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Use of PSInSAR™ data to infer active tectonics: Clues on the differential uplift across the Giudicarie belt (Central-Eastern Alps, Italy)

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ABSTRACT

The Permanent Scatterers Synthetic Aperture Radar INterferometry (PSInSAR™) methodology provides high-resolution assessment of surface deformations (precision ranging from 0.8 to 0.1 mm/year) over long periods of observation. Hence, it is particularly suitable to analyze surface motion over wide regions associated to a weak tectonic activity. For this reason we have adopted the PSInSAR technique to study regional movement across the Giudicarie belt, a NNE-trending trust belt oblique to the Southern Alpine chain and presently characterized by a low to moderate seismicity. Over 11,000 PS velocities along the satellite Line Of Sight (LOS) were calculated using images acquired in descending orbit during the 1992–1996 time span. The PSInSAR data show a differential uplift of around 1.4–1.7 mm/year across the most external WNW-dipping thrusts of the Giudicarie belt (Mt. Baldo, Mt. Stivo and Mt. Grattacul thrusts alignment). This corresponds to a horizontal contraction across the external part of the Giudicarie belt of about 1.3–1.5 mm/year.

1. Introduction

Since the 1993 work of Massonet et al. dealing with the co-seismic ground movements related to the Landers earthquake (California, 28 June 1992, Mw 7.3; e.g. Kanamori et al., 1992; Sieh et al., 1993), the remote sensing Synthetic Aperture Radar INterferometry (InSAR) has been extensively used for active deformation assessment. InSAR provides a one-dimensional measurement of change in distance between the surface and the spacecraft along the Line Of Sight (LOS or slant-range) of the Synthetic Aperture Radar (SAR) sensor. In the field of fault tectonics InSAR processing has been extensively applied to record co-seismic (e.g. Zebker et al., 1994; Massonet et al., 1994; Tobita et al., 1998; Pedersen et al., 2003; Wang et al., 2006) and post-seismic (e.g. Peltzer et al., 1996; Atzori et al., 2008) signatures, derive focal mechanisms, fault geometry and in general source models (e.g. Feigl et al., 1995; Acoglu et al., 2006; Peyret et al., 2008; Sudhaus and Jonsson, 2009) and even evaluate inter-seismic strain (Cavaliè et al., 2008).

However, the major draw-back of the classical InSAR techniques, which rely on a stack of several interferograms, is the possible lack of coherence between the time delayed SAR couples acquired on vegetated and/or mountain areas and/or in different atmospheric conditions. A recent InSAR technique, the Permanent Scatterers Synthetic Aperture Radar INterferometry (PSInSAR™) (Ferretti et al., 2000, 2001; Colesanti et al., 2003), allows the identification and use, during the interferometric process, of radar phase stable points normally corresponding to buildings or single outcrops (i.e. permanent scatterers). This strongly minimizes phase dispersions and the consequent loss of coherence between time delayed acquisitions. Hence, although this method does not give regional uniformly distributed information on surface movements as the classic InSAR procedure, it is particularly suitable for high-resolution assessment of surface deformations (precision up to 0.1 mm/year) to be realized over a long period of observation using a great amount of SAR images. For these reasons PSInSAR has recently proved to be very effective in resolving surface motion of seismic areas during inter-seismic periods or even of wide regions presently involved by very low tectonic movements (provided that a detection of a considerable amount of PS is guaranteed) (Bürgmann et al., 2006; Vilardo et al., 2009).

In this work we have applied the PSInSAR method to obtain new insights into the present-day deformation pattern of the southern Giudicarie belt, which is a key sector of great tectonic complexity within the post-collisional south-vergent thrust system of the Southern Alps (Italy) (Castellarin et al., 2006; Massironi et al., 2006; Viganò et al., 2008).

