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LATE MIOCENE COUNTERCLOCKWISE ROTATION OF THE PIENINY ANDESITES AT THE CONTACT OF THE INNER AND OUTER WESTERN CARPATHIANS

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Abstract: The Pieniny andesite line is a 20 km long zone, which cuts obliquely the contact between the Pieniny Klippen Belt which separates the Inner and Outer Western Carpathians and the Magura Nappe (the innermost nappe system of the Outer Western Carpathians). The andesites (dykes and sills) were formed during two intrusion phases. The older dykes are subparallel to the andesite line, while the younger ones are perpendicular to it. Formerly, the andesites were thought to be of Sarmatian age, recently obtained K/Ar ages are in the 10.8–13.5 Ma range. For paleomagnetic study, we drilled macroscopically fresh material from both generations of the andesites. The samples were subjected to detailed alternating field and thermal demagnetization. Isothermal remanence acquisition experiments, Curie-point measurements and microscopy analysis of polished sections were carried out in order to identify magnetic minerals. The results are as follows. The second phase andesites and some sites in the first phase andesites have complex natural remanent magnetizations (NRM) with two stable components: one is isolated below, and the other above the Curie-point of magnetite. It is remarkable that thermal demagnetization was often needed to reveal all components of the NRM although the rocks we studied were Neogene igneous rocks which are considered ideal targets for the less time-consuming alternating field method. The lower temperature component follows a great circle containing the expected stable European direction of corresponding age. The higher temperature component has counterclockwise rotated declination. The remaining sites of the first phase andesites have practically a single component remanence, which corresponds to one or the other of the directions described above. The components with counterclockwise rotated declinations cluster around an overall-mean direction of D=133°, I=–56° with k=26, α_{95}=12° (based on 7 site-mean paleomagnetic directions). Neither the magnetic minerals, nor their degree and type of alteration are different in the two generations of andesites. Thus, the agents of remagnetization were probably hot fluids acting after the emplacement of the second generation dykes. The tectonic implication of our results is that the Pieniny andesite area must have rotated counterclockwise, after emplacement of the second phase dykes.

Key words: Western Carpathians, Neogene andesites, paleomagnetism, complex magnetic remanence, CCW rotations.

Introduction

The Carpathian orogenic belt (Fig. 1) is subdivided into the Inner Western Carpathians (in some tectonic models they are called the Internides, e.g. Maheľ 1986; Plašienka et al. 1997) and the Outer Western Carpathians. In the West Carpathian region, the Outer Carpathians are separated from the Inner Carpathians by the Pieniny Klippen Belt. Both the Inner and Outer Carpathians are characterized by complicated nappe structures, but the time of nappe transport is different for the two areas. In the former, it is of Late Cretaceous age, while for the latter it is of Paleocene (Tokarski & Świerczewska 1998) through Late Miocene age (Wójcik et al. 1999). The Pieniny Klippen Belt is a narrow zone of Mesozoic and Tertiary strata that underwent extreme shortening and wrenching (Birkenmajer 1986 and references therein).

The contacts of the Pieniny Klippen Belt with the Outer and Inner Carpathians are subvertical (Birkenmajer 1986). The Belt was folded first during the Late Cretaceous through Paleocene, then in the Early Miocene (Birkenmajer 1986 and references therein). The Pieniny andesite line (Fig. 2), the object of the present paleomagnetic study, obliquely cuts the Pieniny Klippen Belt and the Magura Nappe which is the innermost nappe in the studied part of the Outer Carpathians. The Pieniny andesite line is clearly younger than the folding in the Magura Nappe (Birkenmajer 1986; cf. Świerczewska & Tokarski 1998).

Recent paleomagnetic studies on Paleogene flysch in the Inner Carpathians (Podhale and Levoča Basins) revealed that the Internides must have rotated about 60° counterclockwise (CCW), after the Oligocene (Márton et al. 1998a,b, 1999a). Sporadic paleomagnetic observations for the Magura flysch (Márton et al. 2000) also suggest CCW rotation of similar magnitude for the central segment (south of Cracow). In addition, there are several paleomagnetic observations from the foredeep of the Western Carpathians which indicate moderate CCW rotations (Márton et al. 1999b, 2001) of post-Karpatian age in the western segment, post-Badenian age in the central segment and probably post-Pannonian age in the eastern segment (Karpatian, Badenian, Pannonian are Central Paratethyan stage names; for correlation with the Mediterranean stages refer to Rögl 1996, and Fig. 8). The upper age limit of the rotations is not yet constrained, apart from a single Upper Badenian paleomagnetic result (showing no rotation) from the Nowy Sącz Basin (a piggyback basin sitting on the Outer Carpathians). We decided, therefore, to start a new paleomagnetic study on the Pieniny andesites, which, at the time of our first sampling (1997), were thought to be of Sarmatian age (Birkenmajer et al. 1987).

In the 1960's, Birkenmajer & Nairn (1968) carried out paleomagnetic investigation on the Pieniny andesites. They used the standard paleomagnetic technique of partial alternating field (AF) demagnetization to distinguish between unstable and stable natural remanent magnetization (NRM) components. With this method, they obtained statistically acceptable results only for some sites in the western part of the andesite line, which were mostly characterized by steep inclinations and reversed polarity. However, one site had a definitely CCW rotated direction. Subsequently, Kruczyk (1970) studied the paleomagnetic and rock magnetic properties of the second phase andesites, and obtained statistically well-defined paleomagnetic directions for 4 sites, also with steep inclinations and reversed polarity. Though the majority of the statistically satisfying paleomagnetic directions obtained by the above named authors did not indicate CCW rotation, the one site (belonging to the first phase) which did, suggested that rotation could have occurred during the activity of the andesite volcanism. This explains our interest in the Pieniny andesites.

