SEISMICITY ALONG THE NORTHWESTERN EDGE OF THE ADRIA MICROPLATE

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Keywords: Seismicity, stress, extension, rotation pole, western Alps, Adria.

Abstract This contribution is an overview of the seismic activity observed along the northwestern edge of the Adria microplate over the last 15 years. The study area stretches from Lyons to Turin, and from Geneva to Nice. The discussion focuses on several key zones where significant earthquakes occurred during this period, or where the connection between seismicity and tectonics provides clear-cut results. Our main conclusions are: E–W to NW–SE compression in the Ligurian Sea and at depth beneath the southwestern Po plain; in the core of the western Alps, widespread extension radial to the chain, with a component of right-lateral strike slip along faults longitudinal to the chain; in the European foreland, almost exclusively strike slip, either right-lateral along faults longitudinal to the chain or left-lateral in a conjugate direction. The observed right-lateral strike slip is consistent with an anticlockwise rotation of Adria about a pole in the Po plain, but the extension observed in the root zone cannot be explained with a simple rigid-plate model. This extension probably also involves gravitational collapse and/or slab roll-back or break-off.

INTRODUCTION

Curved in a smooth arc from the Mediterranean coast to Geneva, the western Alps form a 400-km-long, 200-km-wide segment of the great Alpine chain. Their geodynamic evolution, though complex, can be minimally summarized as follows: a long pre-rifting period during the Triassic and Lower Jurassic (225–165 Ma) eventually gave birth (165–100 Ma) to the Piedmont and Valais oceans, which formed contemporaneously with opening in the central Atlantic Ocean. This extension process stopped and inverted when the North Atlantic Ocean opened, the two newly-born pre-Alpine oceans progressively closed (100–65 Ma), culminating with the continental collision between Adria and stable Europe from 65 My onwards (Tapponnier, 1977; Platt et al., 1989; Lemoine et al., 2000).

Although their frequency has long been underestimated, felt earthquakes are reported in the western Alps in the order of several tens each year. Only a few of these felt events have had sufficient impact to leave a written trace in newspapers, scientific articles or reports. Rothé (1941) was the first to identify two active seismic zones in the French and Italian western Alps: the Briançonnais and Piedmont seismic arcs. Since the middle of the 20th century, when instrumental data have progressively become more generally available, many studies have detailed the seismic activity in several additional seismic zones in Switzerland, Italy, and France. Relatively few studies of the overall seismicity of the western Alps exist. They include Fréchet (1978), Guyoton (1991), Thouvenot (1996), Béthoux et al. (1998), and Nicolas et al. (1998).

Since the inception of plate-tectonic theory, earthquakes have been used to delineate major plate boundaries, while focal mechanisms provide constraints on relative plate motions. In the case of the western Alps, such an exercise is subtler. First, regarding Adria as a microplate is still considered controversial. Second, the limits of a possible Adria microplate are not as clearly defined as are boundaries between major plates. Third, the seismicity level in the western Alps is much lower than elsewhere in the circum-Adria orogenic belts, including the southern Apennines and Dinarides. The last two points are closely linked, but can be overcome by an increase in earthquake location accuracy and a decrease in detection threshold. Both involve developing more robust monitoring networks in the region.

1. SEISMIC MONITORING

In the mid 1980s the Swiss and Italian short-period seismic networks monitored the seismicity to the north and to the east to very low levels. However there were very few seismic stations in the French Alps, which proved insufficient to monitor the seismicity there stretching over an 80,000-km^2 area. The aim of the Sismalp project was to fill in this gap. Since that time, 44 seismic stations fitted with 1-Hz sensors now cover the area from Geneva to the south of Corsica and from the French Massif central to the Italian border (Thouvenot et al., 1990; Thouvenot, 1996). They complement the 9 stations that LDG (Laboratoire de Détection et de Géophysique) runs in southeast France, the 12 stations of IRSN (Institut de Radioprotection et de

