DELINEATION OF THE GEOMETRY OF THE NODES IN THE
ALPS-DINARIDES HINGE ZONE AND RECOGNITION
OF SEISMOGENIC NODES (M ≥ 6)

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Abstract

In the junction zone between the Alps and the Dinarides, one of the most seismically active areas in Europe, we delineate a total of sixteen nodes which are capable of $M \geq 6.0$ earthquakes using large-scale cartographic data. Seven of them have already experienced the occurrence of sufficiently well located earthquakes with $M \geq 6.0$. Using these seven nodes as a learning set, we identify, by means of the pattern recognition methodology, three other nodes prone to earthquakes with $M \geq 6.0$: one node in the Alpine domain and two in the northernmost Dinarides.
Introduction

The Alps-Dinarides junction zone is studied with the goal to identify seismogenic nodes capable of $M \geq 6.0$ earthquakes. The region is a prominent seismoactive area characterized by a number of destructive earthquakes (e.g. Slejko et al., 1989; Carulli et al., 1990). The active tectonics of the region has been intensively studied during the last two decades (Aoudia, 1998; Benedetti, 1999; Aoudia et al., 2000; Meletti et al., 2000; Bajc et al., 2001; Valensise and Pantosti, 2001; Carulli et al., 2002; Galadini et al., 2001, 2005; Fitzko et al., 2005).

Nodes are specific structures formed at the intersections of fault zones. The methodology used combines a Morphostructural Zoning (MZ) method, which defines a set of nodes, and a pattern recognition technique which classifies the nodes by similarity of geomorphic-geologic-geophysical features (Gorshkov et al., 2003). In this study, we attempt to delineate the geometry of node boundaries using large-scale cartographic sources including topographic and geological maps at the scale of 1:150,000. The possibility of identifying the structural boundaries of a node has been proved by extensive field-work in the Pamir-Tian Shan and the Greater Caucasus (Rantsman, 1979; Gvishiani et al., 1986).

1. Morphostuctural zoning of the study region

The morphostructural map shown in Fig.1 has been compiled, with the formalized Morphostuctural zoning method (Rantsman, 1979; Gorshkov et al., 2003), for the identification of earthquake-prone areas ($M \geq 6.0$) in the Alps and Dinarides (Gorshkov et al., 2004) using topographic, geologic, tectonic maps and satellite images.

A blow-up of the morphostructural map (Fig.1) covering the study region is shown in Fig.2. The morphostructural boundary between the Alps and the Dinarides is shown in Figs.1 and 2 by the first rank lineament extending from D1 to D6. Two knee-like bends break the boundary strike and shift the boundary in an en-echelon way to the south. Near the town of Tolmin, the D1-D2-D3-D4 en-echelon lineaments (Fig. 2) exhibit an offset of about 15 km. We hypothesize that the offset is due to the dextral cumulative displacements along the NW-SE Idrija fault which is represented in Fig. 2 by the lineament D2-D17. According to Šušteršič (1996), the largest dextral offset inferred for the Idrija fault is about 12 km. The bend of the Alps-Dinarides boundary near Ljubljana might be caused by the dextral displacements along the lineament passing from A108 to D5 that corresponds to the NW-SE Žužemberk fault (Buser and Draksler 1990).

The first rank lineament going from A104 to D1 separates the study region from the Friuli plain. The first rank lineament going from D1 to D15 separates the plain from the External Dinarides. Recent tectonic deformations within the boundary zones are evidenced from active fault studies by Aoudia (1998), Benedetti (1999), Aoudia et al. (2000), Galadini et al. (2005).
To the east, the study region is limited by the second rank lineament, crossing the Alps from A109 to D6. To the north, it is limited by the longitudinal second rank lineament, extending from A97 to A109 that corresponds to the Periadriatic line, which is a transpressive fault cross-cutting a large part of the Alps (Doglioni, 2000). The western boundary is the NE lineament going from A97 to A103 that corresponds to a sinistral strike-slip zone (Meletti et al., 2000; Carulli, 2006). The near E-W lineament from A100 to A108 corresponds to the Fella-Sava line (Castellarin and Vai, 1986). The NW lineament from D3 to D17 corresponds to the Idrija fault (Placer, 1981; Bajc et al., 2001). The lineament going from D2 to A99 was traced by Gorshkov et al. (2004), along topographic alignments, as a boundary between the Tolmezzo Alps and the Julian Alps that differ in the height of the relief.

