Photo: Dauner Maare. Gemünder Maar in front, last erupted ~30ka

A Buoyant Eifel Mantle Plume Revealed by GPS-Derived Large-Scale 3D Surface Deformation

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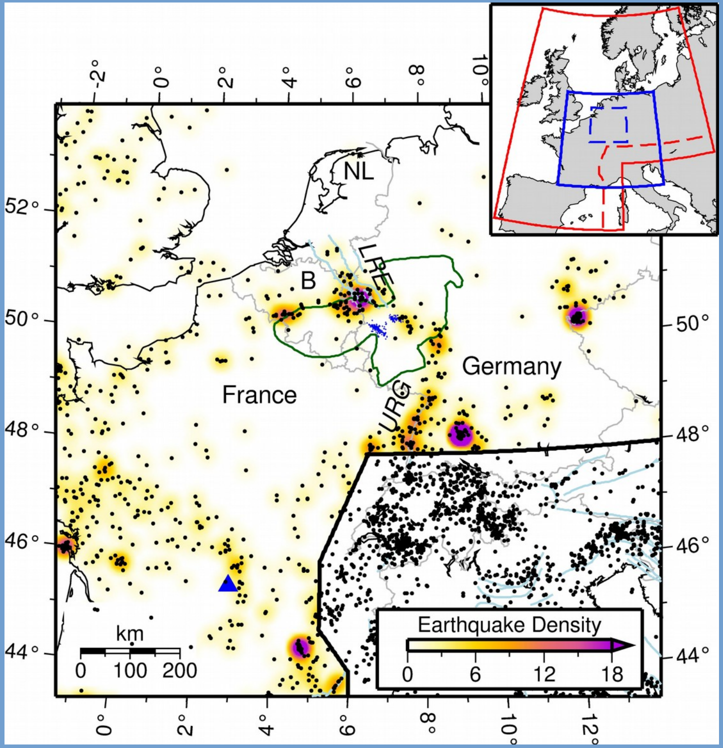


Smoothed seismicity based on the SHEEC-SHARE database (Grünthal *et al.* 2013, Stucchi *et al.* 2013). Also shown is outline of Rhenish Massif (green polygon), location of Massif Central (blue triangle) and Eifel volcanic centers (tiny blue dots).

Synopsis

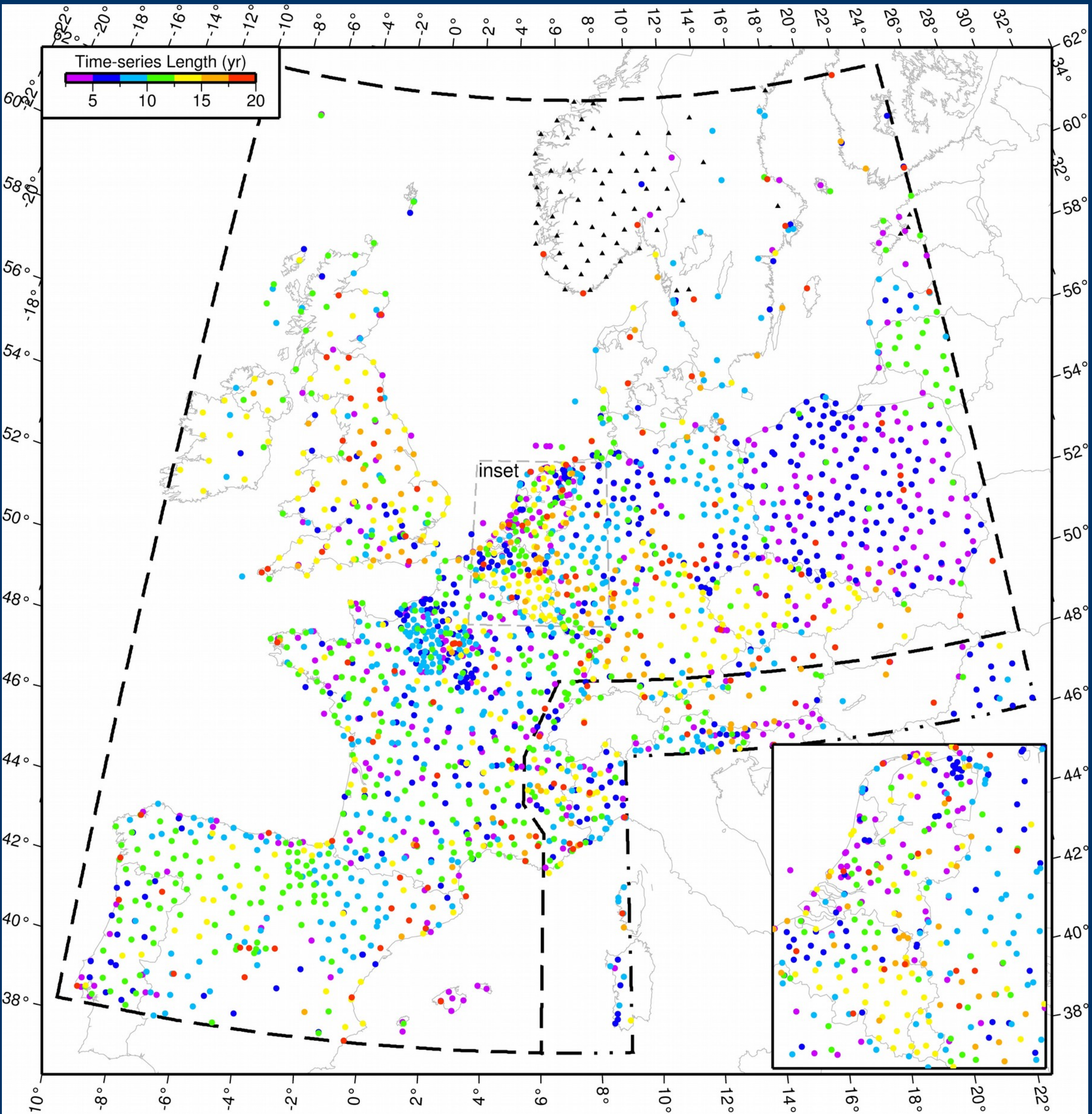
- "Intraplate" western Europe is seismically rather active. Additionally, it has a couple of areas with Quaternary volcanism, notably the Eifel and Massif Central.

- Low seismic velocity anomalies (plumes?) have been found underneath both areas, but most clearly for the Eifel

- Thus far geodetic studies of vertical motion or strain rate have not found any signal related to physical processes, except for Glacial Isostatic Adjustment and uplift/extension in the Alps.

