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MAGNETOSTRATIGRAPHIC AND MICROPALEONTOLOGICAL INVESTIGATIONS ALONG THE JURASSIC/CRETACEOUS BOUNDARY STRATA, BRODNO NEAR ŽILINA (WESTERN SLOVAKIA)

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Abstract: Results of micropaleontological and magnetostratigraphic investigations concern the determination of the Jurassic/Cretaceous (Tithonian/Berriasian) boundary at the locality of Brodno near Žilina, Western Slovakia. These studies were preceded by petromagnetic and paleomagnetic investigations of pilot samples, collected from five localities in the Western Carpathians, in N. Moravia and W. Slovakia, namely Štramberk, quarry "Kotouč"; Štramberk, quarry "Skalka"; Brodno near Žilina, abandoned quarry; Strážovce, section along a road; Hlboč near Smolenice, outcrop in a forest. All of the above mentioned localities were found suitable for magnetostratigraphic investigations, but the locality Brodno was given preference due to its suitable geological and paleontological conditions. A detailed micropaleontological study was carried out along a renumbered strata sequence in reference to previously established numbering by Michalík et al. (1990). The base of the standard zone with *Calpionella*, the Jurassic/Cretaceous boundary, was placed between the newly numbered beds BC-15A and BC-15B. (Fig. 2 shows the new numbering and also indicates the correlation with the previous one). Sedimentation in a quiet basin was one of the basic pre-requisites for reliable derivation of high-resolution magnetostratigraphic data. The pattern of normal and reverse polarity magnetozones from M 17 to M 21 correlates well with data derived in the regions of Foza (north Italy), Bosso Valley (Umbria, central Italy) and with marine M (Mesozoic) anomalies. A very narrow reverse sub-zone was found in the younger part of the magnetozone M 19n well correlating with a similar sub-zone derived from marine magnetic M anomalies. The base of the standard Calpionella Zone, i.e. the Jurassic/Cretaceous boundary, was placed in the younger part of the older half of the magnetozone M 19n. The base of the standard Crassicolaria Zone lies approximately in the middle of the magnetozone M 20n in the Brodno section.

Key words: Western Carpathians, locality Brodno near Žilina, Jurassic/Cretaceous boundary, micropaleontology, petromagnetism and magnetomineralogy of limestone, magnetostratigraphy, global correlation.

Introduction

In the year of 1992, the Paleontological and Paleomagnetic Departments of the Geological Institute of the Academy of Sciences of the Czech Republic in Prague started a joint project of magnetostratigraphic investigations of the Tithonian-Berriasian boundary strata at two localities in the Western Carpathians, Brodno near Žilina, W. Slovakia, and Štramberk, N. Moravia, respectively. The aim was to determine the principal biostratigraphic boundaries in reference to magnetostratigraphic scales (geomagnetic polarity time scales — GPTS) and to prepare data for the next correlations between biostratigraphic zonations in the Tethyan and Boreal realms. Through financial support from the Geological Institute of Dionýz Štúr in Bratislava, Grant Agency of the Academy of Sciences of the Czech Republic and the Ministry of Environment in Prague, both the above localities could be studied in sufficient detail corresponding to detailed micropaleontological studies. At the same time, a certain volume of work was also devoted to petromagnetic and magnetomineralogical investigations focused on some paleoenvironmental problems.

In this paper, we summarize the principal results obtained at the locality Brodno near Žilina. Magnetostratigraphic and biostratigraphic investigations carried out at this locality confirmed fully the geological assumption that a sedimentation in a quiet basin is one of the principal conditions for preservation of a continuous fossil record of well defined geomagnetic polarity reversals. This is the reason why this locality was studied in detail. In combination with detailed micropaleontological studies, paleomagnetic data derived from this locality contributed to the elaboration of high-fidelity (high-resolution) magnetostratigraphy. Regular alteration of limestone strata as well as continuous profile with rich calpionellid associations enabling studies of morphological changes of respective taxa and changes of their abundance, are the basic pre-requisites for definition of zones suitable for studies of Milankovitch cycles.

Samples for micropaleontological and magnetostratigraphic analyses were collected independently, but in reference to the same strata labelled with numbers. Boundary positions of biozones and magnetozones were interpreted more accurately during additional and repeated collection of samples. Ammonites are missing at the locality Brodno, consequently only associations of calpionellids could be used for correlation.

