Current strain regime in the Western Alps from continuous GPS measurements, 1996-2001

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ABSTRACT
Four to six years of continuous measurements at 10 permanent GPS sites in the Western Alps show horizontal residual velocities with respect to stable Europe less than 2 mm/yr, with uncertainties ranging from 0.3 mm/yr to 1.4 mm/yr. These velocities and the associated strain rate field indicate that the central part of the range is currently dominated by E-W extension, whereas the southern part shows N-S to NW-SE compression. The geodetic and seismotectonic data are consistent with a model where strain is essentially controlled by the counterclockwise rotation of the Adriatic micro-plate with respect to Eurasia. This rotation, together with the arcuate shape of the contact between the Adriatic microplate and the Alps, induces dextral shear kinematic boundary conditions across the Western Alps, with an additional divergence component in their central part and in Switzerland, and a convergence component in their southern part.

Keywords: Western Alps, continuous GPS, extension, Adriatic plate.

Introduction
The western part of the Alpine range, hereafter called the Western Alps, is among the best-studied collisional belts in the world. Its present-day tectonic activity is demonstrated by moderate seismicity and sparse geological and geomorphological observations of recent deformation. However, the present day kinematics of the deformation in the belt is still largely unknown. The current strain regime in the Western Alps is often thought of as the continuation of Miocene to early Pliocene crustal shortening. However, Seward and Mancktelow (1994) showed that the distribution of zircon and apatite fission-track ages southeast of the Mont Blanc and Belledone massifs implies a reactivation of the Pennine thrust as a major crustal-scale normal fault in the Neogene-Quaternary. In addition, earthquakes principally accommodate extension and are mostly concentrated in the inner parts of the range and down to a depth of 15 km, except for a cluster of deeper compressional events at the transition with the Po plain along the Ivrea body (Figure 1B). In this paper, we use a network of permanent GPS stations covering the Western Alps and their surroundings to determine the strain distribution and far-field kinematic boundary conditions across the range.

GPS network and data processing
Permanent GPS stations provide unique data sets for assessing crustal deformation in regions of low strain rates because they provide continuous position time series to rigorously estimate measurement accuracy, reduce the amount of time necessary to detect a significant strain signal, and minimize systematic errors. In 1997, we started the implementation of a network of permanent GPS stations in the Western Alps and their surroundings (REGAL network; Calais et al., 2001). We have processed a continuous GPS data set over Europe spanning the 1996-2001 time period with the GAMIT software (King and Bock, 2001), using a homogeneous processing strategy (Calais,1999). The precision of our daily GPS measurements, quantified by their long-term daily repeatabilities, is 2-3 mm horizontally and 5-10 mm vertically, typical for such networks. Using a noise model that combines white and flicker noise (e.g. Mao et al., 1999) we find velocity uncertainties ranging from 0.5-1 mm/yr for the 9 oldest stations, to 4-5 mm/yr for the 3 most recently installed ones. We routinely combine each independent daily solution into a single unconstrained multi-day solution (called hereafter the REGAL solution).

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In a second step, we combine the REGAL solution with (1) a subset of the International Terrestrial Reference Frame (ITRF2000) solution containing the 37 best determined sites over western Europe, (2) a solution derived from the European permanent GPS network (EUREF-EPN) weekly analysis, (3) a solution derived from the French national permanent GPS network (RGP). The combination methodology consists of removing a priori constraints from individual solutions, applying minimal constraints to each solution, rescaling the variance of individual solutions in order to obtain realistic formal errors on velocities, and solving for a unique velocity field from the four data sets. The combined solution is expressed in the ITRF2000 datum. This combination strategy ensures maximum redundancy in order to minimize systematic errors potentially present in the individual solutions. The wrms (weighted root mean square) of the individual solutions in the combination indicates the level of agreement between the four input solutions for their common stations. It is on the order of 0.4 mm/yr or better for horizontal velocities (Table 1).

Velocity and Strain Rate Fields

In a third step, we derive a stable Europe reference frame by removing a rigid rotation calculated using the velocities of 12 stations located in central Europe, away from major active deformation areas. We find a stable Europe-ITRF2000 rotation pole located at 55.8°N/10.2°E with an angular rate of 0.25±0.003°/Ma. The weighted rms of the residuals at the sites used to define stable Europe is 0.4 mm/yr. This approach is independent from the NNR-NUVEL-1A plate motion model and benefits from the consistency of our velocity field combination over Europe. It makes use of all the available geodetic techniques and of the full covariance matrix of the ITRF2000 SINEX file.

