MODELING SURFACE GPS VELOCITIES IN THE SOUTHERN AND EASTERN ALPS BY FINITE DISLOCATIONS AT CRUSTAL DEPTHS

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In the Eastern and Southern Alps a complex fault geometry accommodates the northward indentation of the Adria plate, the uplift of the Tauern Window, and a lateral extrusion towards the Pannonian Basin. The northeastern edge of the Adria is associated with the seismically active Friuli (Anderson and Jackson, 1987; Bressan et al., 1998, 2006; Schmid et al., 2004, 2008). The compressive $M_w=6.5$ earthquake of May 6, 1976 is the largest recorded event in Friuli. The area of the Southern and Eastern Alps is characterized by significant crustal thickness variations (Brückl et al., 2007, 2010). Seismic profiles show that the Eurasian and Adriatic plates interact with a thinner Pannonian unit as a structurally separated entity (Brückl et al., 2007, 2010). Late Oligocene-Middle Miocene indentation tectonics is considered as the primary agent driving substantial lateral material transfer, or “lateral extrusion” (Ratschbacher et al., 1991a; Neubauer et al., 2000; Willinghoffer and Cloetingh, 2003; Wölfler et al., 2011). The indentation tectonics and resulting lateral extrusion is driven by a free boundary in the east due to subduction of a remnant land-locked basin within the present-day Carpathians (e.g., Wortel and Spakman, 2000). From the structural point of view, increasing evidence demonstrates inversion of the entire Alpine-Carpathian-Pannonian system at ca. Miocene/Pliocene boundary (ca. at 5 Myr before present, e.g., Peresson and Decker, 1997) and the sudden onset of surface uplift (e.g., Genser et al., 2007; Hergarten et al., 2010; Wagner et al., 2010). Extension and related normal and transtensional faults as well as subsidence in sectors of the Eastern Alps including the Pannonian basin were replaced by E-W shortening structures and related surface uplift.

Using the analytic model of finite dislocation in an elastic half space of Okada (1985) and a dense set of GPS velocities, we present in this paper a first map of slip at depth. Based on structural surface data we identify a number of rectangular faults, which approximate the largest geological structures and which have the potential to accommodate the slip required to fit the GPS data (Fig. 1). We show that the GPS velocities, of the order of a few mm/yr, are consistent

![Figure 1](image-url)
with a dynamic process where indentation and lateral extrusion involve slips at crustal depths ranging between 10 and 30 mm/yr. The available velocity data are consistent with slip taking place on at least six rectangular faults located in the upper crust: we associate them primarily with the Giudicarie Fault, the North Alpine Wrench Corridor, the Brenner fault, the SEMP fault along the northern part of the Tauern window, the Pustertal-Gailtal fault and the Dinarides, e.g., the Idrija and the eastern segments of the Fella-Save faults (Fig. 2). Whereas most of these zones represent well defined fault zones, the North Alpine Wrench Corridor corresponds to a zone of distributed seismicity close to the northern margin of Eastern Alps (Reinecker and Lenhardt, 1999; Lenhardt et al., 2007) and consequently a zone of distributed deformation. Using the root mean square (r.m.s.) of the (observed-minus-modeled) velocities as an indicator of the goodness of the fit, we constrain the geometrical parameters of the rectangular faults and slip rates. There are nine parameters for each fault: three dimensional coordinates of an origin, length and width of the fault, two-dimensional slip vector, strike and dip angles. The least squares adjustment is done on a neighborhood of a priori values of these parameters, which come from independent information such as structural geology, average direction of P/T axes of fault plane solutions, and regional strain rate field from GPS velocities.

Fig. 2 – Geometry of the six rectangular slip planes (grey rectangles) projected onto the topographic surface. The grey line parallel to one of the sides of each rectangle represents the intersection of the fault plane with the topographic surface. The ‘beach balls’ give a pictorial view of the data in Tab. 1. The number in black above each beach ball refers to the indexing in Tab. 1. The blue arrows represent the measured velocities with 1σ error ellipse, and the white arrows the predicted model velocities based on Tab. 1. To = Tonale fault, PG = Pustertal-Gailtal, Gi = Giudicarie fault, TW = Tauern Window, NAWC = North Alpine Wrench Corridor, La = Lavant Fault, MF = Möll Valley-Hochstuhl fault, Di = Dinarides, Mo = Montello, Fr = Friuli, SEMP = Salzachtal-Ennstal–Mariazell–Puchberg fault, Go= Görtshitztal fault, IdF= Idrija fault, KF= Katschberg Fault. Vergence and faults style are from the Structural Model of Italy (CNR, 1990).
Shear heating is likely to increase the temperature on the fault planes. The resulting heat flow adds to that generated by radiogenic sources in the upper continental crust. The available data (Della Vedova et al., 2001; Viganò et al., 2008, 2011; Clark, 1961) indicate that the total heat flow observed on the surface does not exceed 60 to 80 mW/m$^2$, although in middle Jurassic values as high as 85 to 105 mW/m$^2$ have been reported by Carminati et al. (2010) using organic matter maturity data from outcropping sediments.