Samples for magnetostratigraphic studies were subjected to demagnetization. High efficiency was achieved through the use of the MAVACS apparatus, a thermal demagnetizer securing creation of a high magnetic vacuum during the laboratory process and enabling simultaneous demagnetization of a bigger set of laboratory samples (about 23 samples, if they are weakly magnetic). Each sample was also studied petromagnetically, so that unblocking temperatures could be derived and investigations of phase changes of minerals — carriers of magnetization and paleomagnetization — could also be carried out. Moreover, X-ray analyses combined with magnetomineralogical investigations were concentrated on the defining of minerals contributing to magnetization and carrying the fossil components of remanence.

Some general remarks on the geomagnetic polarity time scales

During the last thirty years, we have witnessed the development of the paleomagnetic method, including development of the geomagnetic polarity time scales (GPTS), cf. eg. Cox et al. (1963), Tarling (1971), Cox (edit.,1973), La Brecque et al. (1977), Ness et al. (1980), Butler (1991), Soffel (1991) and many others. However, records of fossilized reversals of the main geomagnetic field were published earlier, by Melloni (1853a, b), Hospers (1953a, b), cf. Krs (1969). Systematic development of GPTS started with the Pliocene-Pleistocene. Discovery of marine magnetic anomalies and formulation of the sea-floor spreading hypothesis (Vine & Matthews 1963) resulted in the interpretation of the origin of marine magnetic anomalies. Heirtzler et al. (1968) were the first to use the marine magnetic anomalies for construction of the GPTS. Later on, the GPTS were systematically improved a great deal by extension of studies to rock formations on continents. In particular, a close collaboration between geophysicists and paleontologists is very efficient, and attempts for development of high-fidelity (high-resolution) magnetostratigraphy are priority targets in the investigations. The newly derived results may contribute considerably to corrections of biostratigraphically determined zones or boundaries and can make correlations between the Tethyan and Boreal realms possible. There are, of course, many other aspects of utilization of improved magnetostratigraphic scales, in geophysical, geological, paleontological and paleoenvironmental studies (origin of magnetization, investigation of Milankovitch cycles, etc.).

Magnetostratigraphic results obtained from the pelagic limestone sequence of the Upper Cretaceous portion of the Scaglia Rossa section in the Umbrian Apennines near Gubio, Italy, were of primary interest due to the calibration significance and the subsequent discovery of iridium-enriched sediment at the Cretaceous-Tertiary boundary and the development of the impact hypotheses (Lowrie & Alvarez 1977; Alvarez et al. 1980). Late Cretaceous to Cenozoic magnetostratigraphic scales (GPTS) could be derived, due to mapping of the marine magnetic anomalies and their interpretation, with paleontological dating of deep-sea drill cores providing "spot checks" on the polarity time scale. Cox (1982) presented such a scale numbered by magnetic anomalies (polarity chron numbers) from 1 to 115 covering the time period from 0 to 118 Ma.

The oceanic crust also provided magnetic anomalies covering the period from the Late Jurassic to the Early Cretaceous. The anomalies are denoted as M-anomalies, in which M stands for Mesozoic. Lowrie & Ogg (1986) elaborated GPTS from the Aptian to the Oxfordian with numbered M-anomalies from MO to M29. Combining the above scales, a broad normal superchron was defined between 85 and 119 Ma from the Santonian to the Aptian.

In our studies, we have adopted the folloving nomenclature: *1* — Polarity magnetic sub-zone is of approx. 10^4–10^5 years duration, in the geochronological scale it corresponds to subchron and in the chronostratigraphic scale to sub-chronozone. *2*—Polarity magnetic zone is of approx. 10^5–10^6 years duration, with corresponding chron and chronozone. *3* — Polarity magnetic super-zone is of approx. 10^6–10^7 years duration, with corresponding super-chron and super-chronozone. The term magnetic polarity zone, or magnetozone, refers to a particular rock stratigraphic interval (Butler 1991). Due to (minor) variability in the pattern of magnetic polarity zones, it is always necessary to check the continental magnetic anomaly profiles with the marine ones. Moreover, such correlations contribute to the improvement of magnetostratigraphic corrections of biostratigraphically dated rocks.