- A main reason could be the lack of large amounts of data available prior to our study. Also, any deformation signal is going to be near the noise level of the data, requiring robust imaging techniques to reveal them.

- We report here definitive evidence for a strain rate and uplift anomaly near the Eifel and which can likely explained by a buoyant plume.



GPS Data

- Data from 2000.0-2020.0 from many sources, incl. many state and commercial networks; some provided data for 1st time for research.

- Position time-series were estimated with GipsyX in IGS14 frame by us (Nevada Geodetic Laboratory; Blewitt et al., 2018).

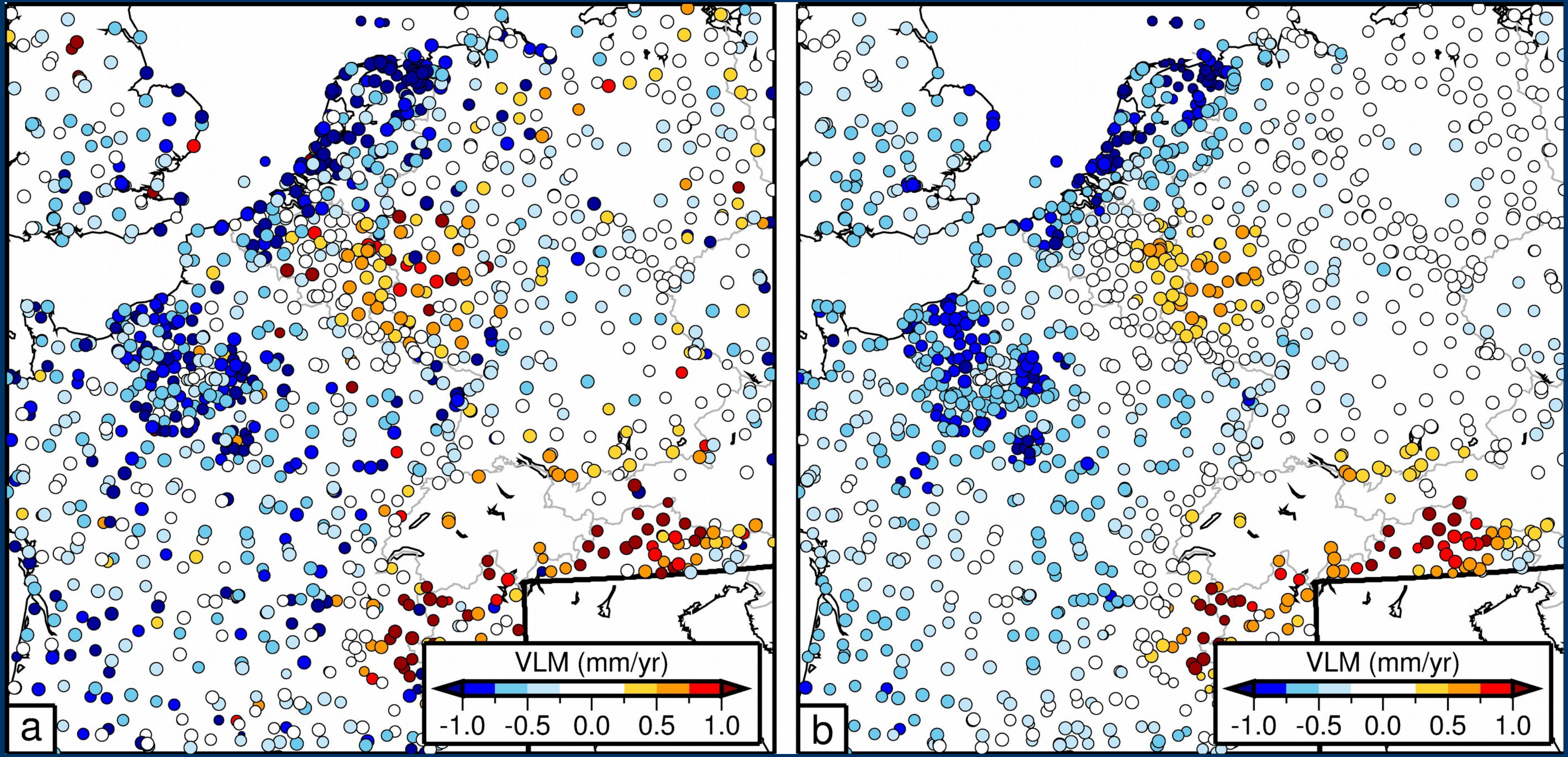
- Time-series were corrected for common-mode signals, and rates (and st.dev) were estimated using MIDAS (Blewitt et al., 2016)

- We estimated 2428 3D velocities for time-series >2.5y (and a minimum completeness).

- We also added 68 published velocities in Scandinavia (Kierulf et al., 2013,2014; Lahtinen et al., 2019)

- We focus here on a sub-area.

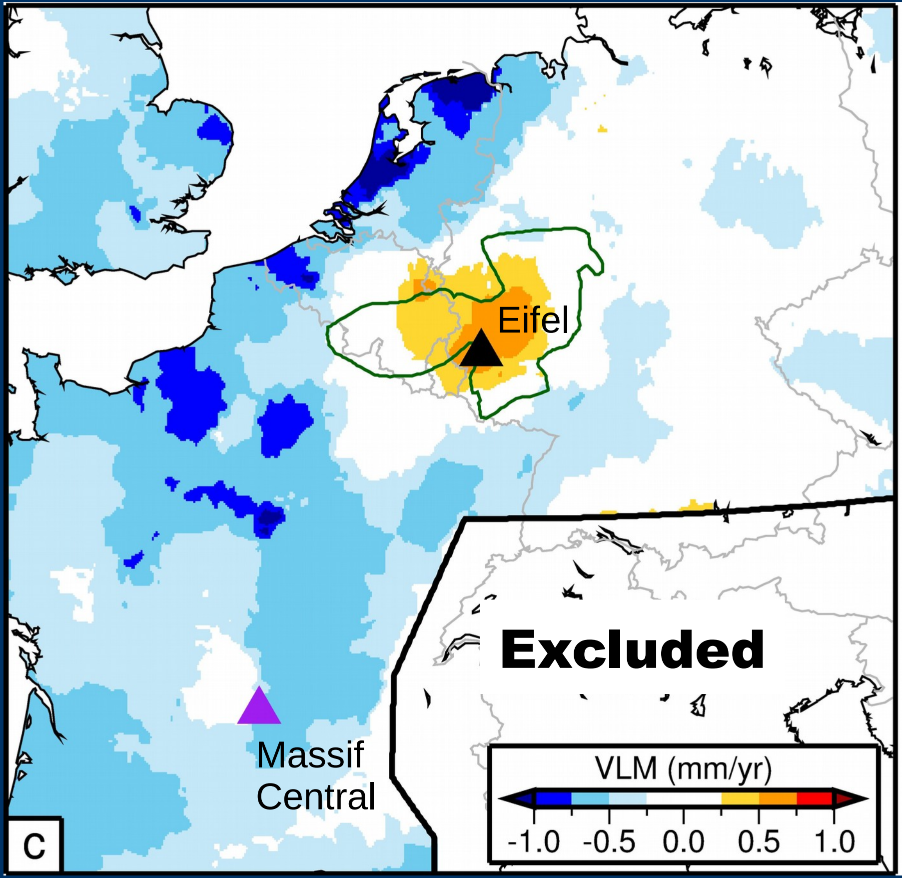
Vertical Land Motion (VLM)