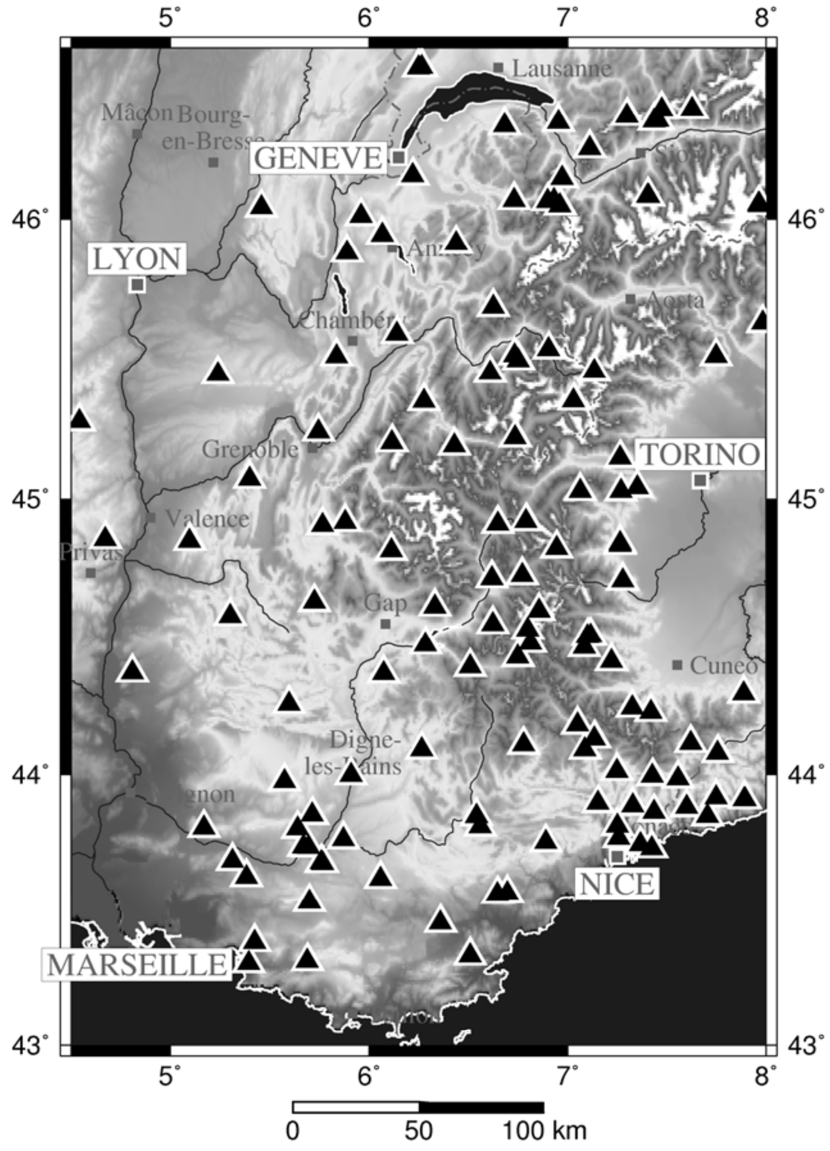

Figure 1. Permanent seismic velocimetric stations in the study area (short-period and broad-band instruments).

Sûreté Nucléaire), as well as the 15-station Provence–Nice network operated by RéNaSS (Réseau National de Surveillance Sismique) close to the Mediterranean coast. Solarino et al. (1997) compiled data from these different networks in France and elsewhere along the Alpine belt to produce 3D tomography of the greater Alpine region.

Since the mid 1990s, the instrumental effort has veered to broad-band velocimetry and accelerometry. The 28 stations of the Swiss Seismic Network are now fitted with 0.02–120-s sensors, Rosalp and TGRS (Très Grande Résolution Sismique) installed 11 broad-band instruments in southeast France, while, in northwest Italy, out of the 29 stations operated by IGG (Istituto Geofisico e Geodetico, Genoa), 7 stations are now equipped with broad-band velocimeters. In addition, the Swiss National Strong Motion Network and Rap (French Réseau Accélérométrique Permanent) have installed several tens of accelerometers over the region.

