Miocene rotations in the Eastern Alps — palaeomagnetic results from intramontane basin sediments

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Received 22 June 1999; accepted for publication 25 March 2000

Abstract

A palaeomagnetic study of late Early Miocene to late Middle Miocene sediments from the Eastern Alpine intramontane basins revealed counterclockwise rotations in the Ennstal, in the western part of the Noric and in the Lavanttal depressions. For the basal strata of the basins, declinations are between 273° and 315°, while for the younger strata they are between 321° and 333°, in perfect agreement with observations from the Klagenfurt basin. The results suggest synsedimentary rotation during the lateral tectonic extrusion of the Eastern Alps (ca. 17–13 Ma), which was also responsible for the formation of the mostly transtensional basins. We propose a model in which domino-shaped blocks, separated by NNW–SSE trending dextral faults, rotated counterclockwise due to faster eastward motion in the south relative to areas further north. The protrusion of the Bohemian spur inhibited eastward motion in the northern part of the study area, thus creating a sinistral wrench corridor. After lateral extrusion had ceased the counterclockwise rotation continued probably as ‘en bloc’ rotation of ca. 30°. Clockwise rotation was observed in the eastern part of the Noric depression, which appears to belong to a limited area with complex rotation pattern near the eastern margin of the Alps. This area is wedged between the counterclockwise rotated Eastern Alps and the similarly rotated North Pannonian area in Hungary.

Keywords: Eastern Alps; intramontane basins; Miocene; palaeomagnetism; tectonic model

1. Introduction

In the last decade several palaeomagnetic studies reported Tertiary rotations from the surroundings of the Eastern Alps (e.g. Márton and Márton, 1996; Márton et al., 1996; Vass et al., 1996; Fodor et al., 1998; Kempf et al., 1998; Márton et al., 1999a,b). From the Eastern Alps, however, very few palaeomagnetic data are published which may be regarded as indicative of Tertiary rotations. Most of them were obtained on metamorphic rocks and interpreted as overprint magnetizations of Tertiary age (Mauritsch et al., 1991; Burgschwaiger et al., 1996), others were observed on Gosau sediments of late Cretaceous age (Agnoli et al., 1989) and consequently, the counterclockwise rotation they exhibited was attributed to Tertiary movements (Márton and Mauritsch, 1990).

The lack of direct evidence for the very likely rotations that must have accompanied Miocene lateral extrusion in the Eastern Alps (Ratschbacher et al., 1991) was the reason why we started a systematic palaeomagnetic study on the sediments...
of the intramontane basins. Our aim was to quantify the movements and constrain the timing of the rotations.

2. Geological background

The Eastern Alps are dominated by the Austroalpine mega-unit (Fig. 1), which represents the rigidly behaving upper plate during Early Tertiary continental collision. The Austroalpine unit acted as an orogenic lid above the Penninic mega-unit, which contains remnants of the Neo-Tethys ocean separating the Austroalpine unit (a former part of the Africa-derived Adriatic plate), and the European plate (e.g. Frisch, 1979; Dercourt et al., 1985). The Penninic domain was rapidly exhumed in Miocene times, forming metamorphic dome structures, which are exposed in windows (Fig. 1; Frisch et al., 1998).

The object of the present study is the area east of the Tauern window, where the Austroalpine mega-unit comprises the crystalline basement, weakly metamorphosed Palaeozoic sequences and subordinate Permian and Mesozoic cover sequences (Figs. 1 and 2). The Penninic windows to the east (Rechnitz window) and west (Tauern window) of this area indicate that the Austroalpine domain floats on the Penninic substratum. Seismic measurements suggest that the Austroalpine/Penninic boundary reaches a maximum depth of ca. 10 km between these windows (Aric et al., 1987; Ratschbacher et al., 1991).

Early Tertiary continental collision was responsible for the formation of a thickened crustal stack. Thermal weakening of the crust with \( T_{\text{max}} \) ca.
30 Ma (Christensen et al., 1994) and Oligocene uplift of the Alps, west of the later Tauern window (Frisch et al., 1998) formed the prerequisites for gravity-driven orogenic collapse in Early and Middle Miocene times (Ratschbacher et al., 1991). Around 17 Ma, when exhumation rates in the metamorphic domes of the Tauern window may have attained values on the order of 5 mm yr$^{-1}$ (Clift et al., 1985), the Austroalpine lid disintegrated into a number of tectonic blocks that moved eastward on top of the softened Penninic substratum and along large-scale strike-slip faults. The combination of orogen-parallel collapse and block escape was described as 'lateral tectonic extrusion' by Ratschbacher et al. (1991).

Transtensional movement along large-scale conjugate strike-slip fault zones created a number of short-lived intramontane basins filled with Ottnangian or Karpatian through Badenian (for correlation with Mediterranean stages see Fig. 3) sediments. Most of the basins represent pull-apart or negative flower structures along the sinistral Ennstal, the sinistral Mur-Murztal (‘Noric depression’), and the dextral Lavanttal fault systems (Figs. 1 and 2).

