of the Po Plain where the thickness of sediments is large enough to prevent the advected heat (see § 7), produced by the tectonic activity of buried structures, to reach the surface (AGIP, 1977; Della Vedova et al., 1995; Pasquale et al., 2012). Also the present day geothermal gradient within the Apennine orogen (30-35 °C/km) has been constrained once again by the collection of temperature measurements in the deep boreholes analyzed in § 5.2 and regional heat flow maps related to the Apenninic chain (AGIP, 1977; Della Vedova et al., 1995; Pasquale et al., 2012).

The *a priori* estimate of the exhumation rate, shown later, has been constrained by taking into account previously published estimates related to other portions of the Northern Apennines (Balestrieri et al., 2003, Bartolini et al., 1996, Bartolini et al., 2003) and the results obtained with Pecube (see § 7).

The thermochronological data taken into account constitute the whole dataset for the Northern Apennines published by Thomson et al. (2010), integrated with the new data presented in this work (fig. 4.10, §4).

Within the Northern Apennines, nine control points have been set. These control points constitute three SW-NE oriented transects almost equally spaced within the NE slope of the Northern Apennines (fig. SM2.1), and are characterized by three control points each, located: a) at the main ridge (roughly corresponding to Zone 1 in fig. 3.1); b) in the NE mid-slope area (roughly corresponding to Zone 2 in fig. 3.1); c) at the foothills of the chain, at the boundary of the Po Plain (roughly corresponding to Zone 3 in fig. 3.1).

The SW (Tyrrhenian) slope of the chain has been taken into account by the model, but not by the control points. In this area the location of the single thermochronological ages, in fact, is deeply affected by the widespread extensional tectonics active since ~5 Ma (see § 5), which altered the location (mainly the elevation) of the data, which cooled under their relative closure isotherm during previous stages of the Apenninic evolution (~25-6 Ma).

Presented model

After various attempts made initially with wide ranges of parameters, in order to test the dataset, it has subsequently been possible to do a first refinement and to select a new set of parameters that are more suitable for the Northern Apennines. The constraint of the past and present geothermal gradients within the orogen (see above) allowed to find an *a priori* estimate of the exhumation rate of 0.73 km/My.

The considered parameters for the Northern Apennines, therefore, are the following:

- DTM of the analyzed area: 90 m resolution;
- *a priori* estimate of the average exhumation rate and uncertainty: 0.73 ± 0.1 km/My;
- correlation length scale: 25 km;
- length of time steps: 1, 2 and 3 My;
- model starting time: 12 Ma;
- thickness of the exhuming layer: 90 km;
- temperature at surface: 14 °C;
- temperature at the base of the model: 1820 °C;
- thermal diffusivity: 30 km^2/My;

The following series of images are the plots of the calculated exhumation rates for each time step, in three models characterized by 1, 2 and 3 My time step length. Each resolution map is coupled to an uncertainty map, which shows how much the calculated exhumation rates are close to the ones extracted directly from each natural sample data (figs. SM2.2a, SM2.2b, SM2.2c).

At the end of this supplementary material 2, fig. SM2.3 shows how the exhumation rate (and the related uncertainty) varies through time, from 12 to 0 Ma, for each control point, whose location is indicated in fig. SM2.1.

The following results are only preliminary, and won't be discussed here, because still further detailed exploration of the single parameters is required. Above all it is necessary to calculate the resolution and covariance matrices, which allow to infer the reliability of the chosen parameters: how each single parameter is correlated to the others and how much it affects the model results without being biased by the variation of the other parameters.

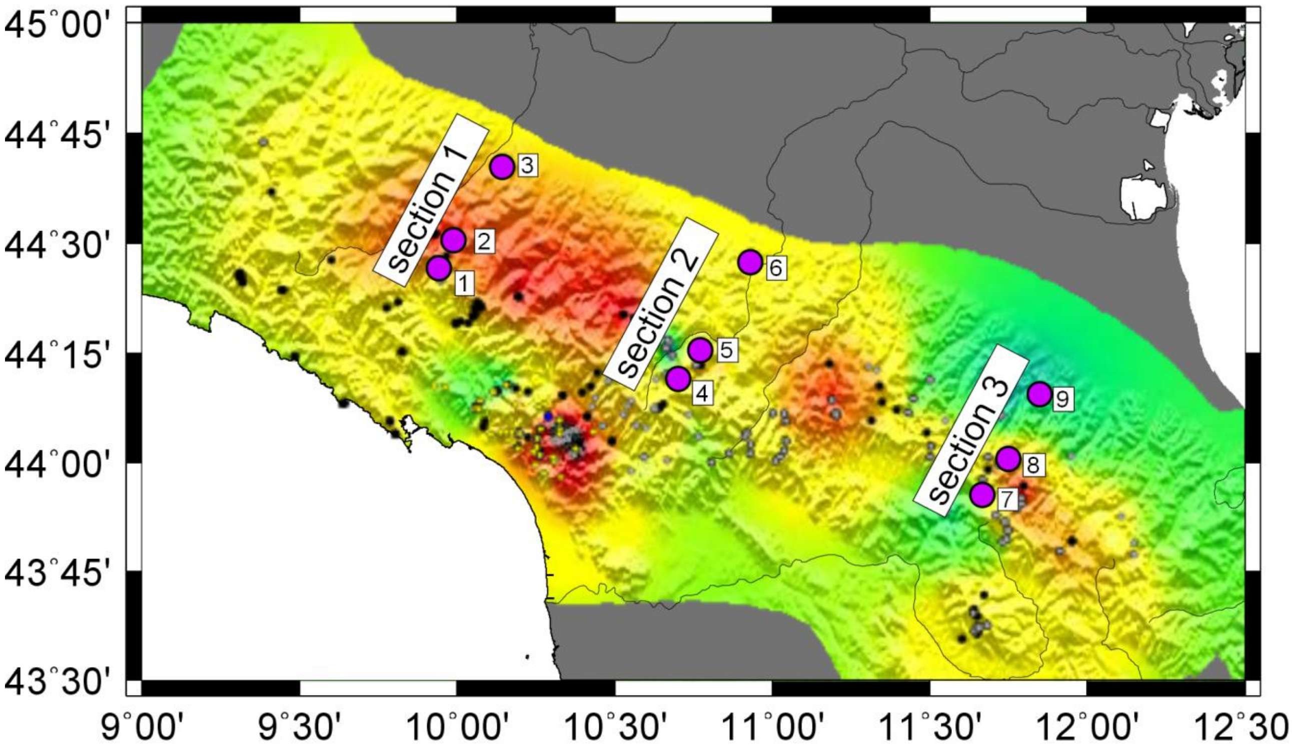
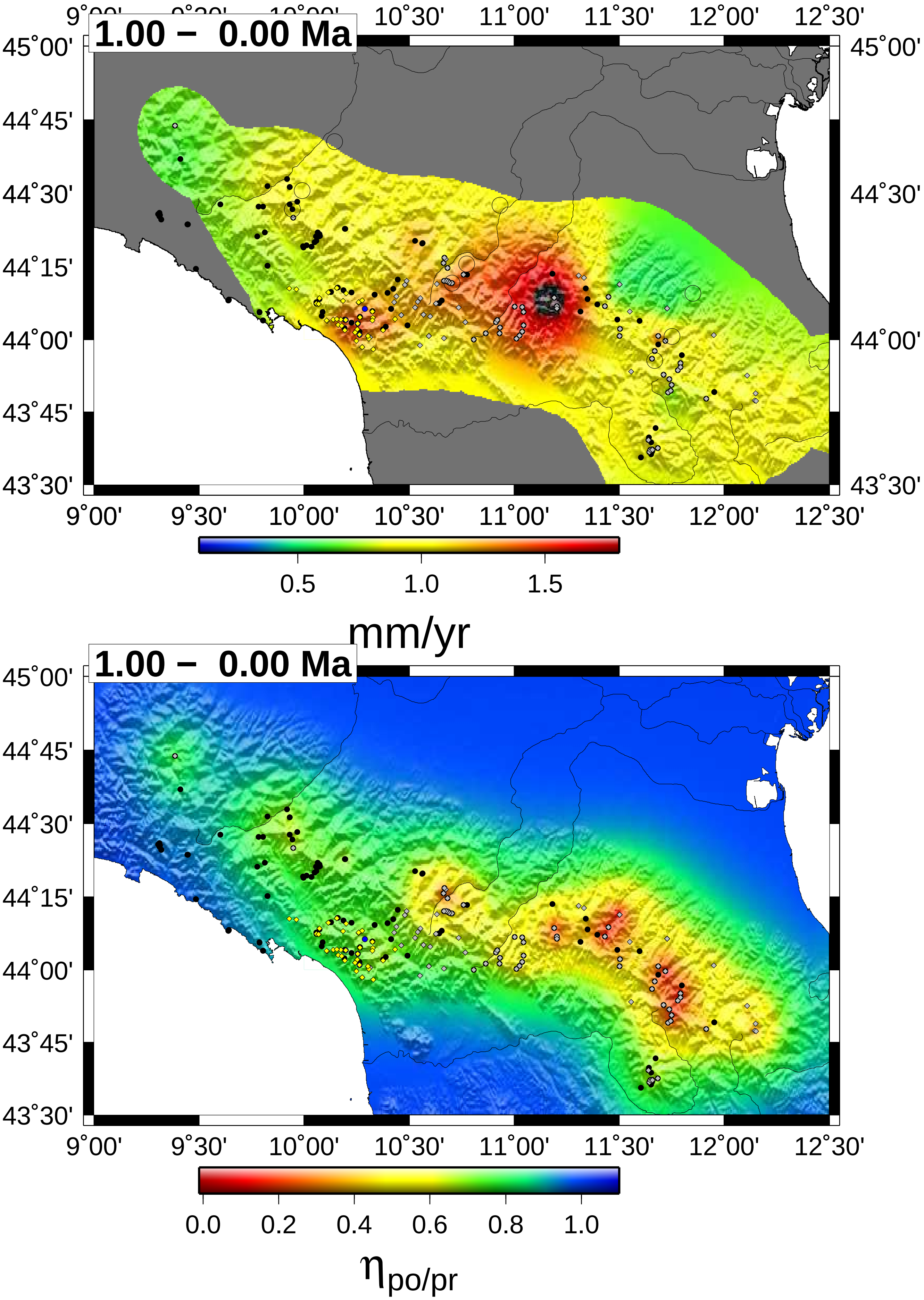
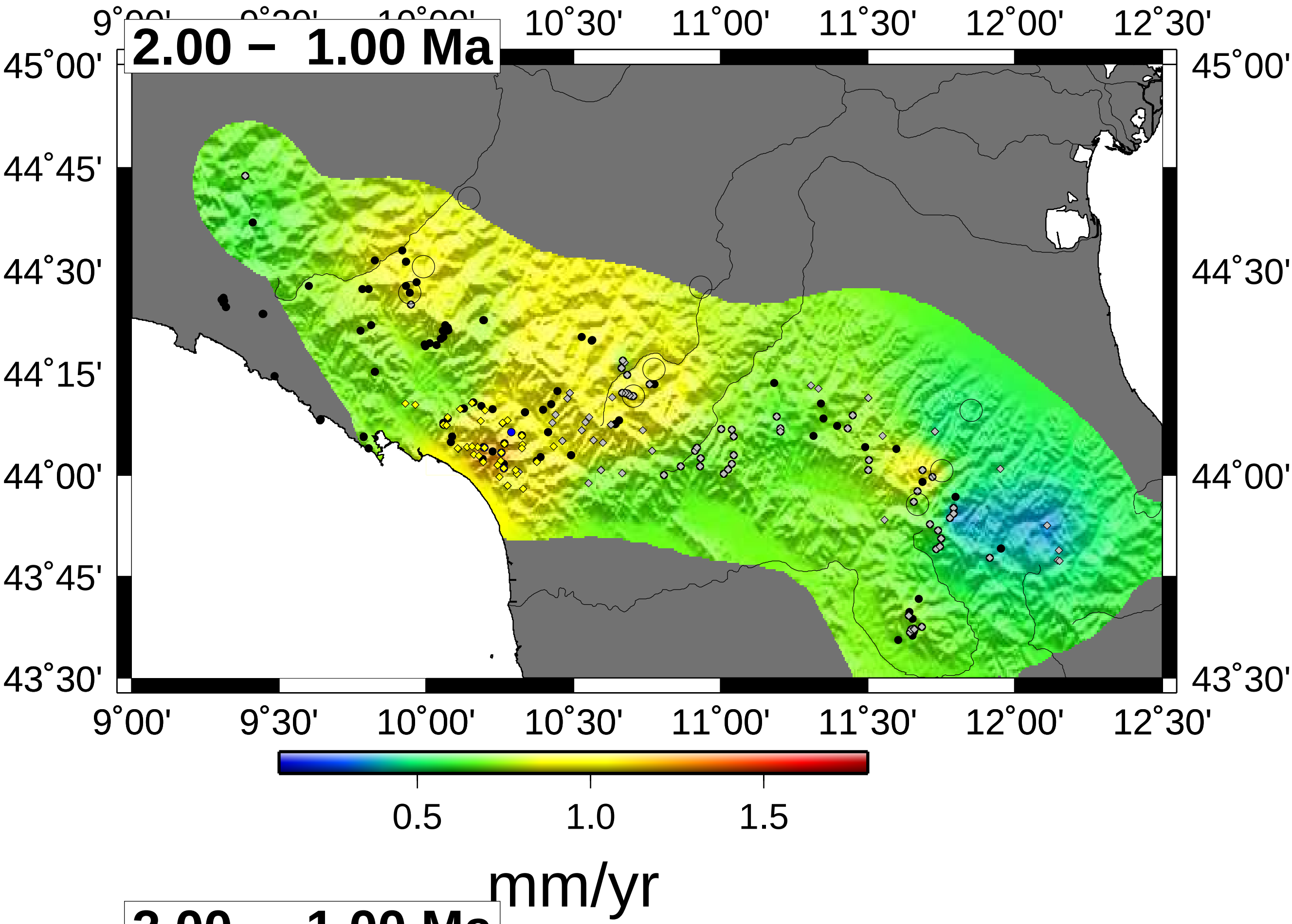


Fig. SM2.1 – sample exhumation maps, used to show the location of the nine selected control points, whose exhumation histories are plotted in fig. SM2.3.

