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# Spatial Heterogeneity of Uplift Pattern in the Western European Alps Revealed by InSAR Time-Series Analysis

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# Geophysical Research Letters

## RESEARCH LETTER

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### Key Points:

- We use four years of Sentinel-1 radar acquisitions to derive interseismic line-of-sight velocities over the Western European Alps
- InSAR-derived velocities are consistent with other geodetic studies and provide increased spatial resolution of surface velocity patterns
- Short-wavelength spatial variations show locally higher velocities localized on crystalline massifs, interpreted as higher uplift rates

### Supporting Information:

Supporting Information may be found in the online version of this article.

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## Spatial Heterogeneity of Uplift Pattern in the Western European Alps Revealed by InSAR Time-Series Analysis

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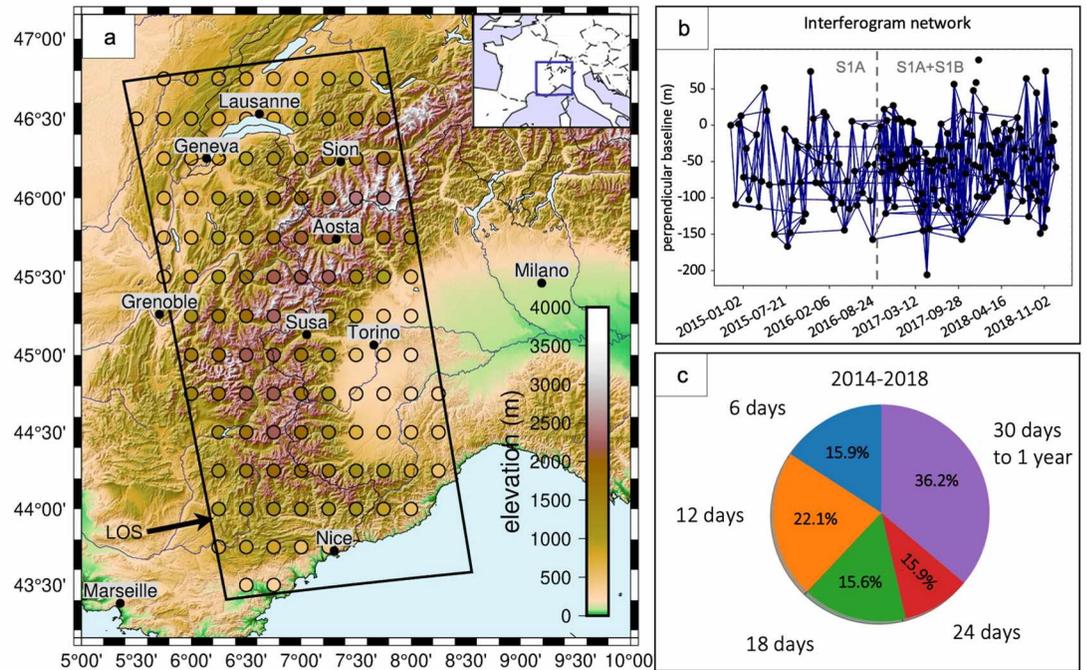
**Abstract** The Western European Alps display measurable surface deformation rates from leveling and GNSS data. Based on the time-series analysis of 4 years of Sentinel-1 data, we propose for the first time an InSAR-based mapping of the uplift pattern affecting the Western Alps on a  $\sim 350 \times 175$ -km-wide area. This approach provides a denser spatial distribution of vertical motion despite the high noise level inherent to mountainous areas and the low expected deformation signal. Our results show consistency with other geodetic measurements at the regional scale, and reveal smaller-scale spatial variations in the uplift pattern. Higher uplift rates are found within the external crystalline massifs compared to surrounding areas, in agreement with the variations expected from recent deglaciation and long-term exhumation data. This work brings the first InSAR-based geodetic clue of differential uplift within the Alpine belt in response to the surface and deep processes affecting the belt.

**Plain Language Summary** The surface of the Earth is constantly moving from about a few millimeters to a few centimeters per year in response to geological processes such as tectonic plate motions and gravitational re-equilibrium. In the Western European Alps, where the mountain-building phase of the belt is over, the processes at the origin of surface motions are under debate. Mapping surface displacements at the highest possible resolution is mandatory to better understand the evolution of the Alpine belt. Among other techniques, radar satellites can provide measurements of such displacements. Here, radar images from the recent Sentinel-1 satellite allow us to improve the spatial resolution of vertical surface displacements in the Western Alps compared to previous techniques. Thanks to the unmatched frequency of acquisitions from this satellite, we are able for the first time in our study area to measure small-scale spatial variations within the vertical motions. These variations appear correlated to distinct geological units. This brings new insights into the geological processes acting nowadays on the Western Alps.