The sediment fill of the basins is not metamorphosed, the age of the deposition is poorly constrained by palaeontological data (Table 1). Nevertheless, it is generally accepted that the climax of subsidence and sedimentation in the different basins was synchronous, that is, in the time span between 18 and 15 Ma (Weber and Weiss, 1983; Tollmann, 1985). Younger sediments than 15 Ma occur in the Lavanttal (up to 10 Ma) and in the Klagenfurt basins. The latter is a relatively large, asymmetric basin, where sedimentation started in Sarmatian times (ca. 12 Ma). The formation of this basin was probably related to the eastward extrusion of the Bakony escape block (Frisch et al., 1998).
3. Sediments of the intramontane basins and palaeomagnetic sampling

The intramontane basins contain conglomerates, sandstones, siltstones, claystones and marls (Tollmann, 1985, and references therein). Conglomerates are generally dominant in the basal parts of the sequences and are derived from local sources. Coal seams and layers are frequent in the Miocene sediment pile. In fully preserved profiles, sandy to clayey or marly materials dominate, representing low-energy fluvial and lacustrine environments. In the latter, turbidites are common. It is only in the Lavanttal basin where marine deposits are present. The intramontane basins are lined up along valley-like depressions. However, there are some Miocene occurrences in uplifted position that are considered as having been continuous with the valley-fills nearby [e.g. locality 19 situated 1000 m above the Tamsweg basin with localities 7, 8 and 16 in the basin itself (Fig. 2)].

3.1. Ennstal depression

The formation ages of the basin remnants related to the Ennstal fault system (Fig. 2) are estimated through correlation with other basins and palaeogeographic reconstructions. Thus, the
<table>
<thead>
<tr>
<th>No.</th>
<th>Locality</th>
<th>Age</th>
<th>Reference for age</th>
<th>Map no. / name</th>
<th>YM31-45P</th>
<th>NGKRM</th>
<th>Elevation (m)</th>
<th>Colour</th>
<th>Grain Structures</th>
<th>Structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Niederhof uphill</td>
<td>Pannonian</td>
<td>Beck-Mannagetta</td>
<td>205 St. Paul i.L.</td>
<td>642850</td>
<td>175550</td>
<td>450</td>
<td>Grey</td>
<td>Yellow</td>
<td>Silty clay</td>
</tr>
<tr>
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<td>646700</td>
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<td>370</td>
<td>Dark brown</td>
<td>Clayey silt</td>
<td>Stratified</td>
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<td>3</td>
<td>Ettendorf</td>
<td>Badenian</td>
<td>Beck-Mannagetta</td>
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<td>637750</td>
<td>178700</td>
<td>395</td>
<td>Dark grey</td>
<td>Silty clay</td>
<td>Strongly biotubated</td>
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<td>4</td>
<td>Mühlbach</td>
<td>E. Badenian</td>
<td>Papp (1957), Schmid (1974)</td>
<td>205 St. Paul i.L.</td>
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<td>172850</td>
<td>550</td>
<td>Red</td>
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<td>Poorly stratified</td>
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<tr>
<td>5</td>
<td>St. Paul</td>
<td>Otta-Karp.</td>
<td>Klaas, 1999</td>
<td>204 Volkmehrad 592790</td>
<td>172850</td>
<td>550</td>
<td></td>
<td>Yellow</td>
<td></td>
<td>Poorly stratified</td>
</tr>
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<td>6</td>
<td>Mildenau</td>
<td>L. Stamm.</td>
<td>Papp (1957)</td>
<td>204 Volkmehrad 549500</td>
<td>156350</td>
<td>570</td>
<td></td>
<td>Red</td>
<td>Yellow</td>
<td>Stratified</td>
</tr>
<tr>
<td>7</td>
<td>Tamsweg, Uttersdorf</td>
<td>E. Karpatian</td>
<td>Heinrich (1970)</td>
<td>157 Tamsweg 492900</td>
<td>222500</td>
<td>550</td>
<td></td>
<td>Dark brown</td>
<td>Clayey silt</td>
<td>Stratified</td>
</tr>
<tr>
<td>8</td>
<td>Tamsweg, Górnauch</td>
<td>L. Karpatian</td>
<td>Heinrich (1970)</td>
<td>157 Tamsweg 484050</td>
<td>224090</td>
<td>1005</td>
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<td>Clayey sand</td>
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</tr>
<tr>
<td>9</td>
<td>Oberndorf</td>
<td>Karpatian</td>
<td>Toftmann (1985)</td>
<td>159 Menau 322600</td>
<td>220600</td>
<td>520</td>
<td></td>
<td>Red</td>
<td>Silt-fine sand</td>
<td>Stratified</td>
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<tr>
<td>10</td>
<td>Ottendorfshütte</td>
<td>Karpatian</td>
<td>Motz (1970), Prössy (1970)</td>
<td>161 Kerselfeld 559600</td>
<td>232550</td>
<td>700</td>
<td></td>
<td>(Dark) grey</td>
<td>Clayey sand</td>
<td>Stratified</td>
</tr>
<tr>
<td>12</td>
<td>St. Marren</td>
<td>Karpatian</td>
<td>Wolf and Weis (1985)</td>
<td>134 Wolfard 670380</td>
<td>236900</td>
<td>555</td>
<td></td>
<td>Dark grey</td>
<td>Clayey silt</td>
<td>Stratified</td>
</tr>
<tr>
<td>13</td>
<td>Gmündern</td>
<td>Karpatian</td>
<td>Sachsenhofer (1988)</td>
<td>120 Gmündern 497400</td>
<td>268050</td>
<td>705</td>
<td></td>
<td>Grey</td>
<td>Clayey sand</td>
<td>Poorly stratified</td>
</tr>
<tr>
<td>14</td>
<td>Hohlsau</td>
<td>Otta-Karp.</td>
<td>Wagner et al. (1996)</td>
<td>100 Hohlsau 559200</td>
<td>274550</td>
<td>810</td>
<td></td>
<td>Grey</td>
<td>Silty clay</td>
<td>Stratified</td>
</tr>
<tr>
<td>15</td>
<td>Rünerhütte</td>
<td>Karpatian</td>
<td>Zeilinger et al. (1999)</td>
<td>157 Tamsweg 476050</td>
<td>210800</td>
<td>1675</td>
<td></td>
<td>Dark grey</td>
<td>Brown</td>
<td>Silty clay</td>
</tr>
<tr>
<td>16</td>
<td>Saalfeld</td>
<td>Karpatian</td>
<td>Heinrich (1970)</td>
<td>156 Seegh. 460900</td>
<td>222000</td>
<td>1100</td>
<td></td>
<td>Grey</td>
<td>Clayey sand</td>
<td>Stratified</td>
</tr>
<tr>
<td>17</td>
<td>Flachau/ sawmill</td>
<td>Karpatian</td>
<td>Sachsenhofer (1988)</td>
<td>126 Radlacht 452530</td>
<td>246800</td>
<td>915</td>
<td></td>
<td>Dark grey</td>
<td>Pebbly silt</td>
<td>Poorly stratified</td>
</tr>
<tr>
<td>18</td>
<td>Mayrdoñfls/ lift</td>
<td>Karpatian</td>
<td>Sachsenhofer (1988)</td>
<td>126 Radlacht 439000</td>
<td>245820</td>
<td>1140</td>
<td></td>
<td>Olive-grey</td>
<td>Clayey clay</td>
<td>Poorly stratified</td>
</tr>
<tr>
<td>20</td>
<td>Nockalmstraße</td>
<td>Morel d’lice</td>
<td>Rohde, personal communication</td>
<td>183 Nockalmstrasse 482700</td>
<td>195058</td>
<td>1540</td>
<td></td>
<td>Grey</td>
<td>Brown</td>
<td>Silty clay, Poorly stratified</td>
</tr>
</tbody>
</table>