Fig. SM2.2a - 1 My timestep




2.00 – 1.00 Ma
9°00'
9°30'
10°00'
10°30'
11°00'
11°30'
12°00'
12°30'
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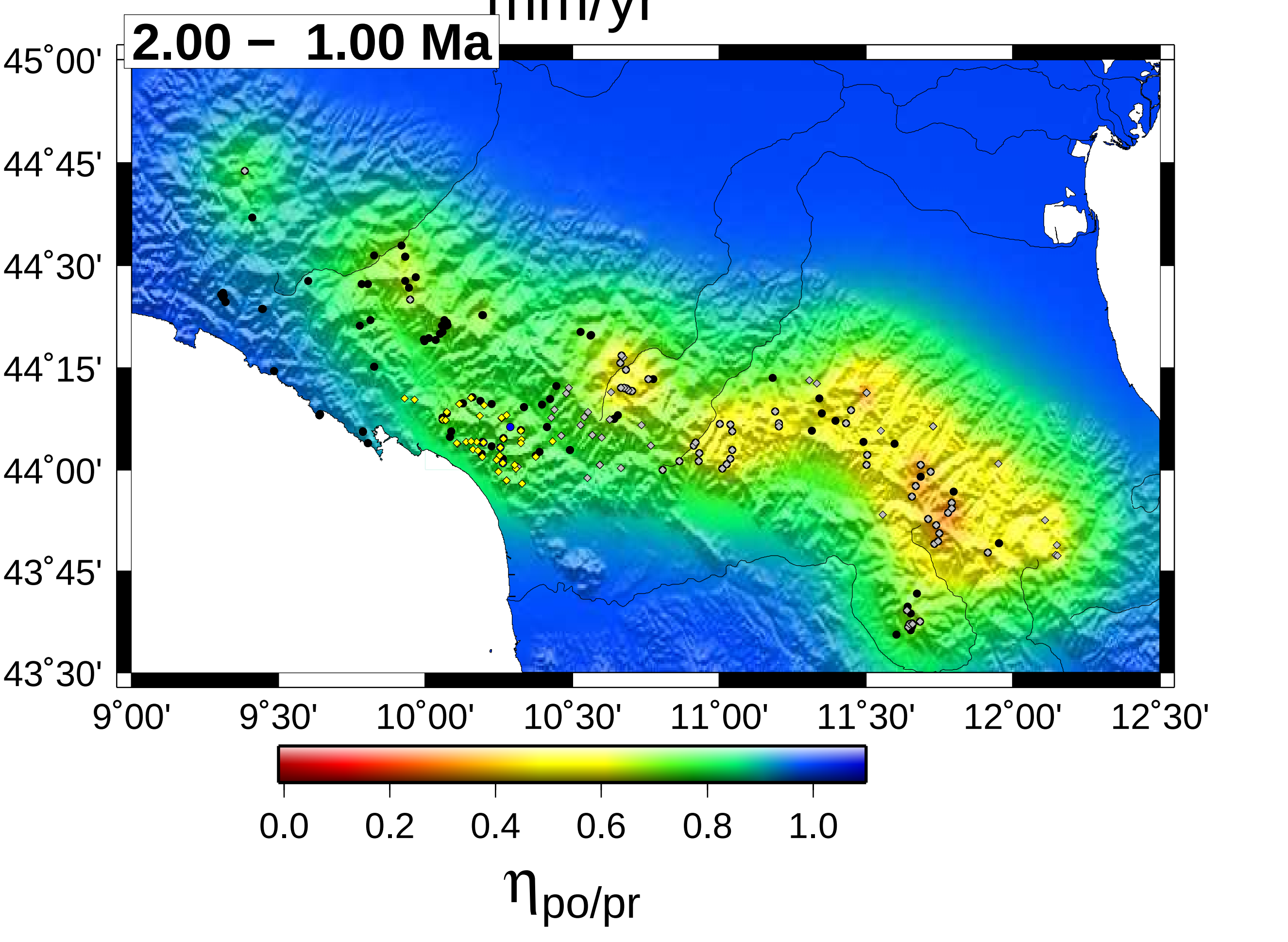
44°45'
44°30'
44°15'
44°00'
43°45'
43°30'
0.5
1.0
1.5
mm/yr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44°00'
43°45'
43°30'
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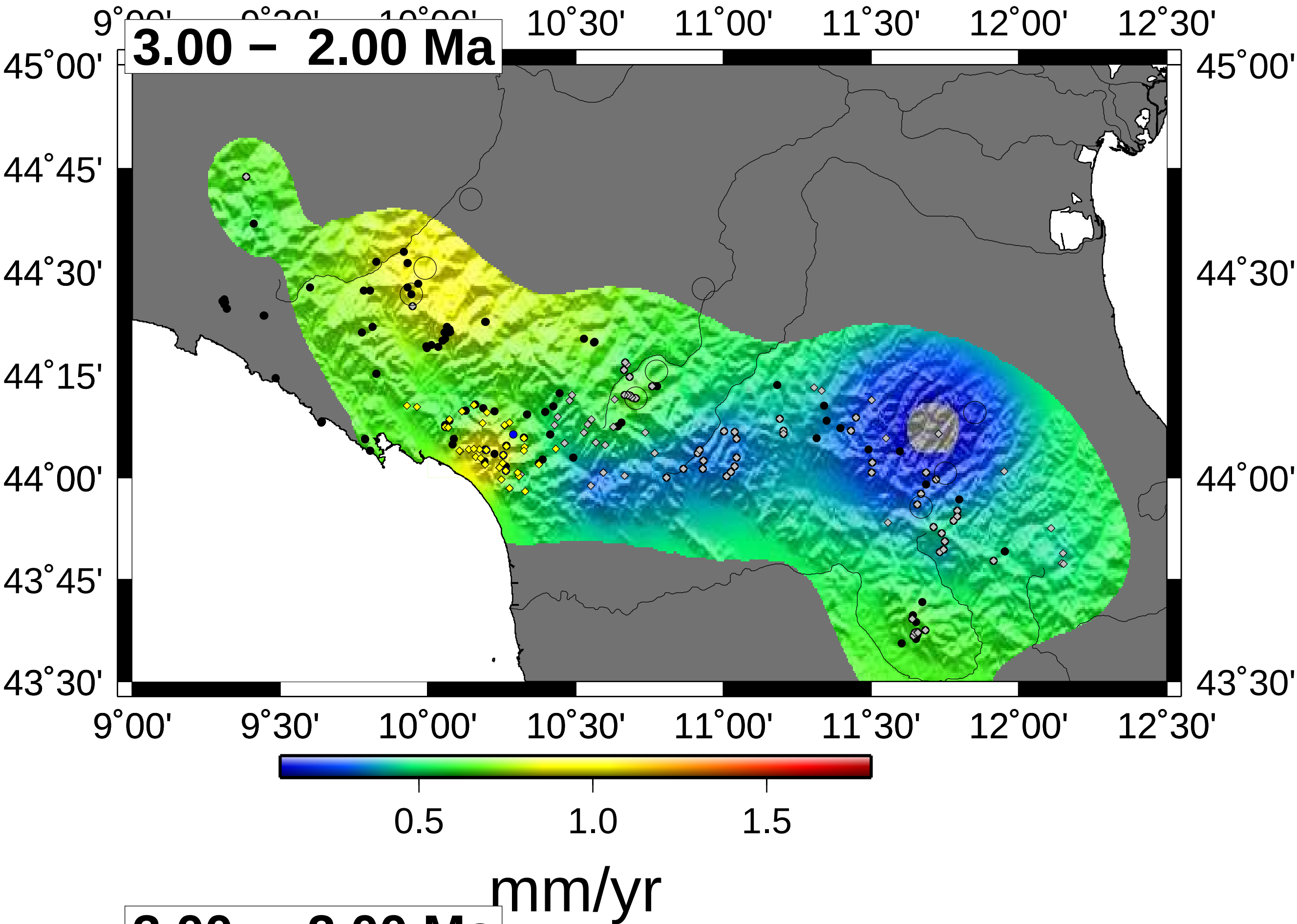
9°30'
10°00'
10°30'
11°00'
11°30'
12°00'
12°30'
0.0
0.2
0.4
0.6
0.8
1.0
$\eta_{po/pr}$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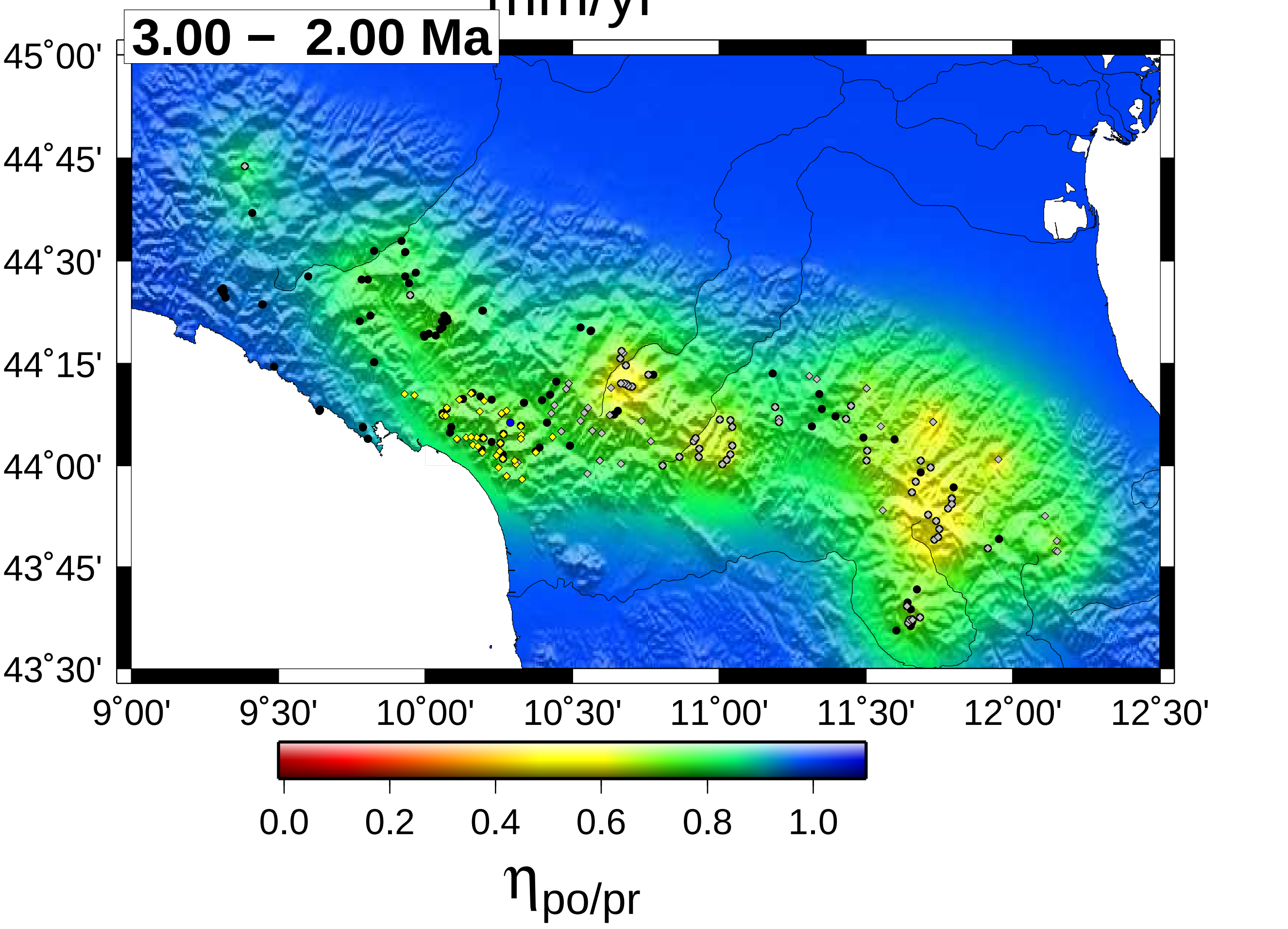
44°30'
44°15'
44°00'
43°45'
43°30'
0.5
1.0
1.5
mm/yr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44°00'
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43°30'
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9°30'
10°00'
10°30'
11°00'
11°30'
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12°30'
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0.2
0.4
0.6
0.8
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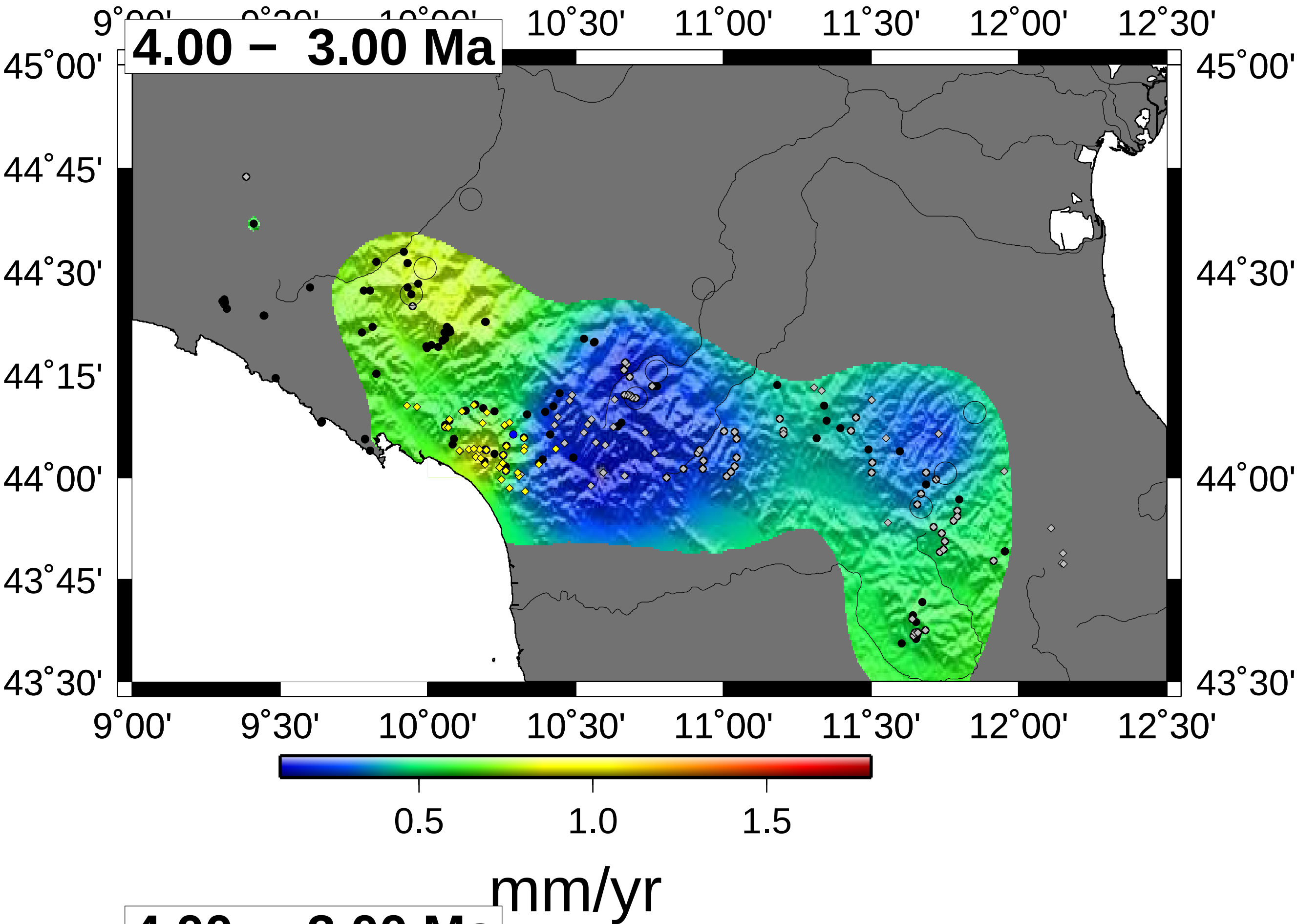
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11°30'
12°00'
12°30'
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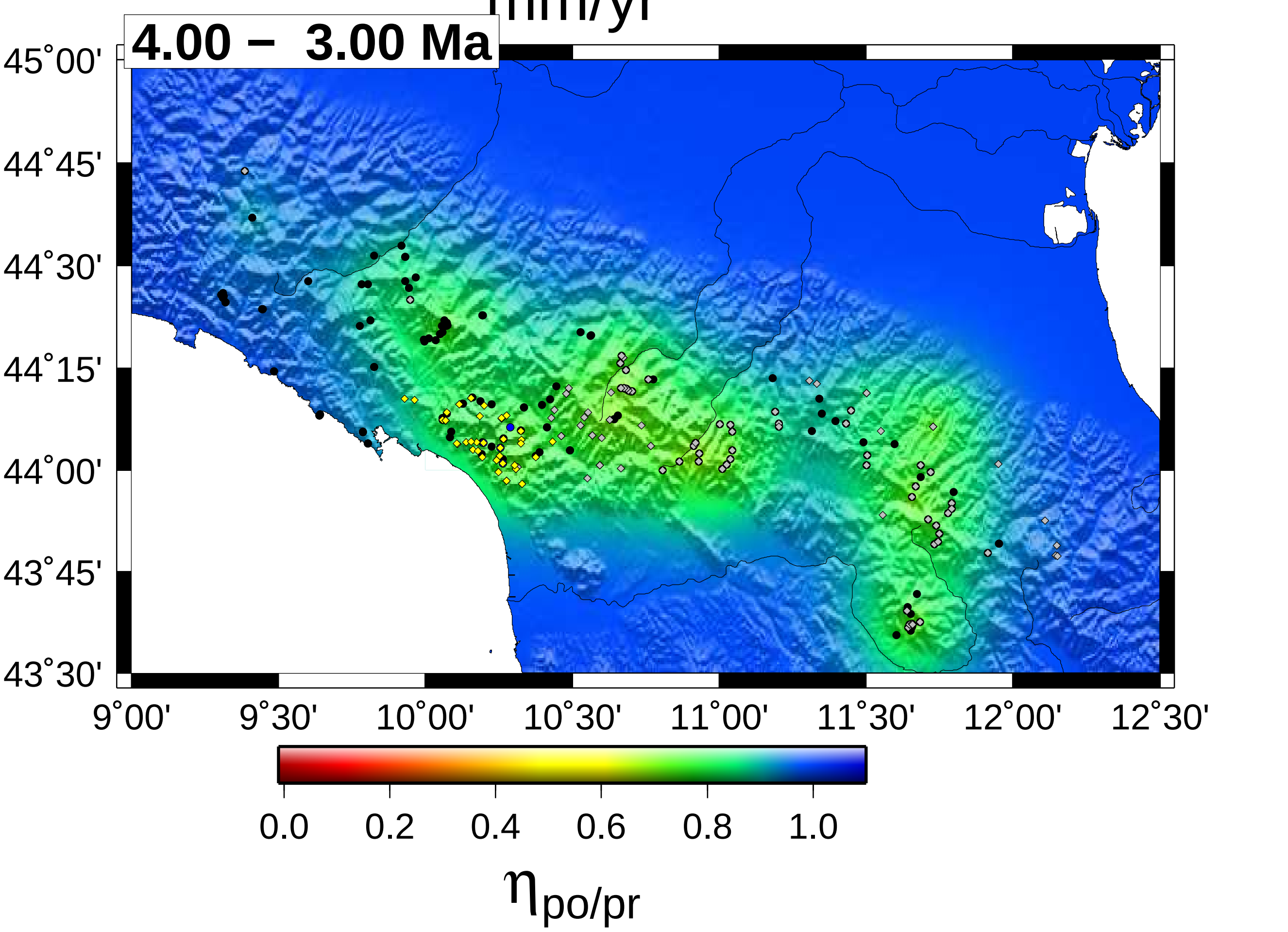
44°30'
44°15'
44°00'
43°45'
43°30'
0.5
1.0
1.5
mm/yr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9°30'
10°00'
10°30'
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11°30'