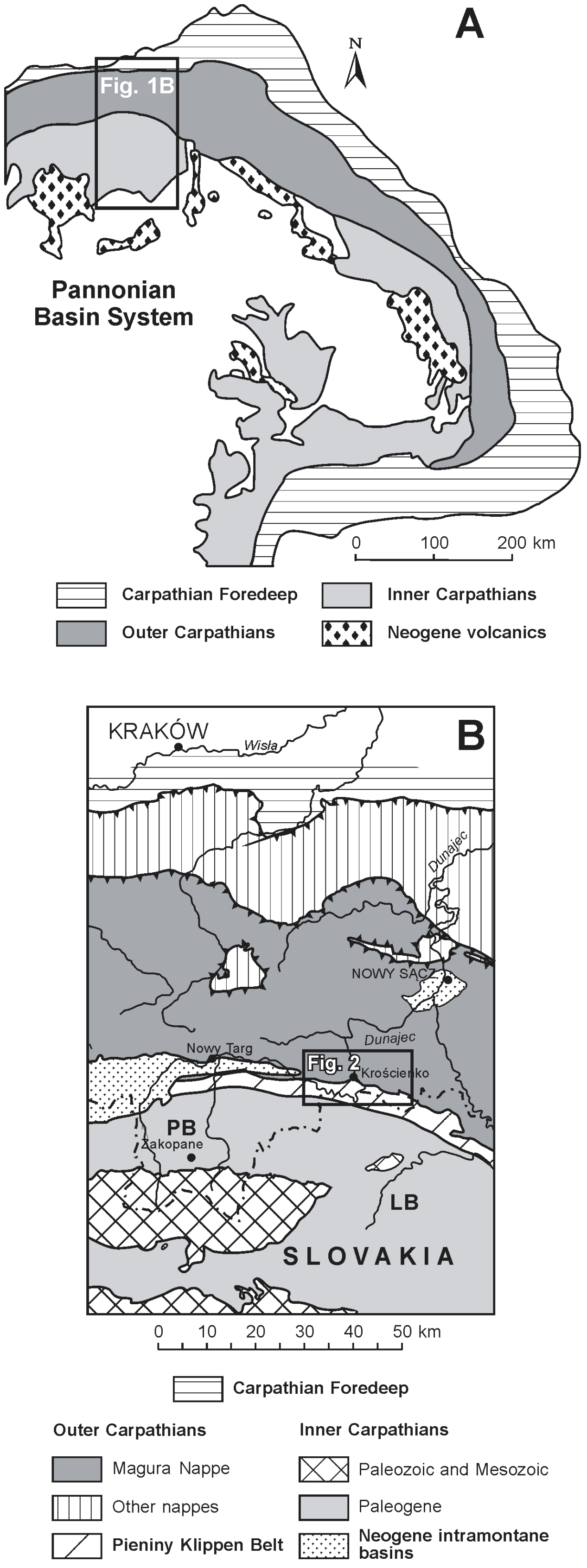

Fig. 1. The location of the Pieniny andesite line in the general framework of **A** — the Carpathians and **B** — in relation to the Inner and Outer Western Carpathians.

Geology and sampling

The Pieniny andesite line is a 20 km long zone consisting of andesite sills and dykes, which cut Jurassic-Cretaceous and Paleogene strata of the Pieniny Klippen Belt and Paleogene strata of the Magura Nappe (Fig. 2). The andesite intrusions were formed during two successive phases of intrusive activity (Birkenmajer 1986, 1996). The older set of intrusions comprises numerous dykes striking subparallel to the Pieniny Klippen Belt. The younger set consists only of three NNW–SSE striking dykes, which cut the Magura Nappe at the western termination of the andesite line. According to Birkenmajer (1986, 1996), the older phase intrusions formed contemporaneously with transverse strike-slip faulting. The faulting continued after the cessation of the older intrusive phase. The younger phase intrusions follow transversal strike slip faults. The intrusions are hypabyssal dykes of small (5–10 m wide) to moderate (over 100 m wide) size, and are composed of several types of andesites, the most common being augite-amphibole andesite (Birkenmajer 1996 and references therein); the igneous activity is related to the southward subduction of the Outer Carpathian basin lithosphere (Birkenmajer & Péc-skay 1999 and references therein).

From the older phase intrusions we drilled samples from 3 abandoned quarries and 2 natural outcrops, from the second phase, two dykes were sampled, in 2 abandoned quarries. In all cases, the samples were distributed between different parts of the intrusions so that our samples represented rocks that cooled at different rates and acquired their magnetization at