*Ottangian (Ott), Karpatian, Badenian, Sarmatian, Pannonian are Central Paratethyan regional stages. For correlation with Mediterranean stages consult Fig. 3.*

*Rechtswert and Hochwert in the Gauss-Krüger coordinates of Austrian ÖK 50 000 sheets.
age assigned to the (coal-bearing) sandstones, claystones and marls of localities 19, 13 and 14 is Ottnangian–Karpatian, localities 17 and 18 are of Karpatian age (Table 1).

3.2. Noric depression

In the western part of the Noric depression (Upper Murtal) and in the related uplifted occurrence Karpatian sediments were sampled (Fig. 2). These were pockets of grey claystones found in gravel (locality 15), grey-brown siltstone, with graded bedding, deposited in lacustrine environment (locality 8), marl (locality 7), a siltstone layer within the basal conglomerates (locality 16), and reddish to yellowish clayey siltstone which forms lenses and pockets in a thick conglomerate sequence (locality 9).

In the Fohnsdorf basin (Fig. 2) which is situated at the junction of two important conjugate fault zones, two localities were sampled, one below and one above a local unconformity: below the unconformity lacustrine marly material of Karpatian age (locality 10), above the unconformity, several silty-sandy horizons from a thick Badenian sequence of immature sandstones and conglomerates (locality 11).

In the eastern part of the Noric depression (Murtal) several silty horizons with different tilt angles were sampled from a Karpatian sequence (locality 12, Fig. 2).

Table 2
Palaeomagnetic results: Ennstal depression

<table>
<thead>
<tr>
<th>Locality</th>
<th>Number of used/collected samples</th>
<th>( D^\circ )</th>
<th>( I^\circ )</th>
<th>( k )</th>
<th>( \alpha_{95}^\circ )</th>
<th>( D_C^\circ )</th>
<th>( I_C^\circ )</th>
<th>( k )</th>
<th>( \alpha_{95}^\circ )</th>
<th>Dip</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>19 Stoderalm AH 361–380</td>
<td>11/20</td>
<td>356 ( \pm ) 57</td>
<td>42</td>
<td>7</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>340/44</td>
<td>c</td>
</tr>
<tr>
<td>13 Großming</td>
<td>A 7</td>
<td>305 ( \pm ) 51</td>
<td>13</td>
<td>14</td>
<td>302 ( \pm ) 13</td>
<td>14</td>
<td>18</td>
<td>13</td>
<td>18</td>
<td>295/65</td>
<td>a</td>
</tr>
<tr>
<td>AH 262–275</td>
<td>B 7</td>
<td>302 ( \pm ) 40</td>
<td>13</td>
<td>14</td>
<td>275 ( \pm ) 74</td>
<td>13</td>
<td>14</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>17 Flachau AH 346–352</td>
<td>6/7</td>
<td>93 ( \pm ) 54</td>
<td>16</td>
<td>17</td>
<td>(31) ( \pm ) (51)</td>
<td>16</td>
<td>17</td>
<td>155/43</td>
<td>c</td>
<td></td>
<td></td>
</tr>
<tr>
<td>14 Hieflau</td>
<td>A 5</td>
<td>342 ( \pm ) 61</td>
<td>75</td>
<td>9</td>
<td>295 ( \pm ) 44</td>
<td>75</td>
<td>9</td>
<td>255/40</td>
<td>a</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AH 276–286</td>
<td>B 4</td>
<td>45 ( \pm ) 59</td>
<td>24</td>
<td>19</td>
<td>306 ( \pm ) 71</td>
<td>24</td>
<td>19</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Subtracted vectors 150–250 °</td>
<td>A 7/8</td>
<td>537 ( \pm ) 67</td>
<td>53</td>
<td>8</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