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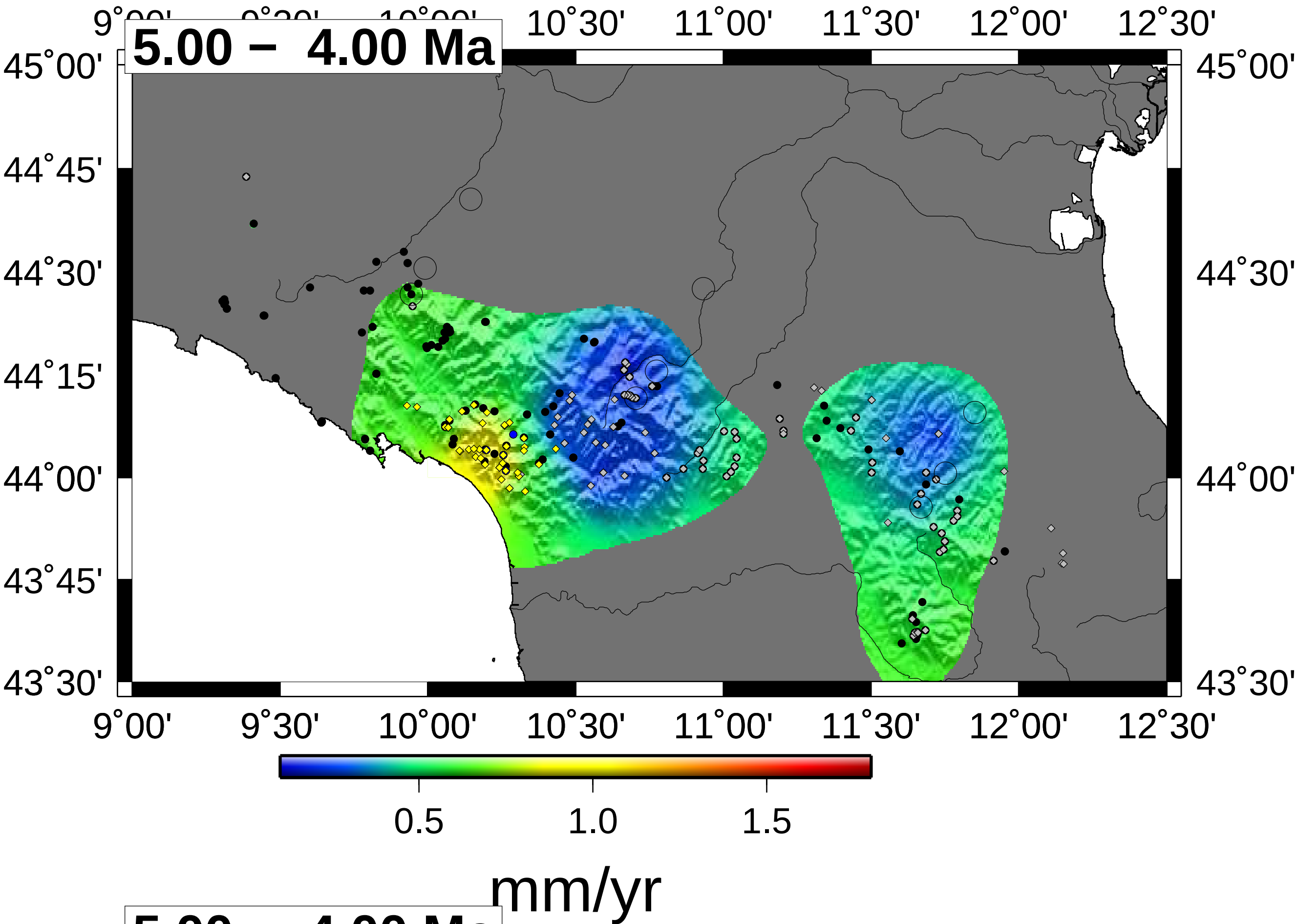
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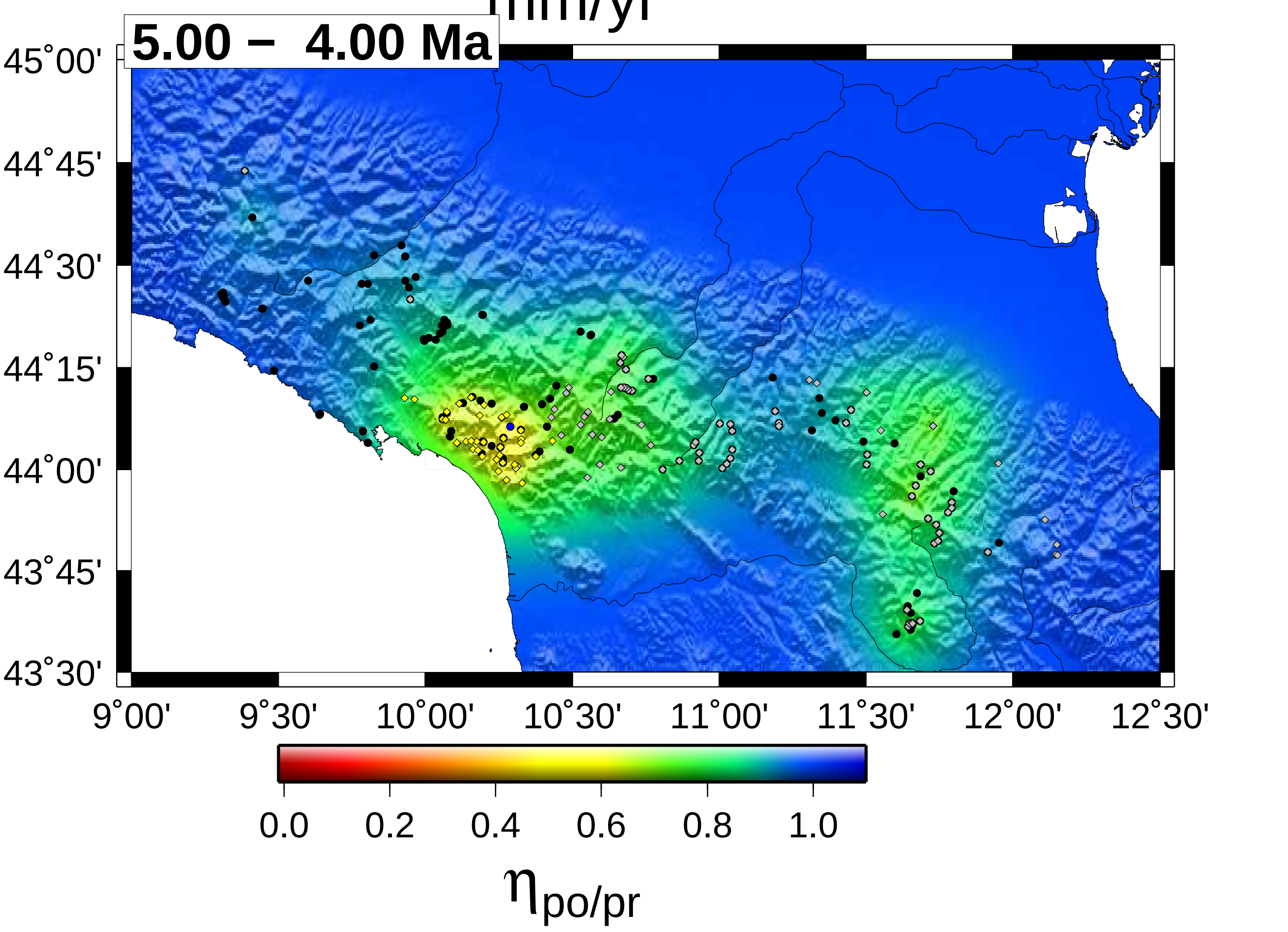
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9°00'
9°30'
10°00'
10°30'
11°00'
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0.6
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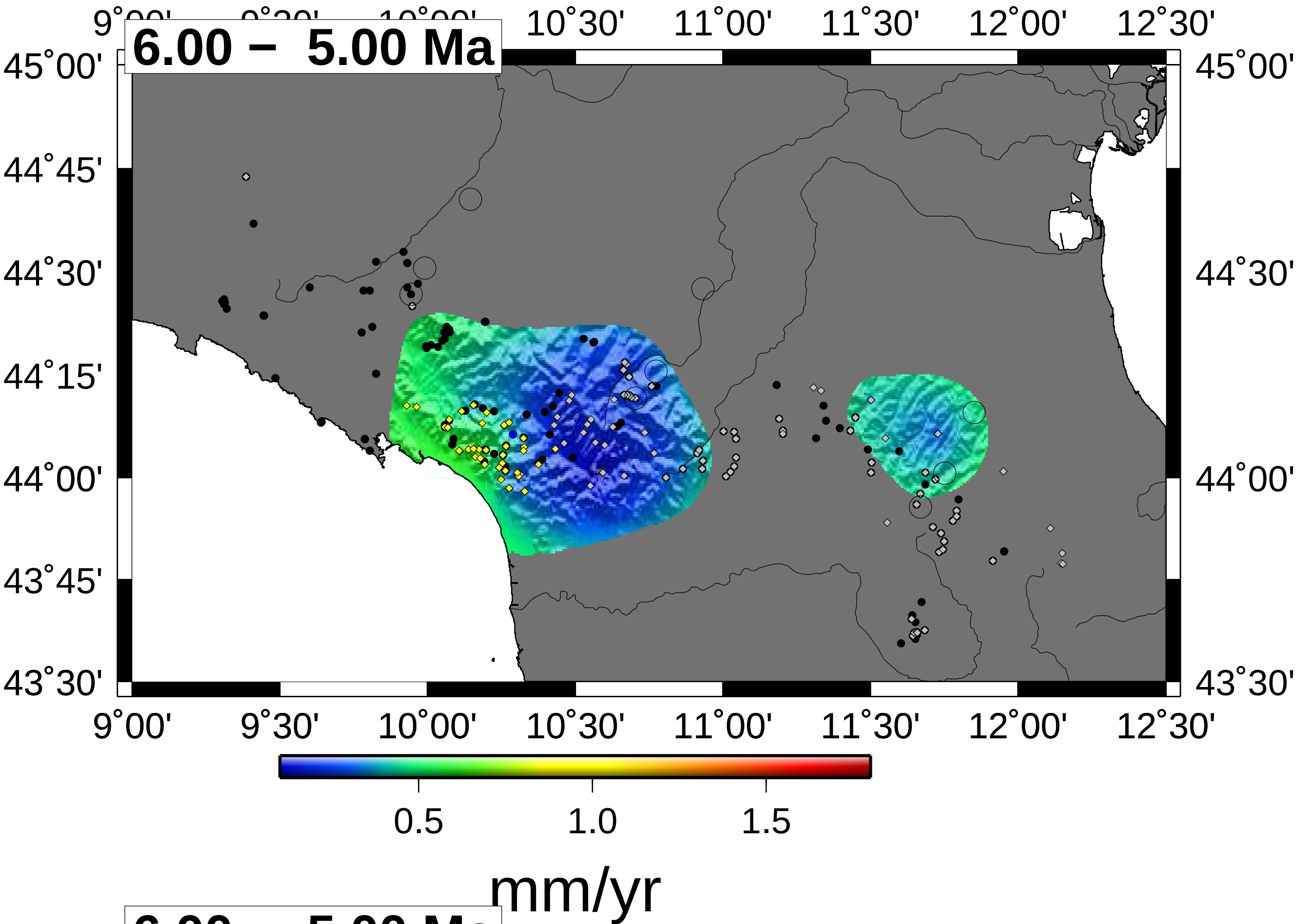
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11°00'
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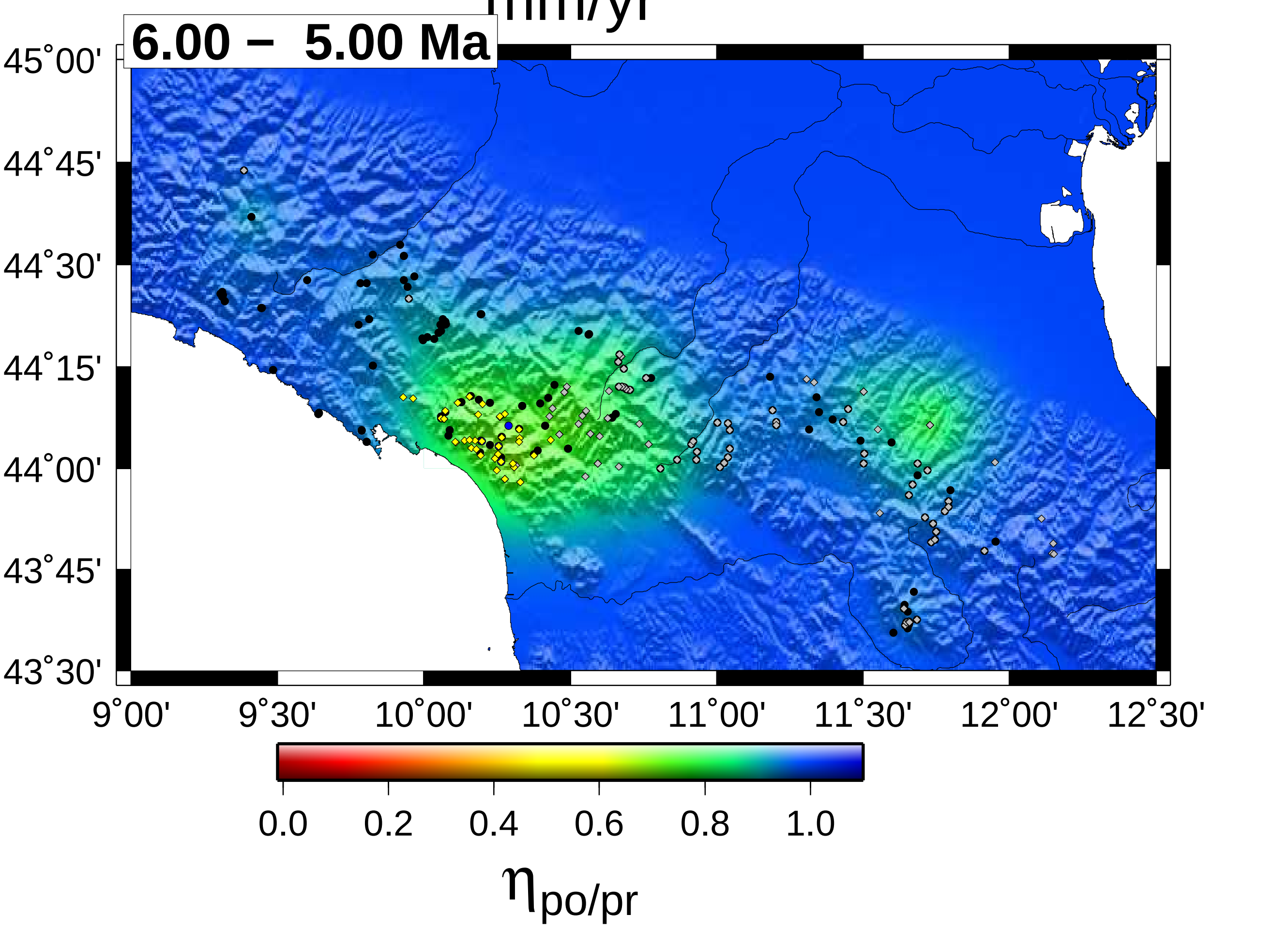
12°00'
12°30'
45°00'
44°45'
44°30'
44°15'
44°00'
43°45'
43°30'
0.5
1.0
1.5
mm/yr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12°30'
45°00'
44°45'
44°30'
44°15'
44°00'
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43°30'
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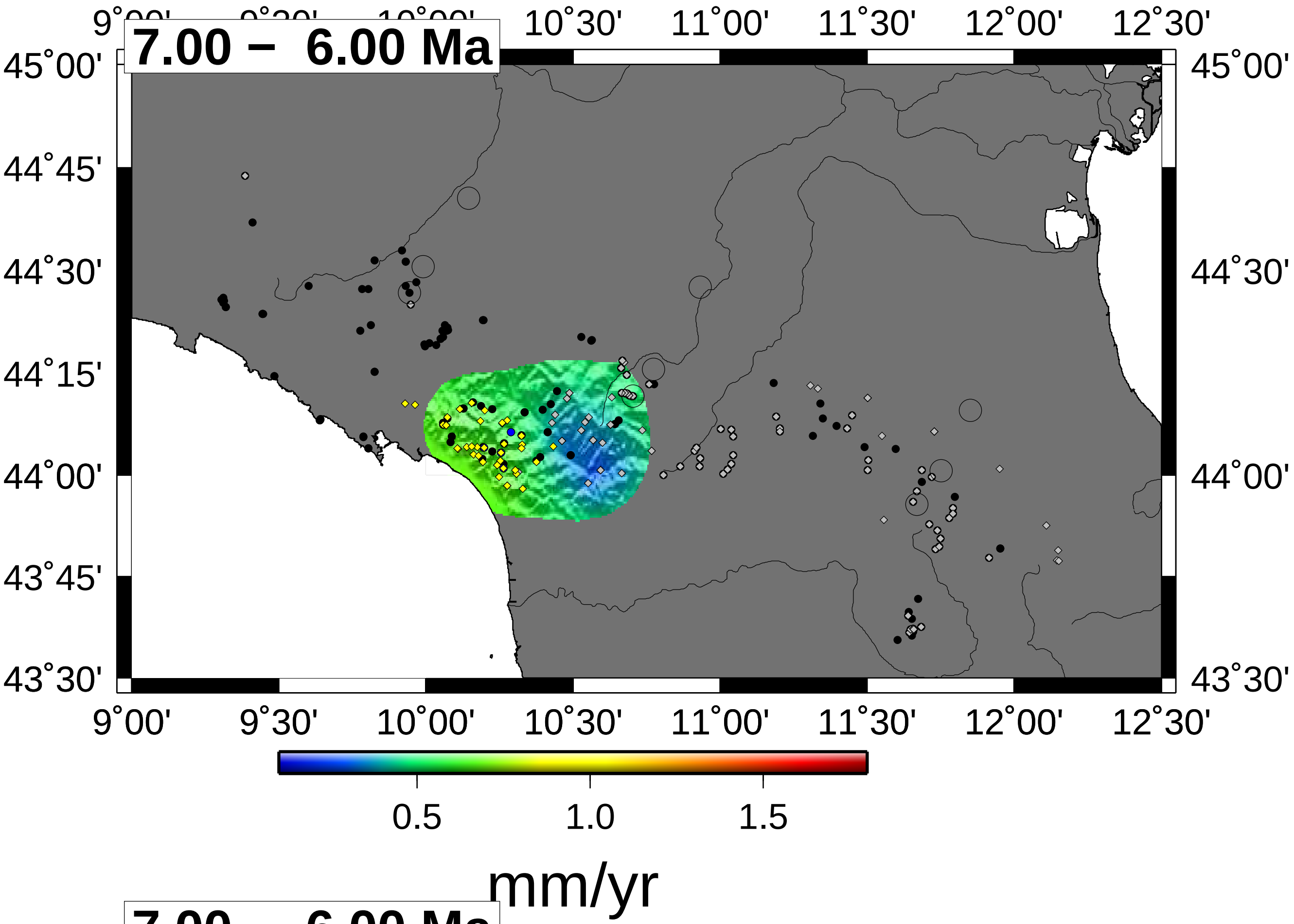
0.4
0.6
0.8
1.0
$\eta_{po/pr}$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9°30'
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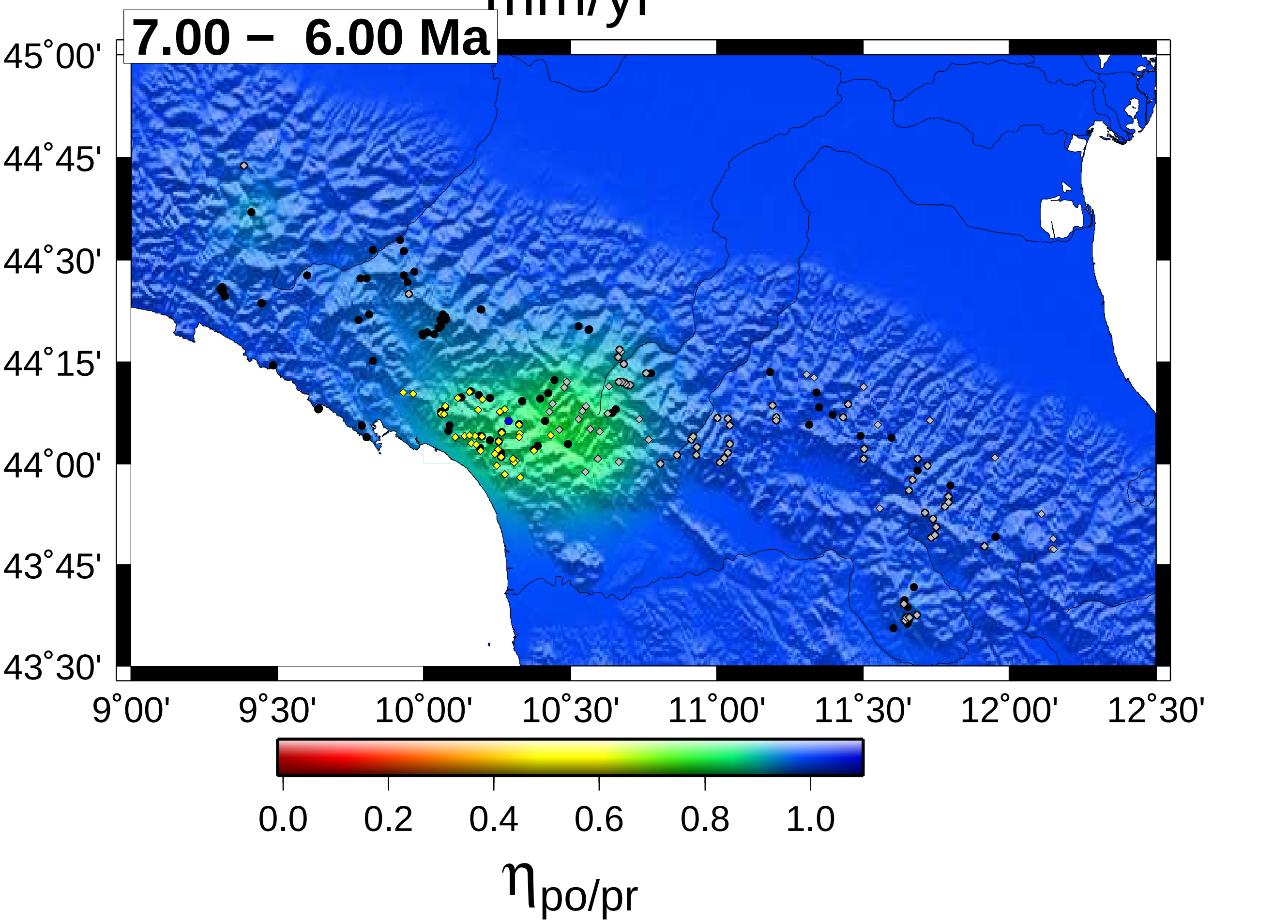
10°30'
11°00'
11°30'
12°00'
12°30'
45°00'
44°45'
44°30'
44°15'
44°00'
43°45'
43°30'
0.5
1.0
1.5
mm/yr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9°30'
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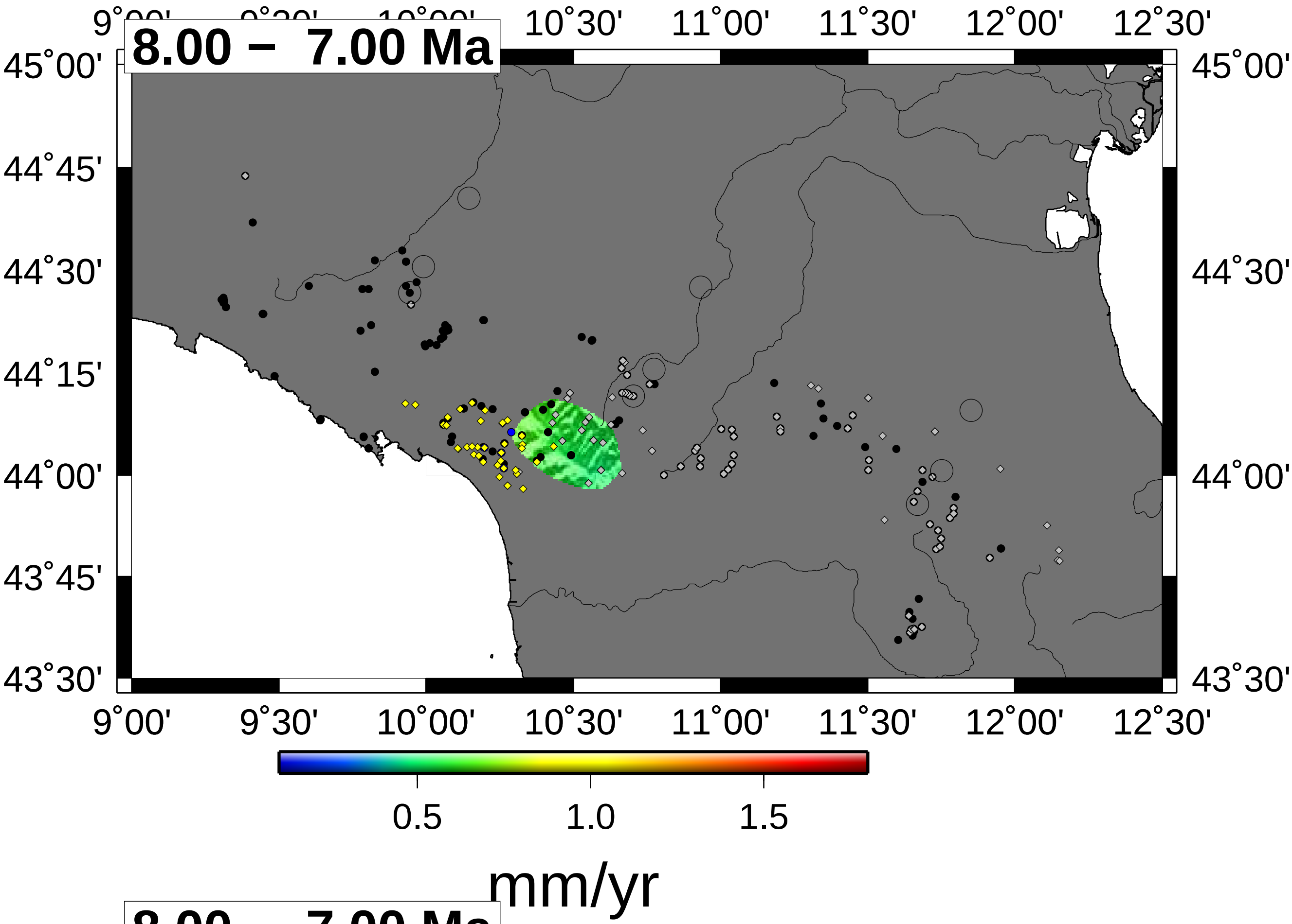
10°30'
11°00'
11°30'
12°00'
12°30'
45°00'
44°45'
44°30'
44°15'
44°00'
43°45'
43°30'
0.0
0.2
0.4
0.6
0.8
1.0
$\eta_{po/pr}$