Due to the accuracy of age determination and thick continuous sections of marine sediments, these rocks are considered as significant source of information on paleomagnetic polarities and generally on rockmagnetic data. It has been found by many geophysicists, that subaerially exposed sections of marine sediments, especially of shallow-water carbonates, show relatively low values of intensities of natural remanent magnetization of 10^{-3} down to 10^{-5} A/m (Butler 1991). In these shallow-water carbonates, the fine-grained magnetite is the principal carrier of magnetization and paleomagnetization. There are other contributors to magnetization of marine sediments. However, the fine grained magnetite of size ≤ 0.1 μm is dominantly cont[illegible] in marine carbonates. Magnetomineralogical analyses of this magnetite and of some additional ferromagnetic minerals contribute to the explanation and/or to the discussion of the origin of the minerals—carriers of magnetization and paleomagnetization in the marine carbonates.

Position of the Jurassic/Cretaceous boundary at the Brodno section

The section in the abandoned quarry east of the Brodno railway station is described in more detail by Michalík et al. (1990). Brownish-red nodular limestones, ranked into the Czorsztyn Formation by the above authors, pass into grey, medium bedded, massive limestones of the Pieniny Limestone Formation in this section. Calpionellids from this locality were thoroughly studied by Borza (1969), and their associations were evaluated biostratigraphically by the above cited authors (1990). The correlation of the local calpionellid zonation with the next significant sections in the Western Carpathians was made by Reháková & Michalík (1992).

Marking of the individual beds of the studied Brodno section by numbers was first started by Borza (1969, p. 24). This numbering has not, however, survived in the outcrop. This author postulated the base of the Berriasian surprisingly at the base of the Calpionella Zone (then, the Jurassic/Cretaceous boundary was mostly placed stratigraphically higher, into the zone with *Calpionella*). The beds were renumbered by Michalík et al. (1990, p. 59) who marked the numbers on the outcropping strata. These numbers mostly survived only because they were repeatedly renewed. In their numbering these authors placed the base of the Calpionella Zone, i.e. the Jurassic/Cretaceous boundary, betwen beds 16 and 17.

For our labelling of samples we first used the numbering marked on the outcrop by the preceding authors. This has been applied to all samples paleomagnetically investigated. This numbering, however, proved to be too rough for a detailed correlation biostratigraphic study of the individual tectonic blocks in the section. It did not respect the tectonic segmentation of the outcrop and a part of the section was even omitted. Hence, we produced a new, detailed description of the section and a new, more detailed numbering of limestone beds. The outcrop was divided into three tectonically independent segments, namely the western block (BL), central block (BC), eastern block (BV) and the so-called crest (BH) as indicated in Fig. 1. The section in Fig. 2 shows the new numbering in the thoroughly studied part of the outcrop, and also indicates the correlation with the older numbering of Michalík, Reháková and Peterčáková. According to our observations, the base of the zone with *Calpionella*, i.e. the Jurassic/Cretaceous boundary, lies between beds BC-15A and BC-15B and is equivalent to the space between beds 18 and 19 in the numbering of Michalík et al. (1990). It is thus situated differently from these authors' concept: about 2.5 m stratigraphically higher, in a younger series. As this boundary represents an important stratigraphic horizon, we wish to explain the reasons for this decision in more detail.

The provisional Jurassic/Cretaceous boundary in the Tethyan region was established at the base of the jacobi-grandis Ammonite Zone (Mémoires du BRGM 86, p. 393, 1975). This level is treated as practically identical with the base of the Calpionella Zone of the standard calpionellid zonation (Remane et al. 1986, p. 10). As ammonites are missing at most localities in the Tethyan realm, the Jurassic/Cretaceous boundary is commonly based on calpionellids. At the studied Brodno locality, the Jurassic/Cretaceous boundary can also be determined by looking only at the calpionellids. For these reasons, we paid attention to the accurate location of the base of the standard Calpionella Zone (i.e. the base of the standard Alpina Subzone).