1.1. Delineation of the geometry of the nodes

We mapped the geometry of the nodes using large-scale cartographic sources. A node is revealed as a block structure of a much smaller size with respect to a morphostructural block. Nodes are formed around the intersections of lineaments. They are characterized by a mosaic combination of topographic forms and by a concentration of topographic alignments of various strikes. Stream offsets and topographic breaks of slopes exhibit a higher concentration at the nodes with respect to the areas along the lineaments. In the vicinity of nodes, faults either split into branches/segments and/or change geometry.

A model proposed by Gabrielov et al. (1996) implies that block interaction along intersecting faults leads to stress and strain accumulation and secondary faulting around the intersection. This causes the generation of new faults of progressively smaller size, so that a mosaic structure, a node, is formed around the intersection. The instability of fault junctions was also studied by McKenzie and Morgan (1969), King (1983, 1986), Cronin (1992), and McCaffrey et al. (2000).

Moving away from the intersection, the boundaries of the node are identified in the field when the different striking landforms recover the original strike of the lineament. These marks indicate parts of the node boundary. To define them, we compile the map of the topographic alignments (Fig. 3) and outline an area around each intersection of lineaments, which includes the most chaotic pattern of the topographic alignments. The node boundary is set at sites where the orientation of the alignments becomes more regular. We constructed rose diagrams (Fig. 4) for each node and for areas between neighboring nodes.

Nodes at the Alps-Dinarides boundary include topographic alignments of both Alpine and Dinaric strikes (Fig. 3). This is the result of the interaction of Alpine and Dinaric structures in the Alps-Dinarides transition zone (Doglioni, 1987; Pinter et al., 2006). The ongoing interference of Alpine and Dinaric structures is suggested by Kravanja and Panza (2005) from the analysis of full moment tensor for earthquake swarms; they hypothesized that the recent stress field operating in southeastern Alps seems to act on faults belonging to the Dinaric system and vice versa.
Based on the above arguments, sixteen nodes of different size and geometry are delineated in this study (Fig. 5B).

2 Recognition of nodes prone to earthquakes with $M \geq 6.0$

Our goal is to separate the nodes into two classes: the nodes where earthquakes with magnitude $M \geq 6.0$ may occur (class $D$) and the nodes where only earthquakes with $M < 6.0$ may occur (class $N$). Using the information on large earthquakes (Sect. 2.1) we select two sample sets of nodes: $D_0$ representing class $D$ and $N_0$ representing class $N$. Each node is described by the topographical, geological, geomorphological, and geophysical parameters (Sect. 2.2). The values of the parameters form a vector that is associated with a node. The vectors are classified into classes $D$ and $N$ using pattern recognition techniques, specifically the CORA-3 algorithm (Gorshkov et al., 2003) that operates in two stages. At the learning stage the algorithm selects the characteristic $D$- and $N$-traits for classes $D$ and $N$, using samples $D_0$ and $N_0$. At the classification stage the algorithm counts the numbers of $D$- and $N$-traits that each node possesses and assigns each node to one of the two classes, in accordance with the number of prevailing traits.

2.1 Selection of the sample nodes for the learning

The synoptic vision of lineament-and-block structure and seismicity, since 1000 till 2006, is shown in Fig. 5A. Earthquake catalogs (Camassi and Stucchi, 1996; Herak et al., 1996; Shebalin et al., 1998; Živčič et al., 2000; Peresan and Panza, 2006) report twelve common large events, located within the study region (Table 1). The 1348 and 1511 epicenters are still a matter of debate (Rybarič, 1979; Hammerl, 1994; Fitzko et al., 2005). Fitzko et al. (2005) found constraints that are consistent with the epicenter of the 1511 earthquakes reported by Živčič et al. (2000). Hammerl (1994) re-located the 1348 event from Carinthia to Friuli but did not provide epicentral coordinates, thus we took the location by Camassi and Stucchi (1996).

The set $D_0$ of samples for the class $D$ comprises seven nodes (2, 3, 4, 5, 6, 8, and 15 in Fig. 4B) where earthquakes with $M \geq 6.0$ already occurred. As in Gorshkov et al. (2004), in the learning stage we did not include node 16, hosting the 567 and 1097 events, in the set $D_0$ because of the poor location of their epicenters (Herak et al., 1996). The set $N_0$ of samples for the class $N$ contains the other nine nodes.

2.2 Parameters of the nodes used for the recognition

The objects are described by a number of parameters (Table 2), which are determined from topographic and geological maps as well as from the MZ map (Fig. 2). Parameters characterizing heat flow and gravity field are determined from the maps by Cassano & Maino (1989), Bigi et al. (1990), Ravnik et al. (1995), and Della Vedova et al. (2001). The study region is the first one where we employ heat flow data for the description of objects of recognition.
We apply the CORA-3 pattern recognition algorithm (Gorshkov et al., 2003) that operates in a binary vector space. Therefore the values of the parameters were transformed into binary vector space by discretization and coding. This is made by dividing each parameter range into two parts by means of a threshold of discretization. After the discretization, the values of the parameters are converted into binary components with the value 1 (“small”) or 0 (“large”) depending on which interval the value belongs to. The thresholds of discretization for parameters are given in Table 2.