8.00 – 7.00 Ma
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10°30'
11°00'
11°30'
12°00'
12°30'
45°00'
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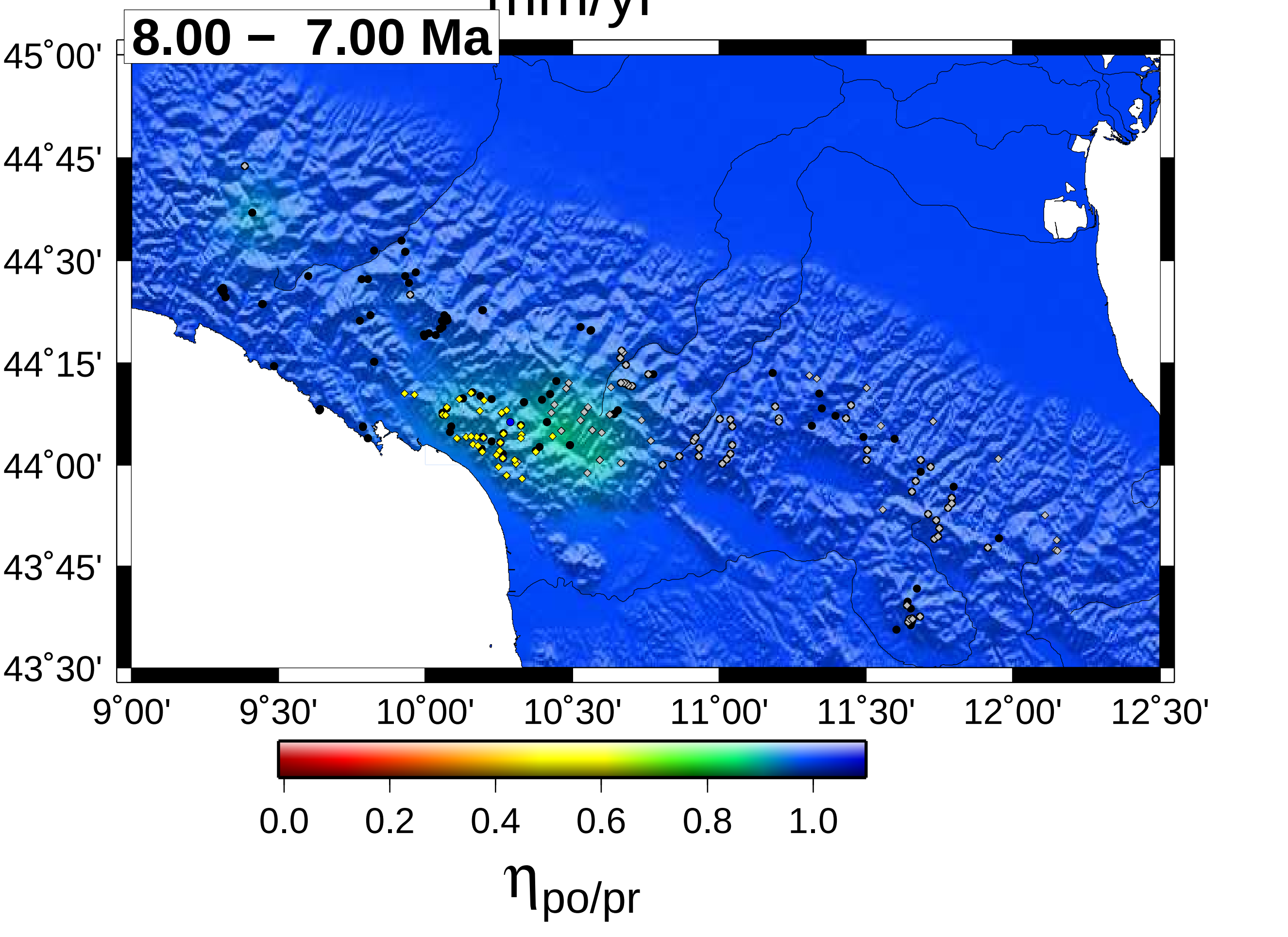
44°30'
44°15'
44°00'
43°45'
43°30'
0.5
1.0
1.5
mm/yr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9°30'
10°00'
10°30'
11°00'
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12°30'
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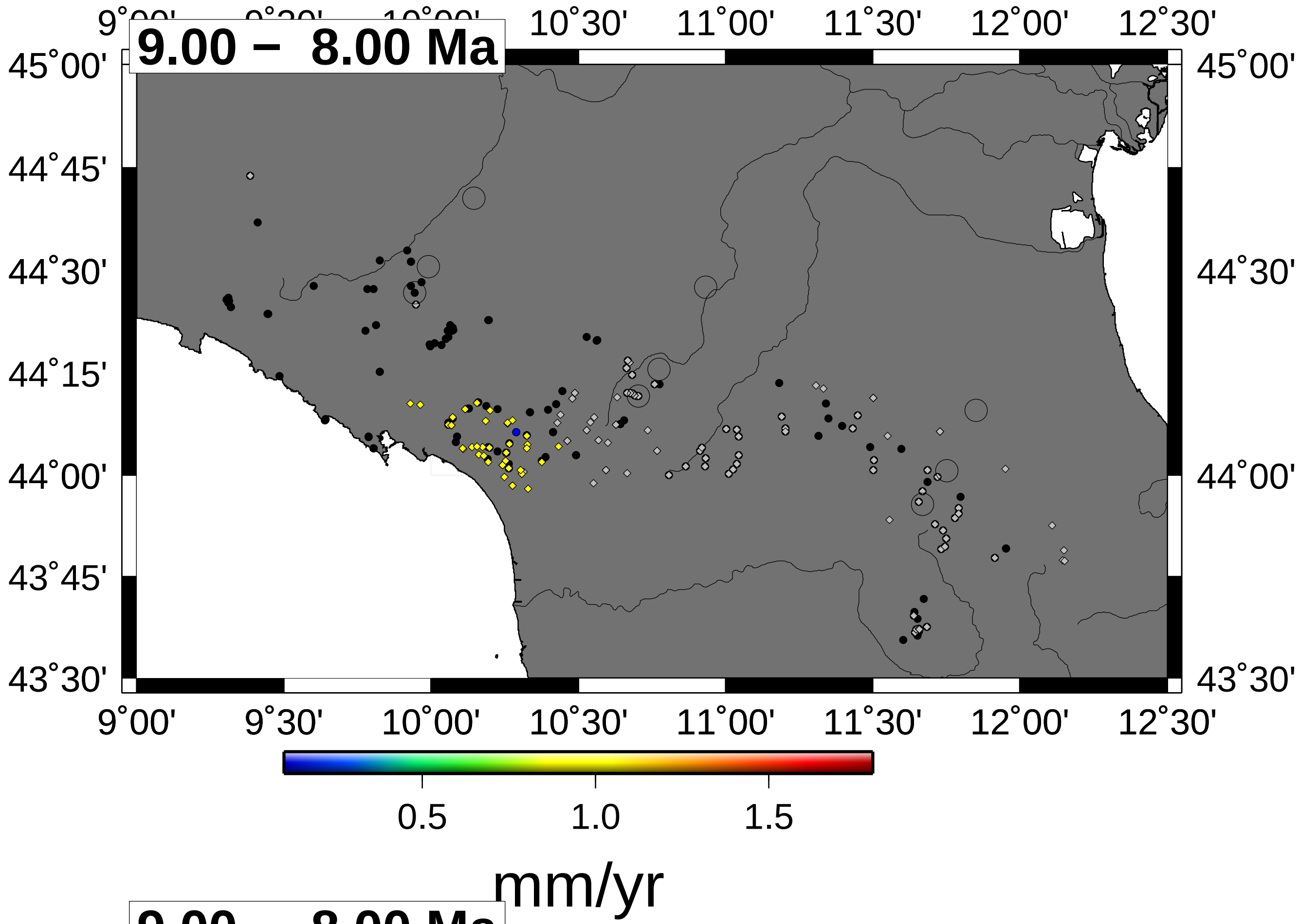
0.2
0.4
0.6
0.8
1.0
$\eta_{po/pr}$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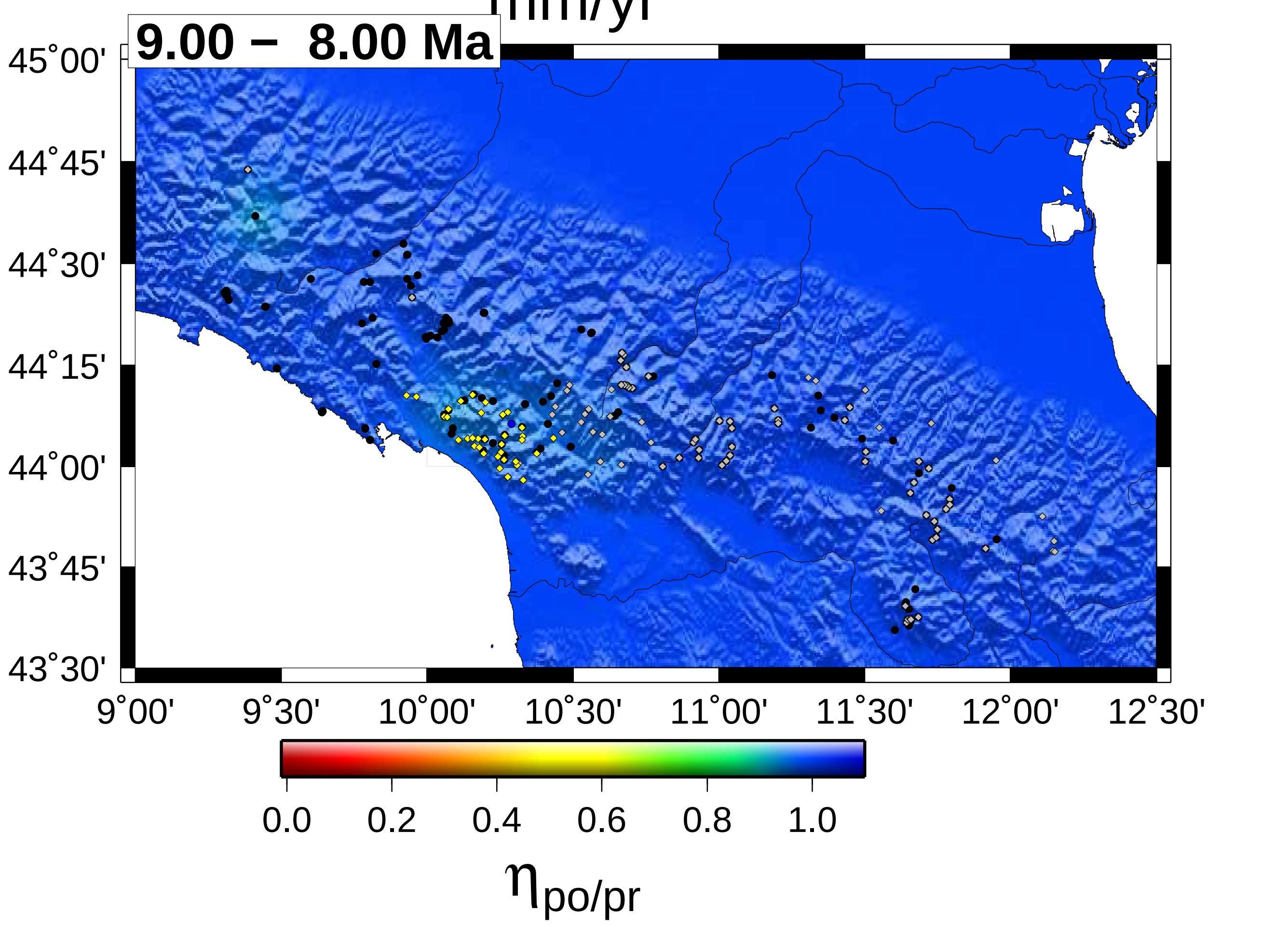
11°00'
11°30'
12°00'
12°30'
45°00'
44°45'
44°30'
44°15'
44°00'
43°45'
43°30'
0.5
1.0
1.5
mm/yr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43°30'
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9°30'
10°00'
10°30'
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0.4
0.6
0.8
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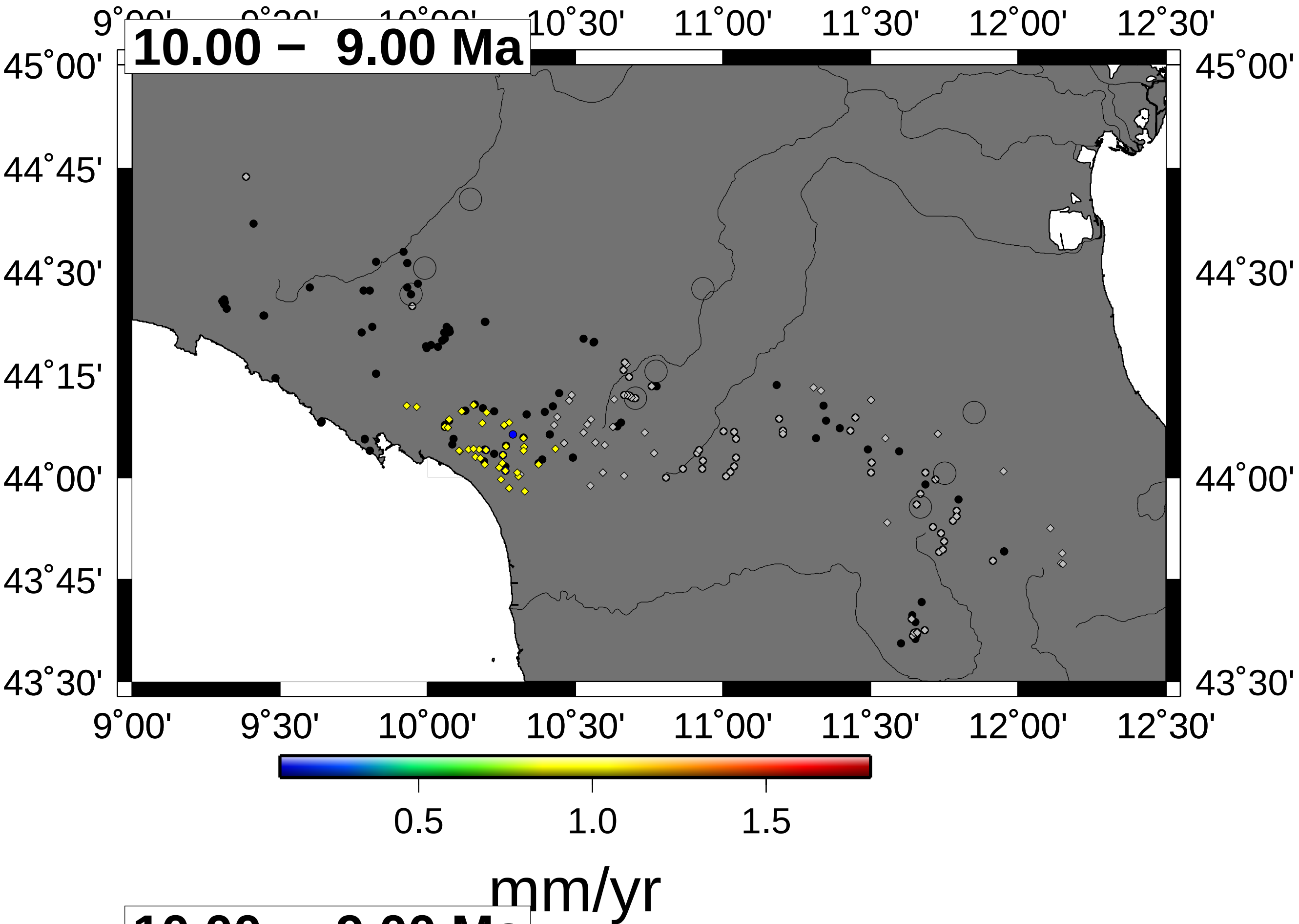
$\eta_{po/pr}$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12°00'
12°30'
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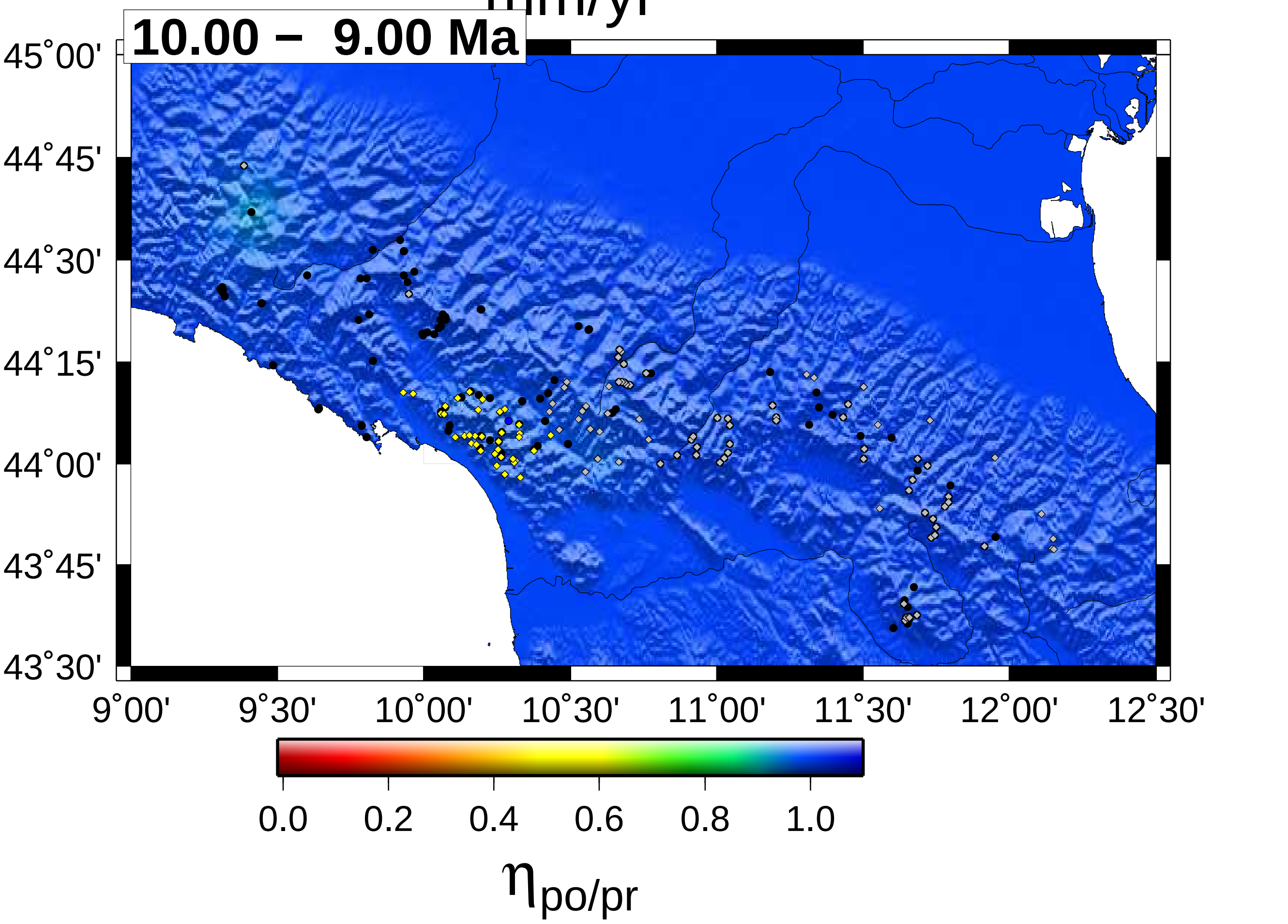
44°30'
44°15'
44°00'
43°45'
43°30'
0.5
1.0
1.5
mm/yr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44°45'
44°30'
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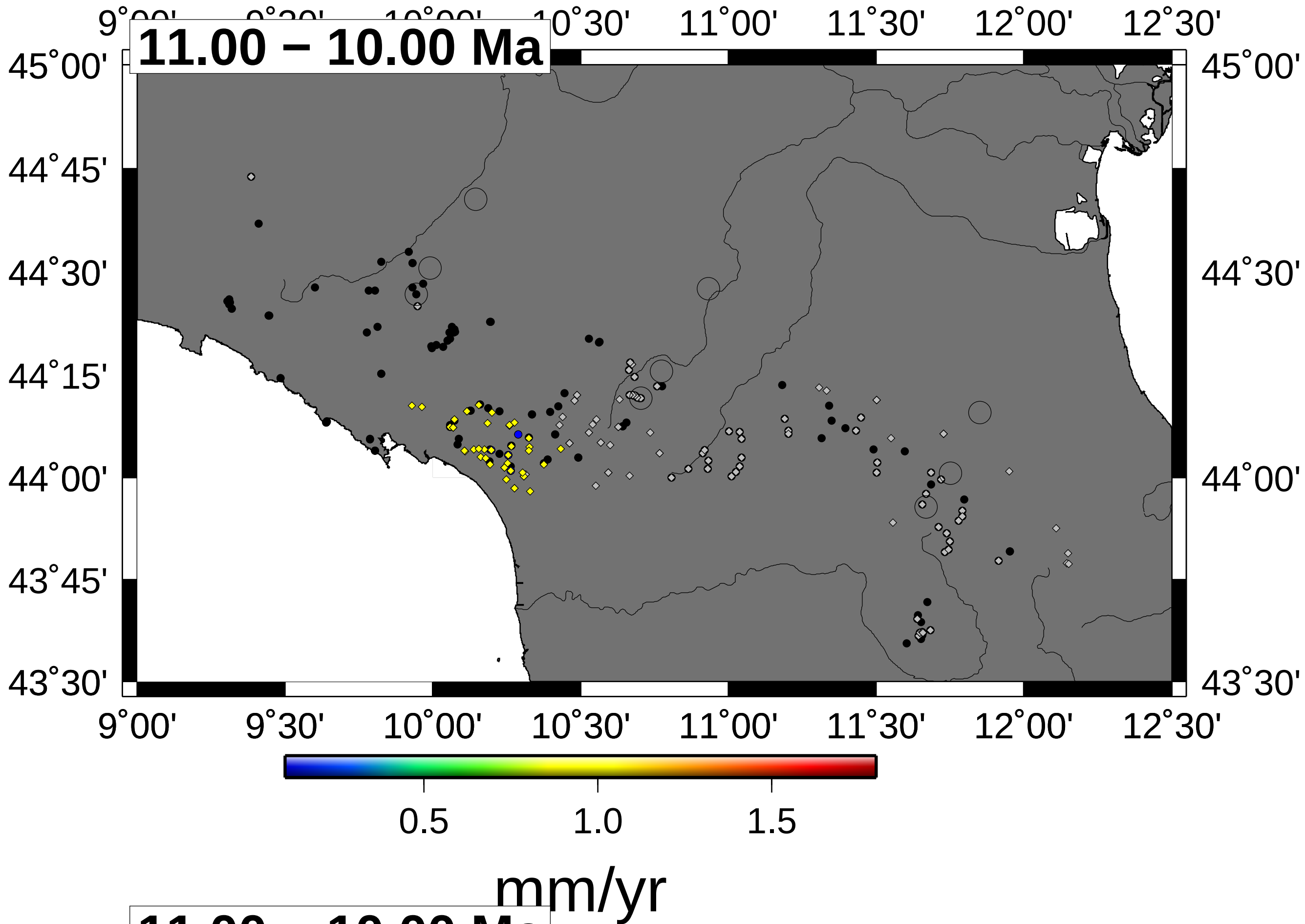
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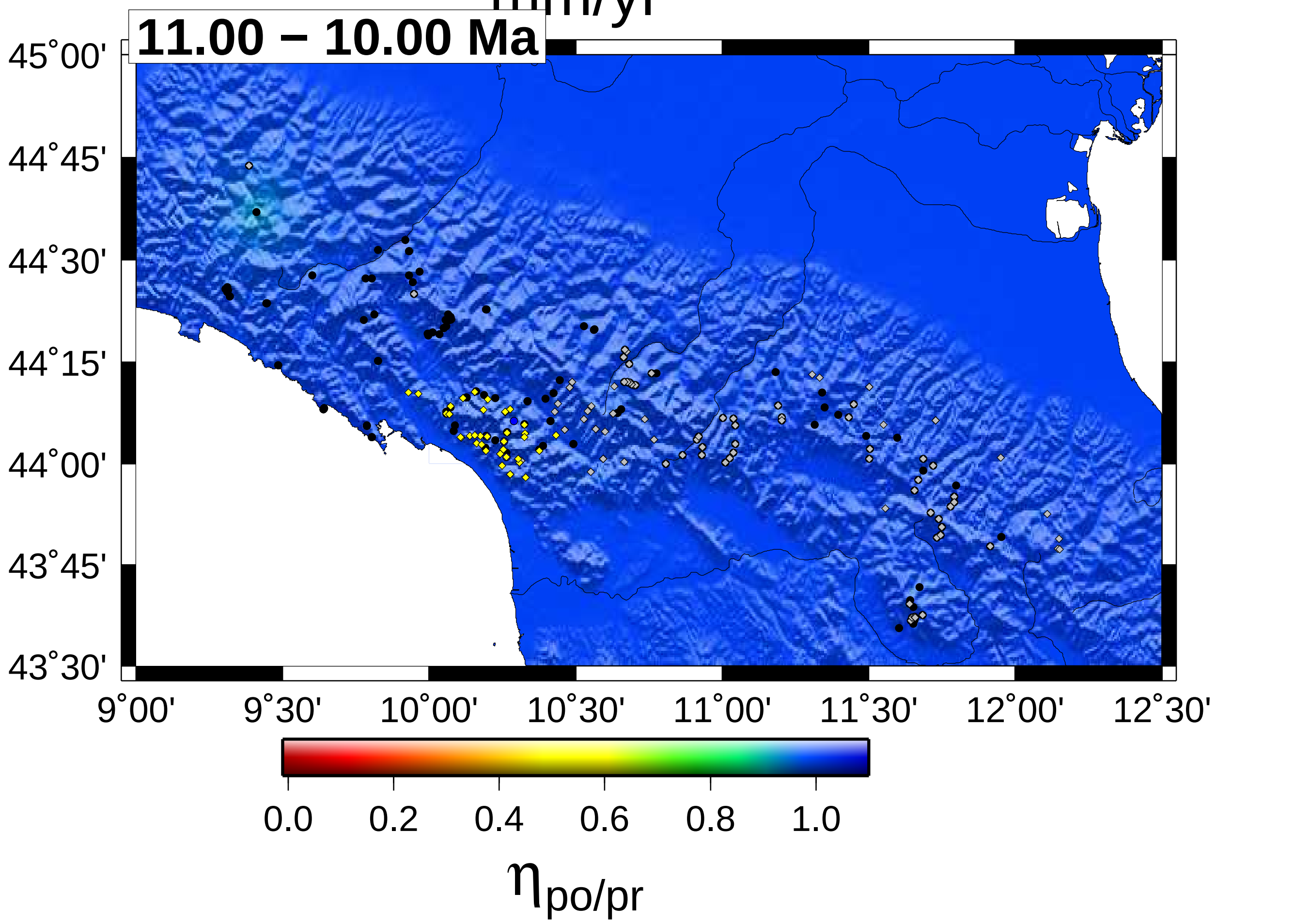
1.0
1.5
mm/yr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44°45'
44°30'
44°15'
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43°30'
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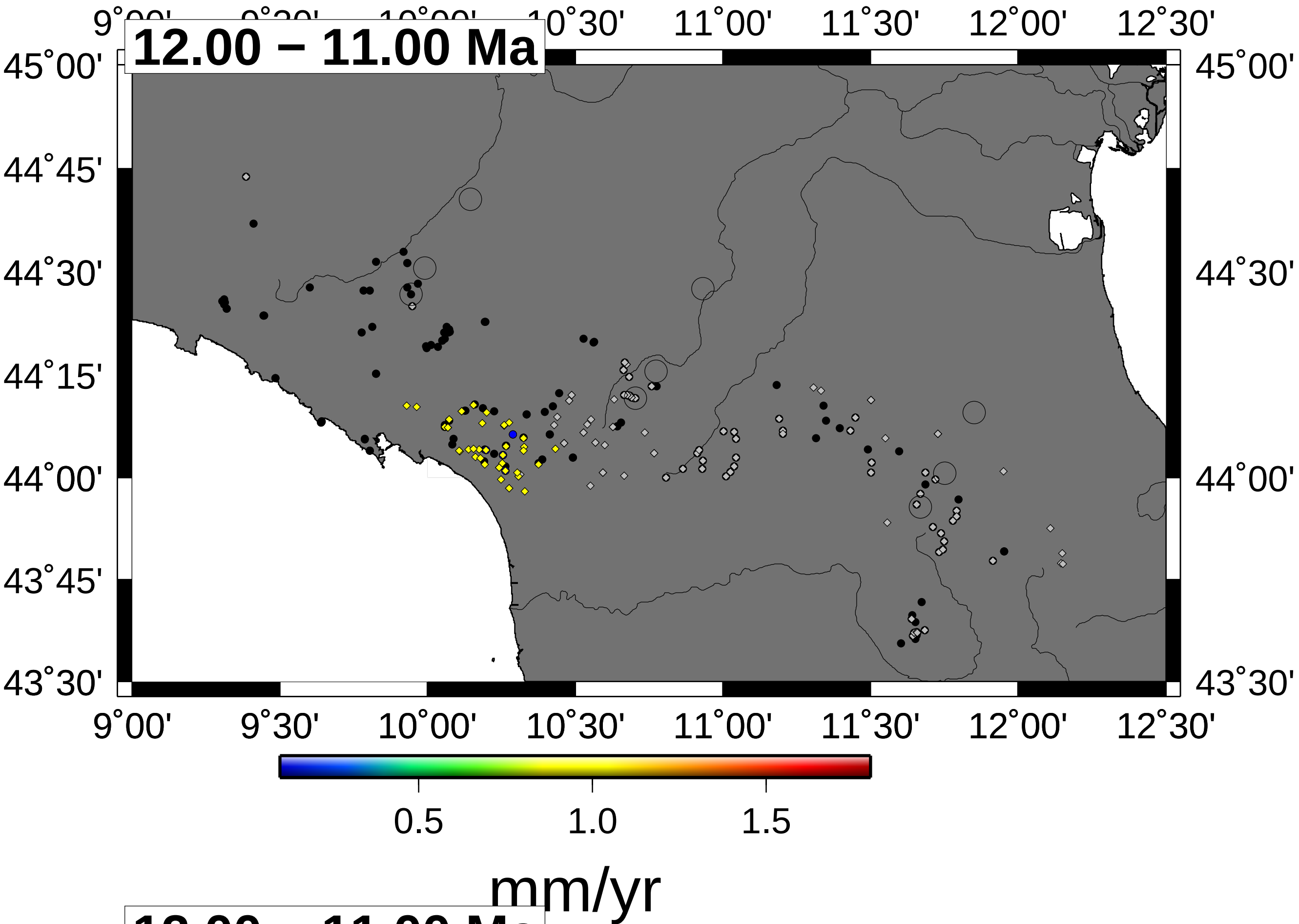
0.4
0.6
0.8
1.0
$\eta_{po/pr}$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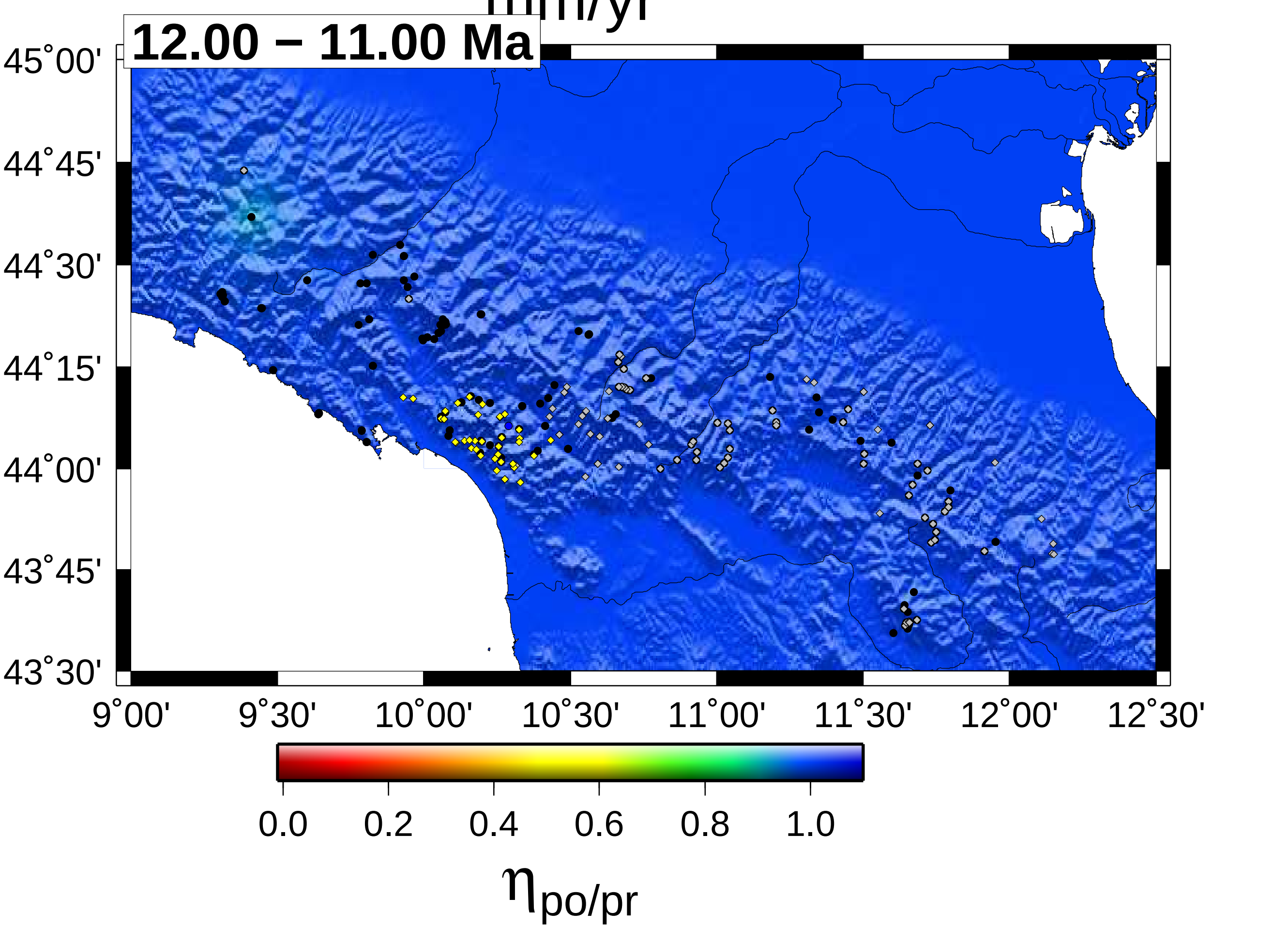
mm/yr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44°45'
44°30'
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0.6
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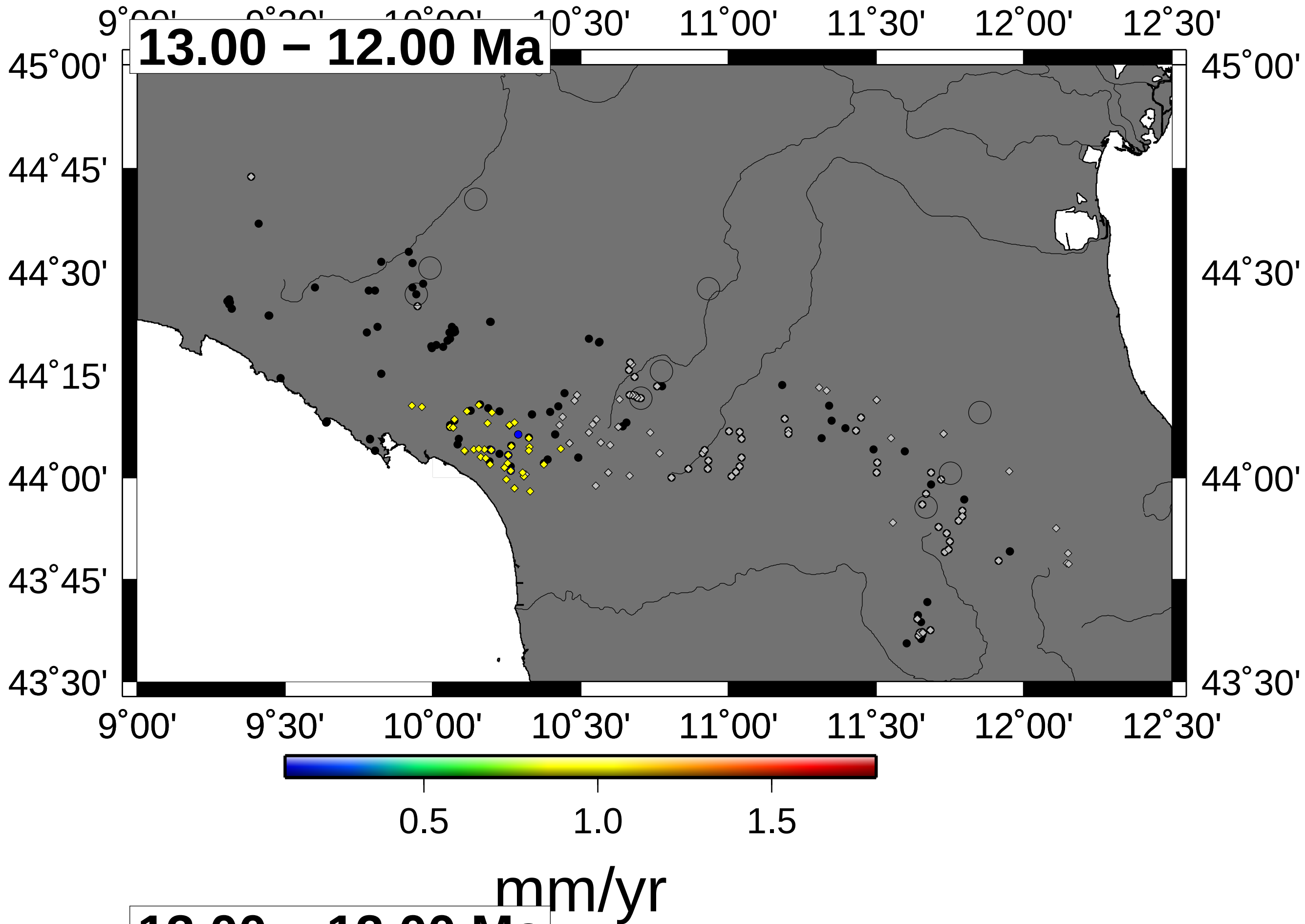
$\eta_{po/pr}$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10°30'
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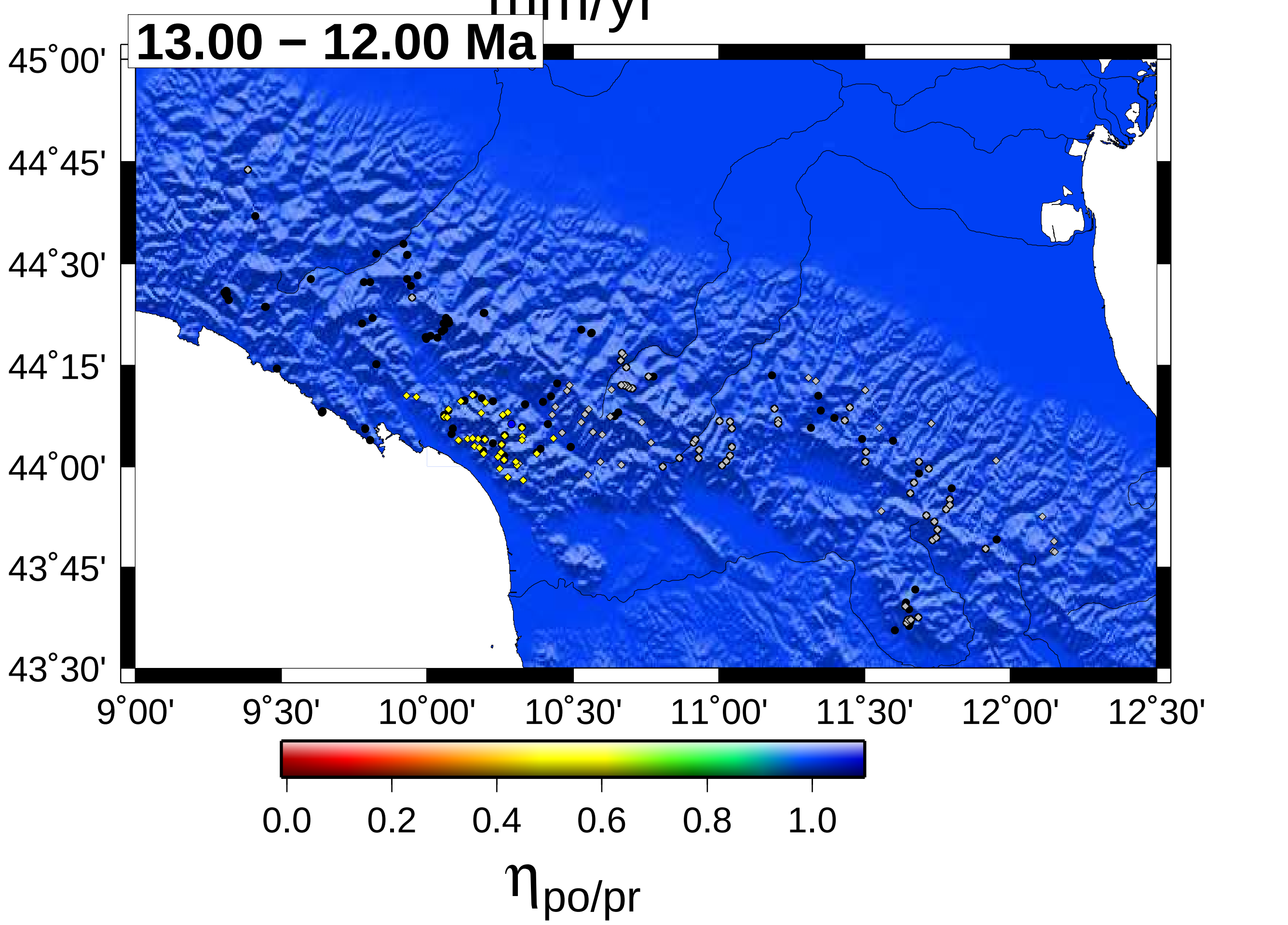
11°30'
12°00'
12°30'
45°00'
44°45'
44°30'
44°15'
44°00'
43°45'
43°30'
0.5
1.0
1.5
mm/yr