The base of the standard Calpionella Zone was defined by Remane (1964) and Allemann et al. (1971) as a morphological change of *C. alpina,* in which the form characteristic of the Late Tithonian, having a relatively big and somewhat elongated lorica, was replaced by a smaller form with a rather spherical lorica. This change was associated with the extinction of three species of *Crassicollaria* (*Cr. brevis, Cr. intermedia, Cr. massutiniana*) abundantly occurring during the Late Tithonian. The smaller spherical form of *Calpionella* occurs in the latest Tithonian already together with the large form and the representatives of the *Crassicollaria.* After the extinction of the three mentioned *Crassicollaria* species, the smaller form of *Calpionella,* however, became a strongly dominant element in the calpionellid associations. This phenomenon is referred to as the "explosion" of the *Calpionella alpina,* and denotes the base of the standard zone with *Calpionella.* Besides this species of *Calpionella,* only *Tintinnopsella carpathica, Crassicollaria parvula* and *Cr. colomi* permanently range across the Tithonian/Cretaceous boundary. Also *Cr. brevis* and the large form of *Calpionella* are the last sporadically represented individuals occurring in the oldest interval of the standard zone with *Calpionella.*

The above mentioned forms (i.e. Tithonian big and somewhat elongated form and Berriasian smaller spherical form) within the *Calpionella* were distinguished by Remane (1964). Being aware of the transitions between the individual forms, he did not call them by separate names. This was done by Nagy (1986) who distinguished seven new species within the genus *Calpionella.* Houša (1990) demonstrated that many of the new names are synonyms, but retained the name *C. grandalpina* Nagy for the big Tithonian form. He also documented that *C. alpina* was described by Lorenz (1902) on the smaller, spherical form characteristic for the standard Calpionella Zone. Thus, the smaller form must bear the name *Calpionella alpina.*

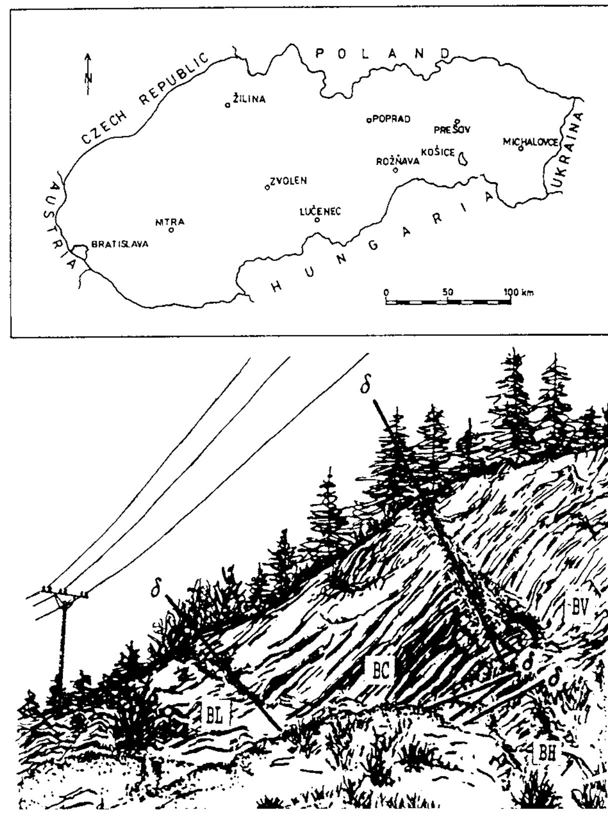

Fig. 1. Schematic sketch of the wall in the north-western part of the abandoned Brodno quarry. Position of the profiles studied: **BC** — central part, **BL** — western part, **BV** — eastern part, **BH** — lower part (Hřbítek). Beds are in overturned position.

Besides the above given changes, Remane (1964) recognized two other characteristic features associated with the base of the standard Calpionella Zone. First, at the very end of the Tithonian (i.e. at the top of the standard Crassicollaria Zone) some large forms of *Calpionella* occur abundantly with strongly elongated loricae, similar to those of the much later occurring *C. elliptica.* This form was named *C. elliptalpina* by Nagy (1986). The second characteristic feature is the short "explosive" boom of *Crassicollaria parvula,* which occurs shortly after the "explosion" of *C. alpina.* After a very short predominance in calpionellid associations *Cr. parvula* rapidly retreated again to be replaced by *C. alpina.*