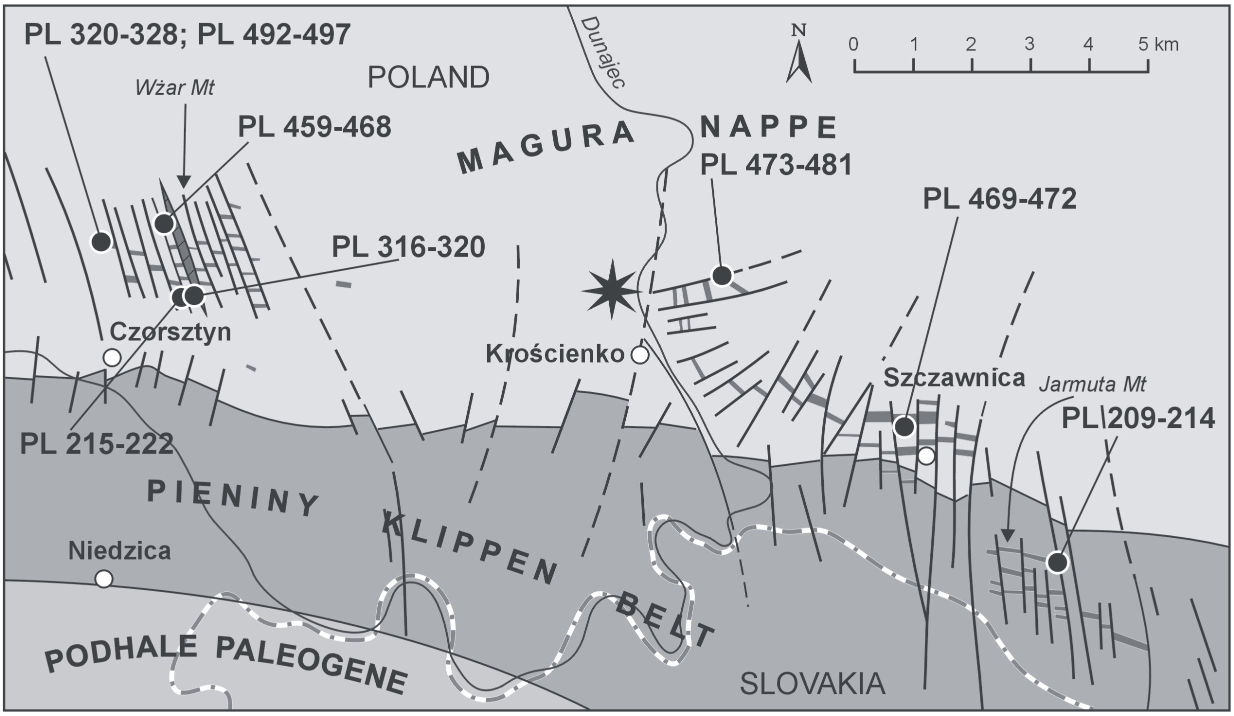

Fig. 2. Paleomagnetic sampling localities in the Pieniny andesite line. Identification numbers are used in Table 1, in the Figures and throughout the text.

different times even within the same intrusion. Such sampling strategy was especially important in the quarries of the younger generation dykes, in order to ensure that the secular variation of the Earth's magnetic field be averaged out in the overall paleomagnetic mean direction. Luckily, in both quarries of the younger dykes, the contact was clearly exposed; due to this situation, it was possible to distribute the sampling sites so that some were very close to the contact, others inside the dykes (the contact rock itself could not be sampled, because it was too weathered). Samples were oriented in the field with both, magnetic and sun compasses.

Paleomagnetic measurements and results

From each core, sister specimens were cut, measured and demagnetized in the Paleomagnetic Laboratory of the Eötvös Loránd Geophysical Institute of Hungary. From most samples one specimen was AF demagnetized in several steps, till the NRM (natural remanent magnetization) signal was destroyed or up to 200 mT; the other specimen was thermally demagnetized, in increments. During thermal demagnetization, susceptibility was monitored. Low-field magnetic susceptibility anisotropy was measured for each site. We found that the degree of anisotropy was low, characteristically 1–2 percent, the magnetic fabric was foliated, and the susceptibility maxima had near-vertical orientation. These features are characteristic of tectonically un-deformed, near-vertical dykes.

AF demagnetization efficiently eliminated most of the NRM signal. However, the magnetic vector often followed a great circle trend and the direction had not stabilized even in high AF fields. On the other hand, thermal demagnetization, sometimes up to the Curie-point of hematite (680 °C), was successful in revealing the components of the NRM.

According to the behaviour and complexity of the NRM, the studied rocks may be subdivided into 3 groups as follows:

1. AF demagnetization is sufficient to eliminate the NRM signal, which only has a single component (Fig. 3, specimen PL 495A);

2. thermal method is needed to demagnetize the NRM, instability sets in above the Curie-point of magnetite (Fig. 3, specimen PL 209B);

3. only thermal demagnetization separates the components of the complex NRM (Figs. 4, 5). Information about the identified components for each site or locality (in the latter case the sampled sites from the same locality yielded identical results) and the method of successful demagnetization is given in Table 1.

It is important to note, that all samples from the second generation dykes (Fig. 5) belong to group 3. Their NRM is characterized by a dominant reversed polarity component (component b) and a small, but well-defined component of high unblocking temperature (component c). The latter persists till the Curie-point of hematite.

Not far from the quarries of the second generation dykes, intrusions belonging to the first generation were also sampled. At one site near the Monument (PL 219–222) and at two sites from Czorsztyn (PL 492–494 and PL 495–497) the NRM had one component, where the direction was similar to component c of the second generation dyke throughout AF or thermal demagnetization. The remaining samples behaved similarly to samples from the second generation dykes (compare Fig. 4 and Fig. 5) or they exhibited a single component NRM with