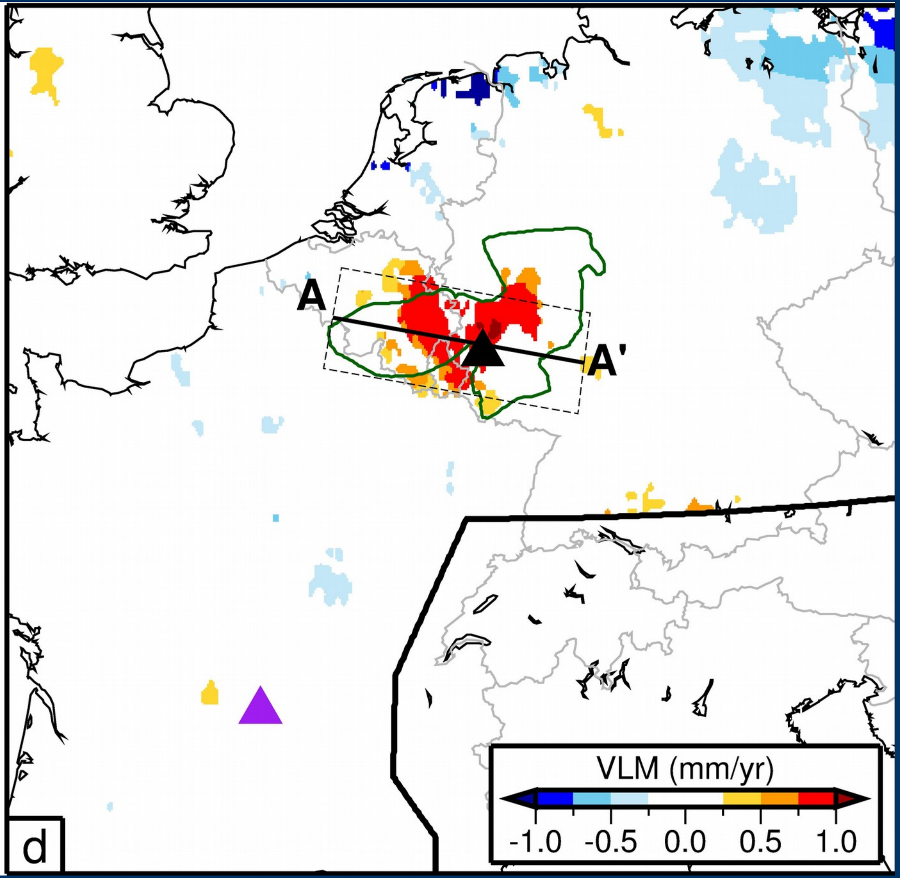
Observed

"Despeckled"
Each station's observed VLM is replaced with a "local" weighted median

Vertical Land Motion (VLM)

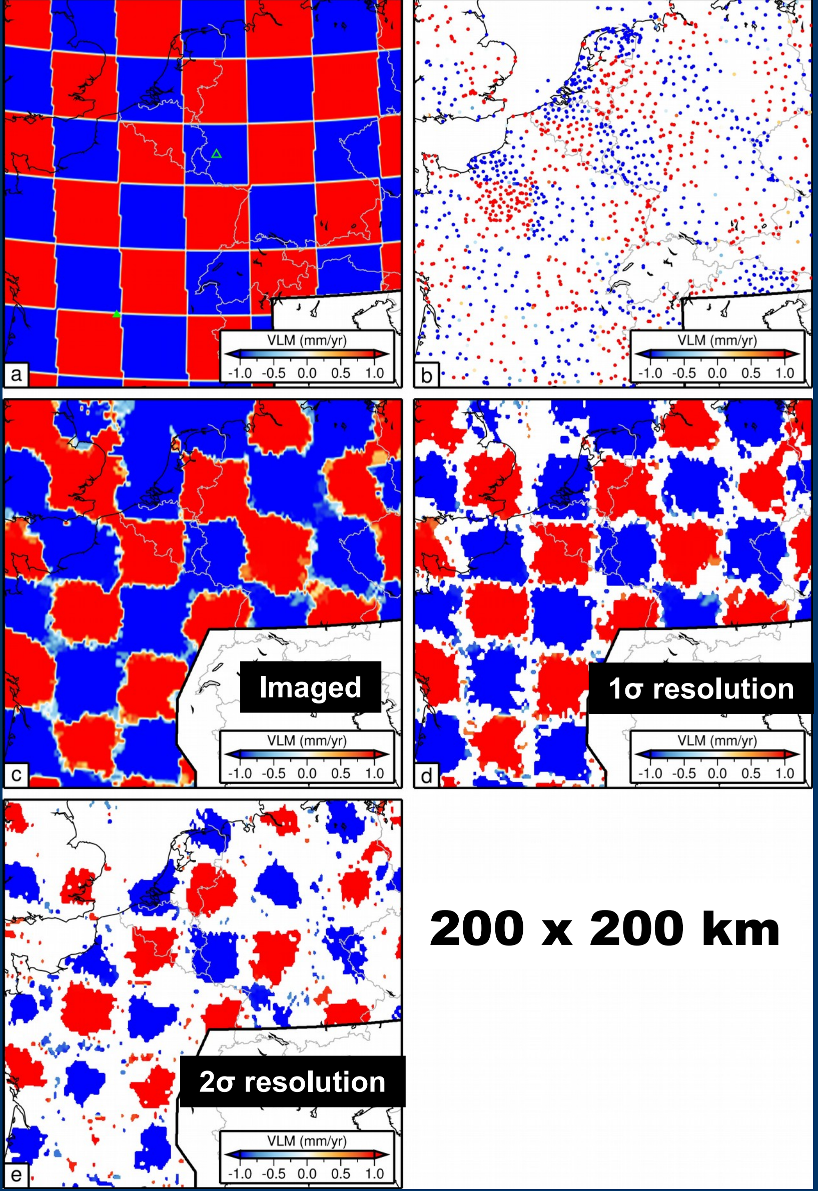


“Imaged”
Using Robust Network Imaging (Kreemer etal., 2020)