2. The Giudicarie belt

2.1. Geological setting

The post-collisional south-vergent belt of the Southern Alps shows its maximum complexity at the Giudicarie belt. NNE-trending system

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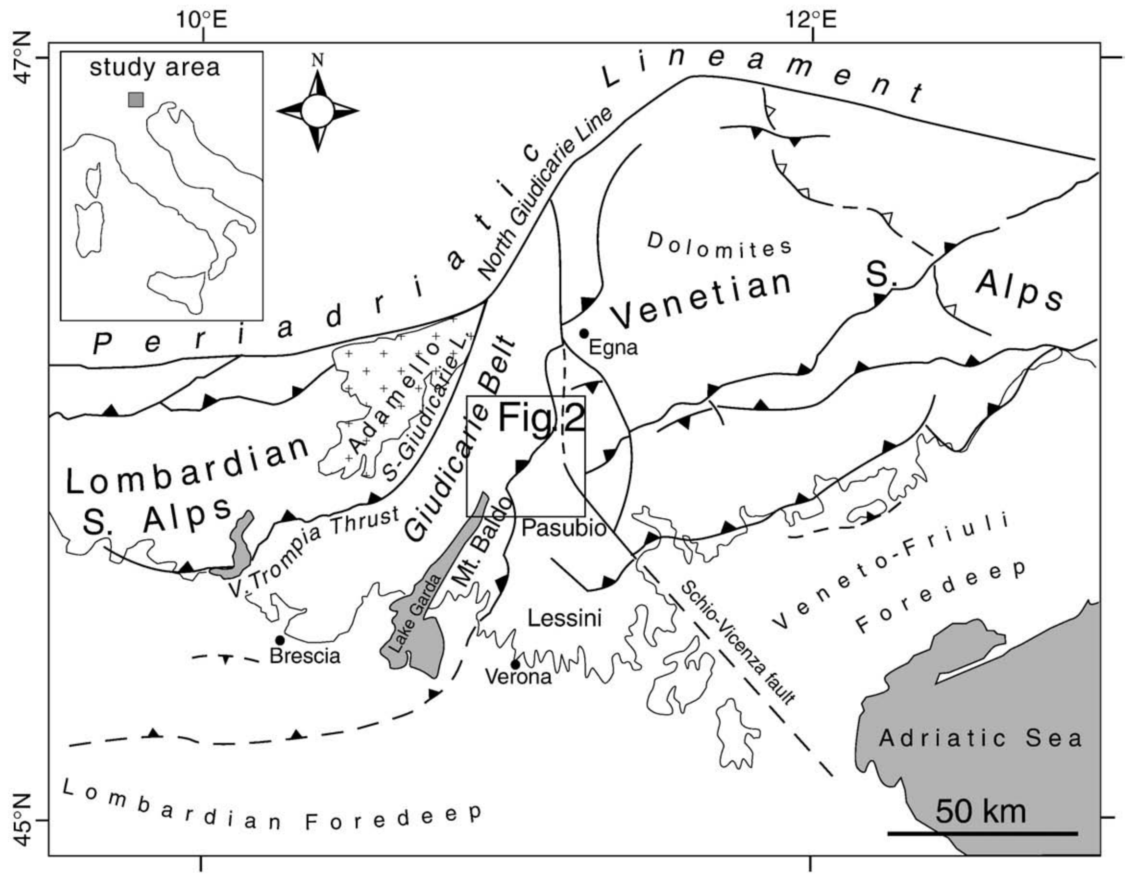

Fig. 1. Structural sketch of the central and eastern Southern Alps.

is oblique to the Southern Alps chain (Fig. 1) and results from tectonic reactivation and inversion of an Early Jurassic extensional domain related to the continental rifting of the Adria margin (e.g., Bertotti et al., 1993). On the whole, the southern Giudicarie belt develops along the transition between basinal (Lombardy basin) and platform (Venetian platform) domains (Trevisan, 1939; Castellarin, 1972), where many sub-basin depocentres have formed. These basins are bounded by steep to middle angle synsedimentary faults, generally dipping towards the west and E–W steep transfer faults (Castellarin and Picotti, 1990).

The Giudicarie fault system exhibits a structural boundary also at crustal (Scarascia and Cassinis, 1997) and lithospheric (Lippitsch et al., 2003) scales.