## 1. Introduction

The European Alpine belt results from the complex continental collision phases between Africa and Eurasia (Coward & Dietrich, 1989; Schmid & Kissling, 2000). While convergence is still active and is attested by Adria indentation in the Eastern and Central Alps, it stopped in the Western Alps, where the present-day kinematics are characterized by the anticlockwise rotation of Adria microplate with respect to Eurasia (e.g., Calais et al., 2002). Global Navigation Satellite System (GNSS) measurements highlight extensive and transcurrent horizontal strain rates in the western part of the belt, without any measured shortening across it (Calais et al., 2002; Serpelloni et al., 2016, 2018). The dynamic processes that have been suggested to affect the Western Alps involve intrinsic surficial (isostatic adjustments to deglaciation and erosion) and deep sources (slab pull or break-off and mantle upwelling), as well as far-field microplate kinematics, but their respective contributions to present-day crustal deformation are an ongoing debate (e.g., Sternai et al., 2019).

GNSS and leveling measurements in the Western Alps indicate that vertical velocities of a few mm/yr are expected, which is an order of magnitude higher than the horizontal motions (Masson et al., 2019; Mathey et al., 2020; Nocquet et al., 2016; Walpersdorf et al., 2018). Increasing the spatial resolution of vertical motions is thus of primary importance to understand the processes at the origin of surface deformation within the belt. Despite the dense coverage of GNSS networks over the Alps, the velocity fields obtained after spatial interpolation of GNSS velocity data strongly depend on the method, and can be highly impacted by the inclusion of one or a few outlier velocities. Interferometric Synthetic Aperture Radar (InSAR) imagery constitutes a complement to GNSS



**Figure 1.** Study area and processed data set. (a) Color shaded map of the digital elevation model (Farr et al., 2007) overlaid by the Sentinel-1 footprint (track A088, black rectangle) and by circles showing ERA5 grid points color-coded according to the smooth ERA5 surface-elevation model. (b) Processed interferogram pairs (blue lines) between radar acquisition dates (black dots) arranged by perpendicular baseline and time. The dotted line shows the starting date of Sentinel-1 B acquisitions. (c) Proportion of interferogram durations corresponding to the interferometric network in (b).

measurements to assess the spatial extent of regional deformation since it provides continuous estimates of surface displacements and a high sensitivity to the vertical component. InSAR data have not been used, up to now, to map slow, large-scale deformation across the European Alps, but only for landslide monitoring (e.g., Aslan et al., 2020; Singh et al., 2005), because of (a) the low expected long-term surface deformation signal compared to the atmospheric noise induced by high topographic gradients within the belt, and of (b) the temporal decorrelation related to vegetation and snow coverage changes over seasons. While several similar works already focused on mountainous areas worldwide (e.g., Daout et al., 2019; Grandin et al., 2012; Hammond et al., 2012), they were all focusing on areas with higher signal-to-noise ratios.

The launching of the Sentinel-1 radar satellite in 2014 now enables us to derive InSAR estimates of tectonic surface velocities for the first time across the Western Alps. Here we assess the spatial extent of the regional vertical signal based on the time-series analysis of more than 700 interferograms computed over 4 years of radar acquisitions.

## 2. Sentinel-1 Data Processing

We use Sentinel-1 acquisitions along ascending track A088 ranging from November 2014 to December 2018. Sentinel-1 interferometric wide-swath mode acquires data on a swath width of about 250 km. We limited our analysis to the sub-swaths 1 and 2, covering our area of interest by 175 km in range and 350 km in azimuth (Figure 1a). To extract the ground velocity signal, data were processed using the New Small BAseline Subset (NSBAS) chain developed by Doin et al. (2011). Single Look Complex (SLC) images were all coregistered on a reference date before computing differential interferograms. Interferograms have first been multi-looked by a factor 2 in azimuth and 8 in range. Precise orbits from the Copernicus Precise Orbit Determination Service (Peter et al., 2017) and the SRTM digital elevation model (Farr et al., 2007) were used in order to correct the geometrical phase difference between acquisitions. The phase correction within each burst due to the backward-forward sweeping of the radar antenna was performed in two steps (Grandin, 2015): first, an azimuth adjustment quantified by image coregistration, and second, a multi-linear adjustment of the backward-forward interferograms

obtained with the spectral diversity method in the burst-overlap areas (Scheiber & Moreira, 2000). Spectral diversity parameters are inverted into time series to avoid a drift due to cumulative noise. Then, the corresponding phase correction is directly applied on the interferograms.