2.3 Result of recognition

The classification has been performed with the following values of the parameters of CORA-3 algorithm (Gorshkov et al., 2003): $k_1 = 5$, $\bar{k}_1 = 3$, $k_2 = 6$, $\bar{k}_2 = 1$, and $\Delta = 0$. At the learning stage two D-trait and one N-trait (Table 3) are selected. At the classification stage, for each object, the numbers of D- and N-trait that it possesses ($n_D$ and $n_N$ respectively) are calculated. The class D is formed (with $\Delta = 0$) by the objects with $n_D \geq n_N$. As result, all the nodes of the set $D_0$ and three nodes (7, 12 and 16) of the set $N_0$ are assigned to class D (Fig. 6). Experiments performed to test the classification stability have given satisfactory results.

Discussions

The criteria for the identification of the seismogenic nodes defined with CORA-3 (see Table 3) can be interpreted as follows. The number of node-forming lineaments (NL) is an indirect measure of the fragmentation of the crust within a node. The recognized seismogenic (class D) nodes are characterized by a “large” number of NL and this fact suggests a larger fragmentation within the nodes than in the surroundings. The second D-trait (Table 3) implies that the seismogenic nodes include a lineament of the 2nd rank and simultaneously the distance (L) between the points, where $H_{\text{max}}$ (maximum topographic altitude) and $H_{\text{min}}$ (minimum topographic altitude) are measured, is “small”. This trait indicates that D nodes sit on high rank boundaries separating large crustal blocks and the topography inside D nodes is highly variable.

Nodes N display a simpler structure: they are characterized by a “small” number NL of node-forming lineaments.

In the study region ten nodes are recognized prone to $M \geq 6.0$ earthquakes (Fig. 6). Nodes 4, 5, and 6 sit at the Alps-Dinarides boundary, node 8 is located on the boundary between the Alps and the Friuli plain, and nodes 2 and 7 are situated in the Alpine mountain domain. In the Dinaric portion of the study region we recognized the nodes 12, 15 and 16 as prone to $M \geq 6.0$ earthquakes. The node 16, hosting the 567 and 1097 events, was not considered in the learning stage because of the poor location (Herak et al., 1996) of these events.

In an earlier and large scale study, Gorshkov et al. (2004) recognized the intersections of lineaments prone to $M \geq 6.0$ earthquakes for the entire Alps and Dinarides domain. The nodes 2, 3, 4,
5, 6, 7 and 8 recognized in this paper in the Alpine part of the Alps-Dinarides junction zone include all the intersections of lineaments that are prone to $M \geq 6.0$ earthquakes according to Gorshkov et al. (2004). Each of these nodes contains at least one of such intersections.

In the Dinaric part of the junction zone Gorshkov et al. (2004) recognized six intersections of lineaments as prone to $M \geq 6.0$ earthquakes. Four of them belong to the D nodes 12, 15, and 16 which are recognized as prone to $M \geq 6.0$ earthquakes in this study as well. On the other hand, the nodes 10 and 14, recognized as N in this work, include intersections recognized by Gorshkov et al. (2004) as prone to $M \geq 6.0$ earthquakes.

This apparent discrepancy can be reconciled when considering that in this study we apply pattern recognition only to the nodes belonging to the Alps-Dinarides junction zone, while (Gorshkov et al. 2004) classified the intersections within the entire Dinarides. The geodynamics of the Dinaric part of the junction zone differs from that of the other Dinaric domains. Unlike the latter, strike-slip focal mechanisms predominate in the Dinaric part of the junction zone (Slejko et al., 1989; Del Ben et al., 1991; Guidarelli and Panza, 2006). The intersections located in the junction zone turn out to be not sufficiently distinguishable against the background of the entire Dinarides.

On the contrary, a good correlation between seismogenic intersections of lineaments recognized by Gorshkov et al. (2004) and seismogenic nodes defined in this work for the Alpine part of the junction zone indicates the structural and geodynamical similarity of the Alpine part of the junction zone to the entire Alps. Specifically, thrust focal mechanisms prevail both in the Alpine part of the junction zone and in the entire Alps (Slejko et al., 1989; Del Ben et al., 1991; Guidarelli et al., 2006).