In its southern sector (south of the intersection with the Tonale fault, Fig. 1) the Giudicarie fault separates the Tertiary Adamello batholith and the Variscan basement to the west and northwest from the sedimentary cover of the Southern Alps with thin basement slices to the east. The South Giudicarie fault system is composed of WNW-dipping steep to subvertical fault planes, which being oblique to the Alpine belt have accommodated transpression. Its Neogene kinematic role is that of an oblique ramp of the S-vergent Val Trompia thrust to which it is connected towards the south (Picotti et al., 1995) (Fig. 1). Slip partitioning has produced distributed sinistral strike-slip movements on steep faults and dip-slip reverse movements on moderate dipping N to NNE-trending faults within a wide belt comprised between the Giudicarie and Adige valleys (Prosser, 1998; Viola et al., 2001; Massironi et al., 2006).

The study area has been affected by strong exogenic modelling related to the Late Pleistocene glacial activity and post-glacial fluvial erosion. Therefore, most geomorphic evidence of Quaternary tectonics has been strongly modified and often completely erased, and the depositional units suitable for dating are quite rare. The only case worthy to be mentioned is the southern Mt. Baldo, an area where several historical earthquakes are reported (Boschi et al., 2000). The ridge of the Mt. Baldo is displaced by a 4.5-km-long normal fault, which originated the narrow Naole valley parallel to the ridge. Trenches excavated at the base of the fresh carbonate bedrock scarp affecting the western slope of the Naole valley have shown an activity of the fault between the Late Pleistocene and Holocene (subsequent to 17,435–16,385 BP, ^{14}C cal. age, Galadini et al., 2001). A mixed gravitational-tectonic origin for this deformation has been suggested by Galadini et al. (2001) and Sauro and Zampieri (2001).

2.2. Seismotectonic setting

The Giudicarie belt is characterized by low instrumental seismicity (Slejko et al., 1989; Carulli and Slejko, 2009) with few moderate earthquakes (Pondrelli et al., 2007), most of which are located in the upper crust (Scarascia and Cassinis, 1997; Viganò et al., 2008). The most important historical earthquakes (I_0 IX MCS) for northern Italy occurred in 1117 in the Verona area and in 1222 near Brescia (Guidoboni, 1986; Guidoboni and Comastri, 2005; Guidoboni et al., 2005; Stucchi et al., 2008), both located just at the southern end of the belt. Along the Adige valley, the Roman archaeological site of Egna shows evidences of destruction related to an earthquake of similar intensity that happened in the mid 3rd century AD (Galadini and Galli, 1999; Galadini et al., 2001; Stucchi et al., 2008). In addition, Quaternary faults have been recently located within the epicentral area of the strong 1222 Brescia earthquake (Sileo et al., 2007; Livio et al., 2009a,b).

The strongest recent events are the Mw 4.8 Merano earthquake, which occurred on 17 July 2001 close to the North Giudicarie Line (Caporali et al., 2005; Pondrelli et al., 2006) and the M_L 5.3 Salò event, which struck the western coast of the Lake Garda on 24 November 2004 (Baer et al., 2005; Pondrelli et al., 2006).

In the seismic source model for seismic hazard assessment (Meletti et al., 2008) this region has been included in a common zone where the NW-trending strike-slip faults of the Schio-Vicenza fault system and the NNE-trending Giudicarie transpressional system interact. In fact, the distribution of the events which occurred during the last decades is clustered around the junction between the Giudicarie and the Schio-Vicenza systems, just north of the apex of the triangular-shaped Lessini block. The calculation of focal mechanisms from relocated events has permitted Viganò et al. (2008) to demonstrate that in the Giudicarie belt the stress regime is consistent with oblique-reverse fault kinematics of the NNE-trending faults and the horizontal compressive stress axis is NW-trending. This regime is quite different with respect to the strike-slip regime of the neighbouring Lessini area, where the direction of the maximum horizontal compressive stress axis is approximately N–S (Viganò et al., 2008).

3. The PSInSAR™ data

Satellite interpherometric data, provided by the Provincia Autonoma di Trento (PAT), allowed the active differential uplift among different crustal blocks across the Giudicarie belt to be assessed. These data were obtained through the “Permanent Scatterers (PS) Technique” (Ferretti et al., 2000, 2001) using a temporal series of 80 ERS1 and ERS2 images acquired in descending orbits and in a period covering the 1992–1996 time span (Track 165, Frames 2673 and 2691).