The European Alps are affected by large snow cover and by vegetation changes in forests and crop lands, which both reduce the interferometric coherence. The former affects mainly winter dates whereas the latter effect has the strongest impact in spring and early summer. As we are interested in large-scale deformation patterns, we must ascertain phase continuity across the Alps, mainly relying on valleys in winter and on summits in summer, with flanks often covered by forests. Therefore, optimizing the interferogram network has the utmost importance: we performed a systematic analysis of each interferogram coherence and of all interferograms with a given acquisition. This led us to discard a few dates because of their particularly large snow cover. Furthermore, the coherence analysis per date helped us to select image pairs with the longest temporal baselines. Acquisitions from September to November were generally found the most appropriate to combine with other dates. Interferograms crossing the snow period in particular were chosen with great care. Finally, 173 dates and 734 interferograms remain (Figure 1b) with temporal baselines ranging from 6 days to one year (Figure 1c). In spite of the selection of the best interferograms in terms of coherence, interferogram unwrapping remained challenging, and required several preceding corrections detailed hereafter.

The Atmospheric Phase Screen (APS) of interferograms due to pressure, temperature, and humidity changes in the atmosphere makes unwrapping particularly challenging in mountainous areas and limits the accuracy of InSAR measurements (Doin et al., 2009; Elliott et al., 2008; Hanssen, 2001; Zebker et al., 1997). Atmospheric changes produce both an elevation-dependent phase, called stratified atmospheric effect, and atmospheric patterns, mostly random in space and time. Steep slopes in the Alps, whose shortening in radar geometry is stronger for the radar facing flanks, produce narrow fringes. This effect, when added to the decorrelation due to forests, can lead fringes on the radar facing flanks to disappear and produce unwrapping ambiguities. To limit this effect, interferograms were corrected before unwrapping using ERA5 atmospheric model reanalysis (Hersbach et al., 2020) as described in Doin et al. (2009) and Jolivet et al. (2011). We validated this correction by comparing it to the empirical phase-versus-elevation ratio (Doin et al., 2009, 2015; Grandin et al., 2012), and found that it successfully removed the seasonal evolution of the phase-elevation relationship and reduced its day-to-day variability. However, the smooth model elevation of ERA5 (Figure 1a) displays values of 1,000–2,000 m for the points closest to deeply incised valleys (e.g., Sion and Aosta Valleys, Figure 1a). As a result, the correction applied along these valleys, which is obtained by downward extrapolation, is less precise (see Section 3).

Once the interferograms were corrected from stratified atmospheric fringes, we replaced the amplitude of the interferogram by the colinearity measurement (Pinel-Puysségur et al., 2012). We then applied a second step of multilooking to  $32 \times 8$  looks, in which pixels are weighted according to the colinearity, thus increasing the overall signal-to-noise ratio. This process makes fringe continuity clearer in noisy areas (Daout et al., 2017). We then applied an adaptive Gaussian filter with a moving window. Phase unwrapping, performed in the spatial domain by region growing (Doin et al., 2015; Grandin et al., 2012), starts in the most coherent area and expands progressively to the lowest coherence areas. Here, we combine the coherence criterion to the topographic slope in radar geometry to prevent the phase-unwrapping path to cross the steepest slopes and those facing the radar. Remaining unwrapping errors were systematically checked for all the 734 interferograms and corrected by adjusting the erroneous number of phase cycles between patches. We then applied a “snow” mask on interferograms, based on a threshold on the averaged coherence per date, for the two dates constituting the interferogram.

Finally, unwrapped interferograms were corrected from orbital ramp residuals by adjusting a linear phase ramp of the form:

$$ax + by + c \quad (1)$$

where  $x$  is the range and  $y$  the azimuth directions and  $c$  a constant.

The  $a$  and  $b$  parameters are then used to invert into time series  $a l$  and  $b l$  for each time step  $l$ . The phase ramp is corrected from interferograms using reconstructed parameters, as shown in Biggs et al. (2007).

Time series of cumulative surface displacements are obtained by the inversion of all interferograms (Doin et al., 2015). Inversion quality depends on the consistency of interferometric phase differences within the interferogram network (López-Quiroz et al., 2009). Remaining unwrapping errors can then be detected and corresponding

interferogram patches are either corrected or, if not possible, masked. Finally, the Root Mean Square of the network phase misclosure (hereafter called misclosure RMS) is around 0.4 radians, indicating a high-quality unwrapping (Figure S1a in Supporting Information S1). A threshold of 0.5 radians on the misclosure RMS map was used to mask the least coherent pixels. Another quality indicator lies in the average misclosure of short temporal baseline interferograms (called hereafter Misclosure of Low Duration Interferograms or MLDI), which can be either positive or negative. The corresponding maps are computed for 6, 12, or 18-day interferograms. They quantify the bias associated with seasonal vegetation growth, which is introduced by interferogram multi-looking nonlinearity, and which fades with interferogram duration (Ansari et al., 2020). Pixels with large positive or negative bias on the 18-day MLDI map were masked (Figure S1b in Supporting Information S1). Since MLDI is in fact a measure of the consistency between short and long temporal baseline interferograms, it cannot be estimated for pixels where only few long temporal baseline interferograms are available. Therefore, pixels with an average temporal baseline below 0.102 years were also masked (Figure S1c in Supporting Information S1).