13.00 − 12.00 Ma
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44°00'
43°45'
43°30'
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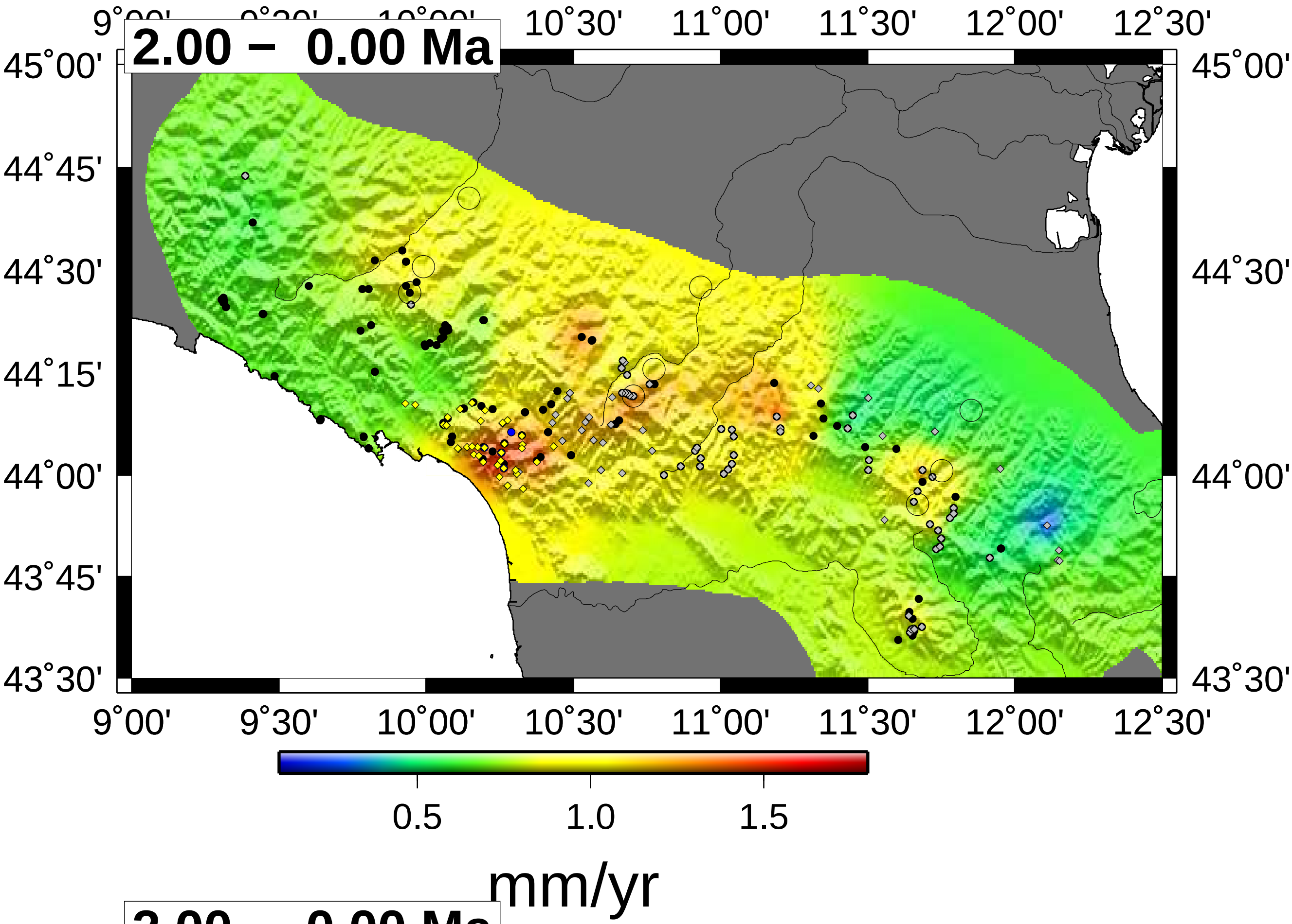
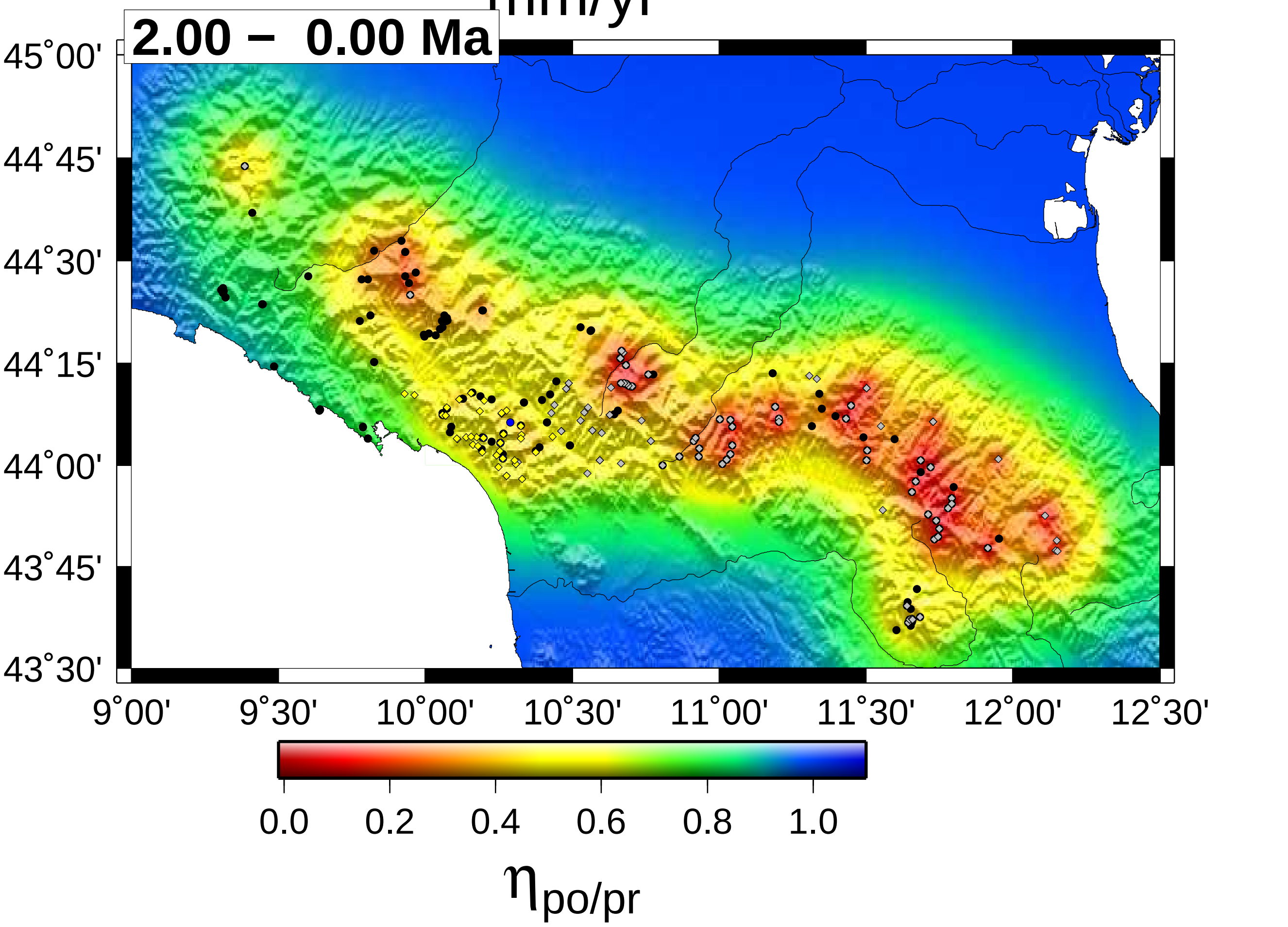
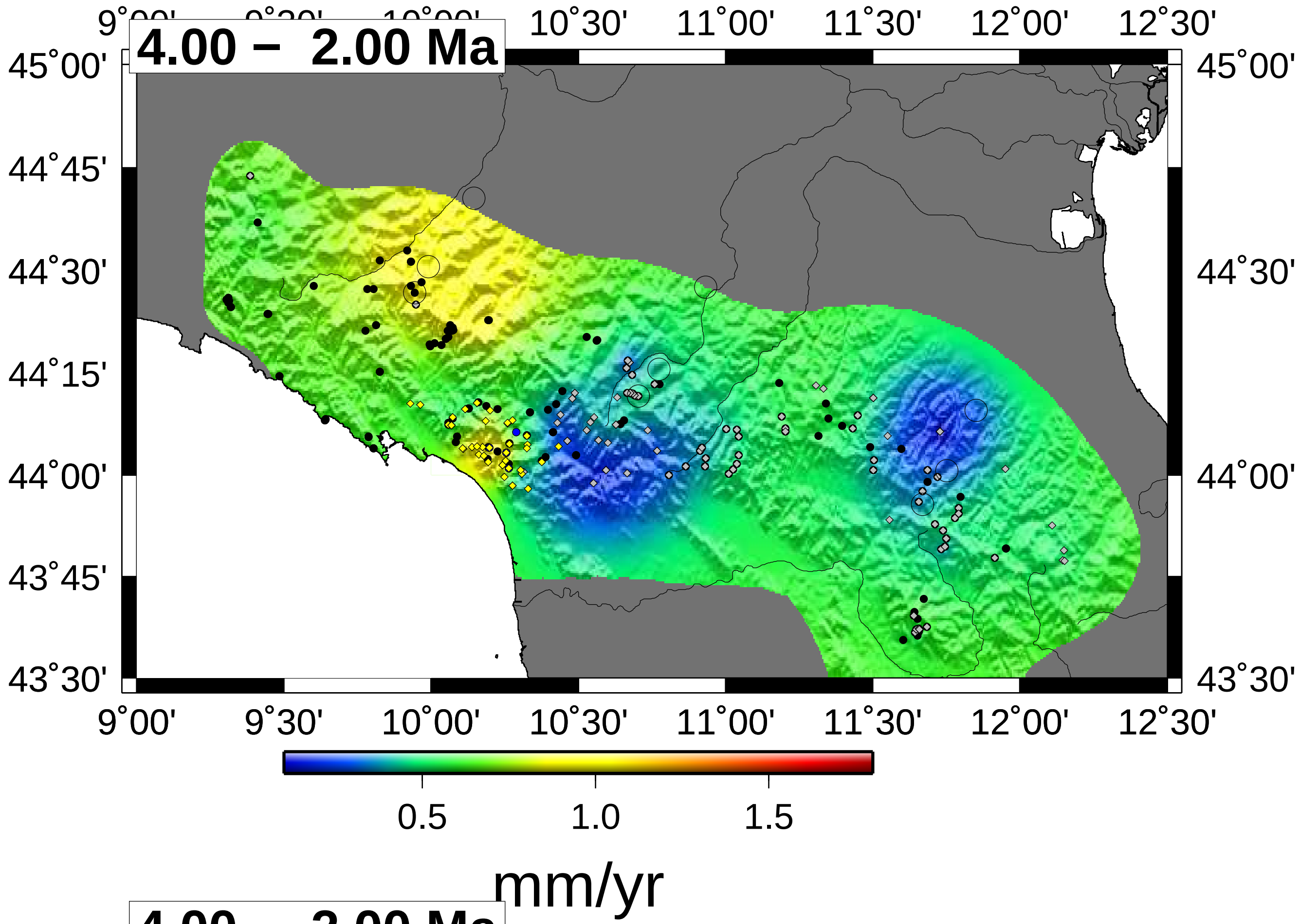
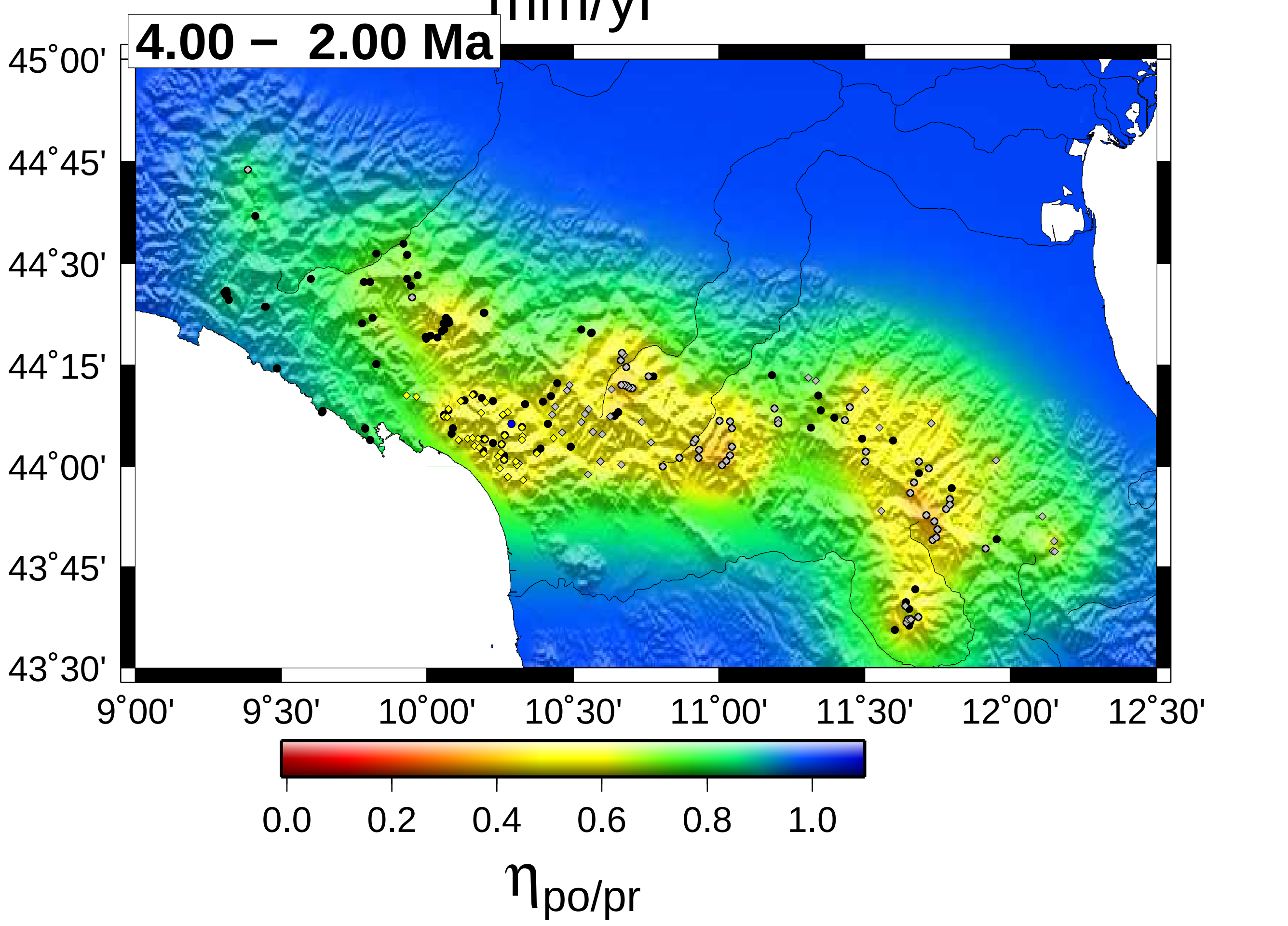
9°30'
10°00'
10°30'
11°00'
11°30'
12°00'
12°30'
0.0
0.2
0.4
0.6
0.8
1.0
$\eta_{po/pr}$