Satellite INterferometry of Synthetic Aperture Radar data (InSAR) is based upon phase comparison of SAR images acquired at different times and views (Curlander and McDonough, 1991). The Permanent Scatterers are high RADAR reflecting objects that do not change their spectral response for different acquisitions (i.e. mainly edifices and other anthropic objects affected by corner effects, and natural exposed polished surfaces). For this reason the phase dispersion due to the temporal and geometrical decorrelation phenomena, that negatively affect RADAR interferometry, is strongly minimized using PS as measurement points. The final result is an accurate measurement of the movements along the SAR Line Of Sight (LOS velocities) of each PS with respect to an assumed stable point (Reference point or REF) during the time span considered. Since the LOS of a descending orbit is west directed and only slightly off-nadir looking (about 23°), the PS movements can be fairly related to the PS uplift (Bürgmann et al., 2000). The surface elevation changes along the LOS, in terms of differential displacement between two PS, can be determined with a precision ranging from 0.1 to 1 mm/year depending on the PS coherence (Colesanti et al., 2003; Ferretti et al., 2007). The PS coherence is a normalized index of the local signal to noise ratio of the interferometric phase (Hanseen, 2001; Colesanti et al., 2003). The data set here considered was calculated using a REF point at Trento town centre (Gauss–Boaga coordinates: north: 5103161.50; east: 1664454.75) and consists of 11,038 points (Fig. 2) with a coherence higher than 0.56 which means a PS annual mean velocity estimates within 0.8 mm/year of accuracy (2003 data set from Tele-Rilevamento Europa - T.R.E. s.r.l.).