### 3. Ground Velocity Estimates From Time-Series Inversion

A preliminary line-of-sight (LOS) velocity map was obtained by linear regression of the inverted phase-delay time series (Figure S2a in Supporting Information S1). This map showed numerous local instabilities affecting valley flanks, as for example in Aosta Valley, almost systematically compatible with downward along-slope displacements. These motions compared well with the geographical extent of the numerous field-based mapped Deep-seated Gravitational Slope Deformations (DSGSD) (Agliardi et al., 2001; Blondeau et al., 2021; Drouillas et al., 2020; Hippolyte et al., 2006), and with InSAR measurements of DSGSD in the southern part of our study area (Aslan et al., 2020). Here, we used the DSGSD inventory made by Andre (2020) extracted as follows: (a) high-pass filtered interferograms were inverted into time series to obtain a high-pass filtered velocity map; (b) a threshold was applied on velocity; (c) additional constraints were applied on size, slope amplitude and orientation with respect to radar viewing angle, and radar visibility. Pixels affected by DSGSD or possibly by other non-tectonic localized processes were then masked on the velocity map (Figure S1d in Supporting Information S1).

Although the amplitude of the residual APS is large compared to deformation, the data set contains  $N = 173$  independent acquisitions, thus reducing the uncertainty on the velocity estimate obtained by regression by  $\sqrt{(N - 2)}$ . However, we must note that: (a) The APS amplitudes vary strongly with the acquisition date, as summer acquisitions are in general noisier than winter acquisitions, and (b) seasonal deformation or residual stratified atmospheric delays break the randomness assumption underlying the uncertainty analysis. We thus compared the velocity maps (Figure S2 in Supporting Information S1) obtained by (a) implementing or not one of the approaches used to reduce APS impact, and (b) including or not a seasonal term in the regression analysis.

One approach to reduce the APS effect is to smooth the time series for each pixel by computing the median over a moving window of 10 subsequent radar acquisitions, thus avoiding the least-square regression to be sensitive to strong outliers. The degree of freedom is then reduced to  $(\frac{N}{5} - 2)$ , although the velocity uncertainty decreases after median filtering (Figure S3 in Supporting Information S1). Another approach is to weight each acquisition by the inverse of the global APS amplitude averaged for each date. In the latter case, we cannot compute a velocity uncertainty on the regression analysis. We also include a seasonal term in the form of sine and cosine functions in the parameterization (see details in Supporting Information S1). We find that seasonal signals are large within the study area, possibly due to hydrological loading or to residual tropospheric delays not corrected by the ERA5 model. Phase delay maps for each acquisition were referenced by subtracting the averaged phase of all pixels having the best misclosure RMS values (see details in Supporting Information S1) prior to the regression analysis.

The reliability of the retrieved deformation patterns can be assessed by comparing the six different velocity maps in Figure S2 in Supporting Information S1. The location and sign of the main patterns are consistent for all maps. However, the amplitude of the LOS velocity anomalies that follow some valleys, such as Sion, Aosta, and Susa Valleys, depends upon the inclusion of a seasonal term and upon the approach used to decrease APS impact. Accordingly, the time series in these valleys contain a clear residual seasonal signal. Furthermore, these valleys display larger velocity uncertainties. Therefore, the velocity patterns along those three valleys can partly be explained by a poorer stratified atmospheric correction, which is based on ERA5 atmospheric variables extrapolated below the ERA5 model elevation (Doin et al., 2009). Figure 1a shows that the aforementioned valleys

are the ones displaying the sharpest topographic gradients with respect to the surrounding summits, as well as the sharpest contrasts between valley floors and ERA5 grid node elevations.

InSAR velocities shown in Figures 2a and 2c were finally referenced to published GNSS rates (Kreemer et al., 2020) by adjusting two ramps in azimuth and range and an offset (Figure S4 in Supporting Information S1). Areas moving toward the satellite concern mainly the areas of high topography as well as the foothills of the Alpine chain, while the chain periphery and coastal areas are dominated by motions away from the satellite. The velocity map derived from the median-filtered time series (Figure 2a) displays a higher amplitude range ( $\pm 3$  mm/yr in LOS) than the one retrieved from the APS-weighted time series ( $\pm 2$  mm/yr in LOS, Figure 2c). Velocities around the Po plain correspond to larger uncertainties, suggesting that they are not well modeled by the linear and seasonal parametric decomposition. This is not surprising, as this area is affected by strong and complex seasonal variations, with multi-annual variability. In the central and eastern Po plain, these variations are possibly due to local hydrology variations such as oscillations of the water table (Romagnoli et al., 2003) or hydrologic loading (Richter et al., 2004; Zerbini et al., 2007, 2010, 2013). For the rest of the study, we focus on the velocity map obtained with the APS-weighted time series (Figure 2c), for which we have a slightly better fit to GNSS data (Figure S4 in Supporting Information S1). However, we use the 1- $\sigma$  uncertainty map associated with the median-filtered time series (Figure 2b).

