Geodynamic processes at the northern boundary of Adria plate: strain–tilt measurements and modelling

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Abstract

The object of the present research is the study of deformational processes at the northern boundary of the Adria microplate, characterised by a complex tectonic setting and by an intense seismic activity, due to its collision with the Eurasian plate.

In the area, a tilt-strain gauge network provided information on the strain field variations for more than twenty years. Spectral and cross-correlation analyses of the strain field variations on a decadal time scale demonstrated that stations 100 km apart show some common behaviour (Rossi and Zadro, 1996). In particular, the long-term deformation involving a large area appears polarised in two main directions, respectively parallel to the maximum horizontal compression acting in the Alpine area and to the one acting on the eastern boundary of the Adria plate, in the Balkan region.

With the aim of providing some possible explanation of the observed stress-strain orientation as a result of plate driving forces, a 3-D linear elastostatic finite-element model of the lithosphere in the study area was constructed, based on geological, seismic and gravimetric evidence. Various hypotheses about the kinematics of the region were tested, imposing in turn to the model different boundary conditions together with diverse far-field perturbing forces simulating the supposed character of the present drift between Adria and Eurasia. The modelling results are compared with the available information about the stress field pattern and seismic activity distribution. In both cases the agreement is good, to testify the validity of the hypotheses and of the model as a study tool of the geodynamic processes in the northern edge of Adria microplate.

1. Introduction.

If already Argand (1924) evidenced the contrast between the apparently aseismic Adriatic Sea and the surrounding mountain chains (Apennines, Alps and Dinarides), seismically active and with a complex tectonic setting, it is in the recent years that Adria geodynamics became one of the most puzzling problems of Mediterranean area. Many hypotheses have been put forward in the last years, that imply very different scenarios and seismotectonic models for various relevant seismic areas (Anderson and Jackson, 1987; Westaway, 1990; 1992; Udis et al., 1992; Ward, 1994; Albarello et al., 1995).

The constraints to the different hypotheses historically came mainly from seismological data, but in the last years many important contributions come from the geodetic data (e.g. Ward, 1994). The present work, focused to the northern edge of Adria microplate, is aimed to bridge
the gap between the two worlds. A finite-element modelling of the region, built up and tested with the available seismological information, is aimed to be a practical tool to study the stress-strain field in the region, giving an explanation in terms of tectonic forces acting at the boundaries. In a next future, the model will hopefully provide also a plausible explanation of the observations of strain field space-time variations recorded in more than twenty years by the continuous monitoring network active in the study area (Mao et al., 1989; 1990; Rossi and Zadro, 1996). In fact, the analysis of the data showed how the strain energy involving a large area appears polarised in two main directions, respectively parallel to the maximum horizontal compression acting in the Alpine area (NNW-SSE) and on the eastern boundary of the Adria plate (NE-SW) (Rossi and Zadro, 1996).

2. The study area

As said, the present analysis takes into account a small portion of the Adria microplate, its northernmost part, mainly formed by NE-Italy, with the neighbouring regions of Austria, Slovenia and Croatia (Fig. 1). In this area the intense seismic activity culminated in the most recent times with the Friuli earthquake of May, 6th, 1976, M=6.4. The epicentres of the seismic events recorded in about twenty years of record (1977-1995) by the North-eastern Italy seismometric network (Slejko et al., 1989) are mapped in Fig. 2. The contour lines are relative to the values of the seismic energy released, a quantity proportional to the magnitude of the events (Kanamori and Anderson, 1975). The highest values are recorded near Tolmezzo, where the aftershock activity of the 1976 earthquake was concentrated and the more intense seismic activity is still recorded. The epicentres are sparse along the curved piedmont area, and small clusters are observed, as for example nearby Trento. The fault plane solutions calculated by different authors agree on a thrust mechanism, with an almost uniaxial compression acting in NNW-SSE direction, which constitutes an important constraint for the different geodynamics models cited above (Mayer-Rosa et al., 1976; Müller, 1977; Cipar, 1980).

![Fig. 1. a) The study area in the frame of the Adria microplate. b) Schematic tectonic map; the direction of the maximum compression stress (from focal mechanisms of seismic events recorded in the area) is indicated with the arrows. TS, VI and CE are three stations of the tilt-strain continuous monitoring network cited in the text.](image-url)
At a smaller scale, however, analysing the data from the local seismometric network, deviations from this scheme are observed. To the east, NE-SW compression is recorded, with a strong shear component (a recent example is the Bovec earthquake of April 12th, 1998). The western part of the region shows on the contrary NW-SE compression, as for the rest of the Alpine area and western Europe (Zoback, 1992; Grünthal and Stromeyer, 1992) (Fig. 1b). Such a behaviour, in contrast with the hypothesis of a simple rigid rotation of the plate, may be explained as partly due to inherited past structures (Bressan et al., 1998).