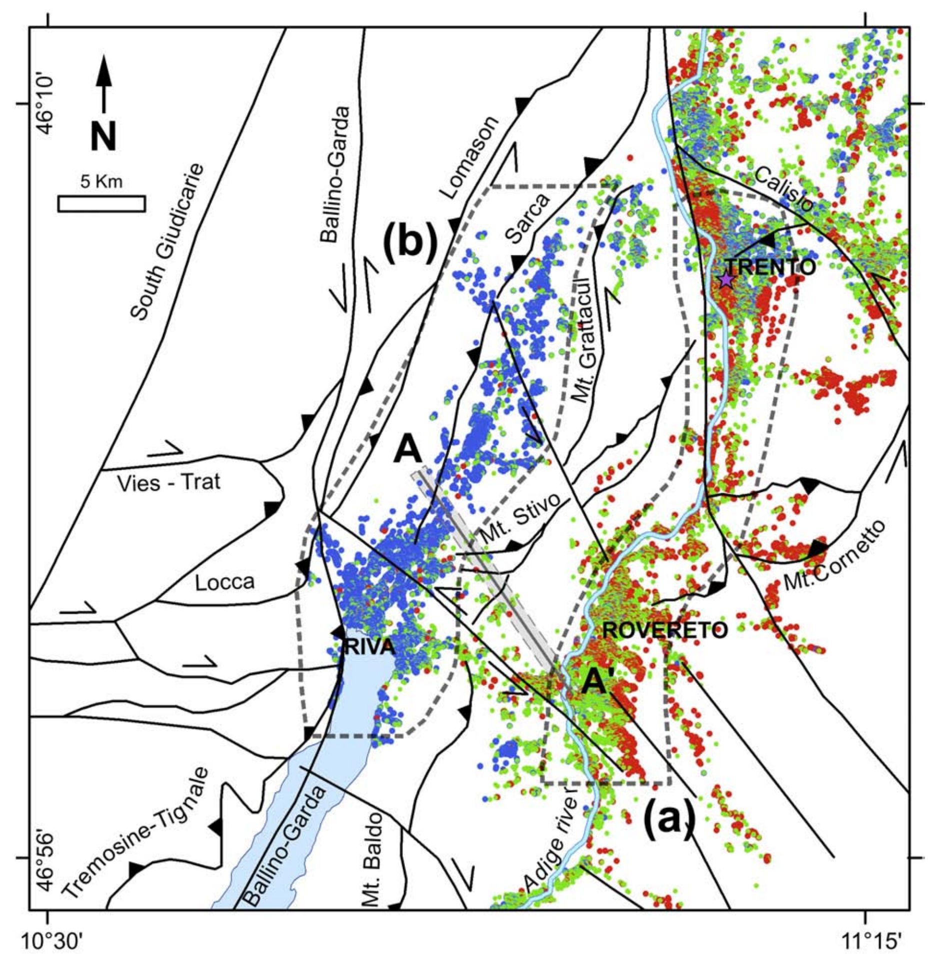

Fig. 2. PSInSAR data of the Adige (a) and Sarca (b) valleys. Blue dots: Uplifting Permanent Scatterers (>0.8 mm/year); green dots: stationary Permanent Scatterers ($0.8 \leq$ velocity ≥ -0.8 mm/year); red dots: subsiding Permanent Scatterers (< -0.8 mm/year). A–A' is the trace of the cross-section of Fig. 4. The PS–LOS velocities within the 1000 m wide grey buffer were plotted in Fig. 4. The star is the Trento Reference point (REF).

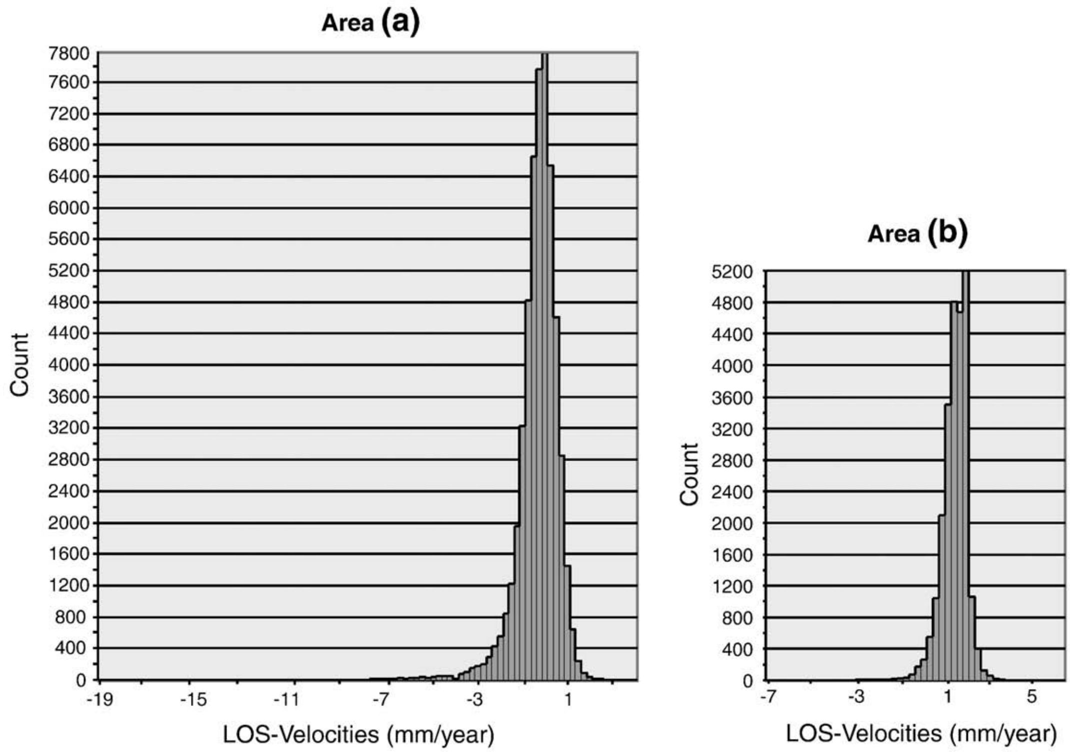

Fig. 3. Histograms of the PSInSAR velocities distribution in the Adige (a) and Sarca (b) valley areas as defined in Fig. 2.