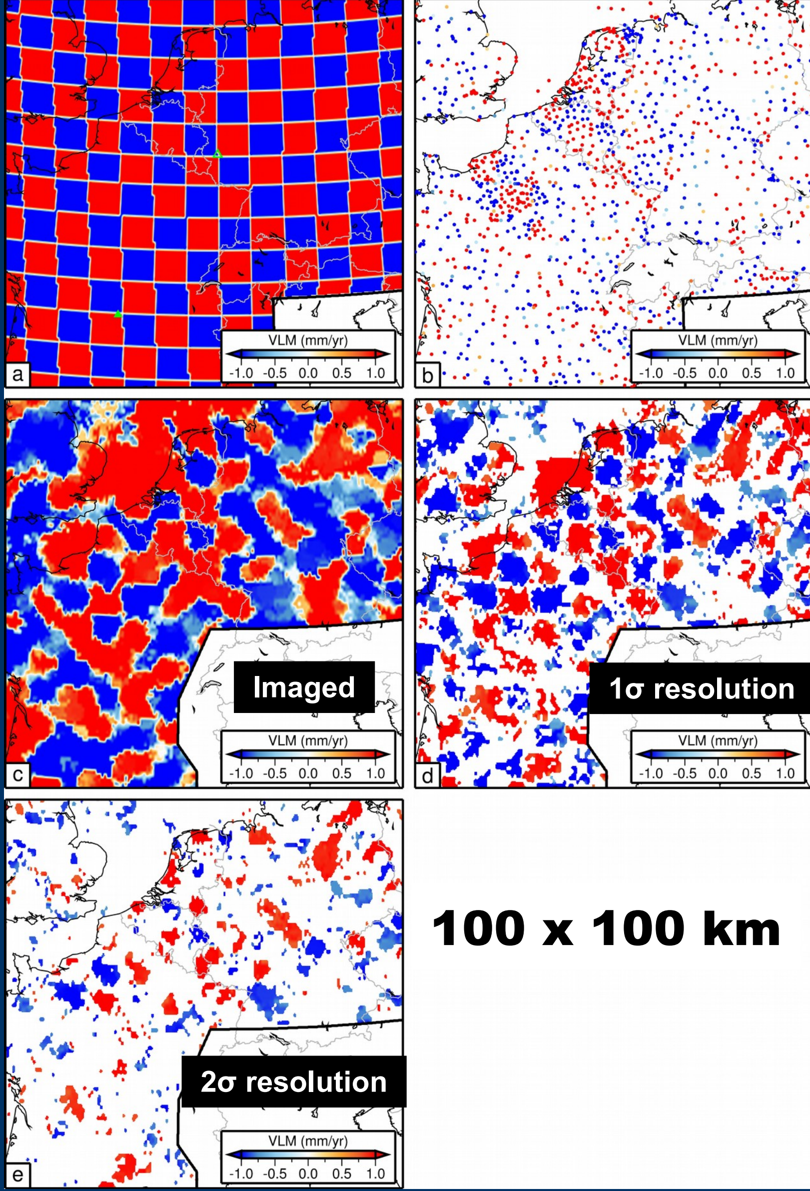
”Imaged” ≥ 2σ
And corrected by the Glacial Isostatic Adjustment of Husson et al. (2018)