To better compare the long-wavelength patterns with those retrieved from other studies, we masked pixels with uncertainty values above 0.8 mm/yr according to Figure 2b and then implemented a spatial smoothing with a 20-km-wide Gaussian filter on the map shown in Figure 2c. The smoothed velocity field (Figure 2d and Figure S5 in Supporting Information S1) is less affected by non-tectonic effects and is compared to the projected LOS velocities of two GNSS solutions, the one from Kreemer et al. (2020) and the vertical velocity field from Sternai et al. (2019), for which we adjusted the reference frame by adding an offset of +0.25 mm/yr. The InSAR LOS velocities reveal an overall consistency with the GNSS projected velocities derived over longer time series. InSAR and GNSS solutions deviate locally though, mainly in places where the two GNSS solutions also differ from one another (e.g., at OSTA station, Figure 2e). While a few GNSS sites may be affected by local processes or by shorter instrumentation time spans, InSAR rates may suffer from strong residual APS locally or may be affected by potential non-tectonic, for example, hydrological, multi-annual trends.

The consistency between InSAR and GNSS is emphasized by the three velocity profiles drawn perpendicularly to the strike of the Alpine belt (Figure 2e). They highlight that no systematic correlation is found between elevation and LOS velocities across the chain, even if the area of highest positive velocities correlates with the area of highest topography (Aiguilles Rouges (AR) and Mont-Blanc (MB) areas), in good agreement with GNSS measurements. These results demonstrate that the LOS velocity field derived from 4 years of InSAR data is well-comparable to the longer-term geodetic measurements and is thus representative of the tectonic deformation affecting the Western Alps.

#### 4. Discussion: Uplift Localization

We make here the first-order assumption that the LOS velocities unraveled by this study mostly represent vertical motions. This is due to (a) the low viewing angle of the satellite from the vertical, which is varying from 29.16° to the west to 41.85° to the east, (b) the very small amplitude of the horizontal deformation across the Western Alps (around 15 nanostrain/yr of extension, see Nocquet et al., 2016; Walpersdorf et al., 2018), and (c) the removal from the velocity map of the majority of DSGSD features, which contain significant horizontal motion. In the following, we will therefore display and discuss the velocity field converted to vertical using local incidence angles.

Figure 3 displays a comparison of the corresponding vertical InSAR-derived velocity field with a set of features derived from previous Alpine studies. Figure 3a presents the ice extent corresponding to the Last Glacial Maximum (LGM, c.a. 18–20 ka) simplified from Ehlers and Gibbard (2004). As already pointed out by Sternai et al. (2019), the area of glacial extent matches at first order the region of uplift. Reciprocally, subsidence along the coast and in the Nice foreland would correspond to the foreland of LGM ice cover. Beside the first order agreement of geodetic uplift with LGM extent already observed in previous studies, we note that two uplifting massifs, the Pelvoux and the Argentera ones, are apparently not well collocated with the LGM ice extent. Figure 2d reveals that no GNSS data are available in the inner Pelvoux massif, while GNSS stations indicate either low uplift or null motion in the Argentera massif. Some deglaciation models predict measurable uplift rates of