Taking into consideration that Gorshkov et al. (2004) analyzed Alps and Dinarides separately obtaining different thresholds of parameter discretization and sets of characteristic traits for both large regions, the present study evidences local properties of the Alps-Dinarides junction zone that were masked by the wider background of Alps and Dinarides, thus evidencing the relevance of multiscale studies for a sound assessment of seismic potential.

Acknowledgments
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References


Table 1. Earthquakes with $M \geq 6.0$ used in the learning stage of the recognition

<table>
<thead>
<tr>
<th>Date</th>
<th>Lat.</th>
<th>Long.</th>
<th>Ms</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>567</td>
<td>45.60</td>
<td>15.30</td>
<td>6.2</td>
<td>Shebalin et al., 1998</td>
</tr>
<tr>
<td>1097</td>
<td>45.60</td>
<td>15.30</td>
<td>6.5</td>
<td>Herak et al., 1996</td>
</tr>
<tr>
<td>1348 01 25</td>
<td>46.50</td>
<td>13.45</td>
<td>6.4</td>
<td>Camassi and Stucchi,1996</td>
</tr>
<tr>
<td>1511 08 08</td>
<td>46.10</td>
<td>14.00</td>
<td>6.9</td>
<td>Živčič et al., 2000</td>
</tr>
<tr>
<td>1690 12 04</td>
<td>46.50</td>
<td>13.90</td>
<td>7.5</td>
<td>Shebalin et al., 1998</td>
</tr>
<tr>
<td>1870 03 01</td>
<td>45.50</td>
<td>14.50</td>
<td>6.4</td>
<td>Shebalin et al., 1998</td>
</tr>
<tr>
<td>1873 06 29</td>
<td>46.18</td>
<td>12.38</td>
<td>6.4</td>
<td>Shebalin et al., 1998</td>
</tr>
<tr>
<td>1895 04 14</td>
<td>46.10</td>
<td>14.50</td>
<td>6.1</td>
<td>Živčič et al., 2000</td>
</tr>
<tr>
<td>1936 10 18</td>
<td>46.07</td>
<td>12.37</td>
<td>6.2</td>
<td>Camassi and Stucchi,1996</td>
</tr>
<tr>
<td>1963 05 19</td>
<td>46.10</td>
<td>14.80</td>
<td>6.0</td>
<td>Peresan and Panza, 2006</td>
</tr>
<tr>
<td>1976 05 06</td>
<td>46.23</td>
<td>13.07</td>
<td>6.5</td>
<td>Camassi and Stucchi,1996</td>
</tr>
</tbody>
</table>

Table 2. Parameters that describe objects of recognition and their thresholds of discretization

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Threshold of discretization</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>A) Topographic parameters</strong></td>
<td></td>
</tr>
<tr>
<td>1. Maximum topographic altitude, $m$ ($H_{max}$)</td>
<td>1200 m</td>
</tr>
<tr>
<td>2. Minimum topographic altitude, $m$ ($H_{min}$)</td>
<td>400 m</td>
</tr>
<tr>
<td>3. Relief energy, $m$ ($\Delta H$) ($H_{max} - H_{min}$)</td>
<td>980 m</td>
</tr>
<tr>
<td>4. Distance between the points where $H_{max}$ and $H_{min}$ are measured, km ($L$)</td>
<td>12 km</td>
</tr>
<tr>
<td>5. Slope, ($\Delta H/L$)</td>
<td>0.08</td>
</tr>
<tr>
<td><strong>B) Geological parameters</strong></td>
<td></td>
</tr>
<tr>
<td>6. The portion of soft (quaternary) sediments, % ($Q$)</td>
<td>5%</td>
</tr>
<tr>
<td><strong>C) Gravity parameters</strong></td>
<td></td>
</tr>
<tr>
<td>7. Maximum value of Bouguer anomaly, mGal ($B_{max}$)</td>
<td>-35 mGal</td>
</tr>
<tr>
<td>8. Minimum value of Bouguer anomaly, mGal ($B_{min}$)</td>
<td>-60 mGal</td>
</tr>
<tr>
<td>9. Difference between $B_{max}$ and $B_{min}$, mGal ($\Delta B$)</td>
<td>20 mGal</td>
</tr>
<tr>
<td><strong>D) Parameters from the morphostructural map</strong></td>
<td></td>
</tr>
<tr>
<td>10. The highest rank of lineament in a node, (HR)</td>
<td>1</td>
</tr>
<tr>
<td>11. Number of node-forming lineaments, (NL)</td>
<td>2</td>
</tr>
<tr>
<td>12. Distance to the nearest 1st rank lineament, km ($D_1$)</td>
<td>0 km</td>
</tr>
<tr>
<td>13. Distance to the nearest 2nd rank lineament, km ($D_2$)</td>
<td>0 km</td>
</tr>
<tr>
<td>14. Distance to the nearest intersection out of this node, km ($D_{int}$)</td>
<td>30 km</td>
</tr>
<tr>
<td><strong>E) Heat flow parameters</strong></td>
<td></td>
</tr>
<tr>
<td>15. Maximum value of heat flow, mW/m², (HF$_{max}$)</td>
<td>48 mW/m²</td>
</tr>
<tr>
<td>16. Minimum value of heat flow, mW/m², (HF$_{min}$)</td>
<td>40 mW/m²</td>
</tr>
<tr>
<td>17. Difference between HF$<em>{max}$ and HF$</em>{min}$, mW/m², ($\Delta HF$)</td>
<td>9 mW/m²</td>
</tr>
<tr>
<td><strong>F) Morphological parameter (Mor)</strong></td>
<td></td>
</tr>
<tr>
<td>This parameter takes one of the following three values in accordance with the contact of relief types in the node: 1 – mountain/mountain (m/m); 2 – mountain/piedmont (m/pd); 3 – piedmont/plain (pd/p).</td>
<td></td>
</tr>
</tbody>
</table>
Table 3. Traits of classes D and N determined by CORA-3