VLM Checkerboard Tests

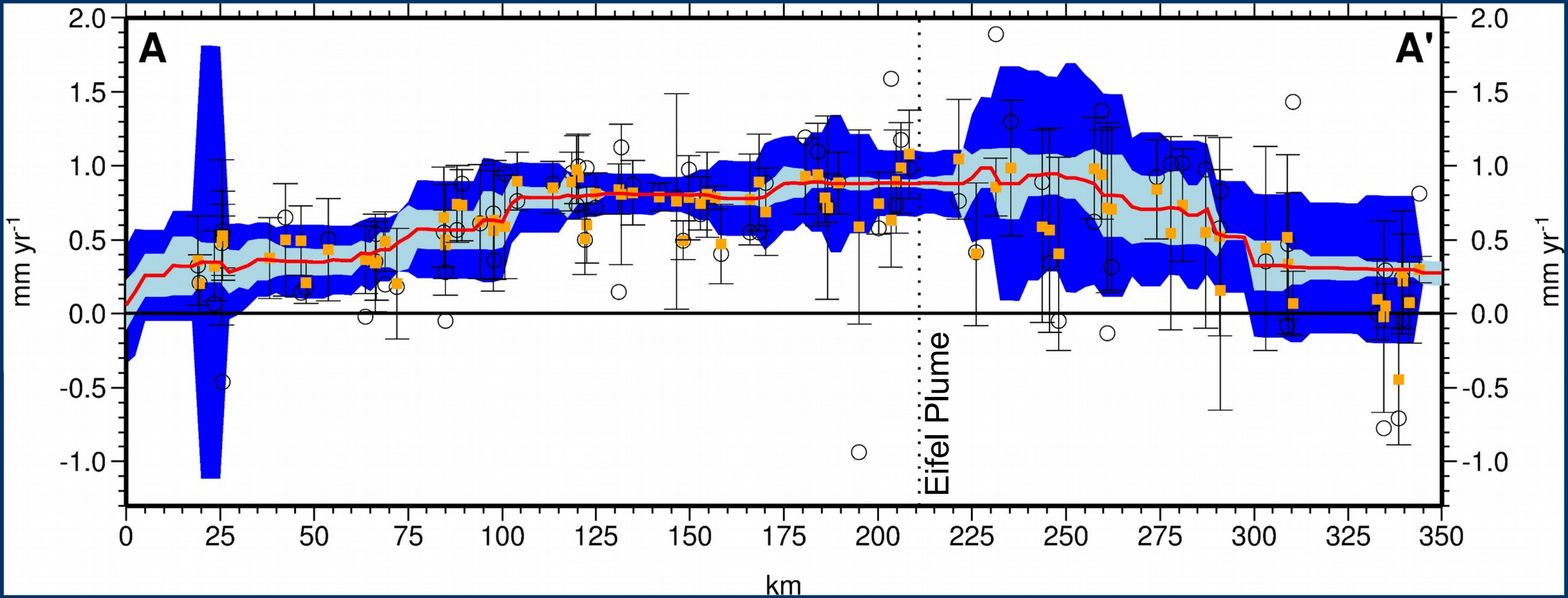


200 km anomaly resolved at 2σ at Eifel and 1σ at Massif Central

100 km anomaly resolved at 1σ at Eifel



VLM Cross-Section across Eifel

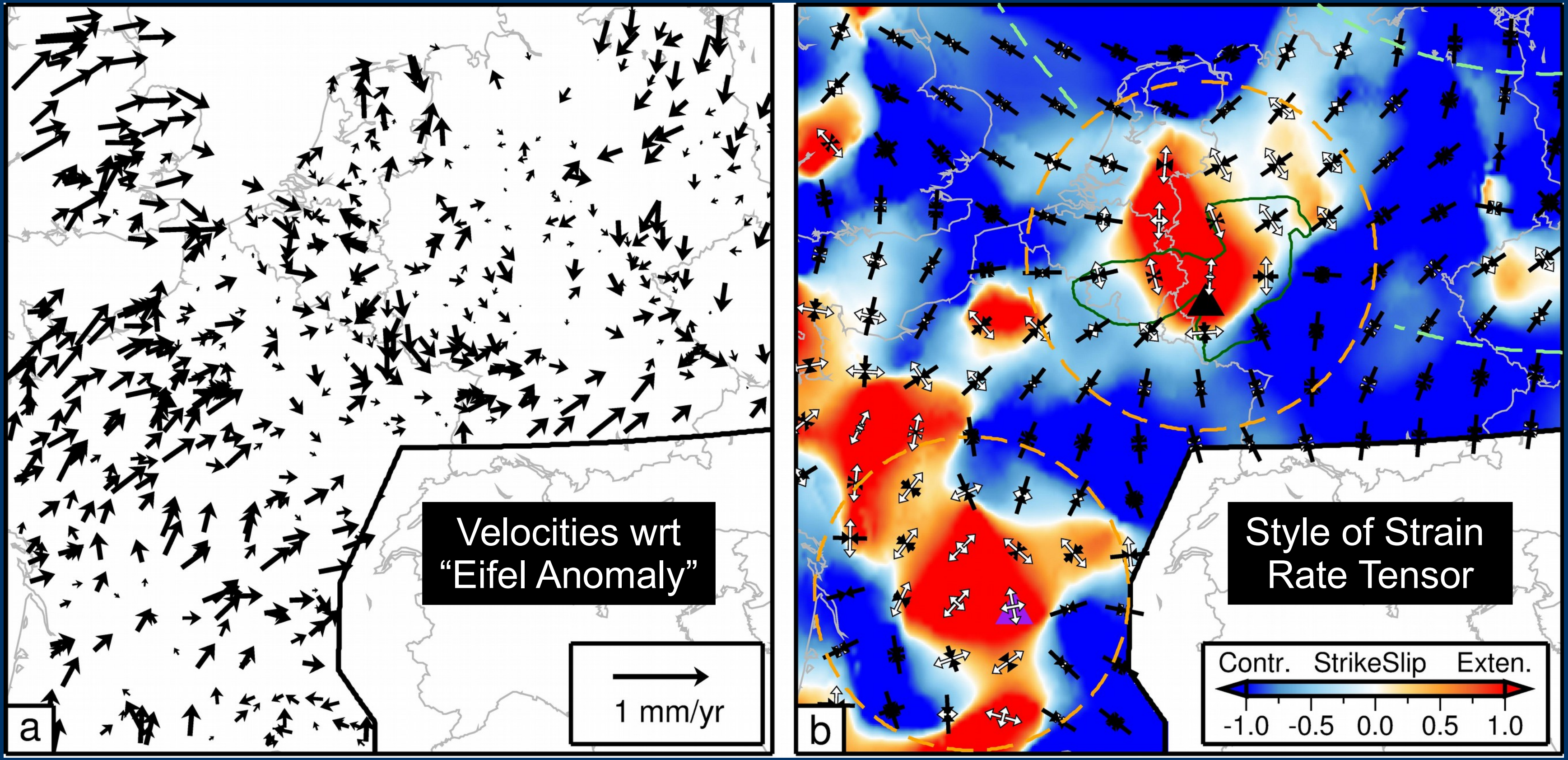


All values corrected for GIA

Open dots: observed
Orange squares: despeckled
Red line: imaged
Light-blue – 1σ based on local variation in despeckled VLM
Dark-blue – 1σ based on local variation in observed VLM

Strain Rates Estimated with modified version of "MELD"

(Kreemer et al., 2018)