In most cases where the number of samples used is less than that of the collected, the samples omitted disintegrated during cutting or demagnetization and measurement. Exceptions are locality 9, where instability on demagnetization accounts for rejection.

\( D, I \) and \( D_C, I_C \): mean palaeomagnetic declination, inclination before and after tilt correction. \( k \) and \( \alpha_{95} \): statistical parameters (Fisher, 1953).

Remarks: a = results of component analysis (Kent et al., 1983); b = combination of stable end points and remagnetization circles (McFadden and McElhinny, 1988); c = last meaningful demagnetization step.

3.3. Lavanttal basin

The Lavanttal basin is a transtensional feature including pull-apart and half graben structures following the NNW-SSE trending Lavanttal fault system (Fig. 2). The Granitztal subbasin was formed prior to the main basin and shows an elongation perpendicular to it.

From the Granitztal subbasin a terrestrial silty clay was sampled (locality 5). From the Lavantal basin fossiliferous, silty clays of Badenian age (localities 3 and 4), Late Sarmatian clayey siltstones and marls (locality 1) were collected.

3.4. Klagenfurt basin

Though the Klagenfurt basin is a large one (75 km long), outcrops are scarce, and secondary oxidation is widespread. Thus, only one locality was sampled from this basin, a claystone of Sarmatian age (locality 6).

4. Laboratory measurements and results

In the Paleomagnetic Laboratory of Eötvös Loránd Geophysical Institute (ELGI) standard-size specimens were cut from the drill cores. Natural remanent magnetization (NRM) of each specimen were measured using either a two-axis...
Table 3
Palaeomagnetic results: Noric depression, Laussnitz occurrences and Gurktal block

<table>
<thead>
<tr>
<th>Locality</th>
<th>Number of used/collection samples</th>
<th>$D$</th>
<th>$I$</th>
<th>$k$</th>
<th>$n_{95}$</th>
<th>$D_c$</th>
<th>$I_c$</th>
<th>$k$</th>
<th>$n_{95}$</th>
<th>Dip</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Noric depression</strong></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tamsweg basin</td>
<td>8</td>
<td>9</td>
<td></td>
<td>139</td>
<td>−71</td>
<td>200</td>
<td>4</td>
<td>134</td>
<td>−54</td>
<td>200</td>
<td>4</td>
</tr>
<tr>
<td>AH 213–219</td>
<td>7/7</td>
<td>199</td>
<td>−72</td>
<td>129</td>
<td>5</td>
<td>159</td>
<td>−63</td>
<td>124</td>
<td>−44</td>
<td>89</td>
<td>13</td>
</tr>
<tr>
<td>AH 220–226</td>
<td>3/7</td>
<td>127</td>
<td>−63</td>
<td>89</td>
<td>13</td>
<td>124</td>
<td>−44</td>
<td>89</td>
<td>13</td>
<td>298/19</td>
<td>a</td>
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<td>Göriach valley</td>
<td>19/25</td>
<td>116</td>
<td>−72</td>
<td>43</td>
<td>5</td>
<td>141</td>
<td>−56</td>
<td>52</td>
<td>5</td>
<td></td>
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</tr>
<tr>
<td>Building site AH 103–118</td>
<td>7/7§</td>
<td>332</td>
<td>+68</td>
<td>12</td>
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<td>6</td>
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<td>Variable a</td>
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<tr>
<td><strong>Laussnitz basin</strong></td>
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<td>Obervoölz basin</td>
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<td>66</td>
<td>19</td>
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<td>19</td>
<td>12</td>
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<tr>
<td>Fohnsdorf basin</td>
<td>11</td>
<td>53</td>
<td>+37</td>
<td>32</td>
<td>16</td>
<td>66</td>
<td>+54</td>
<td>32</td>
<td>16</td>
<td>204/21</td>
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</tr>
<tr>
<td>Kapfenberg-St. Marein basin</td>
<td>12</td>
<td>7.8</td>
<td>311</td>
<td>−65</td>
<td>84</td>
<td>7</td>
<td>236</td>
<td>−56</td>
<td>84</td>
<td>7</td>
<td>14/39</td>
</tr>
<tr>
<td>AH 1–7</td>
<td>7.9</td>
<td>313</td>
<td>−64</td>
<td>141</td>
<td>5</td>
<td>238</td>
<td>−56</td>
<td>141</td>
<td>5</td>
<td>14/39</td>
<td>a</td>
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<tr>
<td>AH 17–24</td>
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<td>171</td>
<td>−24</td>
<td>48</td>
<td>9</td>
<td>163</td>
<td>+40</td>
<td>48</td>
<td>9</td>
<td>26/78</td>
<td>c</td>
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<tr>
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<td>190</td>
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<td>21</td>
<td>17</td>
<td>125</td>
<td>+74</td>
<td>21</td>
<td>17</td>
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<td>32</td>
<td>11</td>
<td>120</td>
<td>+57</td>
<td>32</td>
<td>11</td>
<td>17/95</td>
<td>c</td>
</tr>
<tr>
<td>St Marein</td>
<td>5.10§±</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>AH 270A, AH 225B, AH 18A</td>
<td>6.7</td>
<td>112</td>
<td>−37</td>
<td>118</td>
<td>6</td>
<td>26</td>
<td>−43</td>
<td>118</td>
<td>6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AH 276 and AH 142</td>
<td>5.10±</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>AH 230/230</td>
<td>5.10±</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td><strong>Gurktal block</strong></td>
<td>20</td>
<td>89</td>
<td>+45</td>
<td>15</td>
<td>14</td>
<td>295</td>
<td>+35</td>
<td>14</td>
<td>15</td>
<td>330/12</td>
<td>c</td>
</tr>
<tr>
<td>AH 313–319</td>
<td>6.7</td>
<td>112</td>
<td>−43</td>
<td>118</td>
<td>6</td>
<td>112</td>
<td>−43</td>
<td>118</td>
<td>6</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