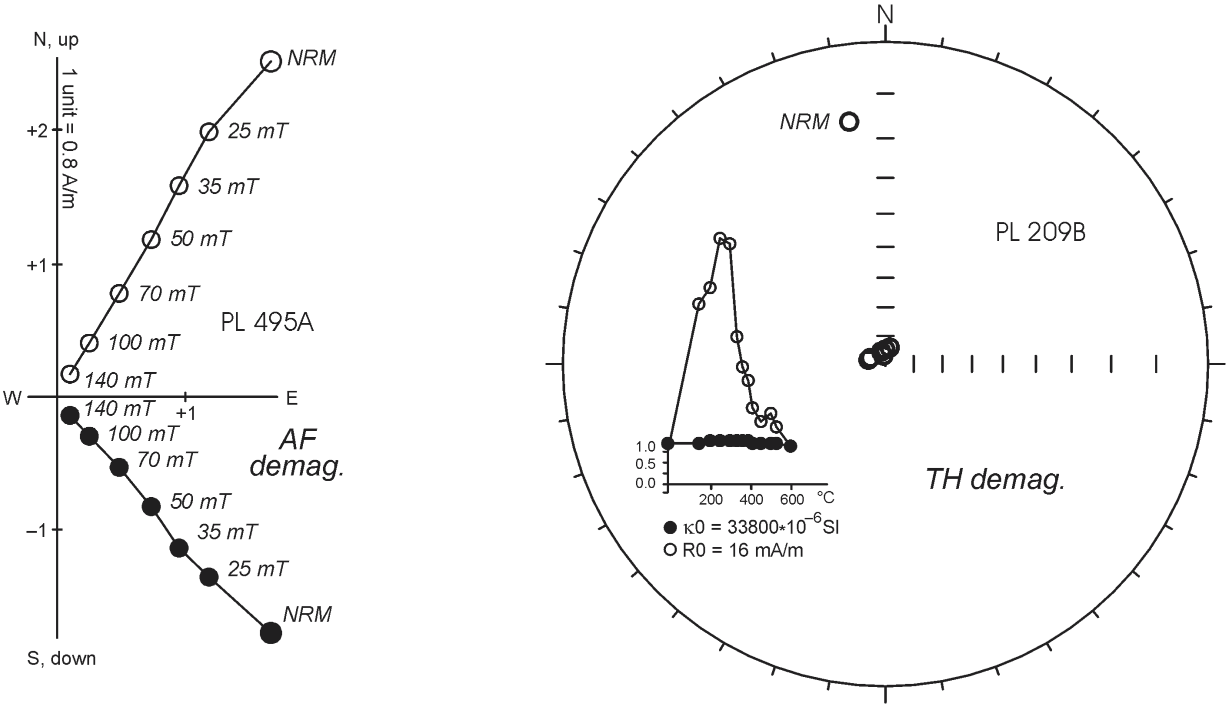

Fig. 3. Pieniny andesites, first phase intrusions. Examples of simple NRM with CCW rotated declination (PL 495A) and with strange direction (PL 209B). In the latter, the magnetic signal became extremely unstable above 590 °C, but the unstable part is not shown in the diagram. Left hand side: orthogonal projection, where solid/open symbols represent projections of the NRM vector onto the horizontal/vertical plane. Right hand side: stereographic projections with all upper hemisphere data; insert: normalized NRM intensity (open symbols) and susceptibility (full symbols) as a function of temperature.