We obtain the velocity field with respect to stable Eurasia by subtracting the stable Europe rotation defined above from the ITRF2000 velocities (Figure 1 and Table DR2). We find that the sites located in the Western Alps have residual motions less than 2 mm/yr with respect to stable Europe, in agreement with earlier studies (Calais, 1999). The velocity uncertainties at the sites presented here range from 0.17 mm/yr at Grasse (derived from Satellite Laser Ranging data and 6 years of continuous GPS data) to 1.2 mm/yr at CHTL (2.5 years of continuous GPS data). We find an insignificant residual velocity at SJDV (0.2±0.3 mm/yr), in the Alpine foreland, and 1.0±0.6 mm/yr in a N180 azimuth at TORI, in the Po plain. Along a profile between SJDV and TORI, we observe SE-directed velocities at FCLZ, CHTL, and MODA, with an increase in rate from west to east, from 0.5±0.9 mm/yr at FCLZ to 1.7±0.4 mm/yr at MODA. The SJDV-MODA baseline, that crosses the Pennine thrust, shows lengthening at a rate of 1.4±0.4 mm/yr (Figure 2).

We find low strain rates, always less than 0.5 ?strain/yr, usually on the order of 0.02 ?strain/yr or less (Figure 1A). Their spatial distribution shows very low values in the external zones and the Alpine foreland (less than 0.01 ?strain/yr), except in the southern part of the Western Alps and in Provence. The strain rates are higher in the central part of the range (greater than 0.02 ?strain/yr). The strain rate tensors in the polygons including MODA and located west of this site all show E-W to NW-SE extension.

Internal deformation of the Western Alps

Our data indicate that the current strain regime in the central part of the Western Alps is extensional. This result is consistent with the seismotectonic data of Eva et al. (1997) and Sue et al. (1999), and with the fission track data of Seward and Mancktelow (1994). The geodetic results further indicate that extension affects the entire central part of the Western Alps. Given the scale of the network (~100 km station spacing) and the precision of the velocity estimates, it is not possible at this point to determine wether this is due to the Pennine fault being locked and accumulating elastic strain or whether extension is distributed over the whole central part of the Western Alps. The strain regime is significantly different in the southern part of the Western Alps and in Provence, with strain rate tensors showing mostly NW-SE to N-S compression (Figure 1A). This result is also illustrated by shortening of the GRAS-TORI baseline at a rate of

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3 GSA Data Repository item 2002##, [Table 1, Weighted root mean squares of individual solutions in the combination], is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA editing@geosociety.org, or at www.geosociety.org/pubs/ft2002.htm.

4 GSA Data Repository item 2002##, [Table 2, Velocity values issued from the combination of EUREF, REGAL and RGP permanent GPS arrays with a selection of ITRF2000 sites], is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA editing@geosociety.org, or at www.geosociety.org/pubs/ft2002.htm.
1.4±0.5 mm/yr (Figure 2). It is consistent with a local geodetic survey (Calais et al., 2000) and seismotectonic studies (Madeddu et al., 1997; Baroux et al., 2000), which also show a current N-S to WNW-ESE compressional regime in the southern part of the Western Alps and in Provence.