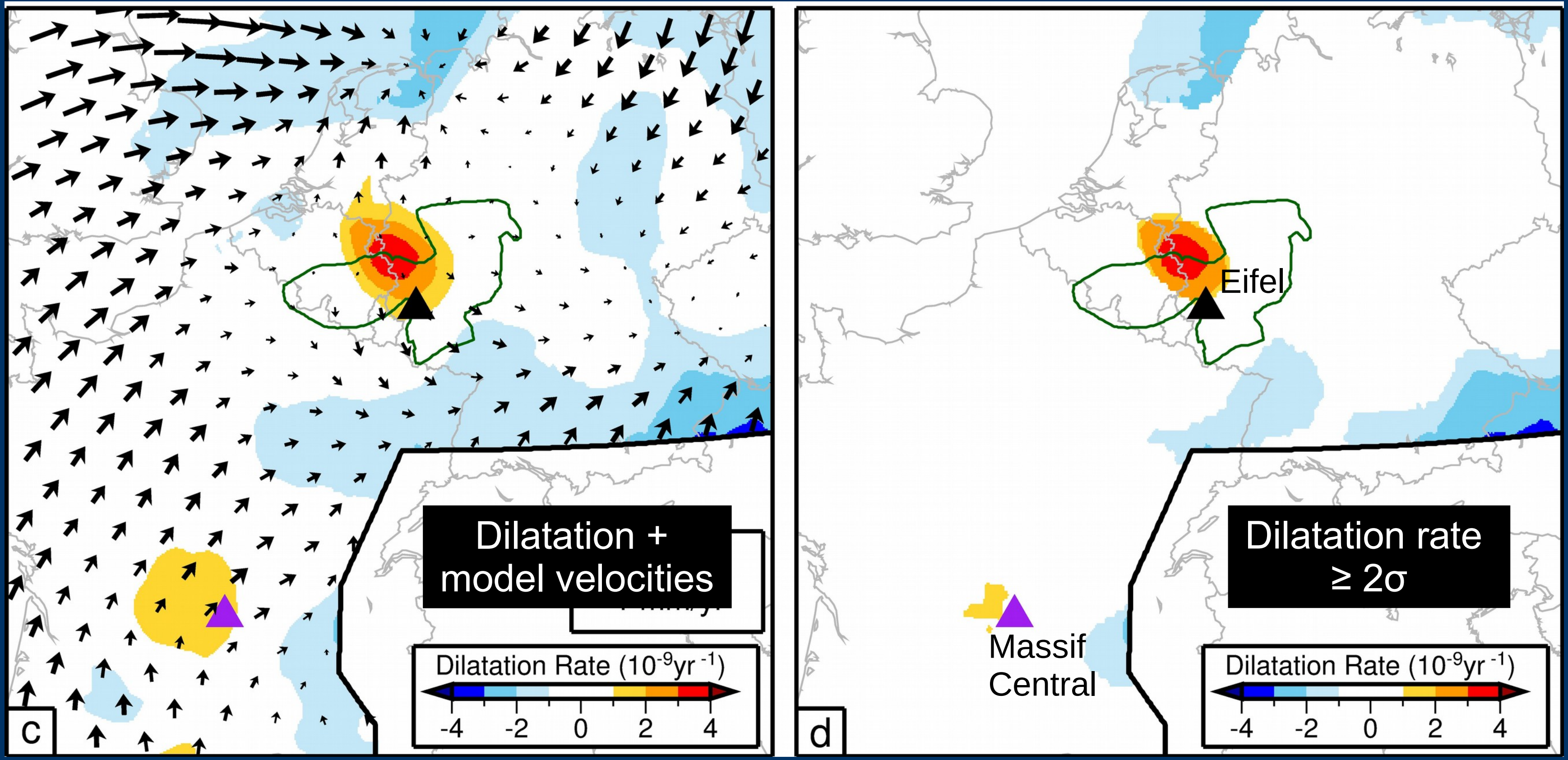


Outliers removed for clarity

Circles added to emphasize radial compression around Eifel and Massif Central extensional anomalies

Strain Rates Estimated with modified version of "MELD"

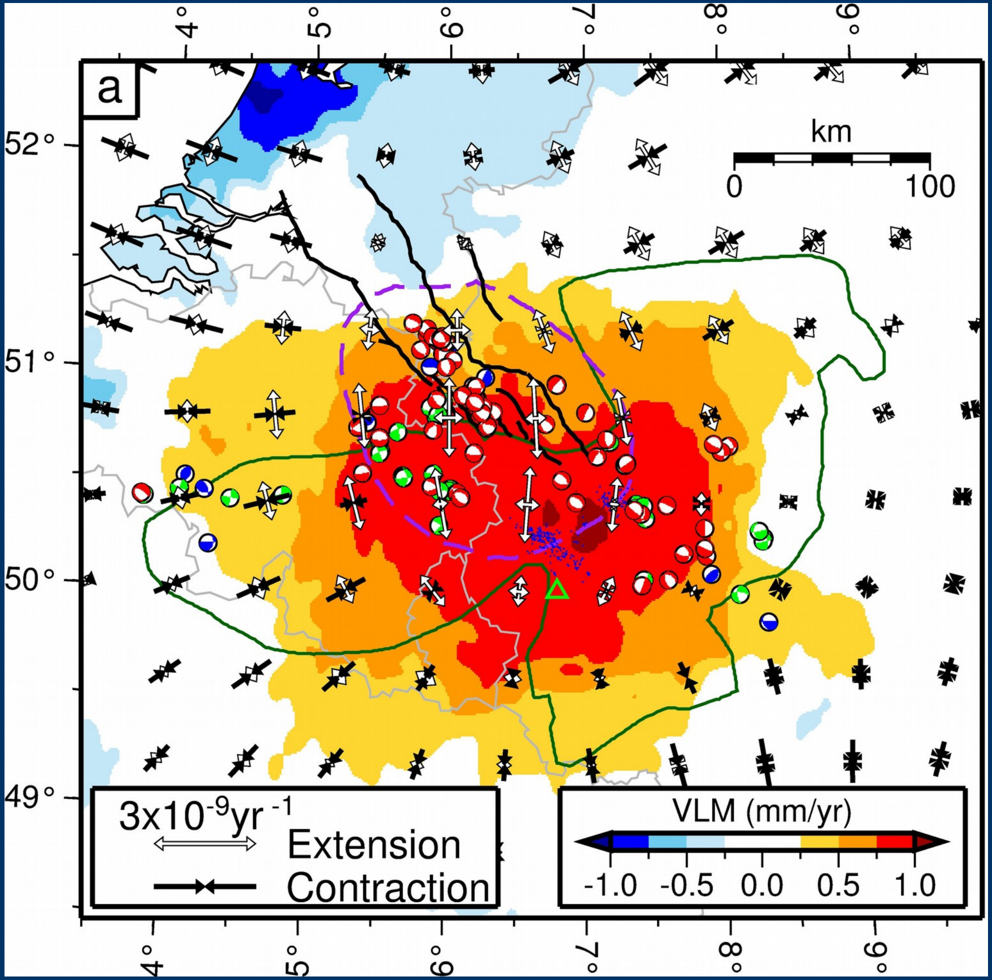
(Kreemer et al., 2018)



Positive dilatation (i.e., extension) anomalies near Eifel and Massif Central

Large significant dilatation anomaly near Eifel. Anomaly near Massif Central has small magnitude and thus lower significance

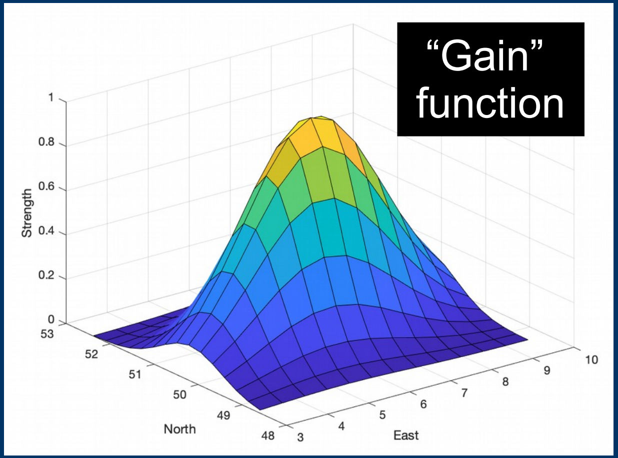
The "Eifel Anomaly"



We define the "Eifel Anomaly" as the area with anomalous and significant uplift (max. 1 mm/yr) that coincides with an area of anomalous and significant ~NS oriented dilatational strain rate. The Eifel anomaly includes the Eifel volcanic centers (where VLM is highest), elevated seismicity (with most of the earthquakes being NNE-SSW extensional), the normal faults of the Lower Rhine Embayment, and the surface projection of imaged mantle plume.