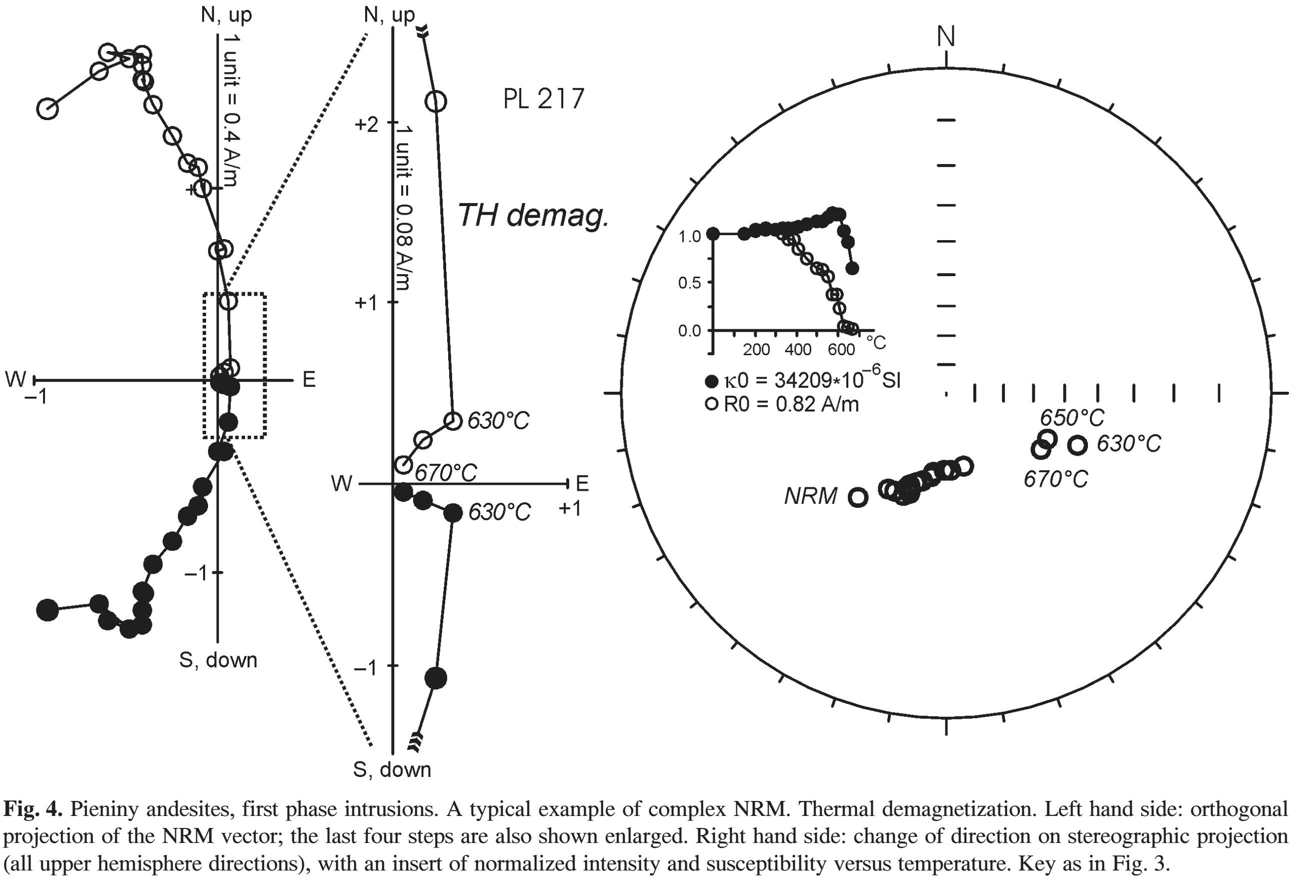

Fig. 4. Pieniny andesites, first phase intrusions. A typical example of complex NRM. Thermal demagnetization. Left hand side: orthogonal projection of the NRM vector; the last four steps are also shown enlarged. Right hand side: change of direction on stereographic projection (all upper hemisphere directions), with an insert of normalized intensity and susceptibility versus temperature. Key as in Fig. 3.

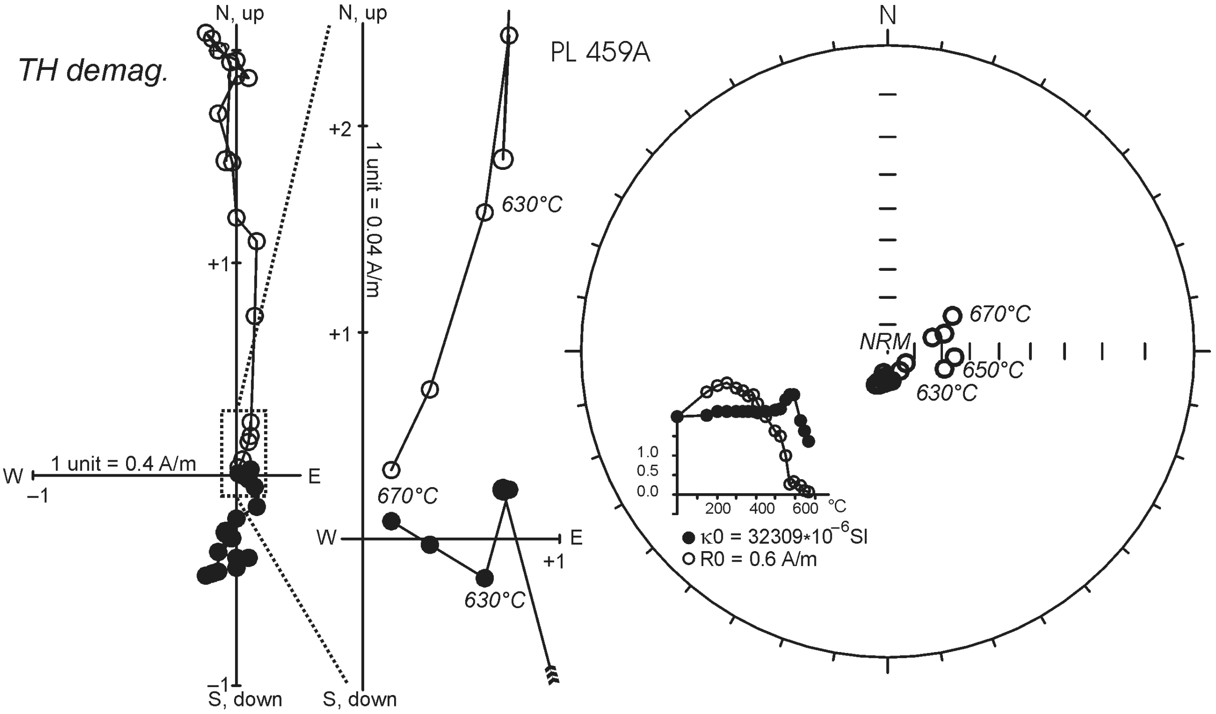

Fig. 5. Pieniny andesites, second phase intrusions. A typical example of demagnetization behaviour, where three components are resolved (see Table 1). Left hand side: orthogonal projection of the NRM vector; the last 5 steps are also shown enlarged. Right hand side: the change of direction at high temperatures is clear on the stereographic projection (all upper hemisphere directions). Insert: normalized intensity and susceptibility versus temperature. Key as in Fig. 3.

strange directions, which was consistent for each of the sites (Table 1, PL 321–324, 325–328).

In the Szczawnica area, the Bryjarka locality was overprinted in the present geomagnetic field (and is therefore not discussed further); the Jarmuta locality exhibited a strange direction. At Krościenko, no stable end point was reached on demagnetization, but a component for each of the sampled sites could be defined (Table 1).

When we plot all the identified NRM components (except Bryjarka) on a stereonet, we can identify two sets of data (Fig. 6). One is characterized by easterly declination and reversed polarity or in one case, westerly declination and normal polarity (Fig. 6A), so that the directions are counterclockwise rotated with respect to the stable European reference direction. The other directions appear to define a great circle, which contains the stable European reference direction for 20–10 Ma (Fig. 6B).