Eva et al. (1997) proposed that extension in the Western Alps results from tensional strain at the crest of a crustal-scale ramp anticline in a general NW-SE or N-S compressional stress regime. Schwartz et al. (1999) proposed the upward extrusion of a rigid mantle indenter in a general E-W compressional regime. That extrusion would reactivate older thrusts, such as the Pennine thrust, as normal faults. These two models require E-W to NW-SE convergence between the Po plain and the Alpine foreland, which is not observed in our geodetic data. Seward and Mancktelow (1994) proposed that the reactivation of the Pennine thrust as a normal fault was the result of the exhumation of the Mont Blanc and Belledone external crystalline massifs in response to right-lateral transpression along the Simplon-Belledone fault zone. This transpression is not observed in the geodetic data, neither at the scale of the Belledone fault, nor at the larger scale of the Western Alps. Also, this model does not explain the fact that extension is not limited to the Pennine thrust, but seem to affect the entire central part of the range. Sue et al. (1999) proposed that boundary forces due to NW-SE convergence between the Po plain and the Alpine foreland are superimposed on buoyancy forces due to a lithospheric instability (slab roll-back or slab detachment). Following up on the idea of Lyon-Caen and Molnar (1989) that buoyancy forces resulting from the detachment of a lithospheric slab drive current uplift of the Western Alps, Sue et al. argue that buoyancy dominates the force balance and induces extension in a radial pattern perpendicular to the range. However, their model does not explain the spatial variation of strain regime from E-W extension in the central part of the Western Alps to NS to NW-SE compression in the southern part. Gravitational collapse has also been invoked to explain tensional strain in areas of overthickened crust such as mountain ranges or Basin-and-Range-type high-elevation plateaus (e.g. Molnar and Lyon-Caen, 1988). Sue et al. (1999) argue that such a process is not compatible with the low average altitude of the extensional areas in the Western Alps. Also, gravitational collapse alone should result in extensional features in the core of the range and compressional ones along its external borders. Such a pattern is not observed in the current seismicity or in the geodetic results. Ménard (1988) and Vialon et al. (1989) proposed that the current strain regime in the Western Alps is driven by transtensional boundary conditions caused the counterclockwise rotation of the Adriatic microplate. Indeed, Anderson and Jackson (1987) had proposed that the Adriatic indenter may actually be an independent microplate, detached from the African plate and rotating counterclockwise with respect to Eurasia around a pole located at 45.8°N/10.2°E. Using VLBI results at MATE and MEDI, Ward (1994) reached a similar conclusion but proposed a rotation pole located at 46.8°N/6.3°E and an angular rate of 0.30±0.06°/Ma. Westaway (1990) used tectonic information and earthquake focal mechanisms to infer a rotation of the Adriatic microplate at 0.3°/Ma around a pole at 44.5°N/9.5°E. In the following, we use our geodetic results to estimate the kinematic boundary conditions across the Western Alps and test whether they can explain the observed strain regime in the range.

**Boundary conditions across the Western Alps**

In order to find rotation parameters for the Adriatic microplate, we use the geodetic velocities at well-determined Italian stations derived from the combined solution described above. The tectonic position of MEDI, located in an actively deforming area of the Apennines, precludes its use for defining a rigid Adriatic microplate. Station UPAD is clearly located on the Adriatic microplate. Since no significant seismicity is known on the Ferrara thrust system south of TORI, nor in the Po plain between TORI and UPAD, we consider that, to first-order, TORI belongs to the Adriatic bloc. Station MATE is located on the Adriatic foreland, east of the Apennine frontal thrusts, but south of an active fault zone cutting the Italian peninsula and the Adriatic Sea in an EW direction from Gargano to Dubrovnik. That fault, clearly expressed in the seismicity, was identified by Westaway (1990) as the southern boundary of the Adriatic microplate. We therefore consider that MATE is not part of the Adriatic microplate.

Inversion of the geodetic velocities at TORI and UPAD together with the earthquake slip vector data set used by Anderson and Jackson (1987) gives a counterclockwise rotation of the Adriatic microplate with respect to stable Europe around a pole located at 45.36°N/9.10°E at an angular rate of 0.52°/Ma (Figure 3). Anderson and Jackson’s (1987) rotation parameters fit the GPS and slip vector data as well as ours, which is to be expected since they both derive from a very similar data set.

Velocities predicted using our rotation parameters with respect to stable Europe along the boundary between the Po plain and the Western Alps are oblique to the Adriatic-Western Alps boundary, indicating that
the current kinematic boundary conditions across the central part of the Western Alps combine divergence and right-lateral shear. Extensional boundary conditions also prevail across the Swiss Alps. In the southern part of the Western Alps, the eastward curvature of the active structures together with the velocities at GRAS, MARS or AJAC imply kinematic boundary conditions that combine convergence and right-lateral shear. This model also predicts that kinematic boundary conditions across the Alps east of 9.22°E (longitude of the rotation pole) should be essentially N-S convergence between the Adriatic microplate and Central Europe.