+ VLM contours corrected for GIA
+ Dashed purple line extent of significant dilatation rate anomaly. Max ~NS extension ~$3x10^{-9}$/yr
+ Focal mechanisms (Hinzen 2003, Camelbeeck *et al.* 2007)
+ Dark lines, Quaternary faults (Basili *et al.* 2013)
+ Green triangle center of Eifel plume (Ritter *et al.* 2001)
+ Blue dots are volcanic centers
+ Green polygon is Rhenish Massif

Effect of a Buoyant Eifel Mantle Plume

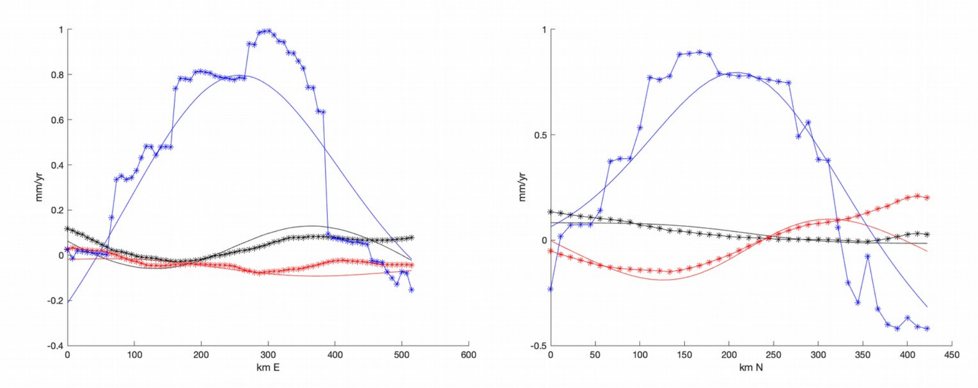


We solve for a buoyant force at the depth of plume head (50 km) by mimicking it as a force multiplied to a bi-modal Gaussian areal distribution (i.e., a gain function) that would best fit the VLM, strain rate and horizontal velocities. We solve for the force and the gain's function center location, orientation and half-widths, while also accounting for constant horizontal gradients in the deformation indicators. We find:

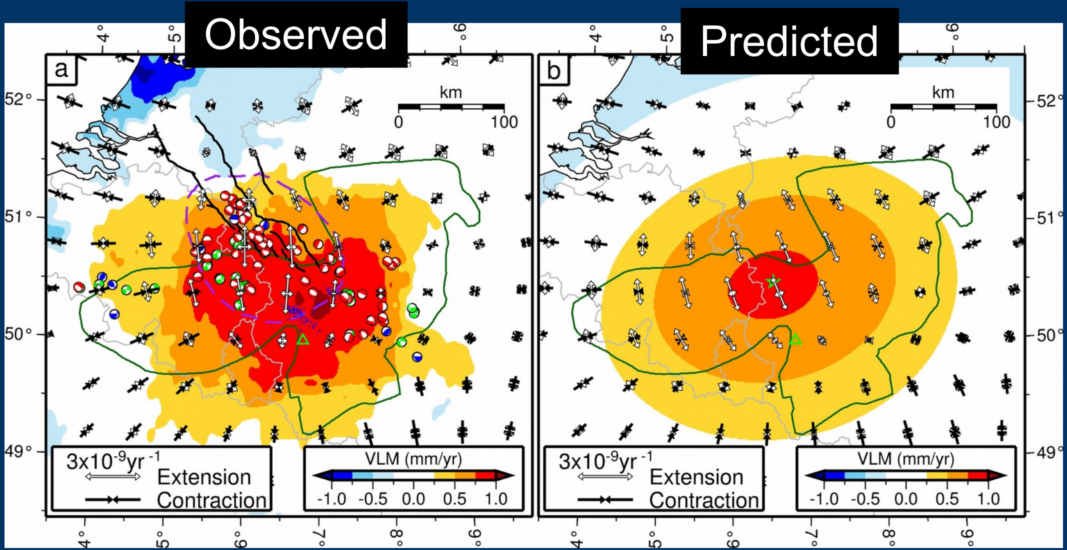
Center: 6.5E, 50.5N (star in figure below)

Half-widths: 187 (EW) and 105 (NS) km. Long axis ~14° CCW from E.

Force: 15.6×10^{11} N



EW (left) and NS (right) cross-section. Solid and dotted line are model/data resp. Blue/red/black = vertical, NS, and EW velocity.



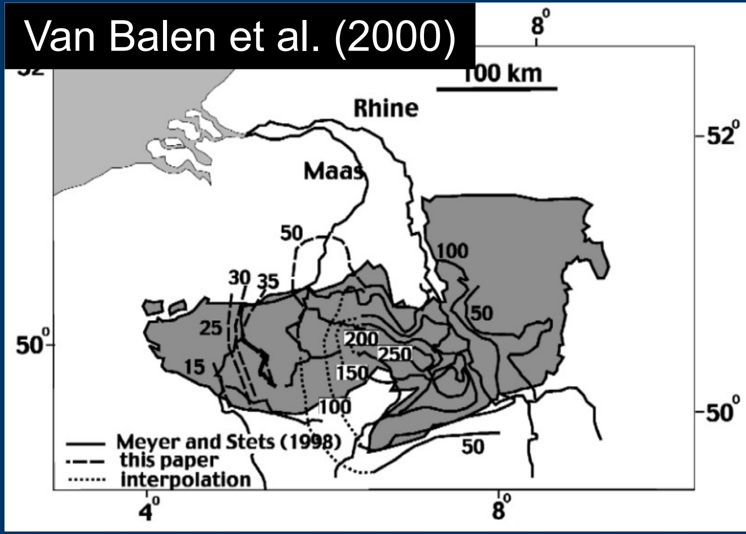
Discussion

- The Rhenish Massif has uplifted up to ~150-250 m since ~800ka (max values shown on right). If constant rate: 0.1-0.3 mm/yr. We find ~1 mm/yr. VLM could have been accelerating or is not constant with time.