In the Brodno section, the first calpionellid representatives with hyaline shells were found in the sample from bed BC-98 (i.e. 25 cm below the base of BC-1). The following succession was determined for the individual limestone beds towards the overlaying strata: *Cr. intermedia, Cr. brevis, Cr. massutiniana* and finally *Cr. parvula* and *Cr. colomi.* These two last species are, however, not diagnostic for the determination of the base of the standard zone with *Calpionella,* except for the short acme of the *Cr. parvula* in the oldest part of the standard Calpionella Zone. The three "diagnostic" species of *Crassicollaria* (the first three mentioned above) are very abundant in beds BC-1 through BC-11. The last specimen of *Cr. intermedia* was found in the sample from the middle part of the bed BC-14 but proved to be absent from its upper part. In the upper part of this bed, only two other species occur sporadically, namely *Cr. brevis* and *Cr. massutiniana* (see Fig. 3). These species are rarely found in the calpionellid assemblage of the immediately following bed BC-15A. *Cr. massutiniana* was not found any higher, but a single specimen of *Cr. brevis* was recorded in a thin section from the bed BC-15B.

The first representatives of *Calpionella grandalpina* occur in the sample from the basal part of the bed BC-5. Their occurrence is a determining factor for the base of the standard Crassicollaria intermedia Subzone. *Calpionella grandalpina* occurs less frequently in the older parts of this zone but becomes increasingly abundant from bed BC-9 (correspondings to bed 17 of Michalík et al. 1990) onwards. The highest abundance of this species is reached in bed BC-15A. The proportion of this species in the calpionellid assemblage rapidly decreases in the lower part of the immediately following bed BC-15B and in other samples from the hangingwall, it occurs only sporadically. In samples from higher levels (younger strata), such as BC-16, it was recorded only rarely.

Calpionella elliptalpina is quite common in beds BC-14 and BC-15A. The first specimens were already recorded in the thin section from bed BC-11 already and the last specimens are present in the sample from the basal part of bed BC-15B. It was not found any higher. The last occurrences of this species are characteristic of the boundary between the standard Crassicollaria and Calpionella Zones (see Remane 1985, p. 559, a.o.).

Calpionella alpina (s.s. — see Houša 1990, p. 361) is present in small numbers in all thin sections from the youngest part of the standard Crassicollaria Zone already. In the sample from bed BC-15A, it is slightly more abundant but still represents a very subordinate element (*Calp. grandalpina* is much more abundant). However, it suddenly becomes a dominant element in the thin section from the lower part of bed BC-15B and clearly prevails in number over other calpionellid taxa in the upper part of bed BC-15B.

For these reasons, we placed the base of the standard zone with *Calpionella*, thereby also the Jurassic/Cretaceous boundary, between beds BC-15A and BC-15B.

We searched for yet another diagnostic feature supporting our interpretation, i.e. the acme of *Crassicollaria parvula*. We found that this feature is also well developed in the Brodno section — in bed BC-20.

The authors did not previously distinguish between the above mentioned taxa of *Calpionella* and included all of them (i.e. *Capionella grandalpina, C. elliptalpina* and *C. alpina*) under one specific name - *C. alpina* (i.e. *C. alpina* s.l.). The Tithonian large form (*C. grandalpina*) is not very abundant for a certain time after its first occurrence in the bed BC-5, however, its abundance rapidly and relatively abruptly increases in the layer BC-9. This fact appears as a marked increase of *C. alpina* s.l. abundance (recte *C. grandalpina*), in the calpionellid association. Then, looking for the base of the zone with *C. alpina* s.l., i.e. for an abrupt increase in *C. alpina* abundance, it is logical that many authors misplaced the J/C boundary at this level, which corresponds to bed BC-9 in the Brodno section (it is identical to bed 17 in the numbering of Michalík et al. (1990) (who did not distinguish *C. grandalpina*). On the factual J/C boundary between beds BC-15A and BC-15B in the Brodno section, no marked change in *C. alpina* s.l. abundance can be statistically observed if this broad taxonomic concept is adopted, because one abundant form of the "same" species (*C. grandalpina* in fact) was replaced here by another abundant form of the same species (*C. alpina* s.s. in fact). This error, i.e.