In most cases where the number of samples used is less than that of the collected, the samples omitted disintegrated during cutting or demagnetization and measurement. Exceptions are locality 9, where the omitted samples had extremely weak NRM’s, and locality 11, where instability on demagnetization accounts for rejection.

$D$, $I$, $D_c$, $I_c$, $k$, and $n_{95}$: statistical parameters (Fisher, 1953).

Remarks: a = results of component analysis (Kent et al., 1983); b = combination of stable end points and remagnetization circles (McFadden and McElhinny, 1988); c = last meaningful demagnetization step.

In thermal remanent magnetization (IRM) acquisition curves in such cases exhibit low coercitivity magnetic mineral, which may be maghemite or iron sulphides (Fig. 4, samples AH 270A, AH 225B, AH 18A). Thermal demagnetization of the three-component IRM (method by Lowrie, 1990) as well as that of the NRM, and the behaviour of susceptibility on heating, both measured at room temperature after each demagnetization step or on continuous heating in a low magnetic field (Fig 5, AH 276 and AH 142) point to iron sulphides (with or without magnetite) as the magnetic mineral. There are only three locali-
Fig. 4 Identification of the magnetic minerals. From top to bottom, IRM acquisition curves, thermal demagnetization of the three component IRM, same normalized, normalized susceptibility versus temperature curve. Examples are from localities 13 (AH 270A), 9 (AH 228B), 8 (AH 225B), 12 (AH 18) and 5 (AH 156). Key to the three component demagnetization curves: open circles, soft component; grey symbols, medium hard component; black symbols, hard component. The components were acquired in magnetic fields of 0.20, 0.36 and 1.00 T, respectively.
Palaeomagnetic results for Lavanttal and Klagenfurt basin

<table>
<thead>
<tr>
<th>Locality</th>
<th>Number of used/collected samples</th>
<th>$D'$</th>
<th>$I$</th>
<th>$k$</th>
<th>$n_{95}$</th>
<th>$D_C$</th>
<th>$I_C$</th>
<th>$k$</th>
<th>$n_{95}'$</th>
<th>Dip</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lavanttal</td>
<td>5 W of St. Paul AH 152–167</td>
<td>11/16</td>
<td>333</td>
<td>+58</td>
<td>36</td>
<td>8</td>
<td>314</td>
<td>+52</td>
<td>36</td>
<td>8</td>
<td>258/15</td>
</tr>
<tr>
<td></td>
<td>4 Mühlendorf AH 119–129, 130–135</td>
<td>11/17</td>
<td>332</td>
<td>+61</td>
<td>35</td>
<td>8</td>
<td>324</td>
<td>+26</td>
<td>35</td>
<td>8</td>
<td>314/36</td>
</tr>
<tr>
<td></td>
<td>2 Niederhof AH 136–147</td>
<td>7/12</td>
<td>333</td>
<td>+54</td>
<td>30</td>
<td>11</td>
<td>325</td>
<td>+33</td>
<td>30</td>
<td>11</td>
<td>247/6</td>
</tr>
<tr>
<td>Klagenfurt basin</td>
<td>6 Miklaushof AH 168–175</td>
<td>6/9</td>
<td>336</td>
<td>+62</td>
<td>44</td>
<td>10</td>
<td>343</td>
<td>+44</td>
<td>44</td>
<td>10</td>
<td>56/4</td>
</tr>
</tbody>
</table>

In most cases where the number of samples used is less than that of the collected, the samples omitted disintegrated during cutting or demagnetization and measurement. Exceptions are locality 9, where the omitted samples had extremely weak NRM, and locality 11, where instability on demagnetization accounts for rejection.

$D$, $I$, and $D_C$, $I_C$: mean palaeomagnetic declination, inclination before and after tilt correction. $k$ and $n_{95}$: statistical parameters (Fisher, 1953).

Remarks: $a=$ results of component analysis (Kent et al., 1983).

In summary, the magnetic fabric of the sediments of the intramontane basins of the Eastern Alps is that of an undeformed or slightly deformed...
rock and both the degree of foliation and lineation is so low, that bias in the direction of the magnetic vector from the direction of the ambient Earth’s magnetic field is highly unlikely.