Magnetic minerals

Detailed thermal demagnetization of the NRM has revealed that most of the NRM unblocks below the Curie-point of magnetite. However, in several samples another component exists, which resides in a mineral with higher unblocking temperatures. In order to obtain more information about the carriers of both NRM components, we carried out IRM (isothermal remanent magnetization) acquisition experiments, measured Curie-points (susceptibility versus temperature curves) and made microscopy observation on polished sections.

Although the NRM in several samples did not unblock completely until the Curie-point of hematite, the IRM acquisition curves suggest that the dominant magnetic mineral is magnetically soft and there is only a weak signal from hard

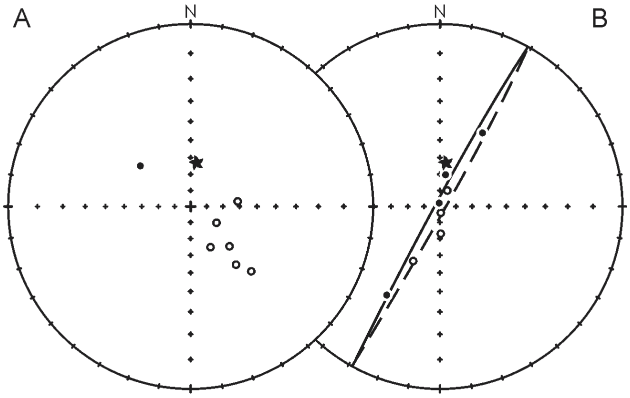

Fig. 6. Pieniny andesites. Paleomagnetic directions on a stereographic projection. **A** — Components exhibiting CCW rotation with reversed (open circles) or normal (full circle) polarity; **B** — components interpreted as later overprints in a stable European framework. Open circles: vectors pointing upward; full circles: vectors pointing downward; star: stable European reference direction calculated from data by Besse & Courtillot (1991). The parameters of the pole of the remagnetization great circle drawn through the isolated components for the Pieniny andesites are: D=119°, I=3° and α_{95}=7.3°. If we include the stable European reference direction, the parameters change only slightly to D=118°, I=4° and α_{95}=8.7°.

Table 1: Summary of the paleomagnetic directions (D° and I°) with (k, α_{95}°) statistical parameters (Fisher 1953) from the Pieniny andesites. Key: n/no: used/collected samples. Numbers with PL prefix refer to Fig. 2 and are used throughout the text. a, b, c, are the components of the NRM when the NRM is complex. Components were defined using principal component analysis (Kent et al. 1983). In "Remark" column the stability range of the NRM (component) is indicated.

Locality			n/no	D (°)	I (°)	k	α_{95} (°)	Remark
Pieniny andesites, 1st phase intrusions								
1 Wżar Mts, Monument	PL 215–218	a	4/4	303	+33	27	17	NRM–300 °C
		b	4/4	209	–53	369	5	300–610 °C
		c	4/4	139	–56	30	17	610–670 °C
	PL 219–222		4/4	157	–62	3120	2	NRM–670 °C, NRM–120 mT
2 Czorsztyn	PL 321–324		4/4	214	+31	297	5	NRM–640 °C
	PL 325–328		4/4	33	+40	273	6	NRM–640 °C
	PL 492–494		3/3	140	–38	292	7	NRM–140 mT
	PL 495–197		3/3	142	–45	1032	4	NRM–140 mT
3 Szcsawnica, Jarmuta Quarry	PL 209–214		6/6	28	–79	165	5	150–590 °C
4 Szcsawnica, Bryjarka Quarry	PL 469–472		4/4	352	+49	80	10	NRM–390 °C
5 Krościenko, Zakijowski stream	PL 473–475		3/3	357	+88	269	8	NRM–25 mT
	PL 476–478		3/3	13	+70	465	6	NRM–550 °C, NRM–25 mT
	PL 479–481		3/3	312	+51	1101	4	NRM–25 mT
Pieniny andesites, 2nd phase intrusions								
6 Wżar Mts, S. Quarry	PL 316–320	a	5/5	356	+34	18	19	NRM–350 °C
		b	5/5	176	–86	51	11	350–550 (585) °C
		c	4/5	87	–61	36	16	585–640 °C
7 Wżar Mts, N. Quarry	PL 459–468	a	5/10	331	+70	120	7	18–25 mT
		b	10/10	181	–73	165	4	25 mT–525 (575) °C
		c	9/10	125	–71	67	7	630–670 °C

magnetic minerals in some samples (e.g. Fig. 7, PL 214, PL 216b); the Curie-point characterizes magnetite or a somewhat oxidized magnetite (Fig. 7).

Polished sections were prepared from the specimens that had provided the IRM acquisition and susceptibility versus temperature curves (11 representative specimens). In all sections, magnetite was identified, both as phenocrysts and as smaller grains in the matrix; mafic-magnetite alteration was also observed in all sections.

Hematite as martite (in magnetite) characterizes both the second and first generation intrusions from the Wżar Mountains (sometimes it is without structure, which suggests that martitization occurred during the formation of magnetite in a strongly oxidizing environment), but is not typical in the Szczawnica area. Hematite also occurs in the samples from the Wżar Mountains (and in Jarmuta Quarry) as spots and along fissures, but it is lacking in Bryjarka and Krościenko.

Small magnetite and hematite grains occasionally occur together as inclusions in mafic minerals. Sulphides, mostly chalcopyrite, are observed in all samples, although their frequency is variable: they are rare in the first phase intrusions of the Wżar Mountains, and frequent in the second phase intrusions. They are also abundant in samples from Krościenko.