The use of PSInSAR measurements for our regional tectonic study of a mountain area affected by a moderate tectonic activity must take into account the following points: i) the limited time of observation (1992–1996); ii) the PS distribution is not uniform since PS are preferentially concentrated in towns, villages and along main valleys, while they are almost lacking on the most relieved areas because they are less inhabited, vegetated and strongly affected by foreshortening, layover and shadowing effects on the related SAR images; iii) the estimations of the PS annual velocities are very accurate in the range of 1 km from the REF (precision around 0.1 mm/year) but decrease in accuracy when larger distances are considered (in our case up to 0.8 mm/year); iv) the velocity outliers (located outside 2 standard deviation of the LOS velocity distribution and reaching up to +6 mm/year and −20 mm/year), are not related to tectonics but to landslides, quarries, excavations and urban growth (see for example blue PS east and north of Trento, Fig. 2); v) although the LOS velocities fairly approximate vertical strains, the true vertical and horizontal components can be estimated only with a data set acquired in both ascending and descending orbits (Vilardo et al., 2009) or, alternatively, GPS-derived horizontal velocity field can be used to eliminate its contribution on the PSInSAR measurements and consequently obtain the true vertical component (Burgmann et al., 2006; Ferretti et al., 2007). Both these procedures can not be applied in our case since only a descending orbit data set is available and the region lacks a dense GPS network.

For these reasons the PSInSAR data were evaluated in a map view considering PS with LOS velocities between −0.8 mm/year and +0.8 mm/year as stable points, PS with LOS velocities >0.8 mm/year as uplifting points and PS with LOS velocities <−0.8 mm/year as subsiding points (Fig. 2). Hence, the PS LOS velocities distribution has been plotted for two wide and representative areas: one at the footwall of the Giudicarie belt frontal thrusts (Adige valley, area "a" in

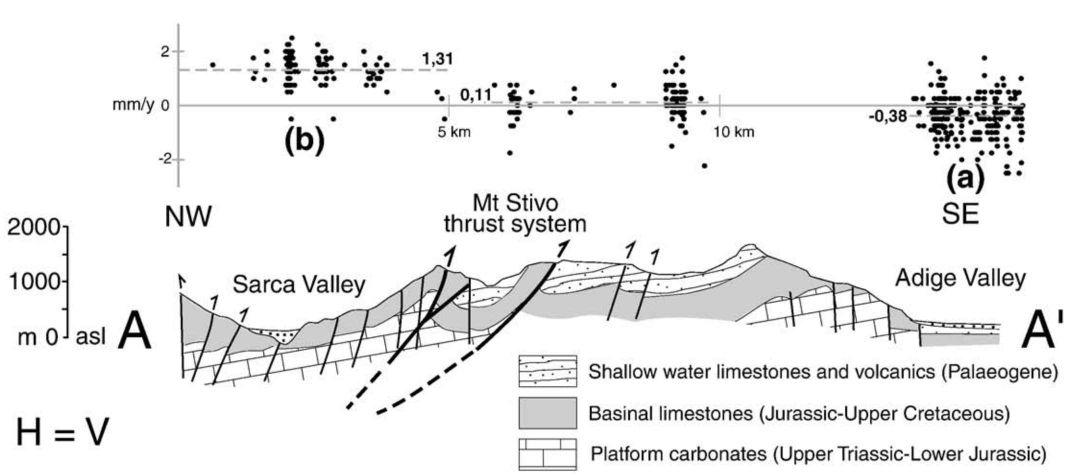

Fig. 4. Schematic cross-section of the frontal part of the Giudicarie belt (trace in Fig. 2; modified from Castellarin et al., 2005) and related PS–LOS velocities. Mean PS–LOS velocities of three subgroups across the Mt. Stivo thrust system show an uplift decrease from the west (hanging wall, sector "b" of Fig. 2) to the east (footwall, sector "a" of Fig. 2).

Figs. 2 and 3) and the other one at the hanging wall (Sarca valley, area “b” in Figs. 2 and 3). In addition, LOS velocities have been plotted also against a key geological section crossing the Giudicarie belt in order to quantitatively estimate the motions across its most external thrusts (Fig. 4). In this case the plotted LOS velocities derive from a 1 km wide corridor containing the geological section and were projected perpendicularly to the section (Fig. 2).