3. Part.1-Tilt data analysis

The Earth tide horizontal-pendulum station (TS) installed in 1959 in the cave named Grotta Gigante on the Trieste Karst (Marussi, 1959; Zadro, 1978), records without interruptions since 1967 the slight movements of the earth crust. In addition, a tilt-strainmeter network (five stations) was installed slightly to the north, in the seismic Friuli area beginning in 1977. Since 1979, the Villanova station (VI) was also equipped with a triad of Cambridge horizontal wire strainmeters (King and Bilham, 1976)(Fig. 1b). The network has been installed and is ruled by the University of Trieste, Dept. of Earth Sciences, with the collaboration of the National Institute of Geophysics (ING) for the Grotta Gigante station.

In the following, the main results of the strain-field decadal observations are summarised.

Analyses of the strain-tilt data, performed throughout the years (Zadro, 1978; Mao et al., 1989; 1990; Zadro and Rossi, 1996) demonstrated that the strain field in the region is subject to time variations, of different frequency and causes, from the earth-tide effects to very long term variations.

In Fig. 3 the long-term trend of some tilt and strain record is shown. Because long-term effects are the main objects of this work, time series with large interruptions, together with those provided by stations of relatively recent installation, have been disregarded. Thus, the stations considered are TS, VI and CE, operating since 1967 (TS), 1977 (VI), 1978 (CE) (Fig. 1b). As may be seen oscillations involving ‘periods’ from two-three years to about ten years characterise all the records, from different instruments and sites. A comparison with
temperature and pressure variations excluded any possible influence of these two quantities (Rossi and Zadro, 1996). It is therefore plausible that these oscillations are in some way related to tectonic processes and structures, and therefore act along a particular direction, let it be the structure orientation, or the stresses orientation.

Fig. 3. Long-period terms of the tilt variations from TS (a, b), VI (c, d) and CE (e, f) EW and NS components. g) ST4 strainmeter variations recorded in VI in N68E horizontal direction.

Fig. 4. Radial distributions of the spectral amplitude versus decreasing frequencies for a) TS , b) VI, c) CE tilt signal. The spectral values are normalized to 10 and contoured (logarithmic scale). The inner circles show some significant periods, in years: origin at 0.5 years (from Rossi and Zadro, 1996, redrawn).
The methodology applied is the following one, based on the tilt spectra computed as azimuth functions, aimed to look for the direction along which the spectral energy of different frequency bands concentrates. The longest time series are the TS ones, which cover 28 years (1967-1994). For computational reasons and in order to improve the spectral resolution the VI and CE time series have been prolonged to the same 28 year time interval (1967-1994) by filling with zeroes the lacking values in the data files.

The tilt resultant vectors of the various stations were projected along azimuths radially spaced by 2 degrees and the relative amplitude spectra computed. The radially displayed spectral amplitudes, normalised to 10 for each station, are mapped in Fig. 4 with contour lines in the logarithmic scale versus decreasing frequencies, starting point at the origin being 2 cycles per year.

The pluriannual energies for TS (Fig. 4a), VI (Fig. 4b) and CE (Fig. 4c) are spread around N50W, N40E and N80W directions respectively. For VI and CE, two zero-tilt directions are observed at all frequencies: N50W and N10E respectively; for TS, for periods less than 5 years the zero-tilt direction is about N30W, whereas for larger periods is about N40E. The following step is to search a common trend between stations close to each other, taking into account that TS, VI and CE are aligned along an approximately NW profile. So, the cross-correlation amplitude spectra are computed for the couple of station TS-VI (the southern area) and VI-CE (the northern seismic zone) respectively. This is simply done by multiplying the spectral amplitudes of Fig. 4 of the two considered stations. The TS-VI and VI-CE cross spectra, each one normalised to 10, are mapped in Fig. 5a and Fig. 5b, with contour lines in the logarithmic scale.

\[ TS \cdot VI \]
\[ V I \cdot C E \]

Fig. 5 a.) Cross spectral amplitudes between TS and VI calculated through the product of the values shown in Fig. 4a and Fig. 4b. b) Cross spectral amplitudes between VI and CE calculated through the product of the values shown in Fig. 4b and Fig. 4c. The white lines evidence the directions of maximum correlation: N20W and N70E. The inner circles show some significant periods, in years. The origin is at 0.5 years (from Rossi and Zadro, 1996, redrawn).