4.3. Palaeomagnetic directions

In general, site and locality mean remanence directions (Tables 2–4) are characterized by excellent to acceptable statistical parameters. Different authors set different limits to what is acceptable. Irving (1964) draws the upper limit for $x_{95}$ at 25°, while more recently van der Voo (1993) at 16°. In Tables 2–4, it is only one of the components for localities 13 and 14 and the locality mean for 17 which do not satisfy the more rigorous criterion. Nevertheless, their $x_{95}$ is well below the less rigorous limit, thus they are also used in the final tectonic interpretation.

Before tilt correction, the mean palaeomagnetic directions differ (except locality 19) from that of the present Earth’s magnetic field. The age of the magnetization with respect to tilting is a matter of consideration, since fold test at outcrop level is not possible.

From the **Ennstal depression** four localities yielded characteristic magnetizations (Table 2). The mean direction for locality 19 is that of the present Earth’s magnetic field in the geographic coordinate system. The result is, therefore, of no value for tectonic interpretation. Localities 13 and 14 are characterized by two magnetic components (Fig. 6a), component B is interpreted to be of pre-, Irving (1964) draws the upper limit for $x_{95}$ at 25°, while more recently van der Voo (1993) at 16°. In component A of post-tilting age (Table 2). The NRM of the samples from locality 17 was extremely hard on AF demagnetization; thermal demagnetization in increments was successful in improving statistical parameters (before demagnetization $D=87°$, $I=-43°$, $k=7$, $x_{95}=25°$), but the intensity of the NRM was hardly reduced at 580°C, the last step of demagnetization, before the susceptibility dramatically increased (Fig. 6b) or

![Typical demagnetization curves in the geographic system from the Ennstal and the western part of the Noric depressions. The behaviour of the NRM on stepwise thermal demagnetization (Zijderveld plots, filled symbols projection of the magnetic vector in the horizontal plane; open symbols, the same in a vertical plane) and normalized susceptibility (dots) versus intensity (circles) versus temperature curves. Examples are from localities 13 (a), 17 (b), 8 (c) and 7 (d).](image-url)
the physical disintegration of the samples. The mean direction was calculated from the NRM measured after 580°C.

In the western part of the Noric depression localities 7 and 8 (Tamsweg basin) are characterized by good demagnetization curves (Fig. 6c and d) and yielded statistically well defined palaeomagnetic directions (Table 3). The sediment of locality 15 exhibits fairly stable behaviour of the NRM on both heating and AF demagnetization, but becomes unstable before the signal is lost. From locality 9 several samples were too weakly magnetic. Those with stronger NRM signal (in the range of $10^{-4} \text{A m}^{-1}$) retained some of the NRM after the goethite was eliminated and served to define the locality mean direction in Table 3.

The majority of the samples collected from the Fohnsdorf basin (localities 10, 11) were unstable. It was only one site (four samples) from locality 10 which yielded acceptable direction.

The eastern part of the Noric depression is represented by locality 12 where all five sites yielded good palaeomagnetic signals (Fig. 7a and b). The mean directions of two of them (AH 1-7, AH 8-16) are in excellent agreement. The other three sites behave similarly during demagnetization, that is, the NRMs move along great circles (Fig. 8), so the remanence measured after the last meaningful demagnetization step may still be a composite NRM. The great circles in the tectonic coordinate system go through or pass very close to the site mean directions (also in the tectonic coordinate system) of the first two sites. Using the combination of stable end points (site mean direc-

Fig. 7. Typical demagnetization curves in the geographic system from the eastern part of the Noric depression and the Lavantal–Granitztal basins. The behaviour of the NRM on stepwise thermal (AF for 7a) demagnetization (Zijderveld plots: filled symbols, projection of the magnetic vector in the horizontal plane; open symbols, the same in a vertical plane) and normalized susceptibility (dots/intensity (circles) versus temperature curves. Examples are from localities 12 (a and b), 2 (c) and 5 (d).
is oxidized magnetite (Fig. 9) and the direction is statistically well-defined (Table 3). As we shall discuss later, this result is relevant to the model we propose to explain the palaeomagnetic results from the sediments of the intramontane basins.

5. Discussion

Miocene sediments in the intramontane basins of the Eastern Alps east of the Tauern window revealed counterclockwise (CCW) rotations, except localities 11 and 12 (Fig. 10a). The overall mean palaeomagnetic direction calculated from the locality mean directions of the former group (Tables 2–4, data in heavy print, the selection of either the tilt-corrected or the uncorrected data is explained partly in the previous chapter, partly in the further discussion) is statistically well-defined: $D = 311°$, $I = 60°$, $k = 34$, $α_95 = 7°$, based on 13 data.

Compared with the stable European reference direction of corresponding age ($D = 7°$, $I = 61°$, same as in Fig. 11), we can see a large and significant CCW rotation, which must have taken place very close to the stable European margin. Though the good statistical parameters would permit to interpret this rotation as a single, rigid block rotation of the whole western part of the study area, such interpretation is not plausible, basically because of space problems. We decided, therefore, to analyse the data further in order to find out if there are differences in the rotation angle between the studied basin systems on one hand, and between the declinations derived from older and younger strata, on the other hand.