A total of about 120 seismic velocimetric stations are available in the study area shown in Figure 1. Although seismic monitoring cannot yet make real-time use of all these networks because of efficiency reasons, arrival times are merged after events. Epicentral uncertainties are smaller than 1 km for most epicentres; all events with magnitudes over about 1.5 can be located; focal mechanisms can be obtained for events as small as magnitude 2, although their reliability depends on focal depth, rupture process, and the epicentre being located in the core of the monitoring network rather than on its periphery.

2. DESCRIPTION OF INSTRUMENTAL SEISMICITY

2.1 Briançonnais, Piedmont, and Padan seismic arcs

Fourteen years of dense monitoring now allow us reliably to identify several seismically active zones (Fig. 2). Most activity concentrates along the two seismic arcs discovered 60 years ago (as mentioned above in the introduction), which are now sharply defined.

The Briançonnais seismic arc (Fig. 2, label 1) coincides with the Penninic Front, a major boundary between the external autochthonous domain and the internal Alpine nappes. Most foci there are shallower than 10 km. The Piedmont seismic arc (Fig. 2, label 2), is active mostly within the 10–15-km depth range and follows the western limit of the Po plain, precisely where the

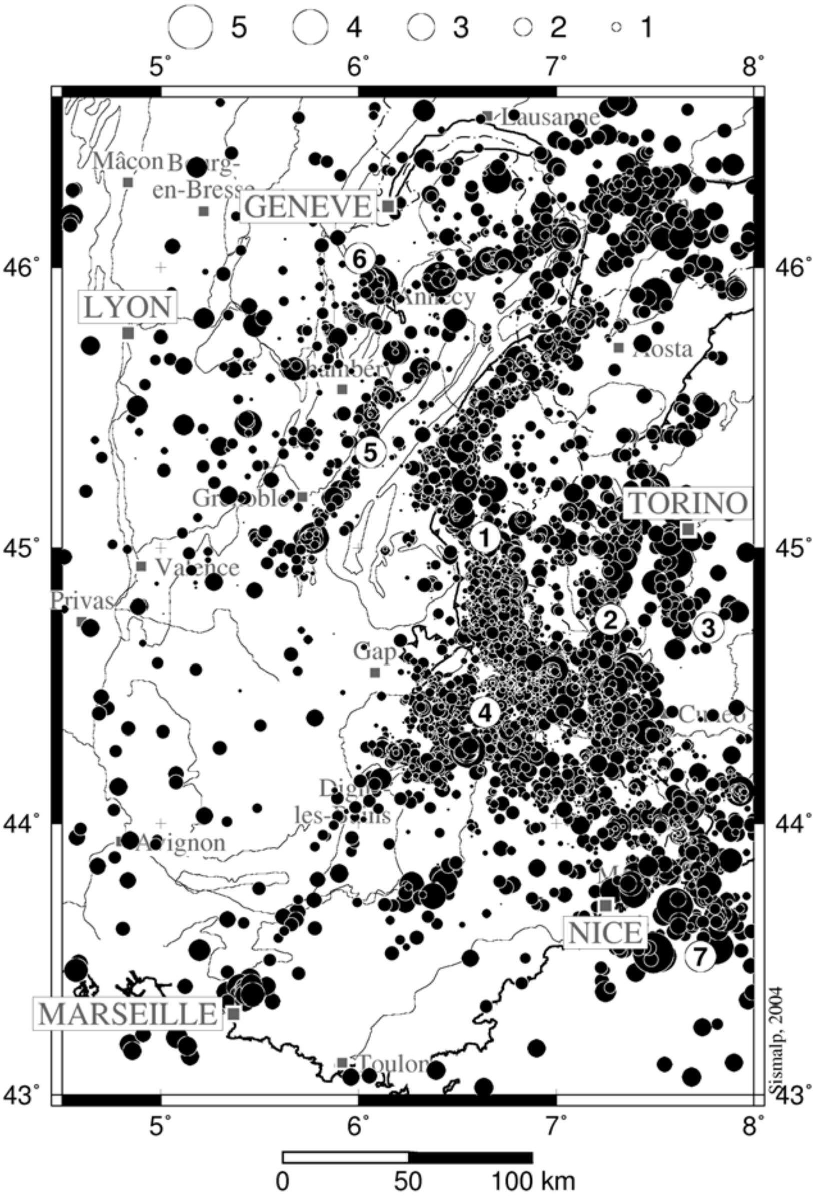

Figure 2. 1989–2002 instrumental seismicity. Background shows the main geological units (see Figure 3 caption for details). Arrival times used for locating earthquakes: Sismalp, RéNaSS, LDG, and IGG. Only events with RMS smaller than 1 s are plotted. Labels refer to seismic alignments or zones discussed in the text: 1 = Briançonnais arc; 2 = Piedmont arc; 3 = Padan arc; 4 = Embrunais-Ubaye; 5 = Subalpine arc; 6 = Vuache Fault; 7 = Ligurian Sea.

upper mantle of Adria comes into contact with the European crust through complex lithospheric flaking (Paul et al., 2001).

Most of the focal mechanisms in these two seismic arcs reveal a general extension radial to both arcs (Sue et al., 1999), a phenomenon previously described by Fréchet and Pavoni (1979), but which was then considered local and not as widespread as is now recognized. Where strike-slip motion is observed, it involves right-lateral displacement along faults longitudinal to the Alpine chain (Thouvenot et al., 1991). In southern Switzerland, between the upper Rhone valley and the Swiss–Italian border, Maurer et al. (1997) also presented evidence for extension in a N–S direction, i.e. more or less perpendicular to the local strike of the belt.