fig SM2.2b - 2 My timestep






4.00 – 2.00 Ma
9°00'
9°30'
10°00'
10°30'
11°00'
11°30'
12°00'
12°30'
45°00'
44°45'
44°30'
44°15'
44°00'
43°45'
43°30'
0.5
1.0
1.5
mm/yr


4.00 – 2.00 Ma
9°00'
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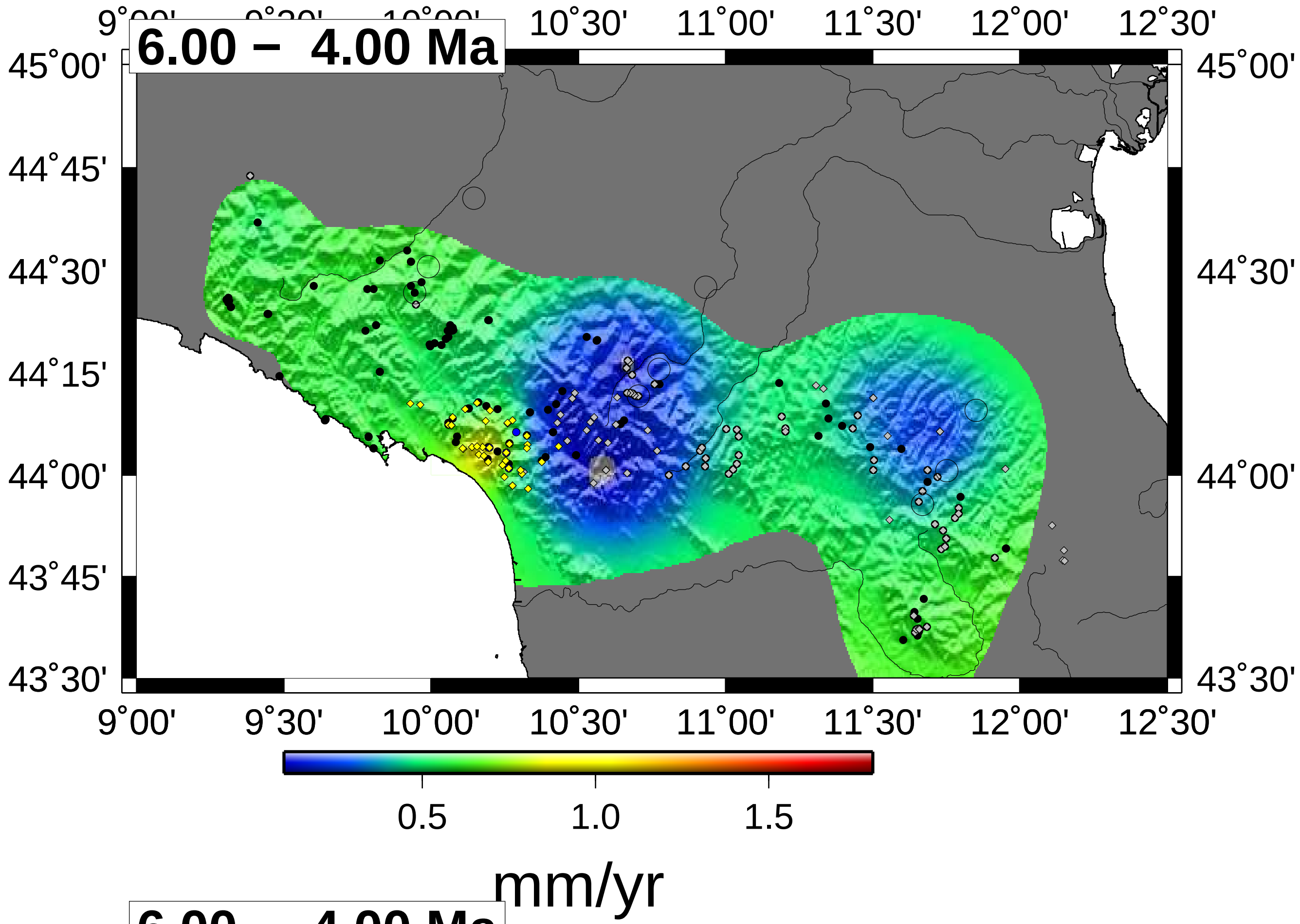
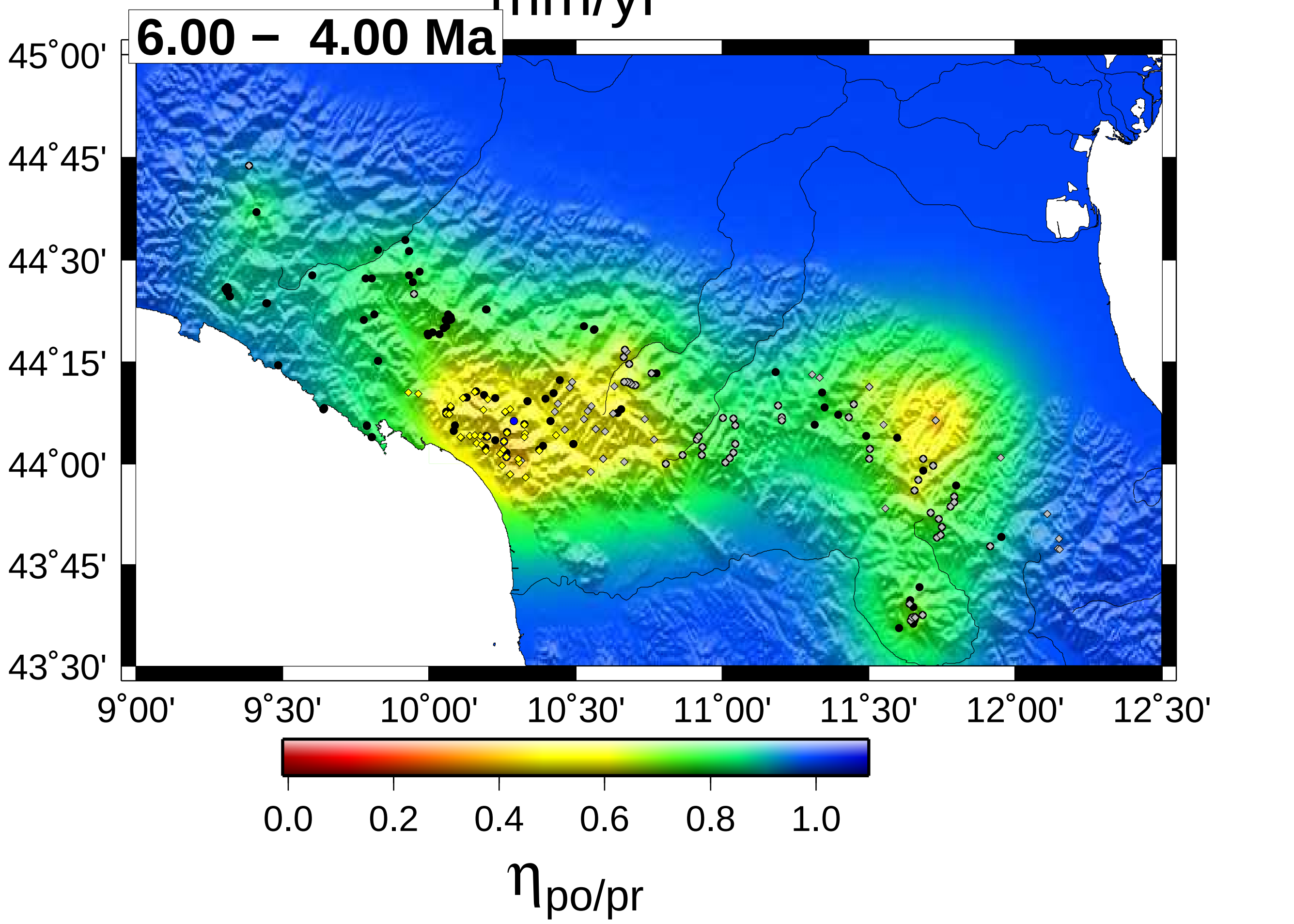
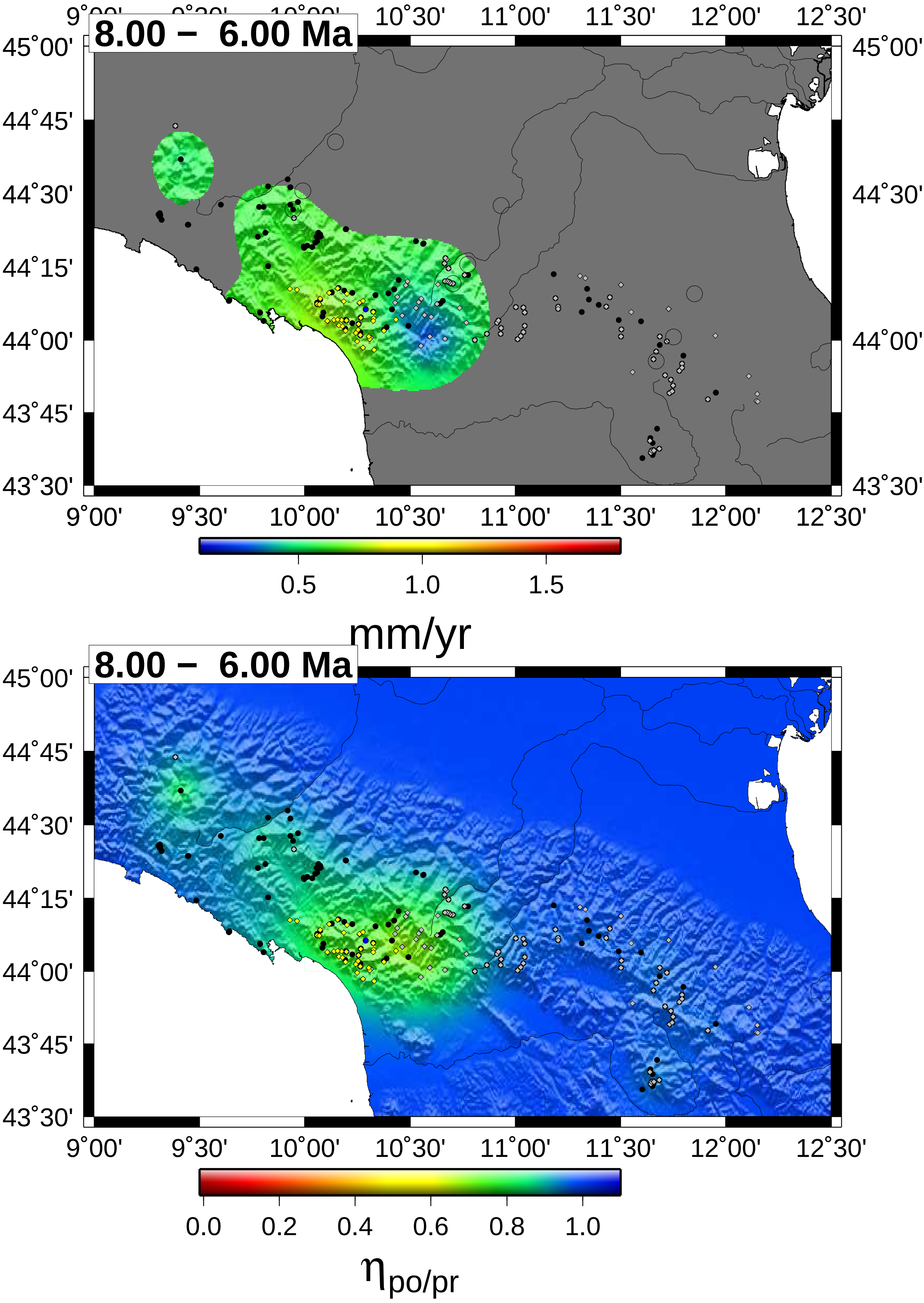
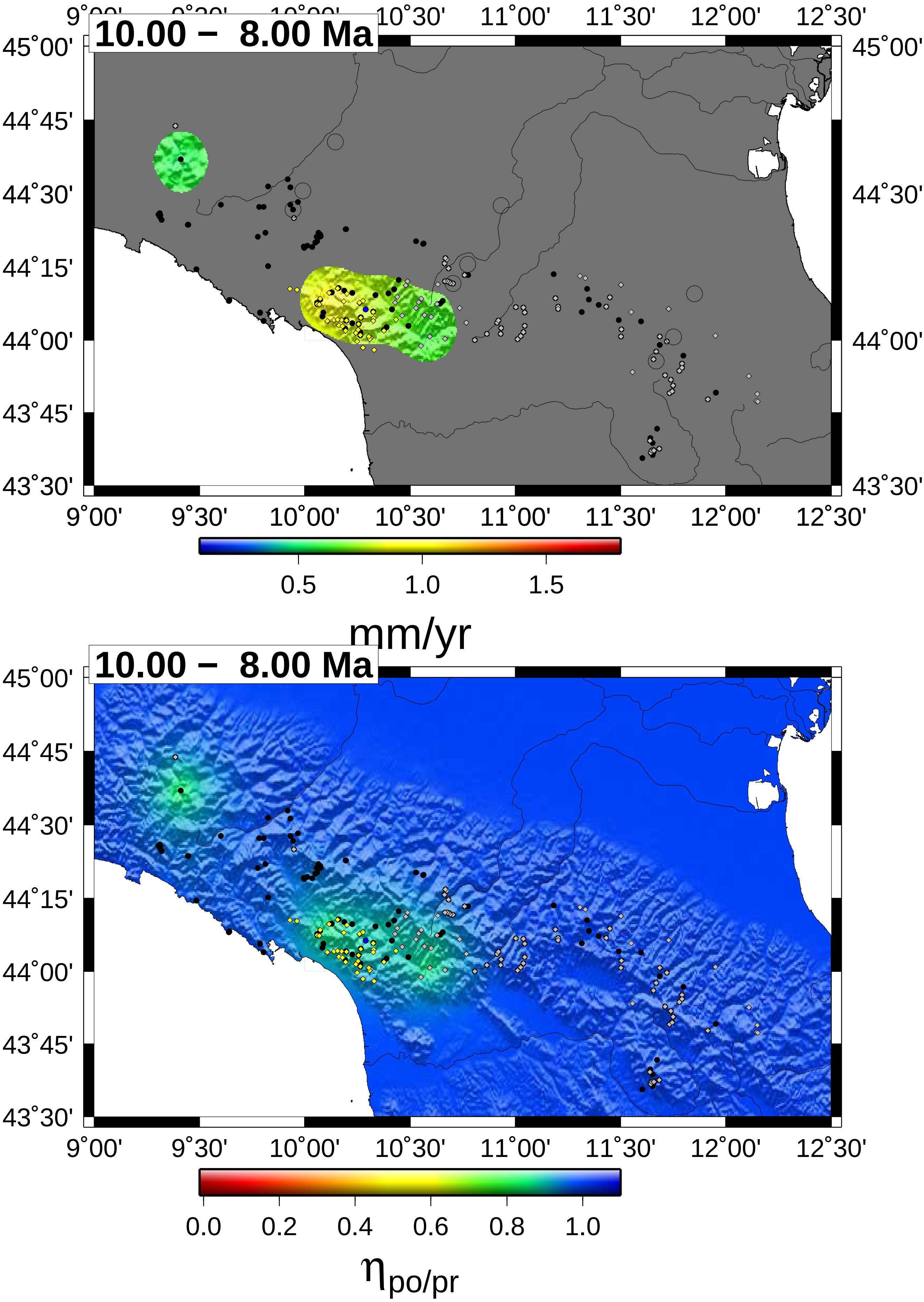
11°00'
11°30'
12°00'
12°30'
45°00'
44°45'
44°30'
44°15'
44°00'
43°45'
43°30'
0.0
0.2
0.4
0.6
0.8
1.0
$\eta_{po/pr}$


6.00 – 4.00 Ma
9°00'
9°30'
10°00'
10°30'
11°00'
11°30'
12°00'
12°30'
45°00'
44°45'
44°30'
44°15'
44°00'
43°45'
43°30'
0.5
1.0
1.5
mm/yr

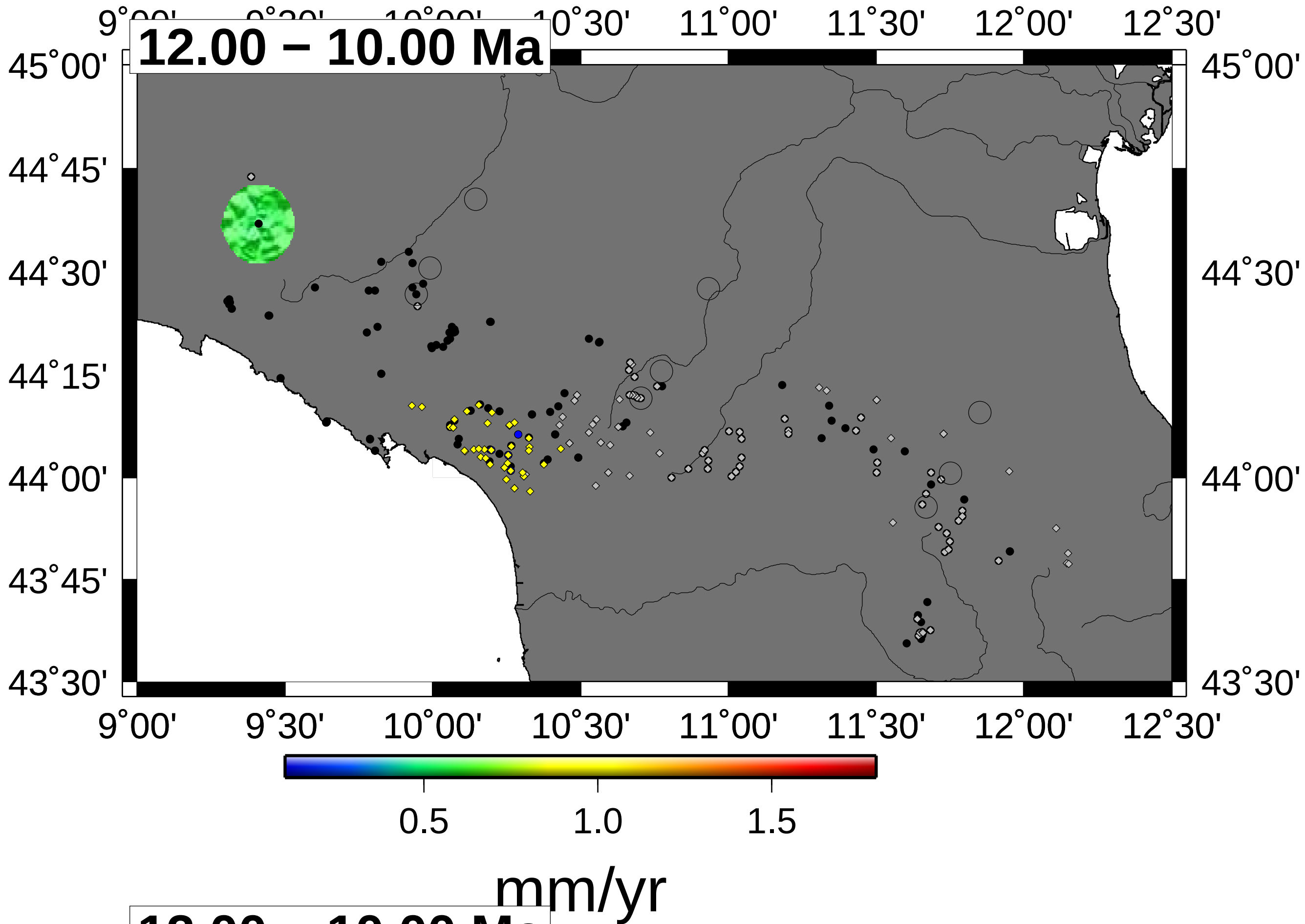

6.00 – 4.00 Ma
9°00'
9°30'
10°00'
10°30'
11°00'
11°30'
12°00'
12°30'
45°00'
44°45'
44°30'
44°15'
44°00'
43°45'
43°30'
0.0
0.2
0.4
0.6
0.8
1.0
$\eta_{po/pr}$



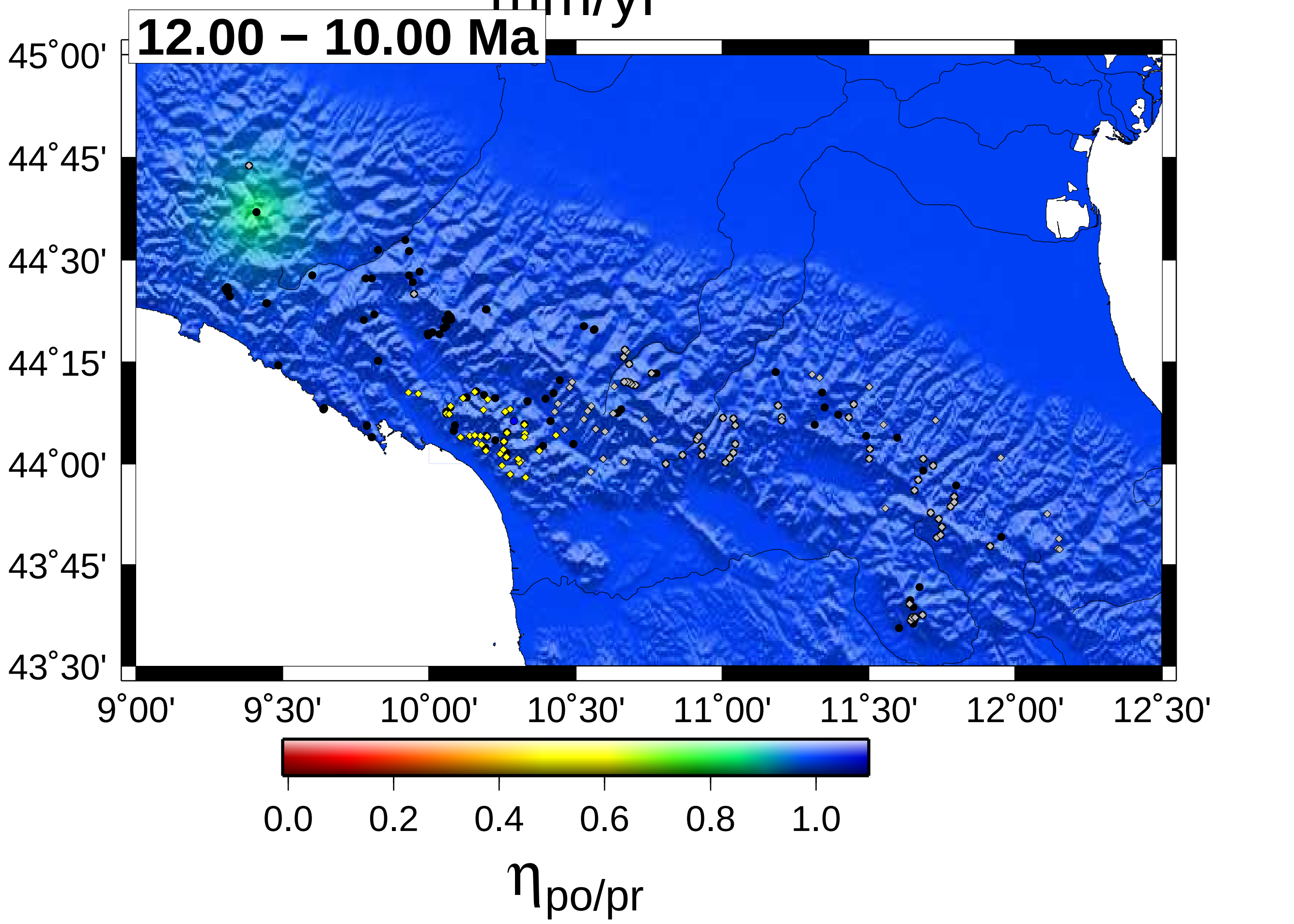
8.00 – 6.00 Ma
45°00'
44°45'
44°30'
44°15'
44°00'
43°45'
43°30'
9°00'
9°30'
10°00'
10°30'
11°00'
11°30'
12°00'
12°30'
0.5
1.0
1.5
mm/yr
8.00 – 6.00 Ma
0.0
0.2
0.4
0.6
0.8
1.0
$\eta_{po/pr}$