In the western Noric depression (Figs. 10a and 11a, localities 7, 8, 9, 15) the grouping of the locality means is best when the mean directions of localities 7, 8 and 9 are in the tectonic, that of locality 15, in the geographic systems ($D = 308°$, $I = 52°$, $k = 34$, $α_95 = 16°$). Since locality 15 is from the Klagenfurt basin behaves similarly to the marine sediments from the Lavanttal.

We also studied an undeformed magmatic dike from the Gurktal block (locality 20), which yielded K/Ar ages between 130 and 145 Ma (Kad. Balogh, 1998, written communication). The dike has good palaeomagnetic properties, the carrier of the NRM
$a_0 = 4^\circ$, but some scatter after bedding correction. Mechanically concluding, this means that the magnetic remanence was imprinted after sedimentation and tilting. However, locality 5 (Granitztal sub-basin) is different from the rest, being a terrestrial sediment, with less sensitive magnetic minerals (magnetite and hematite) to alteration than the others, and may carry a characteristic magnetization of pre-tilting age. If the overall palaeomagnetic mean direction is recalculated from the data in the geographic system of Table 4 without locality 5, we obtain $D = 333^\circ$, $I = 59^\circ$, $k = 327$, $a_0 = 7^\circ$, which compared to the tilt corrected mean of locality 5 (Table 4) shows a bit steeper inclination and ca. 20° less CCW rotation.

The results from the Ennstal basins (Figs. 10a and 11c, localities 13, 14, 17) are interpreted in terms of general CCW rotation. For localities 13 and 14 two magnetic components were identified: one interpreted to be of pre-tilting age, but nevertheless acquired before the rotation of the basins ended. The palaeomagnetic direction of locality 17 matches that of the others without the application of the tilt correction (part of the tilt may be primary, for the samples represent the matrix in a pebbly silt). The overall palaeo-
Fig. 11. Mean palaeomagnetic declinations, inclinations with a 95% confidence level, on stereographic projection (for data refer to Tables 2–4). Overall mean palaeomagnetic direction for the western part of the Noric depression after tilt corrections is $D = 308°$, $I = +52°$, $k = 25$, $a_{95} = 19°$; when locality 15 is taken before tilt correction the overall mean is $D = 306°$, $I = +55°$, $k = 34$, $a_{95} = 16°$. The overall palaeomagnetic directions for the Lavantal and Klagenfurt basins before tilt corrections is $D = 333°$, $I = +59°$, $k = 461$, $a_{95} = 4°$ without locality 5 is $D = 336°$, $I = +59°$, $k = 327$, $a_{95} = 7°$. The overall palaeomagnetic mean direction for the Ennstal basin is $D = 301°$, $I = +64°$, $k = 25$, $a_{95} = 16°$. For comparison, the stable European (Eu.) reference direction is shown calculated from the average of the 10 and 20 Ma old palaeomagnetic poles (Besse and Courtillot, 1991).

Magnetic mean direction for the Ennstal basins is $D = 301°$, $I = 64°$, $k = 25$, $a_{95} = 16°$.

When the overall mean palaeomagnetic directions of the three basin systems are compared, the less rotated declinations in the Lavantal basin system and the Klagenfurt basin compared to the others is clear, while the inclinations are similar. Incidentally, it is the Lavantal and Klagenfurt basins where the sediments are younger than in the other basins and the magnetizations are even younger, being, with the likely exception of locality 5, of post-tilting age. Within the basin systems, the situation is similar: The older strata (localities 5, 9, 13, 14, 15, 17) exhibit declinations between 273 and 315°, while the declinations in the younger strata (localities 2, 4, 6, 7, 8) are between 321 and 333°. This trend suggests that part of the CCW rota-
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tations observed on the older strata is the result of a two-phase rotation. The earlier rotation may have occurred during sedimentation, that is, during the main phase of lateral tectonic extrusion, which, according to radiometric evidence (Dunkl and Demény, 1997; Frisch et al., 2000) and data from the sedimentary record in the Pannonian basin (Royden et al., 1982; Tari and Horváth, 1995; Dunkl et al., 1998) is bracketed between 18 and 13 Ma (Ottunian to Badenian).

The CCW rotations observed in the older strata of the intramontane basins are in line with previous pre-Tertiary results in the study area as well as with the result from the Nockalmsraße dike (locality 20). Earlier published magnetic vectors from Late Cretaceous sediments, forming the cover of the Gurktal block and the Palaeozoic of Graz (Figs. 1 and 10), indicate CCW rotations up to a two-phase rotation. The earlier rotation may have occurred during sedimentation, that is, during 60° (Mauritsch and Becke, 1987; Agnoli et al., 1989). Permian red beds in the Gurktal block also reveal counterclockwise rotations of 50–70° (Mauritsch et al., 1989; Mauritsch, 1993). Due to Demény, 1997; Frisch et al., 2000) and data from the sedimentary record in the Pannonian basin, it seems likely that the rotations observed on pre-Tertiary rocks (which are situated outside of the Miocene fault systems!) are essentially the product of Miocene tectonics.