South of Turin, the Padan arc (Fig. 2, label 3) is yet another seismic arc in the NW Alps. It is characterized by deep earthquakes, down to 112 km according to Cattaneo et al. (1999). The Padan arc seems much less active than the Briançonnais and Piedmont arcs, although the difficulty in monitoring deep, low-magnitude seismic events beneath the densely-populated Po plain might partly explain this difference. It is tempting to relate the Padan arc to steep (80°?) subduction of the European Plate beneath Adria; however no reliable tomographic image has ever been produced for such a slab. More clearly, while the Piedmont arc mimics the western side of the Ivrea gravity high, the Padan arc follows its eastern side, making clear the relation of both of these seismic arcs with anomalous mantle structures beneath. Eva et al. (1997) report E–W compression for focal mechanisms computed along the Padan arc.

2.2 Embrunais-Ubaye nappes

In the study area, the internal Penninic nappes overlap the external domain in several places. This is the case in the Embrunais-Ubaye region (Fig. 2, label 4), which corresponds to a basement depression between the Pelvoux and Argentera crystalline massifs. The seismic activity in this zone is the highest in the French western Alps. This is also where the most significant event of the second half of the 20th century (Saint-Paul-sur-Ubaye, $M_L = 5.5$) took place in 1959. Connecting seismicity to faults mapped at the surface is difficult, partly because the nappes are made up of flysch which lacks clear marker beds.

The main characteristic of the seismicity in this zone is that swarms of variable durations occur frequently (Guyoton et al., 1991). The latest, and one of the longest swarms ever observed in France, the La Condamine swarm, begun in January 2003, with more than 15,000 events (maximal magnitude 2.7) and lasted for more than 20 months. The fault zone that corresponds to the seismogenic source is nearly vertical, 8-km long, 2 to 8-km deep, and in the crystalline basement; it trends NW–SE, i.e. along the local strike of the Alps. About two-thirds of fault-plane solutions show right-lateral strike slip in the NW–SE direction, the remaining one third corresponding to normal faulting with E–W extension. This result is in agreement with that obtained earlier by Sue et al. [1999] in this region, where E–W extension was derived from the inversion of the focal mechanisms available prior to the La Condamine swarm.

2.3 Alpine foreland

The domain to the west of the Penninic Front is much less active than the internal zones to the east. In this part of the Alpine foreland, a further difference is observed south of latitude 45°N where the seismicity—at least the *instrumental* seismicity—is negligible. North of latitude 45°N, seismicity is more active, with earthquakes in the upper 15 km of the crust.