The two figures above are very similar, inasmuch as both display two directions, N20W and N70E (white lines in the figures) around which the largest amount of the cross spectral amplitude is concentrated. The high-amplitude zone is rather restricted in both azimuth and frequency in the former direction, but rather spread in the latter one.

The N20W and N70E directions are respectively normal to the Alpine chain and close to the normal to the Dinaric structures, present at the eastern boundary of the study area. The Alpine about NNW-SSE compression and the stresses acting at the Apenninic and Dinaric fronts might therefore appear at the origin of the long-term tilting.
4. Part.2-Modelling of the region

To come to an ultimate conclusion on the present stress state in the region and on the hypothesis on a possible correlation with the results of the strain-field data, would require the knowledge of the stress status in many points and at different depth within the lithosphere. Costs and practical difficulties hinder to achieve this knowledge from direct in situ measurements, so that the main information comes from seismology (Zoback, 1992). The data are therefore sparse and influenced both by the distribution and magnitude of the seismic events and by the coverage of the seismic networks. However, stress patterns may be also calculated according to elastic models, when the distribution of their material inhomogeneities is known together with their boundary conditions. On this basis, a 3D finite-element model has been built up, using the available information about the lithosphere structure in the area. The modelling is aimed to provide some possible explanation of the observed stress orientation as a result of plate driving forces.

4.1 Geometry and boundary conditions.

The total dimensions of the model are 320 km in longitude (10.5°E-14.5°E) and 40 km in latitude (44.8°N-46.8°N) and about 150 km in depth. The limits of the model have been chosen to avoid boundary effects in the central area. To facilitate future improvements of the model as well as to avoid boundary effects from the bottom, the model comprises the whole lithosphere and the first tens of kilometres of the asthenosphere. The topography is schematically inserted in the uppermost layer of the model.

Fig. 6 The mesh used in the modelling. The lower and upper extremes for each layer are indicated on the side.

The model is therefore composed by five homogeneous layers (from bottom to top: top of low-velocity channel of the asthenosphere, lid plus lower-, middle- and upper-crust).
depth and shape of the layers' boundaries were inferred from the available seismological and gravity data. The whole model was subdivided in more than 800 eight-node brick elements. A coarser and irregular mesh characterizes the deeper layers, while a finer (20 km side) and almost regular grid is adopted for the crustal layers (Fig. 6). Each layer of the model is characterized by different values of density and Young's modulus, whereas the Poisson ratio was fixed equal to 0.25 for all of them (Tab. 1).

<table>
<thead>
<tr>
<th>layer</th>
<th>$\rho$ (g/cm$^3$)</th>
<th>E (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>upper crust</td>
<td>2.63</td>
<td>55.38</td>
</tr>
<tr>
<td>middle crust</td>
<td>2.82</td>
<td>90.38</td>
</tr>
<tr>
<td>lower crust</td>
<td>2.99</td>
<td>117.00</td>
</tr>
<tr>
<td>lid</td>
<td>3.29</td>
<td>175.50</td>
</tr>
<tr>
<td>asthenosphere</td>
<td>3.36</td>
<td>157.00</td>
</tr>
</tbody>
</table>

Table 1: The crustal Young's modulus (E) densities ($\rho$) chosen for the five layers of the model after the gravimetric modelling (crust) or after PREM (lid and asthenosphere.

The orientation of the far-field compression hypothesised by the various authors was taken into account by applying NW-SE, N-S and NE-SW oriented compressive force to the southern boundary, whereas the displacements in the N-S direction were set to be null on the northern side. The order of magnitude of the compressive stresses applied to the southern side of the models is 100 MPa, which allow stresses of the order of magnitude of the stresses observed, i.e. 10-50 MPa (Hast, 1973; Kohlbeck et al., 1980), to be obtained.

The model here presented is in agreement with the surface observations which allowed the hypothesis that Adria rotates counterclockwise with respect to Africa, around a pole located slightly to the west of the study area (Anderson and Jackson, 1987; Westaway, 1990; Ward, 1994). We put forward the hypothesis that the effect of the rotation may be as well simulated by a compressive stress at the southern border, which is larger, the larger the distance from the supposed pole of the rotation. Therefore, a linearly eastwards increasing compressive stress was applied, and a good agreement with observational data was found taking 3 MPa at the south-western corner of the model, and 100 MPa at the south-eastern corner of it. Moreover, the shortening is accomplished by vertical elongation and by sliding along vertical planes oriented as the major tectonic features of the zone (Fig. 7).

![Fig. 7. Boundary condition imposed to the model: plan view. A longitude-depending stress is applied to the southern boundary. The NS displacements for the nodes on the northern side are null. The nodes belonging to the eastern and western sides are free of moving along planes oriented as the main tectonic discontinuities in the area.](image-url)
4.2 Results

The maximum stress orientation obtained for the upper level of the model, directly comparable with the available information, is shown in Fig. 8.