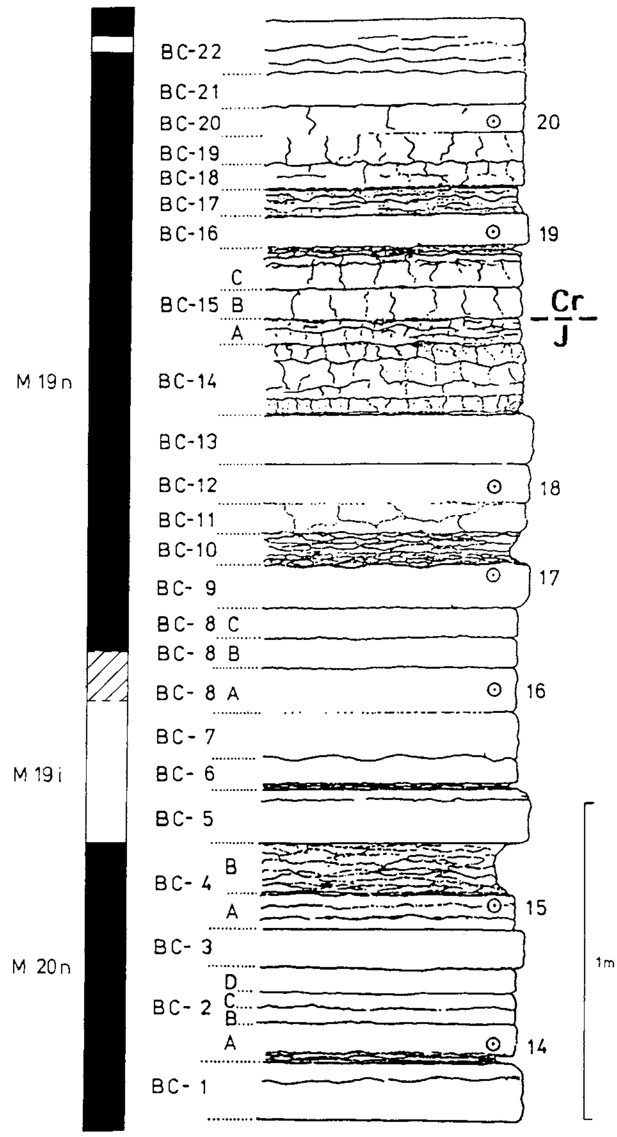

Fig. 2. Schematic sequence of the investigated part of the profile BC near the Jurassic/Cretaceous boundary. Numbers on the left-hand side — our new numbers of individual beds; numbers on the right-hand side — older numbers on the layers according to Michalík et al. (1990).

Species / Sample	Cr.massutiniana	Cr.intermedia	Cr.brevis	Cr.parvula	C.grandalpina	C.elliptalpina	C.alpina	T.carpathica
BC-15C				X	x		■	x
BC-15B			•	X	x	x	■	x
BC-15A	•		•	X	■	■	x	x
BC-14C	x		x	X	■	■	x	x
BC-14B	x	•	x	x	■	■	x	x
BC-14A	x	x	x	x	■	X	x	x
BC-13	x	x	x	x	■	x	x	x

• - rare   x - present   X - abundant   ■ - very abundant

Fig. 3. Distribution of calpionellid species in the Jurassic- Cretaceous boundary beds in the Brodno quarry (W. Slovakia).

to place J/C boundary in the increase of abundance of *C. grandalpina* in the bed BC-9, can be easily unveiled because the species *Cr. intermedia, Cr. brevis* and *Cr. massutiniana* do not disappear at this level but exist up to the level of beds BC-14 and BC-15A. Also the elongated shape of *C. alpina* s.l. (*C. elliptalpina*) characteristic of the boundary interval between the two discussed standard zones does not occur abundantly below beds BC-14 and BC-15A. After the decrease of abundance of *C. elliptalpina* in bed BC-15B, it totally disappears from the calpionellid association.

Rockmagnetic investigations

Prior to systematic magnetostratigraphic investigations, pilot samples were collected from five localities in the Western Carpathians with the aim of determining their basic petromagnetic and paleomagnetic parameters. The pilot samples were collected in five localities, namely: *1* — Štramberk, N. Moravia, quarry "Kotouč", the 6th level within the operating quarry; *2* — Štramberk, N. Moravia, abondoned portion of the quarry "Skalka"; *3* — Brodno near Žilina, W. Slovakia, abandoned quarry; *4* — Strážovce, between the settlements Čičmany and Zliechov, W. Slovakia, cross-section along a road; *5* — Hĺboč near Smolenice, W. Slovakia, cross-section in a forest.