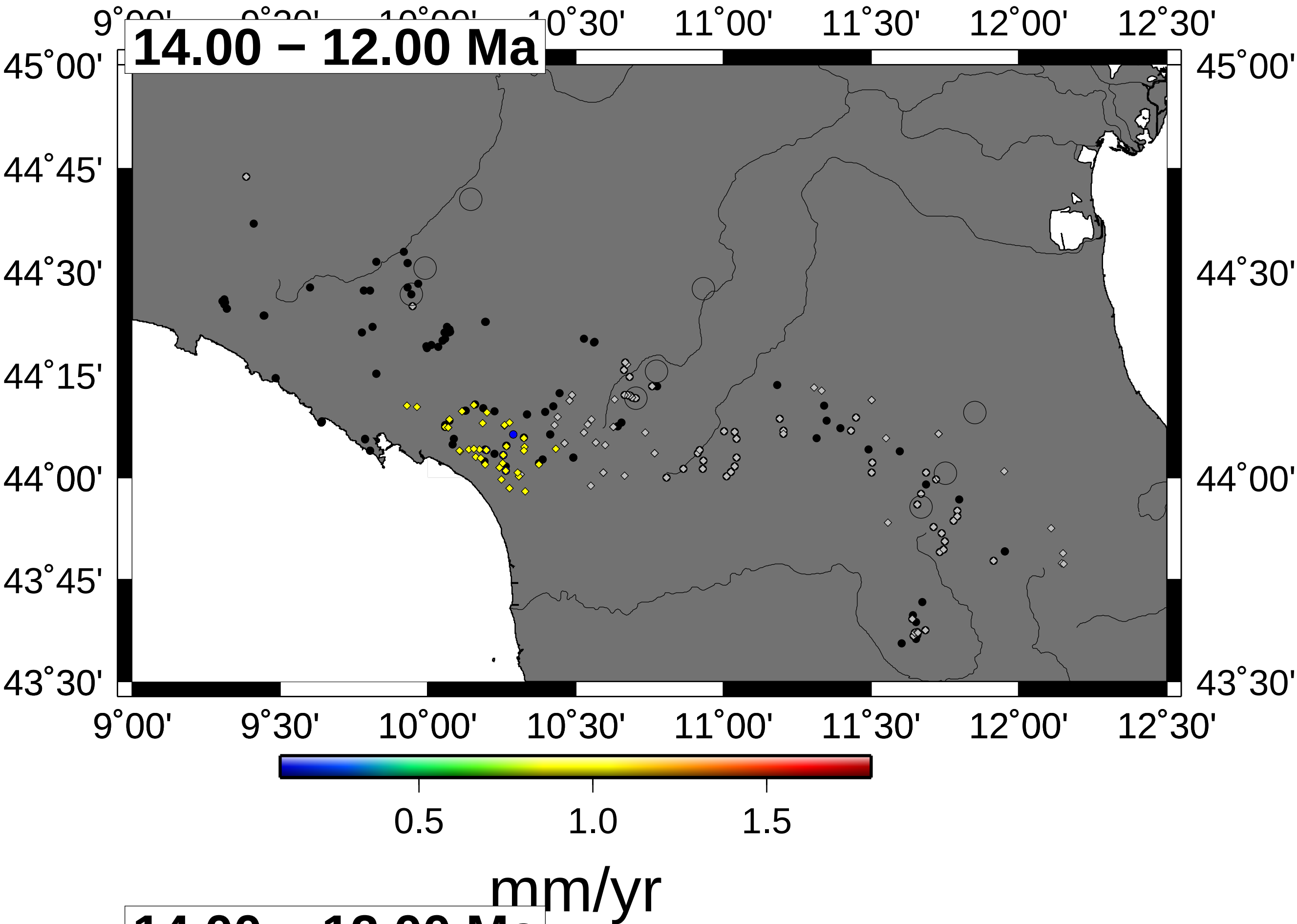
10.00 – 8.00 Ma
45°00'
44°45'
44°30'
44°15'
44°00'
43°45'
43°30'
9°00'
9°30'
10°00'
10°30'
11°00'
11°30'
12°00'
12°30'
0.5
1.0
1.5
mm/yr
10.00 – 8.00 Ma
0.0
0.2
0.4
0.6
0.8
1.0
$\eta_{po/pr}$



12.00 – 10.00 Ma
9°00'
9°30'
10°00'
10°30'
11°00'
11°30'
12°00'
12°30'
45°00'
44°45'
44°30'
44°15'
44°00'
43°45'
43°30'
0.5
1.0
1.5
mm/yr



12.00 – 10.00 Ma
9°00'
9°30'
10°00'
10°30'
11°00'
11°30'
12°00'
12°30'
45°00'
44°45'
44°30'
44°15'
44°00'
43°45'
43°30'
0.0
0.2
0.4
0.6
0.8
1.0
$\eta_{po/pr}$


14.00 – 12.00 Ma
9°00'
9°30'
10°00'
10°30'
11°00'
11°30'
12°00'
12°30'
45°00'
44°45'
44°30'
44°15'
44°00'
43°45'
43°30'
0.5
1.0
1.5
mm/yr

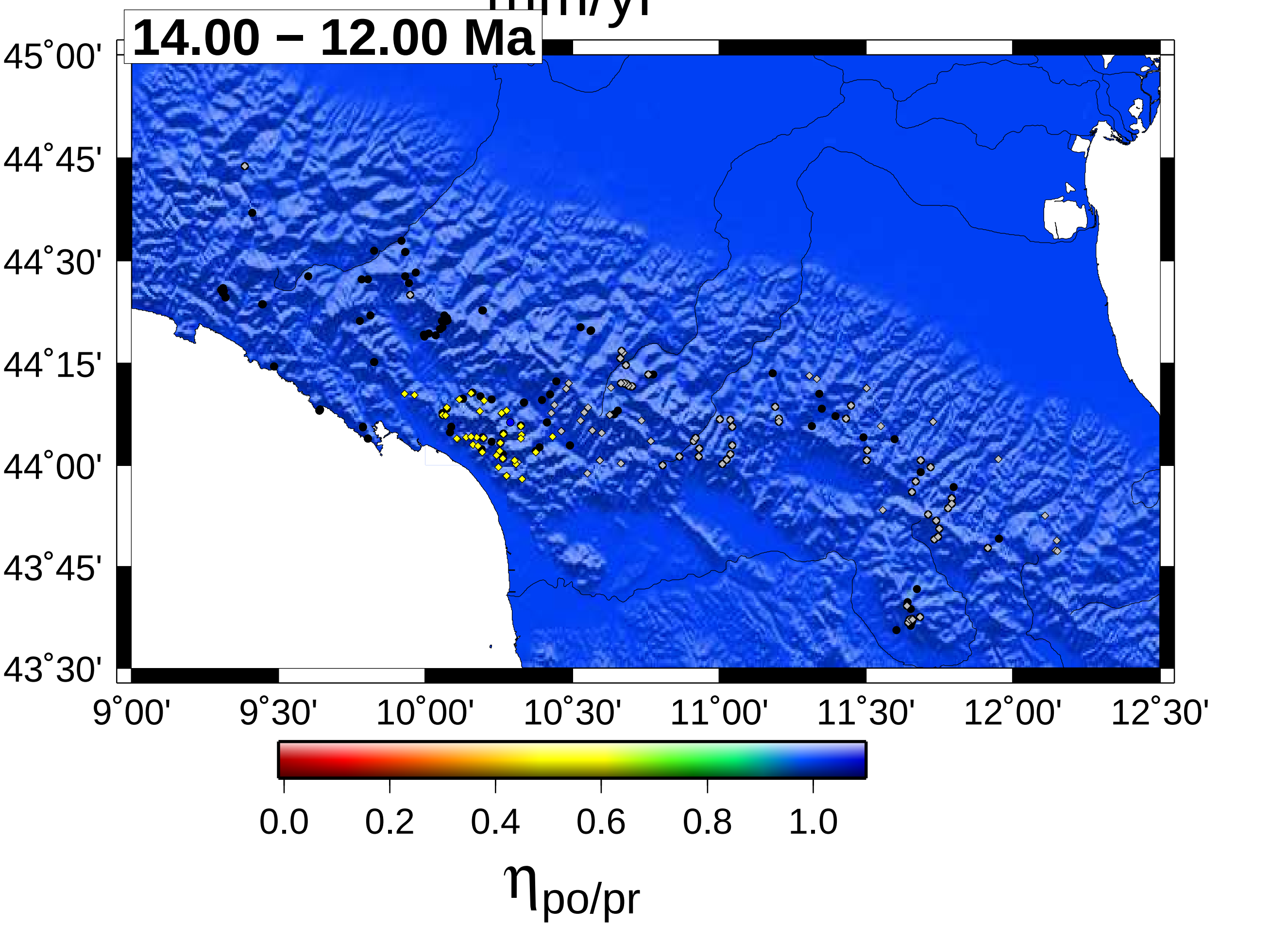
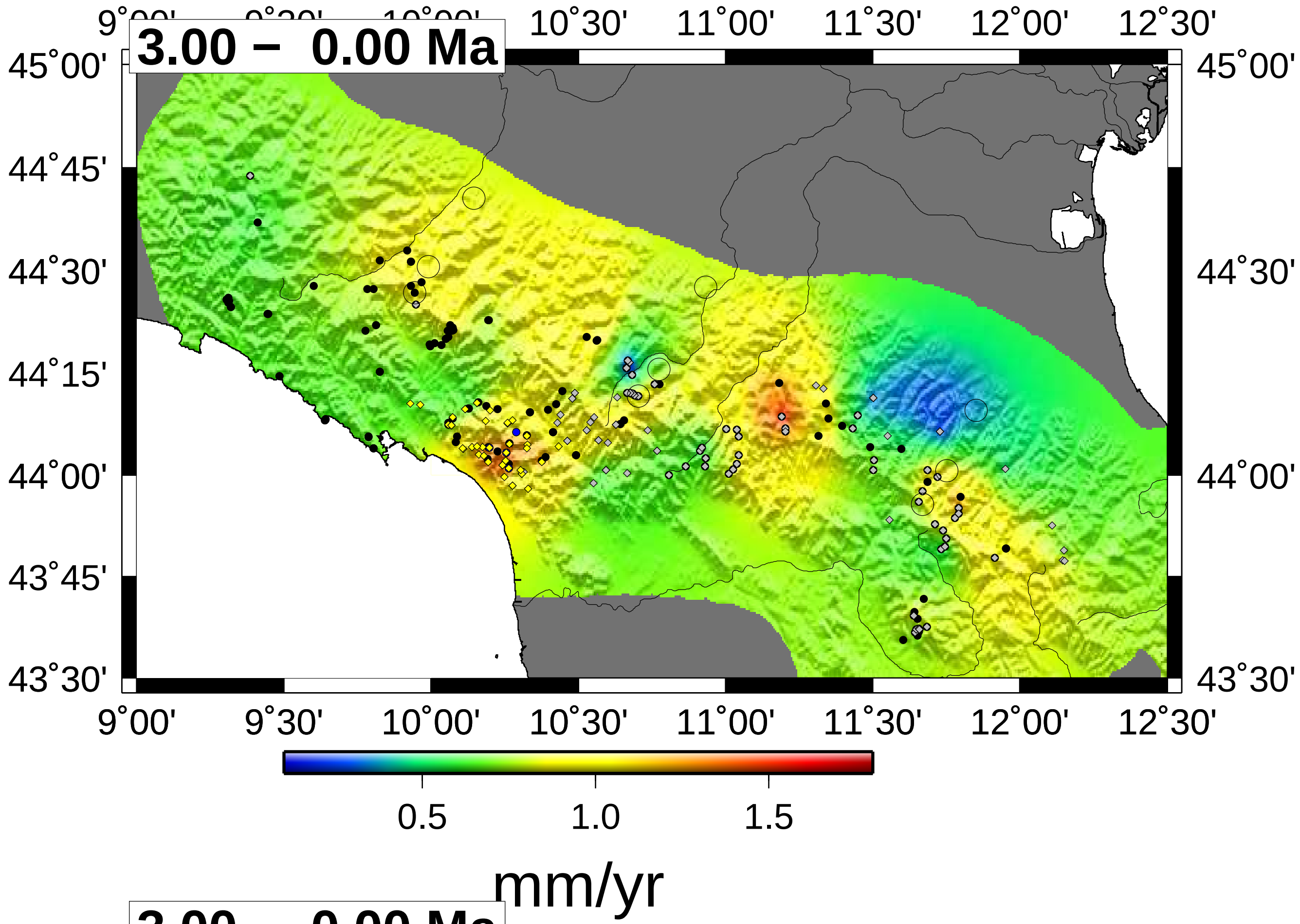
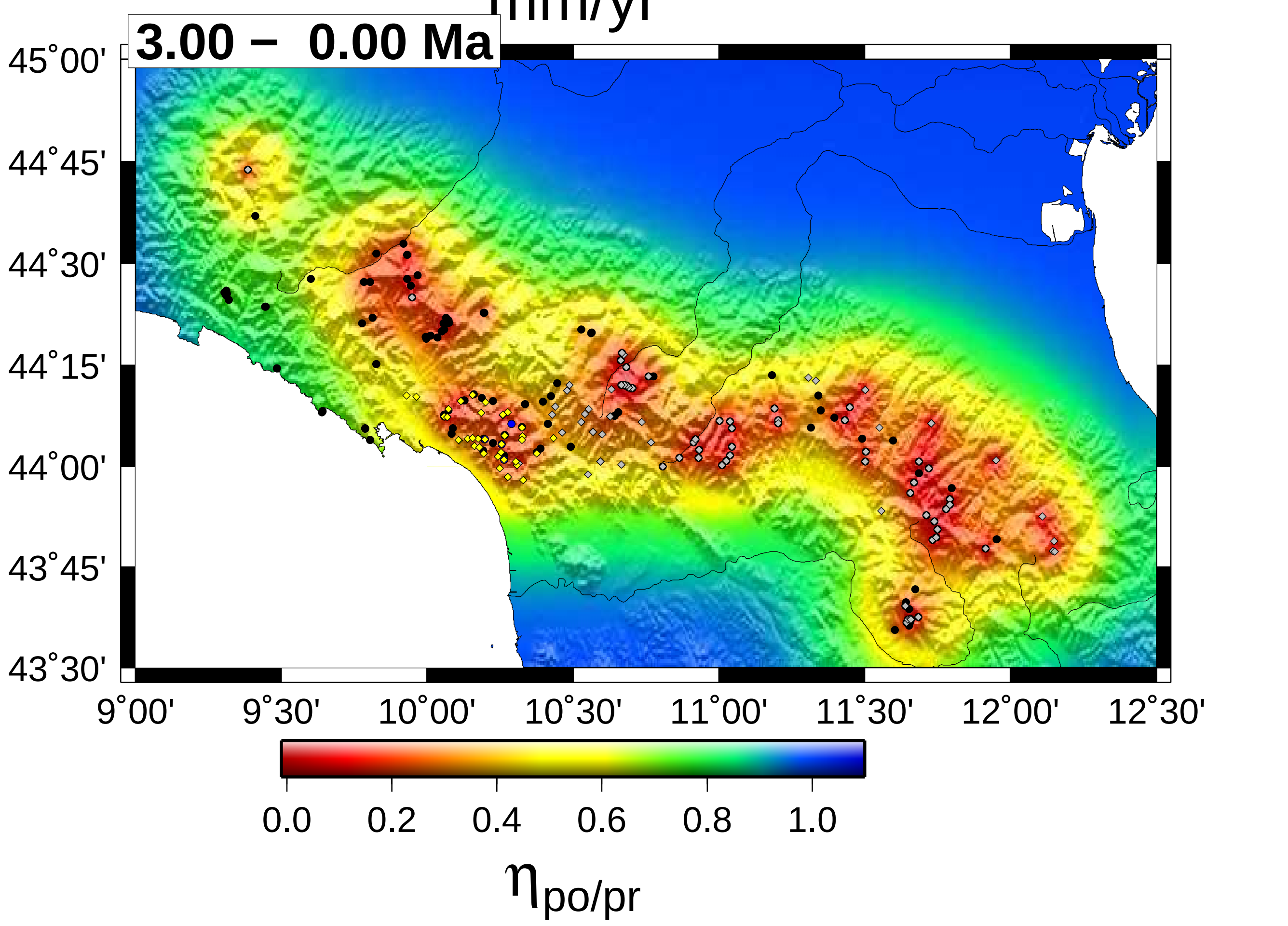
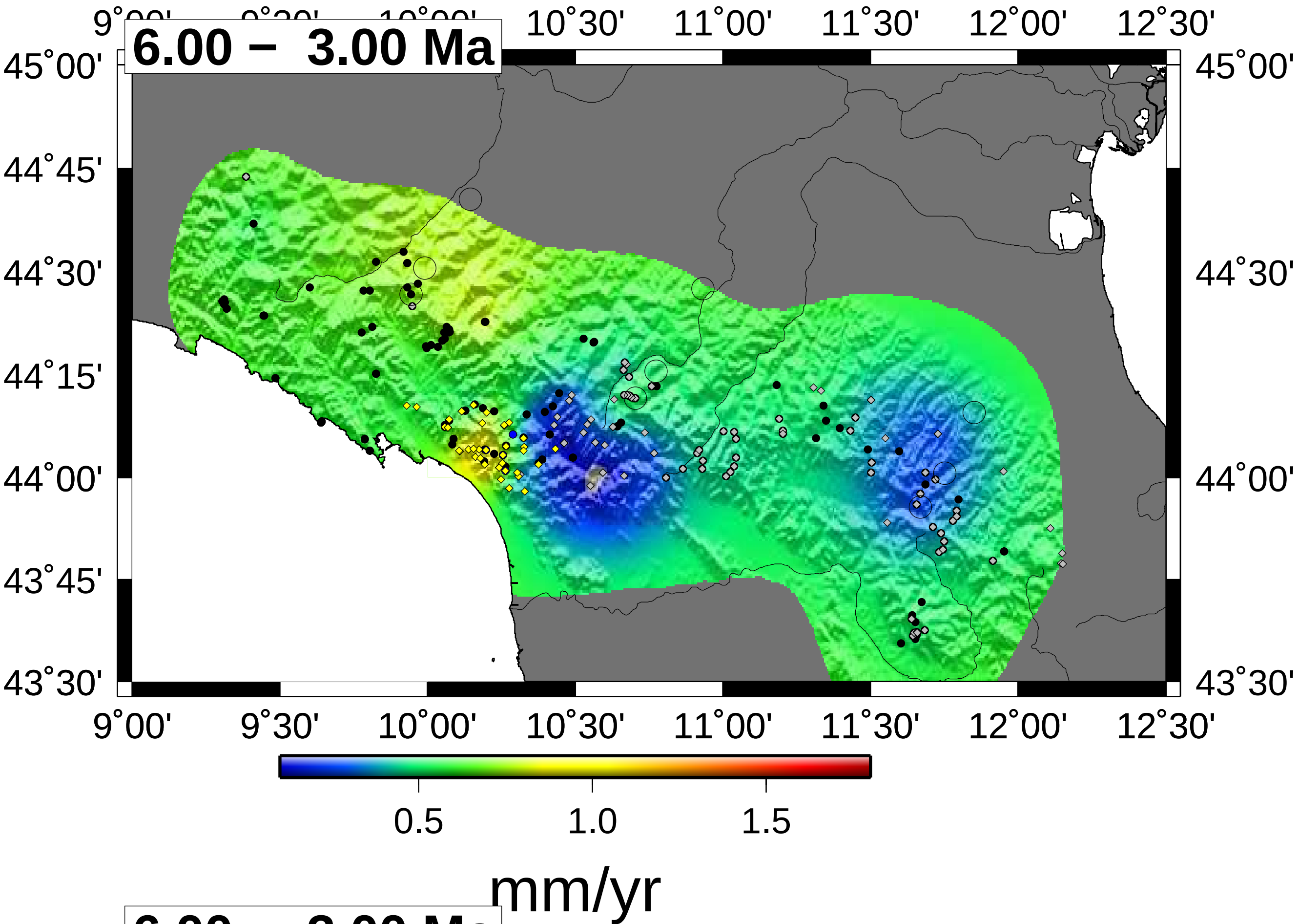
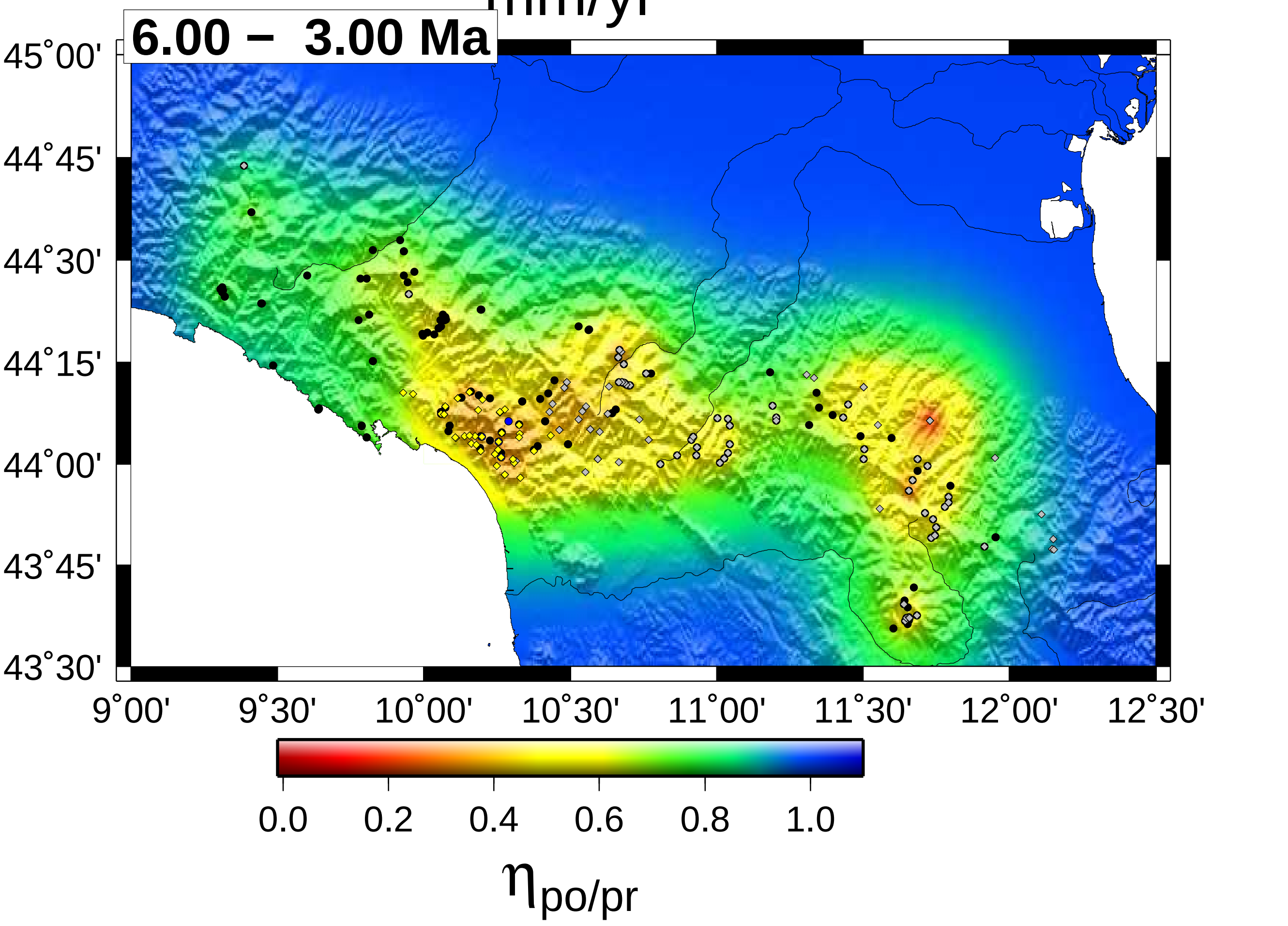

14.00 – 12.00 Ma
9°00'
9°30'
10°00'
10°30'
11°00'
11°30'
12°00'
12°30'
45°00'
44°45'
44°30'
44°15'
44°00'
43°45'
43°30'
0.0
0.2
0.4
0.6
0.8
1.0
$\eta_{po/pr}$