<table>
<thead>
<tr>
<th>Number of node-forming lineaments ($NL$)</th>
<th>Distance between the points where $H_{max}$ and $H_{min}$ are measured, ($L$) $km$</th>
<th>Distance to the nearest 2nd rank lineament, ($D2$) $km$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traits of class D (D-traits)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$&gt;2$</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>$\leq 12$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Traits of class N (N-traits)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure Captions

**Figure 1.** Morphostructural map of the Alps and Dinarides (modified from Gorshkov et al., 2004).

The map shows: 1) homogenous areas — blocks; 2) linear zones separating blocks — morphostructural lineaments; 3) areas of lineaments intersections — morphostructural nodes. The blocks assigned to the lowest 3\textsuperscript{rd} rank are merged into megablocks, 2\textsuperscript{nd} rank areas. The megablocks, in turn, are grouped into the mountain country, 1\textsuperscript{st} (highest) rank area. The homogeneity of blocks is determined by means of the analysis of informative features of relief (height ratio, trend of linear forms of relief, drainage patterns). The hierarchy of blocks determines the hierarchy of lineaments, classifying them as 1st rank, 2nd rank, and 3rd rank.

The grey polygon shows the study region. Thick, medium and thin lines are the lineaments of the 1\textsuperscript{st}, 2\textsuperscript{nd} and 3\textsuperscript{rd} rank, respectively; continuous and dashed lines are the longitudinal and transverse lineaments, respectively. A and D denote Alpine and Dinaric nodes, respectively.

**Figure 2.** Morphostructural map of the hinge zone between the southeastern Alps and northernmost Dinarides. The lines showing the morphostructural lineaments have the same meaning as those in Fig. 1. Names of the physiographic provinces in the Alps are indicated in accordance with Cucchi et al. (2000).

**Figure 3.** Geometry of the nodes at the Alps-Dinarides boundary. The size and shape of the nodes are outlined from the analysis of the topographic alignments traced from topographic maps at a scale of 1:150,000. Thicker gray lines depict lineaments like in Fig. 2, while thin lines show topographic alignments including linear river streams, axes of ranges and elongated scarps on the slopes of the ridges.

**Figure 4.** Rose diagrams of the topographic alignments inside each node and in some areas located between neighboring nodes. The length of vectors is proportional to the number of alignments possessing the same strike. Rose diagrams show that the orientation of the alignments is more variable inside nodes with respect to the areas located between nodes.

**Figure 5.** Panel A gives a synoptic vision of the lineament-and-block structure and seismicity since 1000 till 2006. Earthquake epicenters are from the UCI2006 catalog (Peresan and Panza, 2006). Panel B displays the delineated geometry of the nodes and the events with $M \geq 6.0$. Lines of different thickness show lineaments as in Figs. 1–3. Dashed lines depict the geometry of the nodes.

**Figure 6.** Seismogenic nodes prone to $M \geq 6.0$ earthquakes defined with CORA-3.

The numbered polygons depict the nodes. The polygons defined with continuous lines indicate nodes prone to $M \geq 6.0$ earthquakes; those bounded by dashed lines show nodes with less seismic potential. Dots show the $M \geq 6.0$ earthquakes used, with the exception of the events falling in node 16, to select sample nodes for the learning stage of the recognition.
Fig. 3
Fig. 4