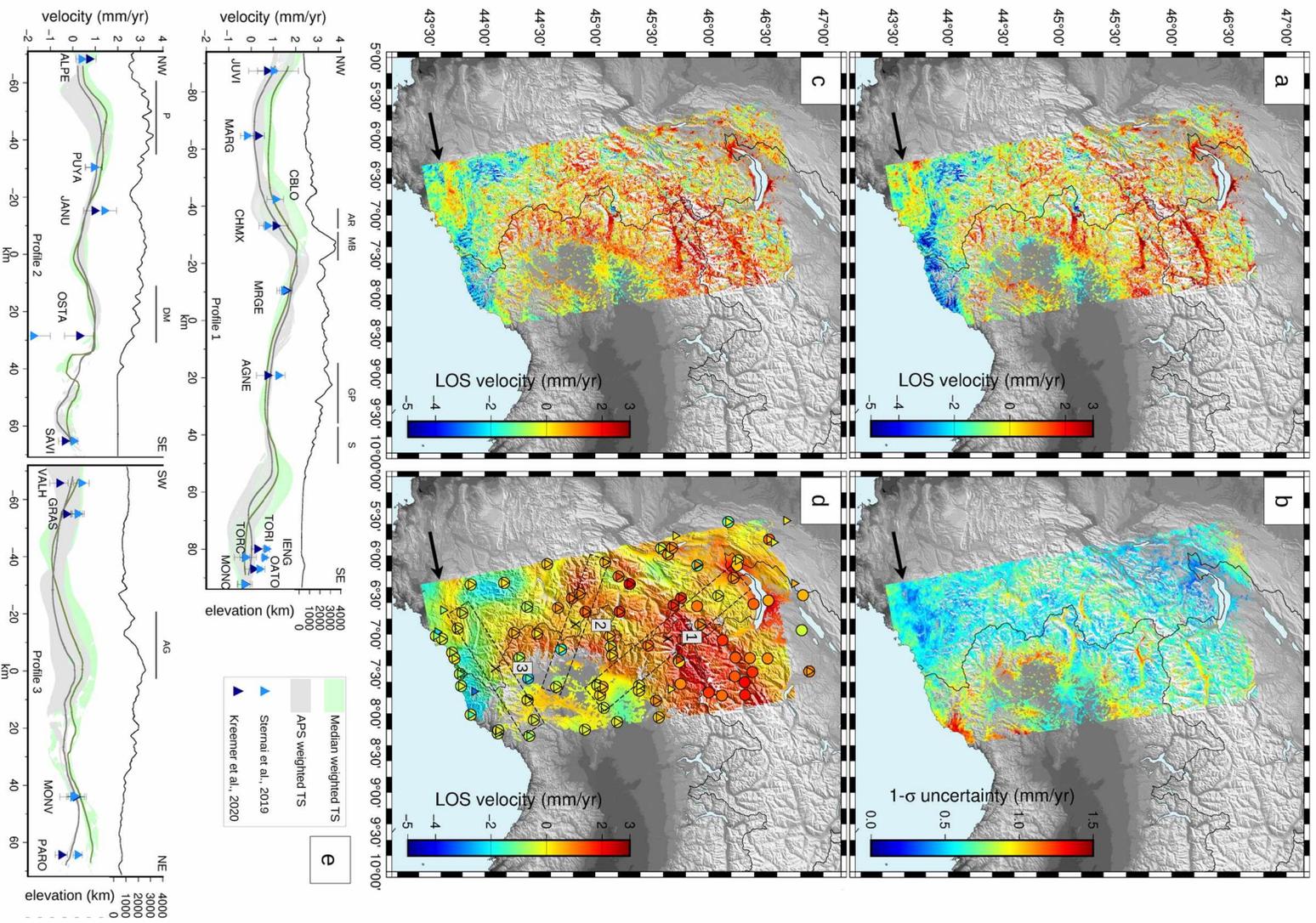
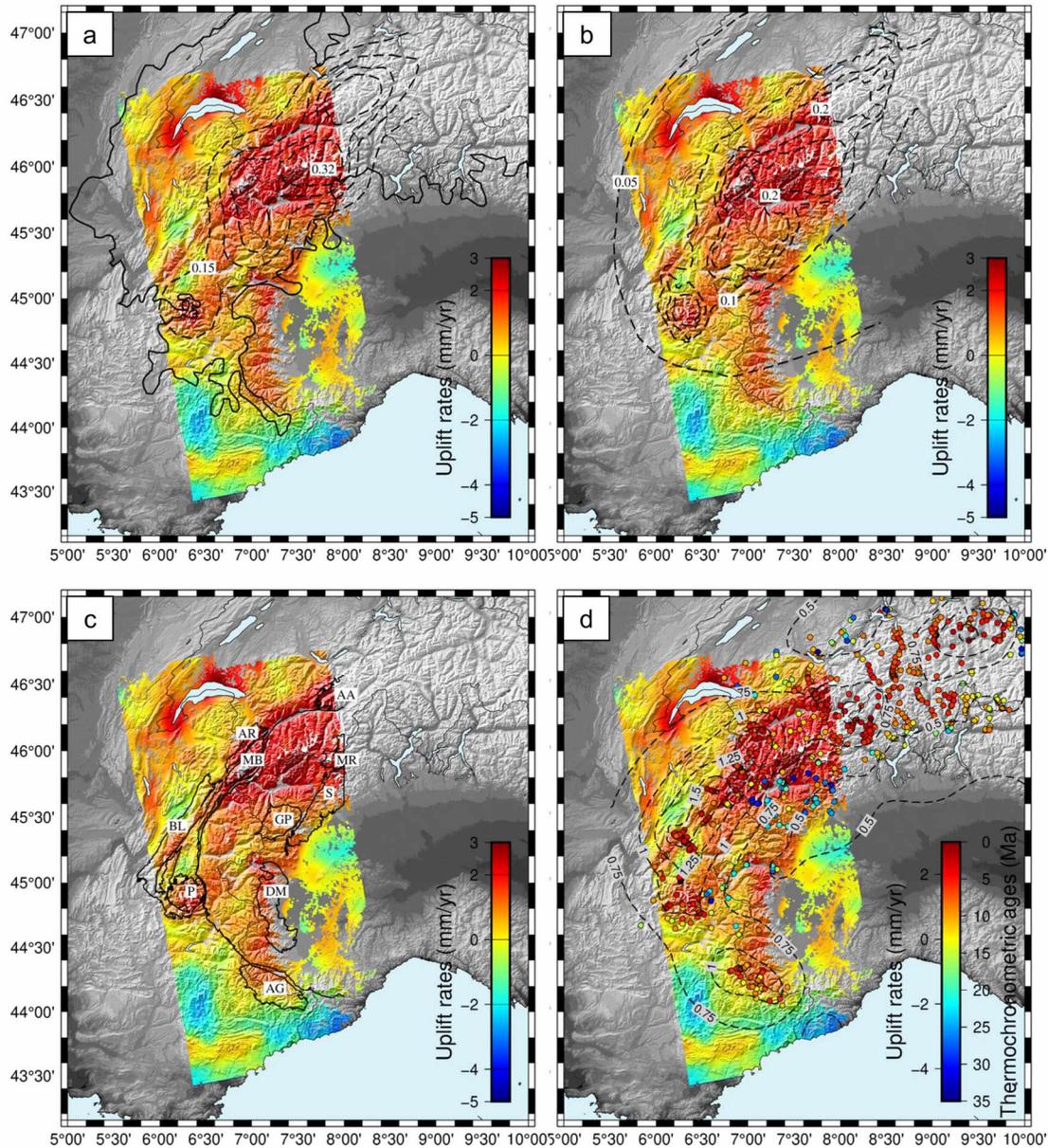