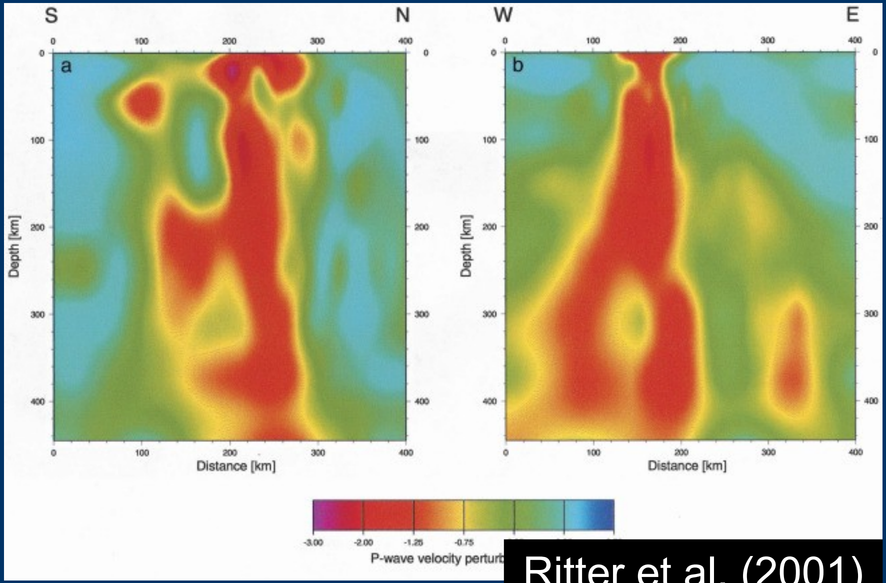
- The faults in the Lower Rhine Embayment (LRE) are relatively active and their activity has also been increasing since ~800 ka (Gold et al., 2017). We speculate that the upward push of plume, and the extension it creates, may have (re)activated the LRE.

- Based on different assumptions of rate, total uplift and period of activity, the spatially integrated force we estimated requires a ~57–184 kg/m^3 density reduction of the plume (i.e., ~0.7–5.6% of a 3300 kg/m^3 reference mantle).

- Our results suggests there being a buoyant plume underneath the broader Eifel area that could explain surface deformation. This adds further evidence of the Eifel being active, as also shown by the magma migration detected by Hensch et al. (2019) as low-frequency seismic swarms.



Van Balen et al. (2000)



Ritter et al. (2001)

Conclusions

- Careful and robust analysis of thousands of CGPS time-series and their rates has revealed a significant uplift and extension anomaly centered on the Eifel volcanic area, but expanding into Belgium, Luxembourg and The Netherlands.

- This “Eifel Anomaly” is unique in Europe. No uplift signal is seen near the Massif Central, although that area does have a small extension anomaly.

- GIA-corrected uplift reach up to 1 mm/yr and max. extensional strain rates of ~3×10^{-9}/yr are found (the latter more centered on the Lower Rhine Embayment).

- Uplift and deformation can be explained by a distributed buoyant force below the lithosphere, which can be attributed to the mantle plume underneath.

- No conclusive evidence for buoyant plume under Massif Central due to absence of clear uplift signal.

<u>Accepted Article</u>: Kreemer, C., et al., Geodetic Evidence for a Buoyant Mantle Plume Beneath the Eifel Volcanic Area, NW Europe. Geophysical Journal International, 2020

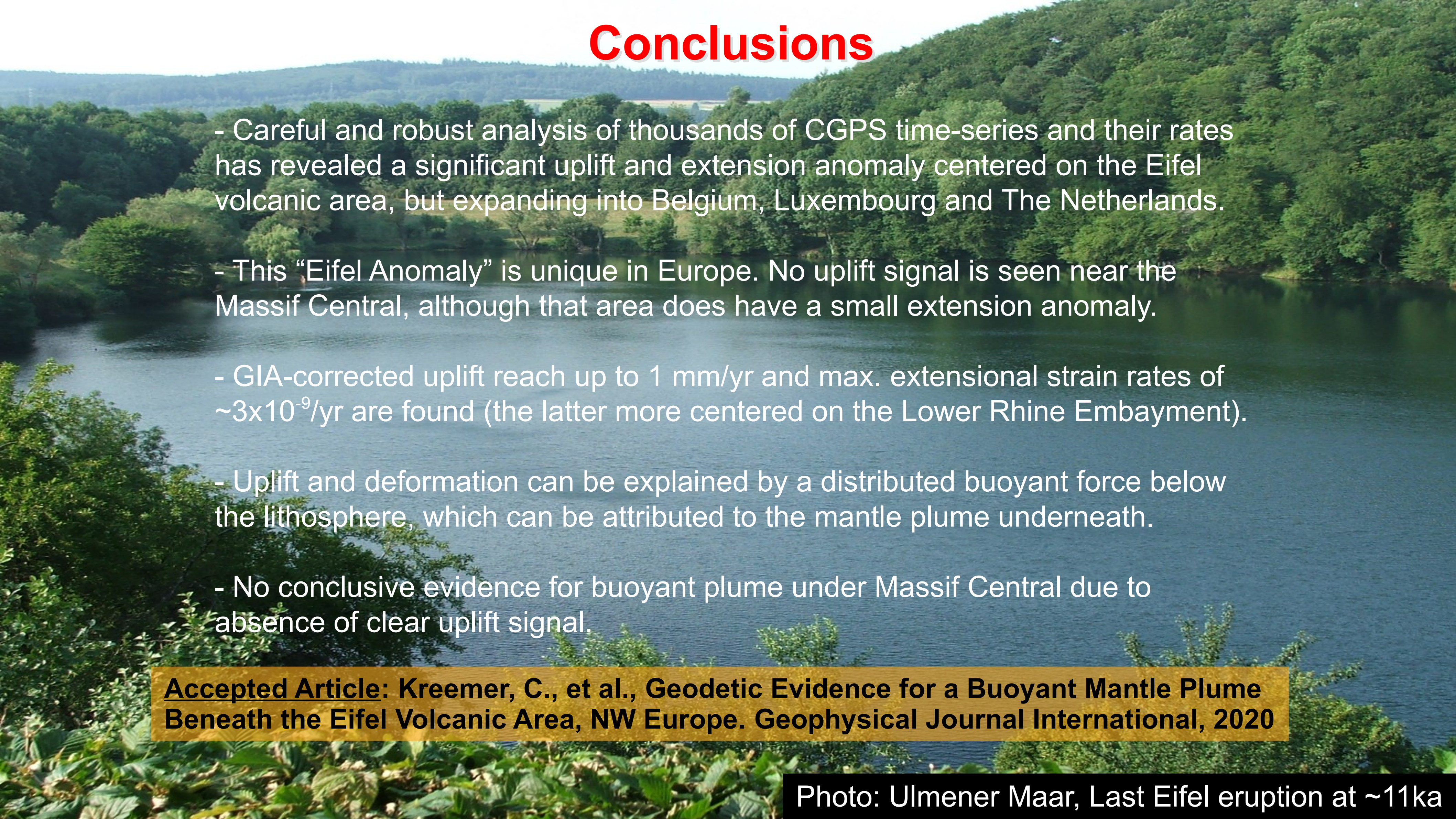


Photo: Ulmener Maar, Last Eifel eruption at ~11ka