Discussion and conclusions

Analysis of the NRM, magnetic mineralogy experiments and inspection of polished sections did not reveal any characteristic differences between the first and second phase intrusions. The most important common features of the two phases are:

1. NRM components indicating counterclockwise rotation;

2. other components defining a great circle, which contains the expected stable European paleomagnetic direction;

3. (oxidized) magnetite as the principal magnetic mineral;

4. high-temperature and hydrothermal alteration of the magnetite (as well as other minerals, like opacitization of amphiboles).

The component indicating counterclockwise rotation of the second phase dykes resides in a mineral with higher unblocking temperature (higher oxidation state) than magnetite; the same is true for the first phase intrusions, except three sites (Table 1, PL 219–22, PL 492–94, PL 495–97), where this component is observed in the magnetite unblocking temperature range. The enumerated common features have the following implications:

First, the area intruded by the Pieniny andesites must have rotated counterclockwise after formation of the 2nd phase

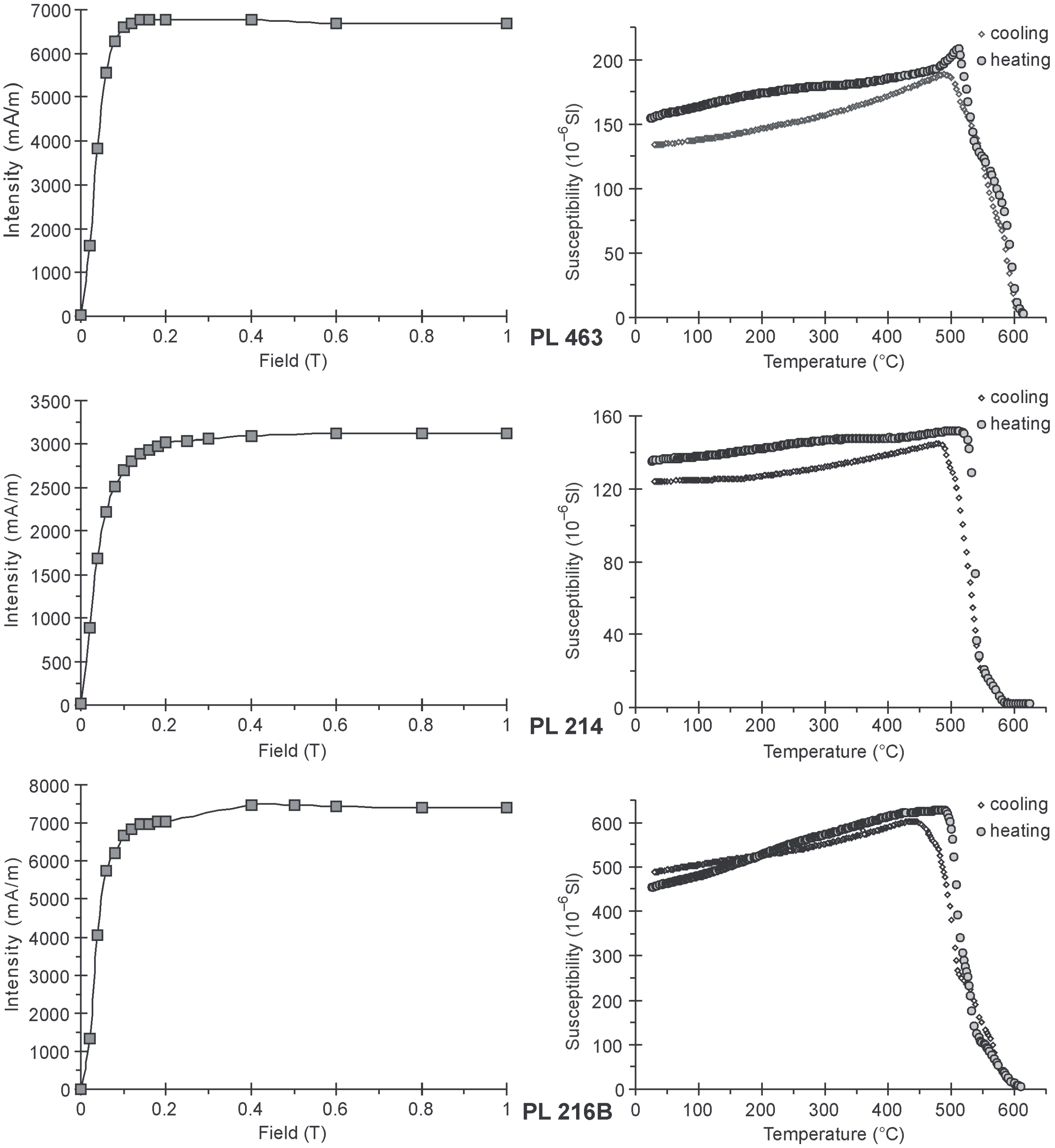

Fig. 7. Magnetic experiments aiming at identification of the magnetic minerals in the Pieniny andesites. Second phase intrusion (PL 463) and first phase intrusions (PL 214 with non-rotated declination only, PL 216B with complex NRM). Left hand side: isothermal remanent magnetization (IRM) acquisition curves. Right hand side: susceptibility versus temperature curves. IRM acquisition curves show exclusively (PL 463) or dominantly (PL 214, PL 216B) low coercivity magnetic minerals, which may be oxidized magnetite, according to the susceptibility versus temperature curves, in PL 463 and PL 216B and typical magnetite in PL 214.

dykes. Second, although the samples are fresh to the naked eye, the effects of high temperature oxidation and hydrothermal alteration are observed under the microscope, in samples with a single component NRM of rotated declination as well as in samples with complex NRM. This means that the process responsible for overprinting postdates even the hydrothermal activity and may be attributed to hot fluids imprinting partial thermoremanent magnetization on the pre-existing thermoremanent or chemical remanent magnetization.