These predictions are consistent with most of the first-order seismotectonic features around the Adriatic microplate, including extension radial to the range in the Western and Swiss Alps (Eva and Solarino, 1998; Eva et al., 1998; Sue et al., 1999), N-S to NW-SE compression in the Friuli area in Italy and further west in the southern part of the Central Alps (Benedetti et al., 2000), and NW-SE to NS compression in the southern part of the Western Alps (Maddedu et al., 1997). These kinematic boundary conditions across the Western Alps may also explain the recent counterclockwise rotations shown by paleomagnetic data in the inner part of the Western Alps (Thomas et al., 1999). Our model predicts 4 mm/yr of NE-SW extension across the central Apennines, consistent with GPS and triangulation results in that area (Hunstad and England, 1999; D’Agostino et al., 2001). Finally, the motion of MATE relative to the Adriatic microplate (convergence in a N74°W direction at 4 mm/yr) is compatible with the compressional focal mechanisms observed along the Gargano-Dubrovnic fault zone.

Conclusions

Continuous GPS measurements at 10 permanent sites in the Western Alps indicate that the central part of the range is currently undergoing about 1 mm/yr of E-W extension, while its southern part is undergoing about 1 mm/yr of NS to NW-SE compression. These results however rely on limited geodetic data, with uncertainties close to the tectonic signal detected. On the basis of additional GPS and seismotectonic data in Italy, we propose that the current strain pattern in the Western Alps results from the counterclockwise rotation of the Adriatic microplate around a pole located in the Po plain. This rotation, together with the arcuate shape of the contact between the Po plain and the Alps, induces dextral shear kinematic boundary conditions across the Western Alps, with an additional divergent component in their central part and in Switzerland, and a convergent component in their southern part.

The onset of widespread extension in the Western Alps has not yet been dated. However, if the kinematic Adriatic microplate controls the strain regime in the Western Alps and the Apennines as proposed here, one should expect it to be contemporaneous in the two mountain belts, possibly late Pleistocene in age (about 800 ka) according to tectonic observations in the northern Apennines foothills (Bertotti et al., 1997).

Our model remains however incomplete and does not integrate the current uplift observed in the inner parts of the Western Alps and Apennines. This may result from flexural uplift of the footwall compartment of major active normal faults such as the Pennine thrust. It may also reflect the superposition of buoyancy forces to the stresses induced by the kinematic boundary conditions described here.

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REFERENCES CITED
King, R.W., and Bock, Y., 2001, Documentation for the GAMIT GPS software analysis, release 10, Massachusetts Institute of Technology and University of California, San Diego, unpublished.
FIGURE CAPTIONS

Figure 1. A. Velocities with respect to stable Europe (explanation in text) and strain rates on a Delaunay triangulation of the GPS network (see also Table 2). B. Major active faults in the Western Alps and earthquake focal mechanisms (from Eva et al., 1997; Eva and Solarino, 1998; Eva et al., 1998; Sue et al., 1999). The table at the bottom of panel B gives, for each site, the duration of the measurements (between brackets) and the velocity (in mm/yr).

Figure 2. Baseline length time series for SJDV-MODA (top) and GRAS-TORI (bottom). Error bars on the daily estimates are 1-sigma formal errors. Weighted root mean square–wrms.

Figure 3. Kinematic model of the Adriatic microplate. Solid symbols: start–our rotation pole for the Adriatic microplate, circle–Anderson and Jackson’s (1987) pole, square–Westaway’s (1990). Black arrows–observed GPS velocities with respect to stable Europe, grey arrows–velocities predicted by our kinematic model. Numbers next to arrows indicate model rates in mm/yr. Numbers below site name indicate model rates in mm/yr for that site. Black bars on the earthquake focal mechanisms show observed slip vectors, grey bars show predicted ones.

Table DR1. WRMS of individual solutions in the combination.

Table DR2. Velocity values issued from the combination of EUREF, REGAL and RGP permanent GPS arrays with a selection of ITRF2000 sites.
FIGURE 1
FIGURE 2

SJDV to MODA [175.19 km]

L - slope = 1.4 ± 0.3 mm/yr, wrms = 2.1 mm

Date [Decimal year, Oct. 17, 1998 to June 29, 2001]

TORI to GRAS [156.95 km]

L - slope = -0.8 ± 0.2 mm/yr, wrms = 1.9 mm

Date [Decimal year, Oct. 4, 1996 to June 29, 2001]
FIGURE 3