4. Results and discussion

The results show a wide and unequivocally uplifting area along the lower Sarca valley west of the Giudicarie belt frontal thrusts (i.e. Mt. Baldo, Mt. Stivo and Mt. Grattacul thrusts alignment) (Fig. 2). This area (“b” in Fig. 2) is strongly dominated by uplifting PS, whereas subsiding points are almost lacking or are due to local effects (landslides, quarries, and excavations). In this case on a total amount of 24,194 PS, only 134 have LOS velocities <-0.8 mm/year, whereas the uplifting PS are 16,940 rising to 23,021 if LOS velocities $>+0.1$ mm/year are considered. By contrast, uplift is almost absent along the Adige valley between Rovereto and Trento, where subsiding and stationary PS prevail. This can be quantitatively evaluated comparing the mean LOS velocities value of the Sarca valley data set (area “b” in Fig. 3: 24,194 points) which is 1.09 mm/year with a sigma of 0.59, with the LOS velocities to the east of the Giudicarie belt (Adige valley area “a” in Fig. 3: 53,432 points) that are distributed around a mean of -0.31 mm/year with a standard deviation of 0.99 (Fig. 3).

Since the velocities considered are referred to a REF point at Trento town, the PSInSAR data record a still active motion between the uplifting crustal block at the hanging wall of the Giudicarie belt frontal thrusts and a sector to the east showing velocities comparable to the REF.

In Fig. 4 LOS velocities are plotted against a geological section derived from Castellarin et al. (2005) and showing one of the major external thrust of the Giudicarie belt, the Mt. Stivo thrust system. The differential uplift across this system actually represents the relative motion between Sarca and Adige valleys. Thanks to the low off-nadir angle of looking direction (around 23°) LOS velocities roughly approximate vertical motions, hence according to Figs. 2 and 4 the Mt. Stivo thrusts and/or the anticlinalic fault propagation folds at their hanging wall should accommodate a total amount of around 1.4–1.7 mm/year of differential uplift (mean LOS velocity at the hanging wall $=+1.31$ mm/year vs mean LOS velocity at the footwall $=-0.38$ mm/year along the cross-section of Fig. 4 or mean LOS velocity of area “b” $=+1.09$ mm/year vs mean LOS velocity of area “a” $=-0.31$ mm/year in Fig. 2). In more detail, this differential uplift seems to be mainly due to the activity of the westernmost thrust fault of the system (Fig. 4). From the geological map and sections of Castellarin et al. (2005) the Mt. Stivo thrusts trend N44E and dip toward the NW with an angle of 48°. On the basis of the regional stress tensor calculated by Viganò et al. (2008) for the Giudicarie belt (principal stress axes: $\sigma_1=142/30$, $\sigma_2=247/24$, $\sigma_3=009/50$; $R=(\sigma_2-\sigma_1)/(\sigma_3-\sigma_1)=0.8$), it is possible to derive the tangential shear resolved on the Mt. Stivo thrusts surface and, consequently, the related slip vector (Fig. 5). This trends N355 with a plunge of 39° showing a nowadays transpressional activity of this structure (pitch = 301°). On the basis of the tangential shear orientation and the relative uplift across the Mt. Stivo thrust system, the movement along the slip vector of all the block at its hanging wall (i.e. the Sarca valley area) can be estimated around 2.2–