Figure 2.



**Figure 3.** Comparison of the vertical-converted velocity map with: (a) LGM extent (solid black line) from Ehlers and Gibbard (2004) and LIA-induced uplift rates (dashed isolines, mm/yr) modeled by Barletta et al. (2006); (b) uplift rates induced by present-day glacier shrinkage (dashed isolines, mm/yr) modeled by Barletta et al. (2006); (c) geological units (crystalline massifs) modified from Sue et al. (1999): AA = Aar, AG = Argentera, AR = Aiguilles-Rouges, BL = Belledonne, DM = Dora Maira, GP = Gran Paradiso, MB = Mont-Blanc, MR = Monte Rosa, P = Pelvoux, S = Sesia; and (d) Thermochronometric ages (colored circles) and corresponding exhumation rates (dashed isolines, mm/yr) shown in Fox et al. (2015).

**Figure 2.** LOS velocity maps and profiles. Black arrows west of the track show the satellite-viewing direction. The incidence angle varies from  $\sim 29^\circ$  in near range to  $\sim 41^\circ$  in far range. Positive/negative velocities represent motions toward/away from the satellite, respectively. (a) Linear velocity estimated on the median-filtered time series. (b)  $1-\sigma$  uncertainty map derived from the error analysis of the time series from (a). (c) Linear velocity estimated on the APS-weighted time series. (d) Comparison of the smoothed InSAR velocity field derived from the velocity map in (c) with GNSS velocities projected in LOS (same scale as InSAR) from Sternal et al., 2019 (circles) and from Kreemer et al., 2020 (triangles). Dashed lines represent the extent of the profiles in (e). (e) InSAR velocity profiles extracted from the median-filtered (green envelopes) and APS-weighted (gray envelopes) time series. Solid curves represent the median of the projected InSAR velocities, solid black lines the topography, and triangles the LOS velocities and  $1-\sigma$  uncertainties of the GNSS solutions from (d). Acronyms refer to the geological features displayed in Figure 3c.

the Pelvoux massif, such as Barletta's (2006) models of uplift rates due to deglaciation following the Little Ice Age (LIA, 18th-19th c., Figure 3a) and due to present-day glacier shrinkage (Figure 3b). The rates predicted by these models remain very low (locally up to 0.3 and 0.2 mm/yr, respectively) compared to the rates derived from geodesy, and their magnitude is hardly constrained, especially for the LIA rebound model (Barletta et al., 2006). Nevertheless, the spatial variations they feature are more robust (Barletta et al., 2006) and highlight a differential uplift in the Pelvoux massif with respect to the surrounding areas. The LGM rebound can explain up to 10%–30% of uniformly distributed uplift rate in the Western Alps according to various models (Barletta et al., 2006; Sternai et al., 2019; Stocchi et al., 2005). On the contrary, uplift rates due to LIA and present-day glacier shrinkage are lower (~6%–10% and ~4%–12% respectively of the maximum observed uplift rates, Barletta et al., 2006; Sternai et al., 2019), but their modeled spatial variations are in better agreement with those imaged here by InSAR.