In this zone, which encompasses the densely-populated Annecy, Chambéry, Geneva, Grenoble, and Lyons regions, no clear seismicity pattern can be recognized. A major exception to this apparent mess is the recently discovered Subalpine seismic arc (Fig. 2, label 5). This rather straight epicentral alignment can be followed from the south of Grenoble toward Annecy to the northeast, where it veers to the ENE. It eventually joins the seismic zone situated north of the upper Rhone valley in the Valais (southern Switzerland), which also trends WSW–ENE. Earthquakes along this arc occur in the 5–10-km depth range, and a corresponding basement fault zone is not known at the surface. The alignment intersects several different geological units, as if seismotectonics at depth have no relation with the surface geologic features.

The proximity to the front of the Belledonne crystalline massif earned the southwestern section of this fault zone its name the Belledonne Border Fault (BBF; Thouvenot et al., 2003). This ~50-km-long epicentre alignment runs in a N30°E direction and includes ~150 earthquakes with magnitudes between 0 and 3.5. Available focal solutions are consistent with the N30°E orientation of the BBF; all but one involve strike slip with right-lateral displacement. The BBF can thus be interpreted as the reactivation of a Hercynian basement fault with almost pure right-lateral strike slip, with an E–W-trending P axis and a N–S-trending T axis.

To the northeast, along the other section of the Subalpine arc with a WSW–ENE orientation, the focal mechanisms are more varied. They often imply strike slip with right-lateral displacement, although transpression exists locally (Fréchet et al., 1996). As for the continuation of the Subalpine arc in

Switzerland, on the northern bank of the Rhone river, Maurer et al. (1997) mainly report strike slip, either with a right-lateral displacement along faults longitudinal to the Alpine belt, or with a left-lateral displacement in the conjugate direction.

Farther to the northwest in the Lyons–Geneva–Annecy–Grenoble area, seismicity in the Alpine foreland is very scattered. This seismicity seems to reflect the presence of active NW–SE-trending faults. One such fault, the Vuache Fault (Fig. 2, label 6), has been identified as seismically active. It connects the Jura to the Alps, and is responsible for the Épagny-Annecy M_L-5.3 earthquake in 1996 (Thouvenot et al., 1998). In the field, impressive slickenlines reflecting fossil slip are observed along this ~30-km-long fault. The focal mechanism of the main 1996 shock, as well as aftershock monitoring indicate left-lateral strike-slip motion on a N130–135°E-striking fault; this orientation is perpendicular to the local trend of the Alpine belt. The P axis trends E–W and the T axis N–S, in agreement with what we observed along the BBF.

2.4 Ligurian Sea

Seismicity observed offshore in the Ligurian Sea (Fig. 2, label 7) is restricted to the northern margin of the oceanic domain created by the rotation of the Corsica-Sardinia block (Béthoux et al., 1992). Reactivation of faults formed during this early tectonic phase, due to E–W to NW–SE compression in this region, is recorded by several reliable focal mechanisms. This leads to a speculation that this aborted oceanic domain is now being closed by northward motion of Corsica-Sardinia. However, GPS measurements such as those processed by Calais et al. (2002) or Hollenstein et al. (2003), suggesting that Corsica-Sardinia is practically immobile relative to stable Europe, do not corroborate this speculation. Another possibility to explain the compression along the Ligurian margin is that it is due to lateral expulsion of the southwestern Alps as Adria collides with Europe.

2.5 Provence

The southwestern part of the study area is not discussed here for two reasons. First, this zone, at least the Marseilles area and the lower Rhone valley, lies a fair distance from Adria, and discussing its seismicity is beyond the scope of this paper. Second, much of it (Figure 2) appears seismically inactive. However, we know from historical seismicity records that several destructive earthquakes have occurred there, the most damaging event being the Lambesc earthquake, north of Marseilles (1909, maximum MSK intensity

IX). In contrast to what happens elsewhere in the study area, a 14-year monitoring is not long enough to provide us with a reliable seismotectonic map of Provence. Clearly, such a map should take into account historical seismicity, no matter how imprecise the corresponding epicentre locations. Suffice it to say that Provence is not as inactive as it might seem at first glance, as indicated by the SW–NE seismic alignment extending from Marseilles to Digne along the Durance valley. This alignment is parallel to the BBF, and suggests a possible similarly reactivated fault, which would also be of Hercynian origin.