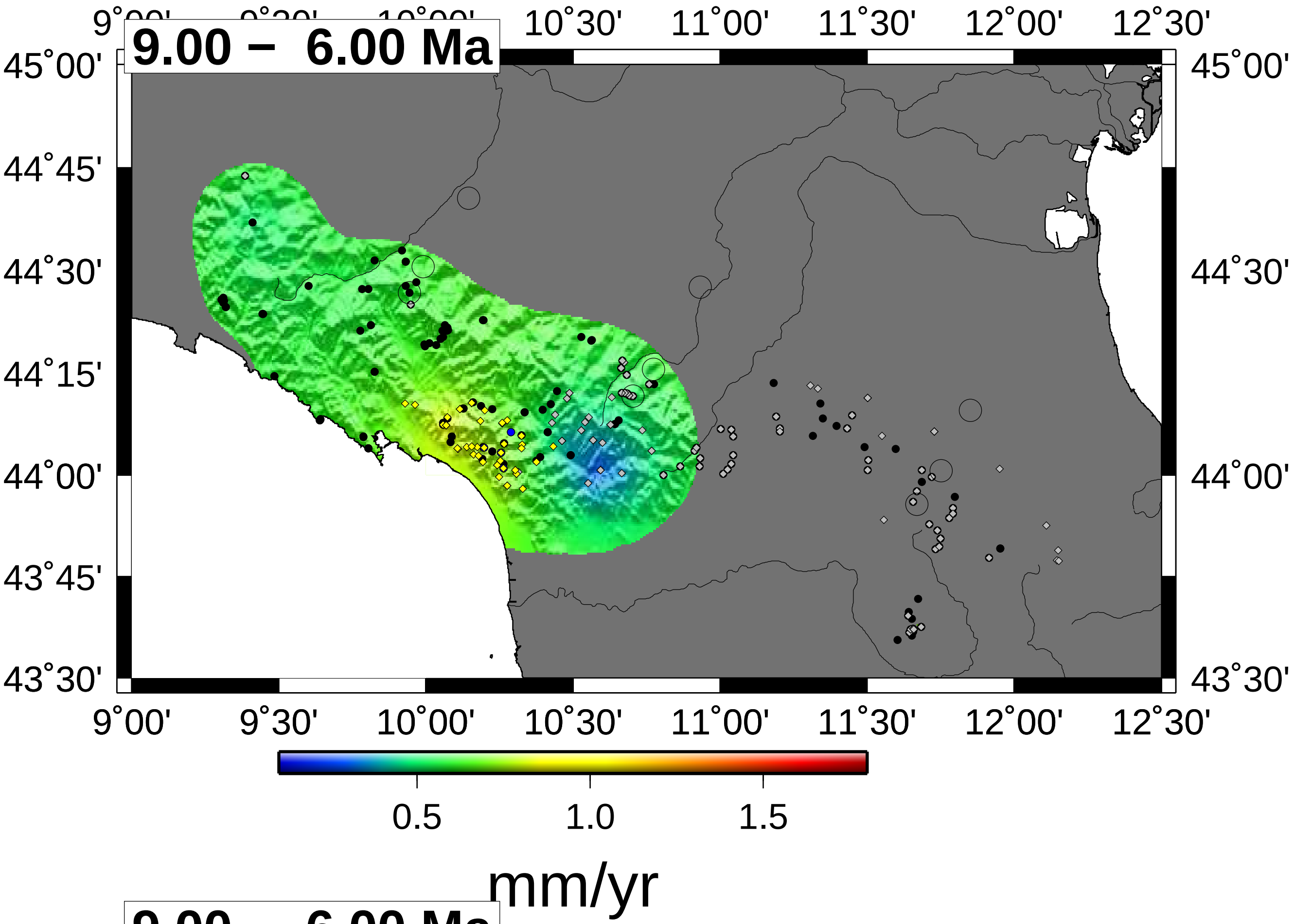
fig. SM2.2c - 3 MY timestep

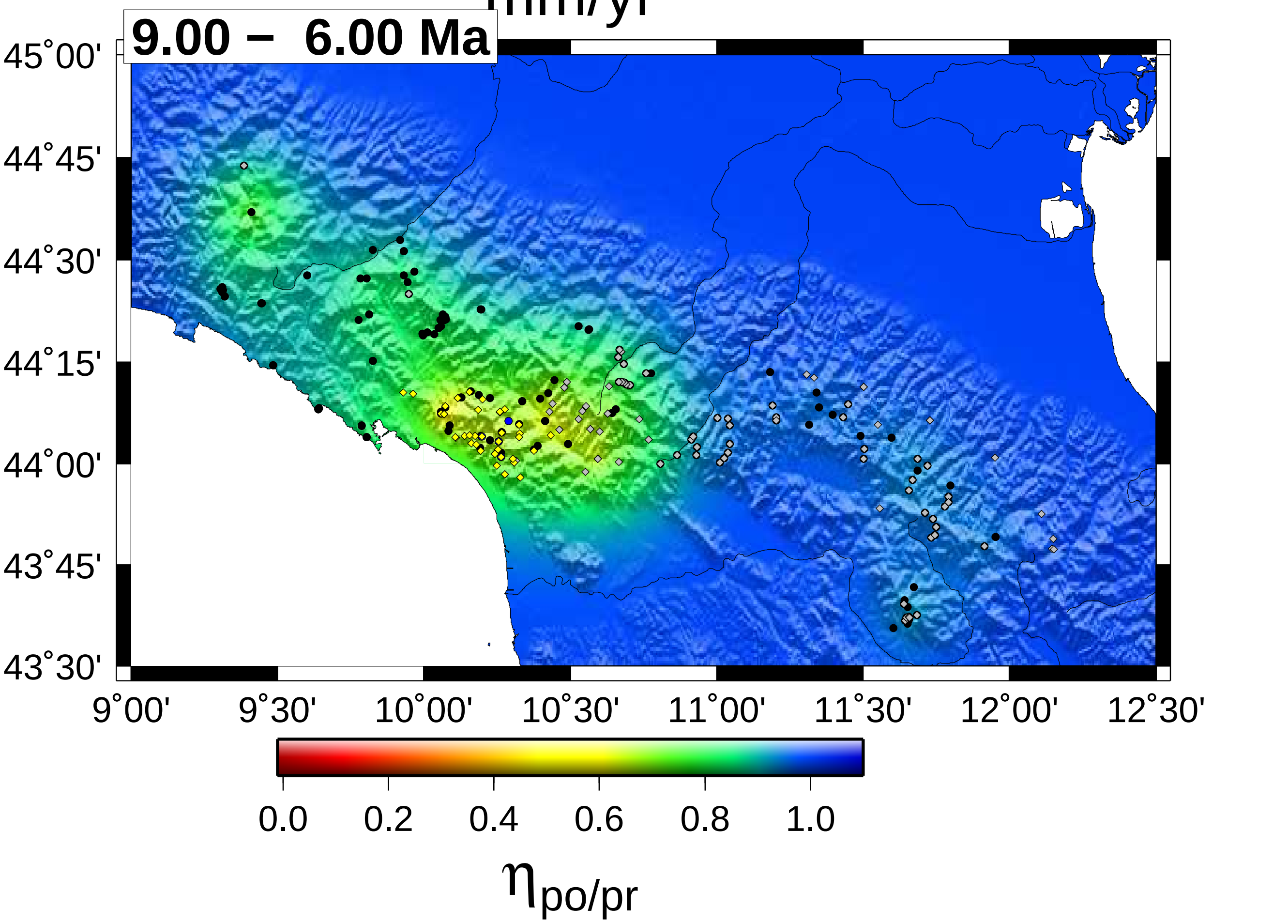


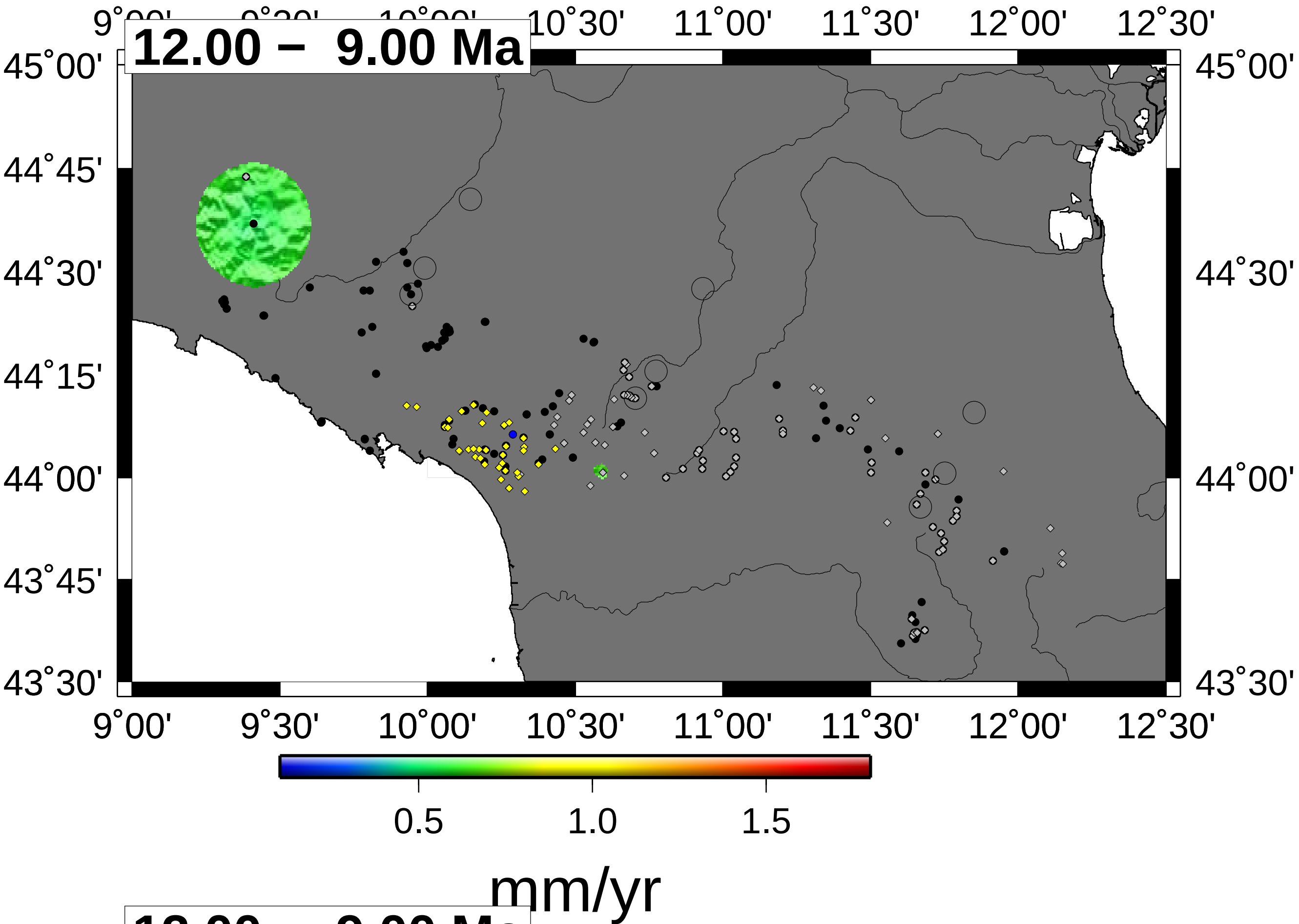


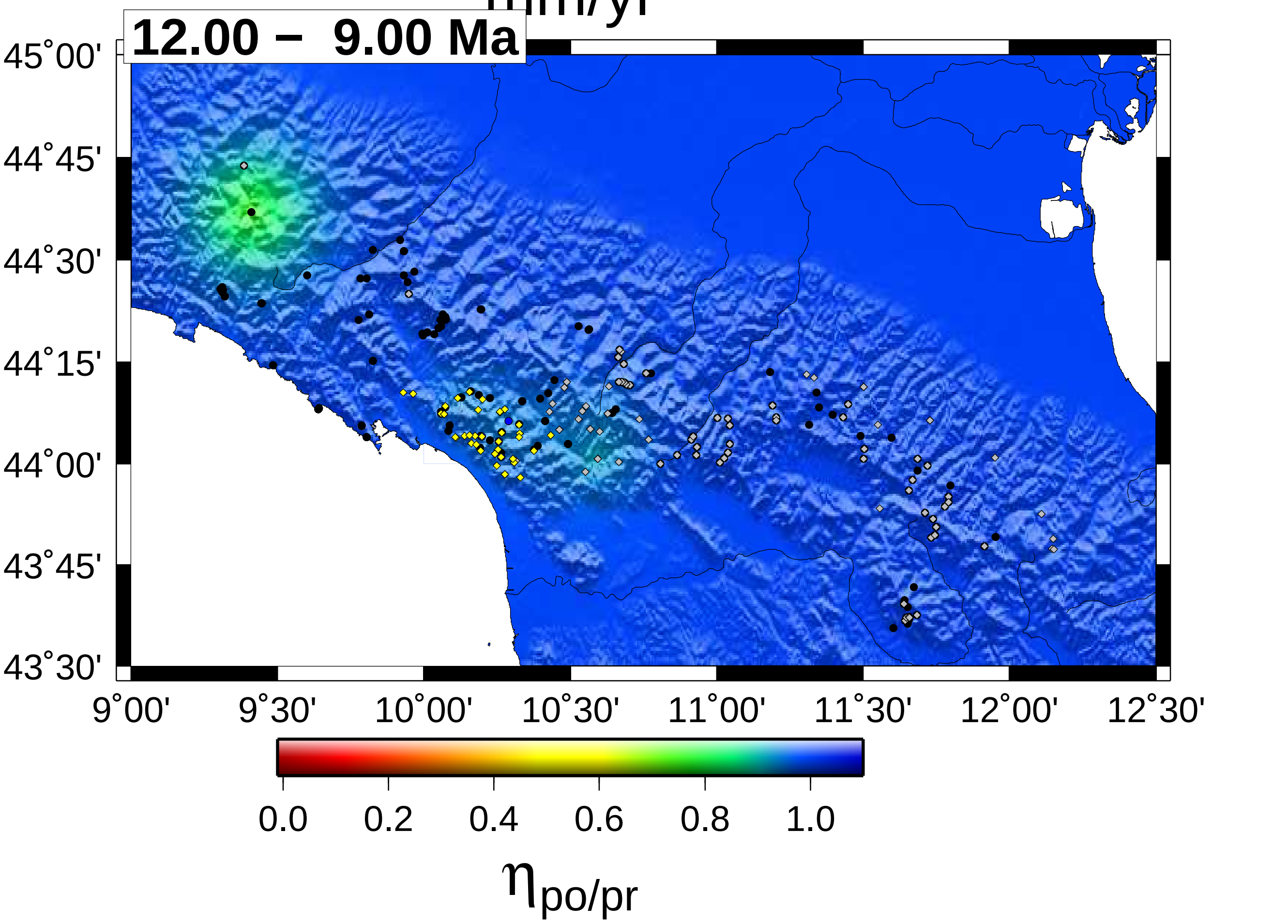

6.00 – 3.00 Ma
9°00'
9°30'
10°00'
10°30'
11°00'
11°30'
12°00'
12°30'
45°00'
44°45'
44°30'
44°15'
44°00'
43°45'
43°30'
0.5
1.0
1.5
mm/yr


6.00 – 3.00 Ma
45°00'
44°45'
44°30'
44°15'
44°00'
43°45'
43°30'
9°00'
9°30'
10°00'
10°30'
11°00'
11°30'
12°00'
12°30'
0.0
0.2
0.4
0.6
0.8
1.0
$\eta_{po/pr}$


9.00 – 6.00 Ma
9°00'
9°30'
10°00'
10°30'
11°00'
11°30'
12°00'
12°30'
45°00'
44°45'
44°30'
44°15'
44°00'
43°45'
43°30'
0.5
1.0
1.5
mm/yr


9.00 – 6.00 Ma
9°00'
9°30'
10°00'
10°30'
11°00'
11°30'
12°00'
12°30'
45°00'
44°45'
44°30'
44°15'
44°00'
43°45'
43°30'
0.0
0.2
0.4
0.6
0.8
1.0
$\eta_{po/pr}$


12.00 – 9.00 Ma
9°00'
9°30'
10°00'
10°30'
11°00'
11°30'
12°00'
12°30'
45°00'
44°45'
44°30'
44°15'
44°00'
43°45'
43°30'
0.5
1.0
1.5
mm/yr


12.00 – 9.00 Ma
9°00'
9°30'
10°00'
10°30'
11°00'
11°30'
12°00'
12°30'
45°00'
44°45'
44°30'
44°15'
44°00'
43°45'
43°30'
0.0
0.2
0.4
0.6
0.8
1.0
$\eta_{po/pr}$

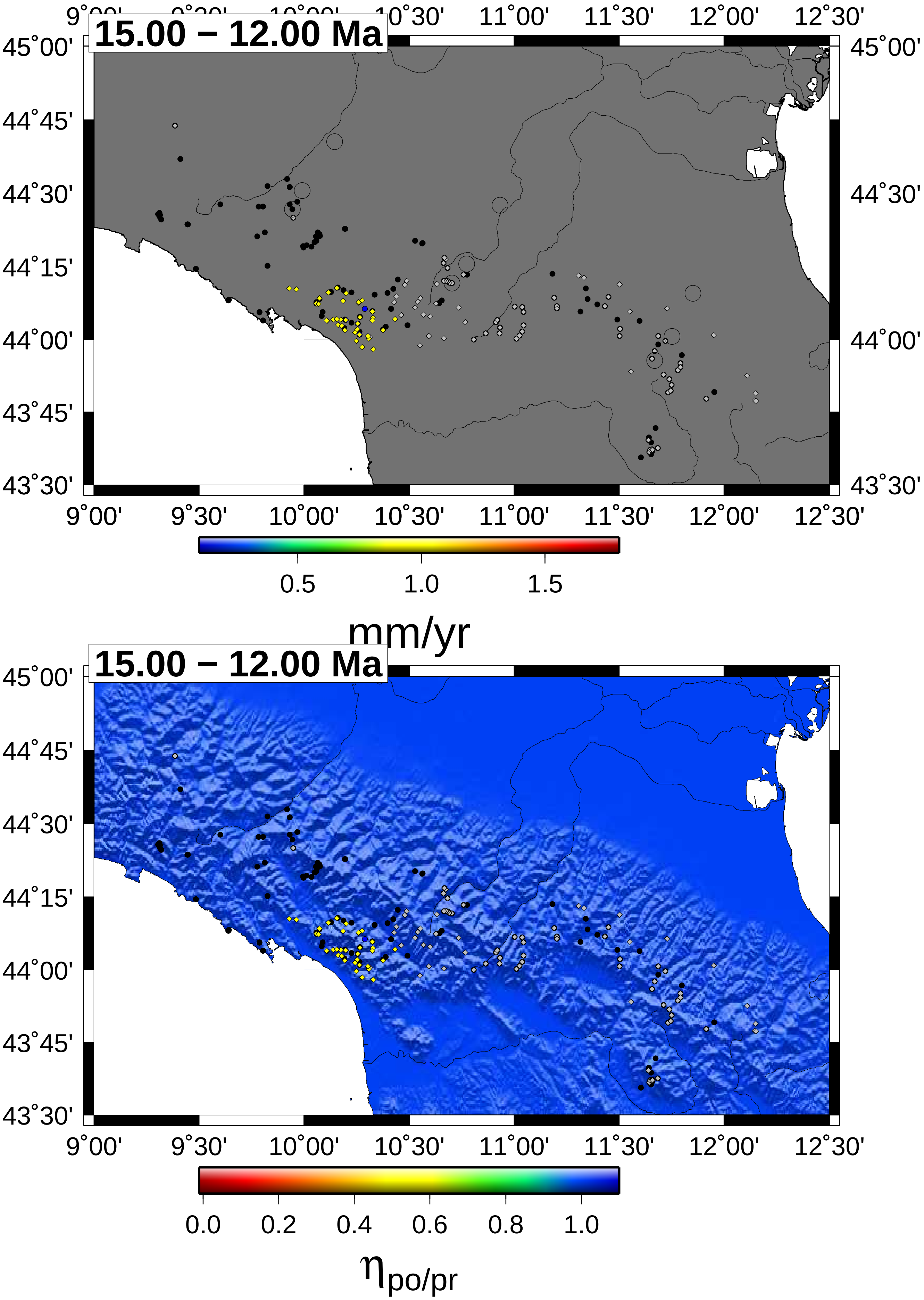
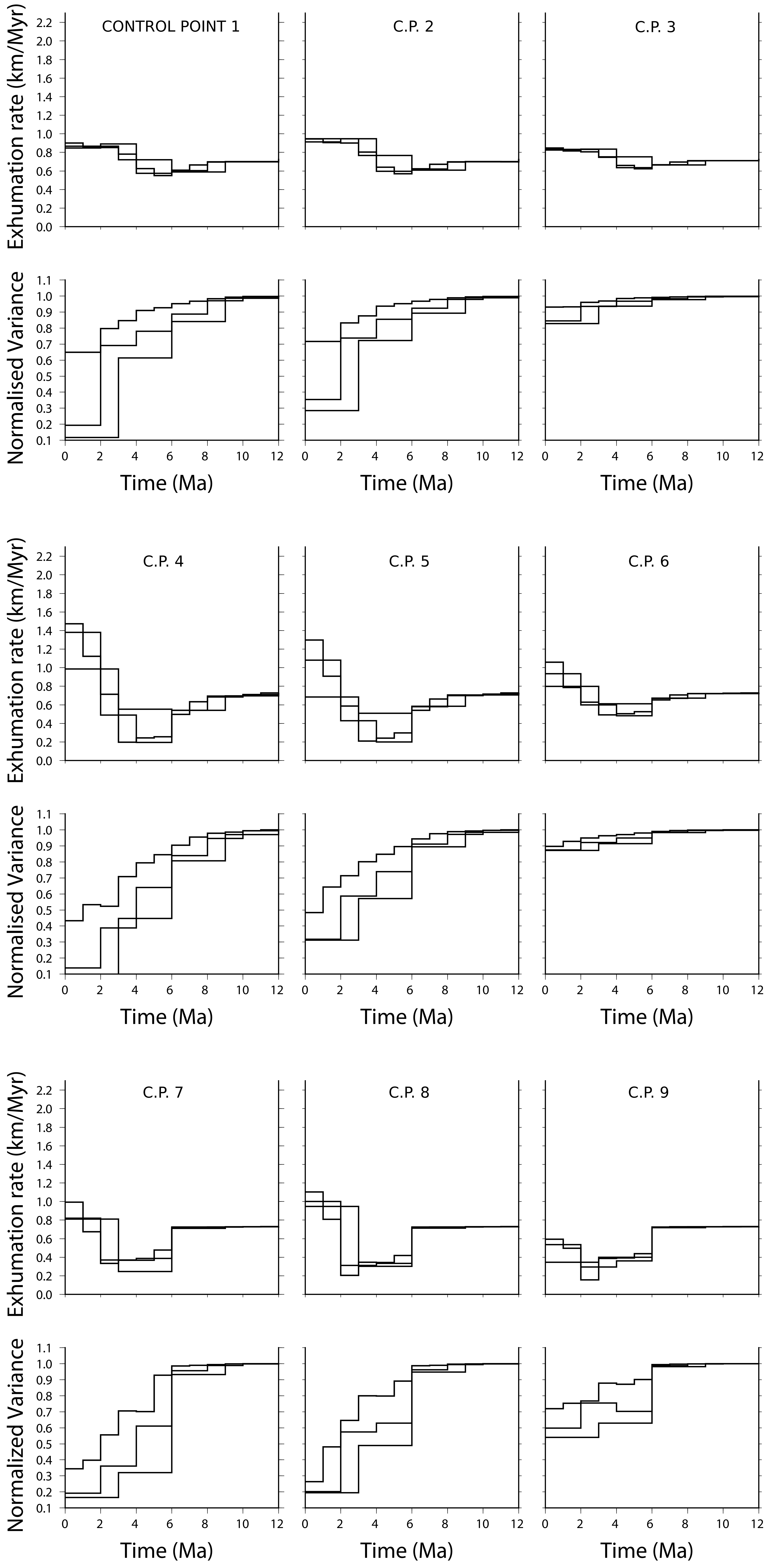

15.00 – 12.00 Ma
9°00'
9°30'
10°00'
10°30'
11°00'
11°30'
12°00'
12°30'
45°00'
44°45'
44°30'
44°15'
44°00'
43°45'
43°30'
0.5
1.0
1.5
mm/yr
15.00 – 12.00 Ma
0.0
0.2
0.4
0.6
0.8
1.0
$\eta_{po/pr}$

Fig. SM2.3 - control points exhumation history and uncertainty



Model parameters:

timesteps: 1 / 2 / 3 Myr
prior exhumation rate: 0.73 Km/Myr
prior variance: 0.1 Km/Myr
T at 90 km: 1820 °C
---> (dT/dz:~32°C/Km)