Normally, it is taken for granted that fresh magnetite in andesites carries a primary magnetization, while the oxidized varieties carry a secondary remanence. In the Pieniny andesite line, there seems to be no correlation between NRM components and magnetic minerals in this sense.

The "non-westerly" components appear to be younger than the CCW rotated ones, since they lie along a great circle that contains the stable European reference direction (Fig. 6B). The andesites were, therefore, emplaced and oxidized before

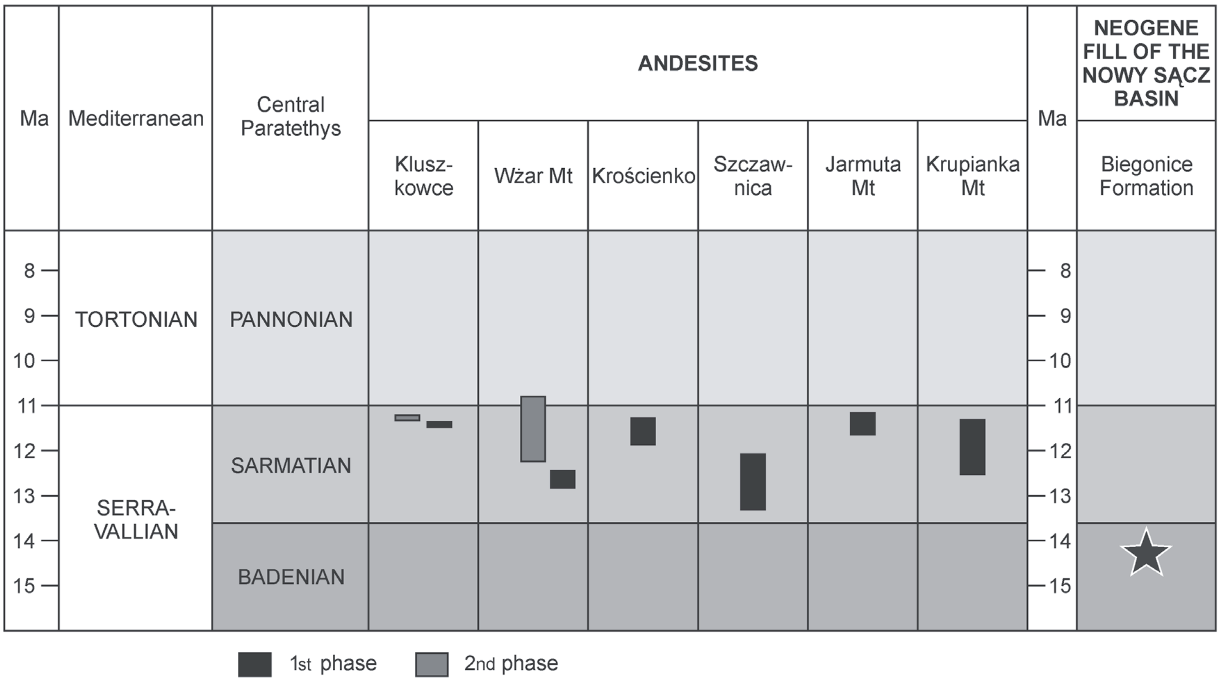

Fig. 8. Ages of Pieniny Mts andesites (after Birkenmajer & Pécskay 2000) and of the Neogene fill (fresh water sediment) of the Nowy Sącz Basin (after Oszczypko et al. 1992). The latter is dated biostratigraphically by the overlying marine strata.

the final rotation of the area. The inferred hot fluids, on the other hand, overprinted the NRM after the counterclockwise rotation event.

From the tectonic point of view, the most important question is the age of the andesites. An older than Late Badenian age would permit us to connect the counterclockwise rotation of the Pieniny andesites to the rotation of the Inner Western Carpathians (and perhaps to movements in the Outer Western Carpathians and in the Foredeep). In this case, the Upper Badenian strata filling the Nowy Sącz Basin (Fig. 1b, Oszczypko et al. 1991) exhibiting a paleomagnetic declination (D=188°, I=−42°, k=36, α_{95}=9°, based on 8 samples) which is aligned with the stable European reference declination (8°) would signify the termination of the large scale movements of the Carpathians. However, recently obtained K/Ar ages for several sites of the Pieniny andesite line (Birkenmajer & Pécskay 1999, 2000) confirm the Sarmatian age of both intrusive phases (Fig. 8). These young age estimates imply that the rotation of the Pieniny andesite line took place in post-Sarmatian times, due to local tectonic causes. It would be tempting to connect the rotation to the sinistral strike-slip movement along the Pieniny Klippen Belt, which was postulated in some tectonic models (e.g. Birkenmajer 1986 and references therein). Unfortunately, the strike-slip movement pre-dates a post-Sarmatian rotation.

The present study on the Pieniny andesites reinforces the conclusion that paleomagnetic results, even from Miocene or younger magmatic rocks, must be treated with caution, when based on partial demagnetization. Full demagnetization may reveal components which are small, but well defined (like the component with high unblocking temperature in the second phase andesites from the Pieniny andesite line), not only in a specimen (Fig. 4), but also on a site level (e.g. good statistical parameters in Table 1, components 6c and 7c). Our results from the Pieniny andesites make clear that thermal demagnetization greatly enhances the reliability of data (since AF demagnetization, which is routinely applied to young igneous rocks, may not lead to the identification of all NRM components) and demonstrates that with careful demagnetization and component analysis it is possible to separate tectonically significant paleomagnetic signals, even in the presence of large overprint NRM components.

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