3. ADRIA ROTATION

Although scrutiny of McKenzie’s (1972) paper reveals that he sketched an almost imperceptibly curved velocity arrow on what he named ‘the Adriatic’, Gidon (1974) can be considered the first to have proposed anticlockwise rotation of Adria about a pole in the western Po plain. This hypothesis was based on the observation of many longitudinal displacements along right-lateral strike-slip faults in the western Alps. Ingenious and innovative at that time, it has been substantiated in the following decades first by paleomagnetic results, then by GPS measurements. Geometric criteria were also used by Ménard (1988), Vialon et al. (1989), Laubscher (1996), Stampfli and Marchant (1997), Schmid and Kissling (2000), and Collombet (2001) when they discussed the importance of successive rotations in the Alpine orogeny. However, there is a consensus that few tectonic, morphological or stratigraphic markers exist with which to identify and quantify these rotations.

Our description of the stress field along the northwestern edge of Adria is summarized in Figure 3. This summary makes clear that the current tectonics in the western Alps is by no means dominated by collision-related radial crustal shortening as expected in a collision belt. Since the late 1980s, several authors have computed an anticlockwise rotation of Adria about an Euler pole in the Po plain, close to 46°N/10°E (Fig. 4). Anderson and Jackson’s (1987) pole position remains a good starting model to describe the overall kinematics of Adria. It fits well with the observations of extension in the Apennines and convergence in the Dinarides. It also explains the right-lateral strike-slip faults that we observed in the western Alps from many focal mechanisms derived from events along faults longitudinal to the belt, and along-strike alignments