Following Turcotte and Schubert (2002) we model the surface heat flow and temperature increase on the fault planes as due to a sudden increase of heat flow caused by shear heating on the fault plane. It is reasonable to assume that the total temperature (for a nominal thermal gradient plus shear heating) on the fault plane is in the range 600-800 °C (Vosteen et al., 2006, for the TRANSALP profile), and that the heat flow on the Earth surface, when added to the radiogenic heat (of the order of 50 mW/m$^2$), does not exceed 60-80 mW/m$^2$. The model then implies that the time of initiation of heat production by shear in the half space must be relatively recent, for shear stresses in the range 100-300 MPa. We infer that such epoch should be somewhere in the Plio-Pleistocene, hence more recent than the late Oligocene to Miocene collision of the Adria indenter with the stable European foreland. According to the analog models of Ratschbacher et al. (1991), this collision is responsible the fold and fault structure. Hence it can be concluded that the collision was ‘head on’ in the first 15-18 Myr, and has been accommodated by slip on inclined fault planes only in the past 5-7 Myr, since a longer slipping phase would imply an exceedingly large amount of frictionally generated heat to reach the Earth surface (Fig.3).

Specific assumptions on the local geotherm are clearly needed to make these concepts more quantitative.
Tab. 1 – The nine parameters of each rectangular faults used in the analysis. The first three columns (Lat, Long, depth) identify the center of the rectangular fault. The last column gives the product of the previous three columns (slip area x slip rate) times the shear modulus $\mu = 30$ GPa. Uncertainties (1σ), in the sense of square root of the corresponding element in the variance covariance matrix scaled by the r.m.s. of the post fit residuals, are: 0.05 deg for Longitude and Latitude, 2 km for depth, 3 degrees for strike and dip, 0.005 m/yr for slip, 5 km and 2 km for Length and respectively Width of the fault.

<table>
<thead>
<tr>
<th>Fault id.</th>
<th>Name</th>
<th>Long. (deg)</th>
<th>Lat. (deg)</th>
<th>depth (km)</th>
<th>strike (deg)</th>
<th>dip (deg)</th>
<th>right lat. (m/yr)</th>
<th>reverse (m/yr)</th>
<th>Length (km)</th>
<th>Width (km)</th>
<th>Moment rate $10^{18}$ J/yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Giudicarie</td>
<td>11.04</td>
<td>46.31</td>
<td>30</td>
<td>211</td>
<td>-0.01</td>
<td>0.03</td>
<td>58</td>
<td>10</td>
<td>0.56</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>NAWC</td>
<td>12.18</td>
<td>47.85</td>
<td>10</td>
<td>84</td>
<td>60</td>
<td>-0.01</td>
<td>0.02</td>
<td>297</td>
<td>12</td>
<td>2.02</td>
</tr>
<tr>
<td>3</td>
<td>Pustertal</td>
<td>12.91</td>
<td>46.68</td>
<td>20</td>
<td>282</td>
<td>89</td>
<td>0.01</td>
<td>0.01</td>
<td>123</td>
<td>30</td>
<td>1.41</td>
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<tr>
<td>4</td>
<td>TW north</td>
<td>12.22</td>
<td>47.34</td>
<td>8</td>
<td>261</td>
<td>89</td>
<td>0.00</td>
<td>0.02</td>
<td>61</td>
<td>20</td>
<td>0.55</td>
</tr>
<tr>
<td>5</td>
<td>Brenner fault</td>
<td>11.49</td>
<td>47.02</td>
<td>2</td>
<td>188</td>
<td>45</td>
<td>0.00</td>
<td>-0.02</td>
<td>35</td>
<td>4</td>
<td>0.08</td>
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<tr>
<td>6</td>
<td>Dinarids</td>
<td>14.13</td>
<td>45.62</td>
<td>5</td>
<td>312</td>
<td>45</td>
<td>0.01</td>
<td>0.01</td>
<td>122</td>
<td>14</td>
<td>0.73</td>
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References