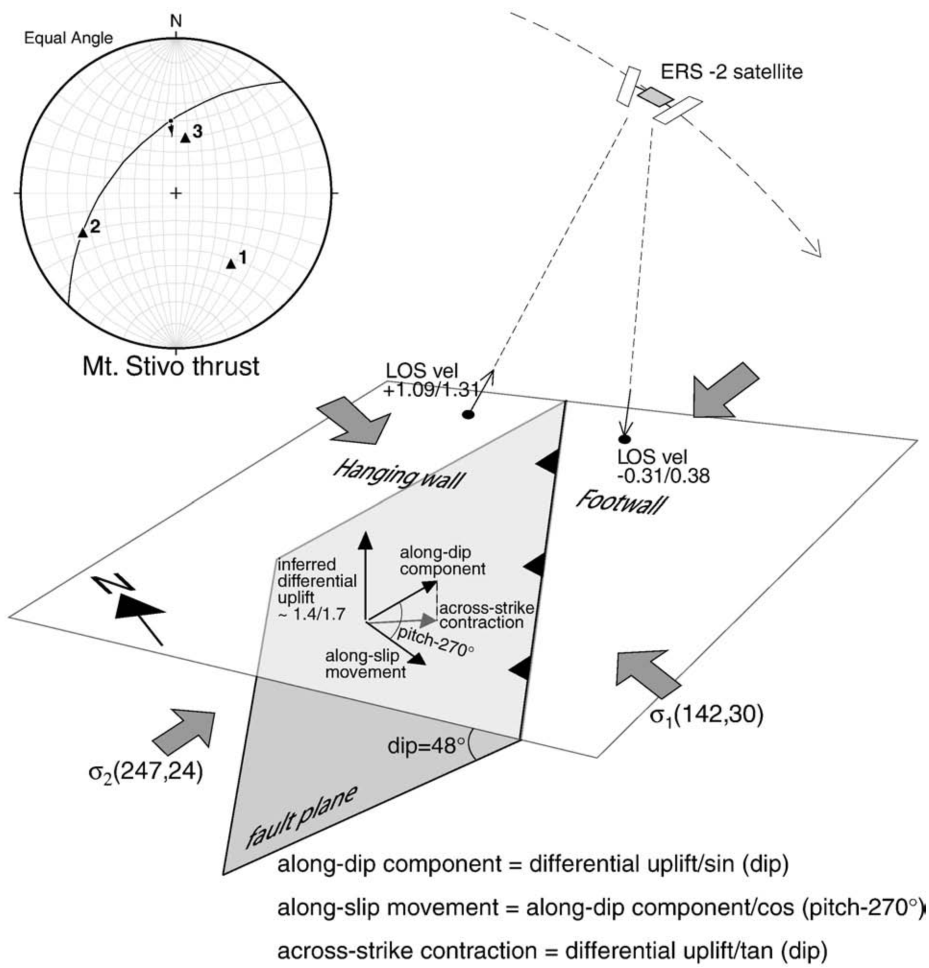

Fig. 5. Sketch of the Mt. Stivo fault plane parameters and kinematics derived from the regional stress field (Viganò et al., 2008) and PSInSAR LOS velocities.

2.6 mm/year (along slip movement = along dip component / cos(pitch − 270°) = [(differential uplift) / sin(fault dip)] / cos(pitch − 270°)).

Hence, the WNW–ESE horizontal contraction (differential uplift / tan (fault dip)) across Mt. Stivo thrust system should be around 1.3–1.5 mm/year and gives a quantitative idea of the relative convergence between the Sarca and Adige valleys accommodated by the most external thrusts of the Giudicarie belt (Fig. 5). This rate is similar to that predicted by the GPS data in the western Southern Alps between Brescia and Varese (Serpelloni et al., 2005), an area struck by historical earthquakes of considerable intensity, hence consistent with the archaeoseismological and paleoseismological data, which indicates the occurrence of strong earthquakes in the region (Stucchi et al., 2008).

5. Conclusion

The PSInSAR analysis has enabled us to quantitatively assess the active deformation across the Giudicarie belt, which is one of the most complex sectors of the Southern Alps and is characterized by a low to moderate seismic activity. In particular, the PSInSAR data show that the Sarca valley is rising with respect to the Adige valley of around 1.4–1.7 mm/year (LOS velocities). According to the regional tectonic framework this differential uplift must be attributed to the transpressional activity of the most external thrusts of the Giudicarie belt: the Mt. Baldo, Mt. Stivo and Mt. Grattacul thrusts alignment. Assuming the PSInSAR velocities as representative of the vertical deformation and using the known attitude of the Mt. Stivo thrust and the seismotectonically derived regional stress field (Viganò et al., 2008) we speculate an average along slip movement of the Mt. Stivo thrust system of 2.2–2.6 mm/year ca. This value roughly corresponds to 1.3–1.5 mm/year of WNW–ESE convergence across the external part of the Southern Giudicarie belt and strongly supports its ongoing activity that, on the other hand, is only poorly expressed by surface features.

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