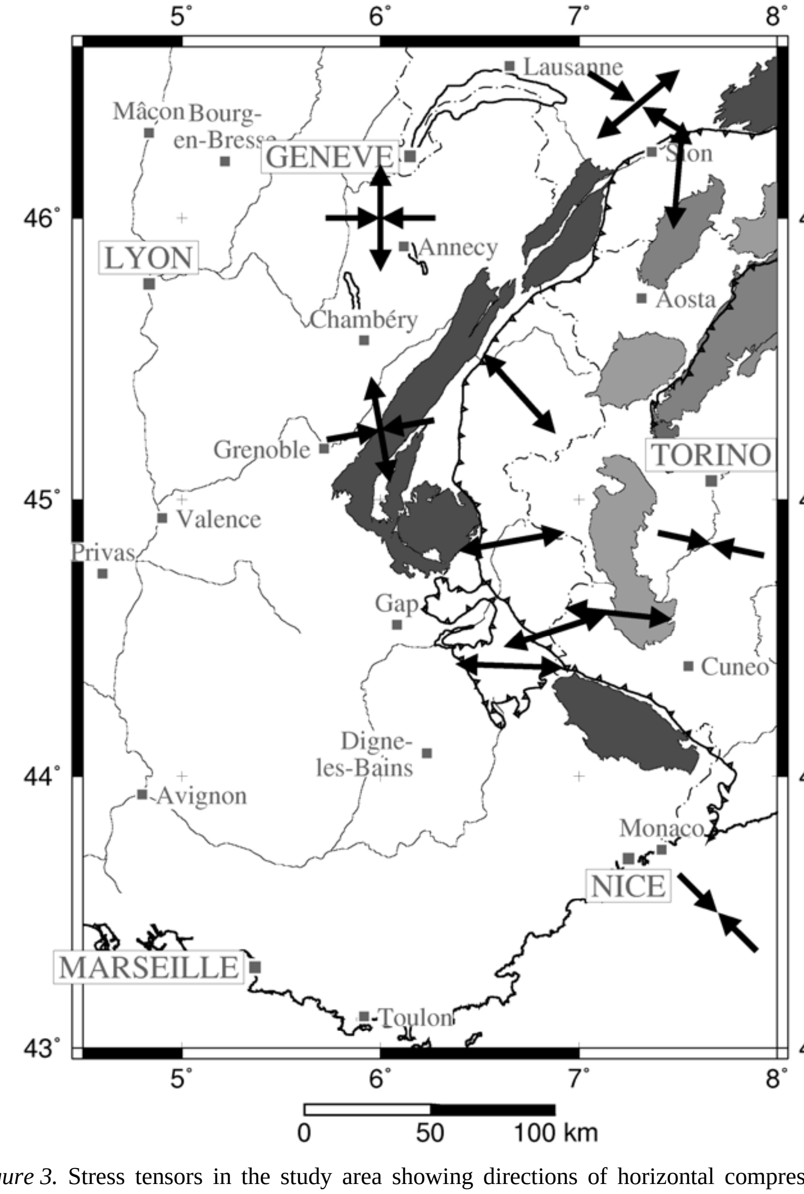

Figure 3. Stress tensors in the study area showing directions of horizontal compression and extension. Crystalline massifs form two arcs separated by the Frontal Penninic Thrust (barbed line). Most results are from stress tensor inversions by Eva et al. (1997), Maurer et al. (1997), and Sue et al. (1999), except in 3 places: east of Grenoble, south of Geneva, and southeast of Nice (*P* and *T* axes from focal mechanisms). Note: extension in the internal zones; strike slip in the foreland; compression restricted to the Po plain and Ligurian Sea.

of epicentres detected either through aftershock studies or long-term monitoring. However, Anderson and Jackson's (1987) pole falls right in the middle of the fairly active Milan-Trient seismic zone, which marks the northern limit of Adria. This is an unlikely position for an Euler pole, since the distance from the pole to the boundary is the shortest, and differential motion between Europe and Adria probably very faint.

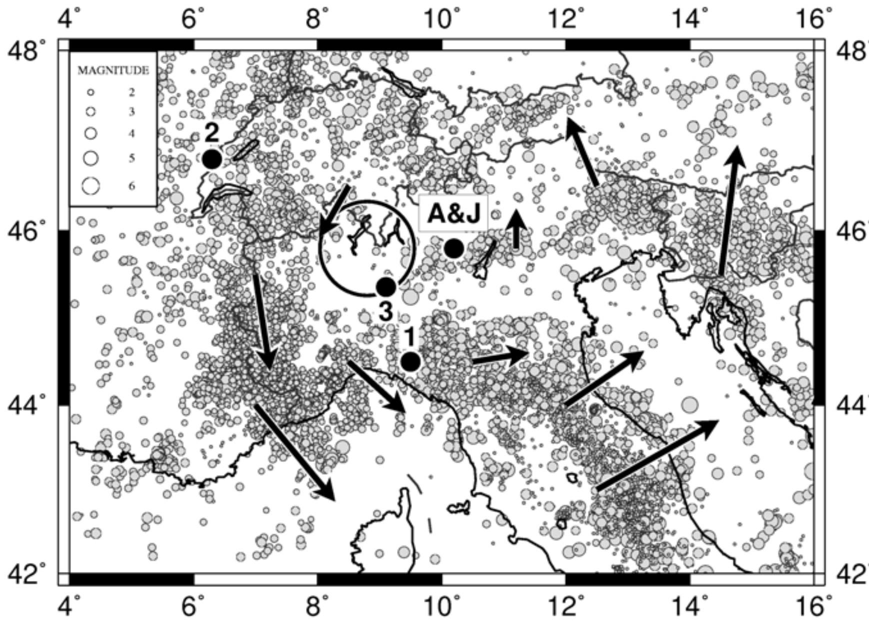

Figure 4. Anticlockwise rotation of Adria about different Euler poles. A&J = Anderson and Jackson (1987), with corresponding relative velocity vectors computed along the Adria-Europe boundary (velocity magnitude is arbitrary); 1 = Westaway (1990); 2 = Ward (1994); 3 = Calais et al. (2002); circle = Lake Maggiore region where the seismicity at the Adria-Europe boundary is almost nonexistent. Seismicity data from USGS (1900–1995).