Southeast of the study area, sediments of Karpatian and Badenian age in the Mura depression, in the Pohorje Mountains (Fig. 12d7) and in the Drauzug (Fig. 12d8) also exhibit moderate CCW rotations (Fodor et al., 1998). This shows

![Fig. 12. Areas of Neogene rotations in the Eastern Alps and Western Carpathians.](image)

Fig. 12. Areas of Neogene rotations in the Eastern Alps and Western Carpathians. (a) Study area of this paper with syn- and post-Middle Miocene CCW rotation; (b) transitional zone with Miocene CCW and CW rotations; (c) Western Carpathians and Bakony unit with Early–Middle Miocene CCW rotation; (d) overall mean palaeomagnetic declinations signifying Miocene rotations d1, d2, Maron and Maron (1996); d3, d4, Maron et al. (1998); d5, Maron (1986); d6, Maron and Maron (1983); d7, d8, Fodor et al. (1998); (e) locality mean palaeomagnetic declinations observed on Eocene rocks, interpreted as connected to Miocene rotations (Maron et al., 1996; Tomi and Maron, 1996). Map contours are after Fuchs (1985).
that the CCW rotating area extends to the SE as far as the Periadriatic lineament.

The area with consistent CCW rotations is bordered in the east by the eastern segment of the Nooric depression, where localities 11 and 12 with CW rotation are situated (Fig. 10a). The area between the Periadriatic line (in the south) and the Ennstal fault system (in the north) exhibits characteristic fault patterns revealed by a digital elevation model (Fig. 10b). There is a pronounced NNW–SSE trending dextral fault array in the Gurktal and Niedere Tauern blocks (Fig. 10b and c), which are parallel to the Lavanttal fault. Along the western part of the Nooric depression a complex interplay of these dextral faults and sinistral faults of the Muratal fault system define individual tectonic blocks of ca. 10 km diameter (Fig. 10b and c).

Based on the palaeomagnetic results and the fault pattern, we suggest that domino block rotations accommodated by dextral strike–slip along NNW–SSE trending faults occurred in the area between the Ennstal fault and the Periadriatic lineament. The basins were formed and sediments filled during fault activity. The consistent dip of the strata in different basins (Tables 2 and 4) imply a uniform mechanism for the opening of the sediments close to the Rechnitz window and one outcrop in the metamorphic Bernstein window suggest moderate CCW rotation (Márton and Mauritsch, 1990). The CCW rotations in the Eastern Alps, east of the Periadriatic lineament, where localities 11 and 12 with CW rotation are situated (Fig. 10a), took place in the time interval of 18.5–17.5 Ma, the second (30°) between 16 and 14 Ma (Mártom and Pieskay, 1998); and the Western Carpathians (d3, d4 and e). Based on the palaeomagnetic constraints and the consideration of Jiricek (1979) on the termination of thrusting in the Carpathians we can conclude that the displacement seems to have migrated from NE to SW (or in the Mura Depression as well as in our study area the rotations are definitely younger than the main rotation period of the Western Carpathians.

Surrounded by areas with Miocene CCW rotations, there is a poorly constrained area in the Alpine/Pannonian transition zone with a complex rotation pattern (Fig. 12). In this area lies our locality (11 and 12), revealing clockwise rotation. In the same transition zone observations from the Rechnitz window (Márton et al., 1987; Mauritsch et al., 1991) and from metamorphics of the Palaeozoic of Graz (Flügel et al., 1980; Burgschweiager et al., 1996) also indicate CW rotations; in contrast, two outcrops of mid-Miocene sediments close to the Rechnitz window and one outcrop in the metamorphic Bernstein window suggest moderate CCW rotation (Márton and Mauritsch, 1990).

The domino mechanism probably did not account for the whole CCW rotation. After the termination of the extrusion process and thus of fault activity, CCW block rotation in the order of 30° (with respect to stable Europe) must have occurred. East and south of our study area, Tertiary CCW rotations are known from several areas (Fig. 12), like the Bakony Mountains (d5 and d6) where post-Eocene rotation of ca. 35° was measured (Mártom and Mártom, 1983; Márton, 1986; Mauritsch and Márton, 1995); the North
6. Conclusions

(1) With two exceptions, the intramontane basins of the Eastern Alps east of the Tauern window show counterclockwise rotation.

(2) There is a tendency of decreasing rotation angles with decreasing age of the sediments. This can be interpreted in terms of synsedimentary rotation during the process of lateral tectonic extrusion (ca. 18–13 Ma, Ottnangian to Badenian), followed by ca. 30° post-Sarmatian rotation.

(3) Rotation during lateral extrusion is explained by a domino block model. CCW rotation of the dominoes was accommodated by NNW-SSE trending dextral faults, which are conspicuous tectonic elements in the study area.

(4) The Miocene CCW rotation is a regional phenomenon in the area east of the Tauern window, between the Ennstal fault system and the Periadriatic lineament, and in the North Pannonian block. The regional CCW rotation may be related to a corner effect of the Bohemian spur during eastward block motion.

(5) Clockwise rotation of Miocene sediments in the eastern part of the Noric depression indicate that they may belong to a transition zone which is positioned in the immediate front of the Bohemian spur.

Acknowledgements

The German Science Foundation financed this study in the frame of the Collaborative Research Centre 275. Further support was obtained by the OTKA Found (Hungarian National Scientific Found.) No. T02219. Kadosa Balogh carried out the radiometric age dating of the dike in this study. Gábor Imre made difficult drilling of soft sediments possible. Balázs Székely processed the digital elevation model for Fig. 10. All help is gratefully acknowledged.

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