When the InSAR-derived velocities are compared to the main crystalline massifs of the Alps (Figure 3c), it becomes obvious that uplift is limited to the geological Alpine belt, affecting both its external and internal massifs (AA to P in Figure 3c). Our results show a marked uplift pattern extending in the higher-elevation areas, especially along the Aar-Mont-Blanc-Belledonne axis, that was previously identified with geodetic measurements but at a lower resolution (Figure 2d; Masson et al., 2019; Nocquet et al., 2016; Walpersdorf et al., 2018; Sanchez et al., 2018). Our InSAR velocity field moreover reveals other areas with sharp contours of relative uplift to the south of this axis, for which spatial correlation with geological features (Pelvoux and Argentera massifs) could not be previously established based on GNSS measurements. We further compare InSAR velocities to exhumation rates estimated from thermochronometric ages in the Western Alps (Figure 3d; Fox et al., 2015). The Pelvoux and the Argentera massifs display young Apatite fission track ages similar to those retrieved in the Aar, Mont-Blanc, Belledonne and Aiguilles-Rouges massifs. The corresponding exhumation rates are above 1 mm/yr, which is 25%–50% more than in the surroundings. Other studies show that these crystalline massifs are associated with important erosion rates. For instance, the postglacial erosion model derived from sediment distribution in Mey et al. (2016) also displays higher erosion rates in the Argentera and Pelvoux massifs than in the surroundings. The observed coincidence of larger uplift rates, larger exhumation rates and larger erosion rates in crystalline massifs points toward retroaction mechanisms that help focus the vertical crustal response to external solicitations (erosional, glacial or slab unloading) or to internal buoyancy forces, in the absence of dominant horizontal convergence. This coincidence suggests that focused uplift is aided by inherited crustal weak features, faults or shear zones, or rheological heterogeneities (e.g., Herwegh et al., 2020).

## 5. Conclusions

This study provides the first velocity field derived by a multi-temporal InSAR analysis at the scale of the Western Alps. The retrieved regional patterns are in good agreement with GNSS measurements, displaying uplift at the center of the belt with a maximum localized on the higher-elevation parts of the belt, associated with subsidence at the periphery. Moreover, we improved the spatial resolution of the global uplift pattern derived from interpolated GNSS data. We observed that the maximum of uplift is localized along the Aar-Mont-Blanc axis, and that short-wavelength spatial variations of the uplift pattern appear correlated with geological crystalline massifs in the southern part of the Western Alps. Measured geodetic uplift rates are provided in the inner Pelvoux massif for the first time. These geodetic uplift patterns moreover mimic exhumation patterns derived on geological timescales (~5°Ma, Fox et al., 2015).

The relative uplift-rate contribution arising from each process affecting the belt today is a matter of debate (Sternai et al., 2019). It nevertheless appears that the spatial variability observed in the uplift pattern cannot be only induced by the LGM rebound, which acts on much larger wavelengths than the ones observed in this study (Barletta et al., 2006; Persaud & Pfiffner, 2004; Schlatter et al., 2005). It requires either additional processes acting at smaller wavelengths and/or differential localization mechanisms allowing large-scale processes to induce a more localized surficial response, in the presence of rheological or inherited lithospheric structural heterogeneities. Isostatic adjustment to LIA and present-day ice mass losses is likely to be included in these short-wavelength additional processes, as well as erosion and drainage. Larger-scale possible driving processes involve the crust buoyancy, the slab pull or detachment beneath the chain associated with the end of the convergence between Africa and Eurasia in the Western Alps. Beyond this undoubted complexity, this study points out the importance of InSAR measurements in low-deforming areas. Such measurements allow enhancing the spatial resolution of

the derived ground motions, thus providing important elements for further analyzing the complex interactions between driving forces and the heterogeneous response of the lithosphere.

## Data Availability Statement

The Sentinel-1 data are available at <https://scihub.copernicus.eu/dhus/>. The InSAR velocity solutions are available at <https://doi.org/10.5281/zenodo.5763672>. This work was made possible thanks to the CIMENT/GRICAD infrastructure (<https://gricad.univ-grenoble-alpes.fr>). The GNSS solution from Kreemer et al. (2020) is distributed online (doi:10.7910/DVN/ONATFP).

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