Other Euler poles fit seismotectonic data more or less correctly. Westaway's (1990) pole located east of Genoa (Fig. 4, label 1) implies compression in the French-Italian Alps and strike slip in the Swiss-Italian Alps; neither phenomena is observed. Ward's (1994) pole north of Geneva (Fig. 4, label 2) explains extension in the French-Italian Alps, but infers compression in the Swiss-Italian Alps, which is not observed. Calais et al.'s (2002) pole (Fig. 4, label 3) is not basically different from Anderson and Jackson's (1987) pole as concerns relative velocity vectors computed along the Adria-Europe boundary. But its position at the western tip of the Milan-Trient seismic zone discussed above makes it more likely for us. In the Lake

Maggiore region (Fig. 4, circle), seismicity of the northern boundary of Adria is almost nonexistent. This is another zone where the Euler pole could be searched for.

4. EXTENSION: GRAVITATIONAL COLLAPSE OR BUOYANCY FORCES?

The Adria rotation pole position computed by Calais et al. (2002) integrates two continuous GPS stations on Adria with Anderson and Jackson's (1987) earthquake slip vectors. Although this pole position is consistent with the extension observed in southern Switzerland, it fits neither the azimuths nor values of velocities observed in the western Alps with respect to stable Europe, as Calais et al. (2002) recognized themselves. The reason invoked by Calais et al. (2002) is the extension revealed by their strain rate analysis in the internal French Alps.

We show that stress tensor inversion yields widespread extension radial to the belt from south Switzerland to the southwestern Alps (Fig. 3). It is difficult to conceive how such extension over such a wide area results from the Adria-Europe rotation discussed above. Moving the Adria rotation pole farther to the west—that is, closer to the Adria-Europe plate boundary—would favour extension in the French-Italian Alps but would also induce convergence in southern Switzerland, which is contrary to observations. One way to explain such extension is to allow deformable plate margins.

Several mechanisms can be invoked for explaining extension in mountain belts, as reviewed for instance by Sue et al. (1999) or Calais et al. (2002). The models of tensional strain within a crustal-scale ramp anticline or an upward extrusion of a rigid mantle indenter can be excluded in the western Alps because both models require active convergence, which is not observed. Gravitational collapse is a more likely candidate. Orogenic collapse normally affects high-elevation plateaus where the crust has been overthickened. The altitudes of the Briançonnais and Piedmont zones are certainly not comparable with that of Tibet or the Basin-and-Range province. Sue et al. (1999) therefore also discarded this model and invoked buoyancy forces such as those produced by a slab retreat or break-off to produce the observed extension in the western Alps. However such a lithospheric-instability model is also difficult to defend. Many lithospheric-scale models of this belt include a European Plate subducted under Adria, and the anomalously deep earthquakes located by Cattaneo et al. (1999) beneath the Po plain might be related to subduction of Europe beneath Adria. But there is still no clear evidence of a European slab beneath the western Alps. Although neither the lithospheric-instability model nor gravitational collapse are satisfactory for explaining the observed extension, they appear less unlikely than the other models. Further investigations are necessary to decide if either of these two models, or a combination thereof, represents the actual cause of widespread extension observed in the core of the western Alps.

5. CONCLUSIONS

This brief description of the stress field along the northwestern edge of Adria makes clear that current tectonics in the western Alps are in no way dominated by collision-related radial crustal shortening as could be expected in a collision belt. Instead, extension and right-lateral strike slip along faults longitudinal to the chain are most prominent. Convergence is eventually restricted to very specific zones, not within the belt, but at its periphery (e.g. Ligurian Sea, southwestern Po plain, Jura). The anticlockwise rotation of Adria about a pole in the central Po plain remains a good starting model for describing the overall kinematics of the circum-Adria orogens, especially the right-lateral strike slip we observe in the western Alps; but this model fails to explain the synorogenic extension we observe there. Among several mechanisms offered to explain the observed extension, gravitational collapse and buoyancy forces, such as produced by slab retreat or break-off, may complement the rigid plate motion.

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