The trajectories are about N-S in the Friuli seismic area, whereas they show a NE-SW trend in the Istria Peninsula and to the east of Trieste. To the west of Venezia they assume a clear NW-SE orientation. From the modelling results, the point where the two orientations converge, possible isotropic point, is off the Istria peninsula, where a relevant Bouguer anomaly is observed (Italian Explosion Seismology Group and ETH, 1981), related to a high of the Moho. The patterns of stress orientation predicted by the model are therefore in good agreement with the stress orientations inferred from the focal mechanisms (Fig. 1b).

Another test criterion of the validity of the model can be found in the comparison between the distribution of the seismic energy within the region (Fig. 2) and the distribution of the second invariant of the deviatoric stress $I_2$:

$$I_2 = (\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2$$

The latter is the yield criterion according to von Mises (Jäger, 1962), whereas the former indicates the zones where stresses exceed the crustal strength, to produce or re-activate fracturing. Because of the uncertainty about the real amplitude of the stresses in the region, the results are only indicative of the areas where, under the far-field compression and the boundary conditions imposed to the model (Fig. 7), the strength of the crust masses is exceeded. However, as said, the range of horizontal stress values obtained throughout the modelling is of the same order of magnitude (10-50 MPa) of the horizontal stress measured in the few in situ stress experiments performed in the region (Kohlbeck et al., 1980; Grünthal and Stromeyer, 1992). The values of $I_2$ are mapped in Fig. 9. It is noteworthy, that the highest values of $I_2$, indicative of the most probable locations of strong earthquakes, are found near Tolmezzo, quite close to the area where the highest seismic energy values are observed, and where the 6th May 1976, M=6.4 earthquake occurred.
4.3. Geodynamic implications

As mentioned above, other kinematic hypotheses have been tested. It is noteworthy, that varying the orientation of the compression acting on the southern side, in agreement with Ward (1994) or Albarello et al. (1995) hypotheses, we did never obtain a fitting of the observed data comparable with the ones here shown. The model here presented, even if consistent with the observational data which allow the hypothesis that Adria rotates counterclockwise with respect to Africa, with the boundary conditions applied allows also for an internal deformation of the study area. However, it can be interesting to see if part of the displacement pattern predicted by the model (Fig. 10) is similar to the ones that would result from a rigid rotation of a plate around a pole. Through a least square minimisation, we simulated the displacements relative to a rigid rotation of the plate around a pole. The location of the pole results 47.03 N, 4.73E, therefore near to the location of Ward (1994), calculated from VLBI data analysis (Fig. 11).

5. Conclusions.

The northern edge of the so-called Adria microplate has been here studied following two different approaches: the analysis of continuous geodetic data, and a finite elements elastostatic modelling. In both cases, the aim is to relate the stress-strain field pattern to the geodynamic processes acting at this collision plate boundary.

From the strain field analyses, and in particular from the tilt data, the long-term component of the strain-energy variation in the region appears to be polarized in two preferred directions: N20W and N70E. Alpine NNW-SSE compression and the stresses acting at Apenninic and Dinaric fronts are hypothesised at the origin of the long-term tilting.
The finite-element modelling revealed a powerful tool to simulate and study the present stress-field characteristics, and to provide a possible interpretation in the frame of the regional kinematics. The good fit obtained between model predictions and the seismological and geodetic observations confirms the validity of this approach and of the hypotheses put forward throughout the experiments. In particular, the results of the modelling allow for the hypothesis that the southern boundary of the Adria microplate is subject to highly varying compressions, which increase on the eastern side. The boundary conditions play indeed a very important role in this approach: the ones imposed to the northern, eastern and western sides of the model are realistic, according to both tectonic and seismological evidences. As far as the southern side, the boundary conditions here applied gave the best agreement with seismologic and geodetic observations. The modelling predictions explained also the apparent rigid counterclockwise rotation of Adria plate observed.
This is however surely not a final modelling, but it merely represents a starting point to stimulate following studies on these problems and the development of more sophisticated rheological models, that can give an answer to some still opened questions about the tectonic processes in this region.

Fig. 10. Horizontal displacements predicted by the finite element model.

Fig. 11. Location of the rotation pole estimated assuming that part of the displacement pattern predicted by the model (Fig. 10a) can be explained in term of rigid rotation of the plate (Fig. 10b). The rotation poles proposed by Anderson and Jackson (1987) (A&J), Westaway (1990) (WE) and Ward (1994) (WA) are indicated, together with the location inferred by the present modelling (Our model).
References.