Laboratory procedures, magnetization of limestone samples

Attention was paid to detailed petromagnetic and magnetomineralogical analyses applied to all samples. The principle magnetic parameters, remanent magnetization and volume magnetic susceptibility, were measured with the use of the spinner magnetometers JR-4 and JR-5 and the Kappa-bridge KLY-2 (Jelínek 1966, 1973). Selected samples were subjected to alternating-field (AF) demagnetization by means of the apparatus Schonstedt GSD-1. Although AF demagnetization was applicable, higher efficiency of magnetic cleaning and/or separation of respective components of remanence was obtained with the use of thermal demagnetizer MAVACS (MAgnetic VAcuum Control System, Příhoda et al. 1989). During thermal experiments, the minerals — carriers of magnetization and paleomagnetization — exhibited phase changes usually at higher temperature intervals than at which data should be provided for derivation of the paleomagnetic components of remanence. Consequently, dependence of magnetic susceptibility with temperature was investigated for each sample. In case of creating high magnetic vacuum during thermal demagnetization, even phase changes of minerals or formation of new ferrimagnetic minerals during laboratory treatments do not mask the original fossil components or their portions with higher unblocking temperatures, and paleomagnetic directions may be derived. Determination of unblocking temperatures may be used for interpretation of the origin of minerals — carriers of respective components of remanence. This is also why dependences of changes of moduli of remanent magnetization with temperature were currently investigated.

The MAVACS apparatus was developed for rockmagnetic and paleomagnetic research securing creation of a high magnetic vacuum needed for precise demagnetization of rock samples. However, this apparatus is suitable for many other purposes, such as calibration of marine, air-borne and satellite magnetometers, registration of industrial, diurnal and other disturbaces of the ambient magnetic and geomagnetic fields, etc. The basic component of the MAVACS device is the ROCOMA (ROtating COil MAgnetometer), which indicates the true magnetic vacuum with a typical deviation not exceeding ± 0.1 nT. The magnetostratigraphic and paleomagnetic investigations are based on analyses of whole sets of samples, which impose higher technical demands on the thermal demagnetizer. MAVACS was devised in such a way, that it provides an automatic creation of magnetic vacuum with an accuracy of ±2 nT in about 5 litres volume, facilitating simultaneous demagnetization of larger sets of laboratory samples. The apparatus, besides other applications, proved to be efficient during studies of several delicate problems such as the derivation of Variscan overprint components (Krs & Pruner in press; Krs et al. in press a), separation of pre-Variscan paleomagnetic components in the Bohemian Massif (Krs et al. in press a; Krs et al. 1987), derivation of paleomagnetic components in the Flysch Formation of the Western Carpathians (e.g. data in a summary report by Krs et al. in press b) and during studies of magnetism of metastable minerals (such as greigite, smythite) of bacterial origin and of their thermal alteration products (Krs et al. 1991, 1992, 1993a). Its high purity during demagnetization is also verified by the magnetostratigraphic investigations discussed in this paper.

Studies of microcoercivity spectra performed on a few selected samples yielded data enabling us to judge the magnetic hardness of the respective ferrimagnetic minerals. The pilot samples collected from the above mentioned localities show clearly that the rocks under consideration are generally low magnetic and their magnetization values fall within the limits of magnetization determined for other localities in the Tethyan realm (Galbrun 1985; Lowrie & Channell 1983; Márton 1986; Moreau et al. 1992; Ogg et al. 1984, 1988, 1991), see Tab. 1. These magnetization values correspond well to those found for the marine sediments, especially for shallow-water carbonates (Butler 1991).

Results of laboratory demagnetization of representative samples

Selected samples were subjected to both alternating-field (AF) and thermal demagnetizations. AF demagnetization by means of the apparatus Schonstedt GSD-1 proved not to be very effective, typical examples are shown in Fig. 4 for locality

Table 1: Natural remanent magnetization (J_n) and volume magnetic susceptibility (κ_n) of pilot samples, Jurassic-Cretaceous boundary strata, Western Carpathians.

Locality	J_n $\times 10^{-6}$ [A/m]	κ_n $\times 10^{-6}$ [SI]	Number of samples
Štramberk, N. Moravia, quarry "Kotouč"	98±75	|8|±|3|	24
Štramberk, N. Moravia, quarry "Skalka"	373±462	|7|±|7|	7
Brodno near Žilina, W. Slovakia	758±315	14±8	10
Strážovce between Čičmany and Zliechov, W. Slovakia	542±289	60±6	10
Hĺboč near Smolenice, W. Slovakia	1800±627	351±335	5

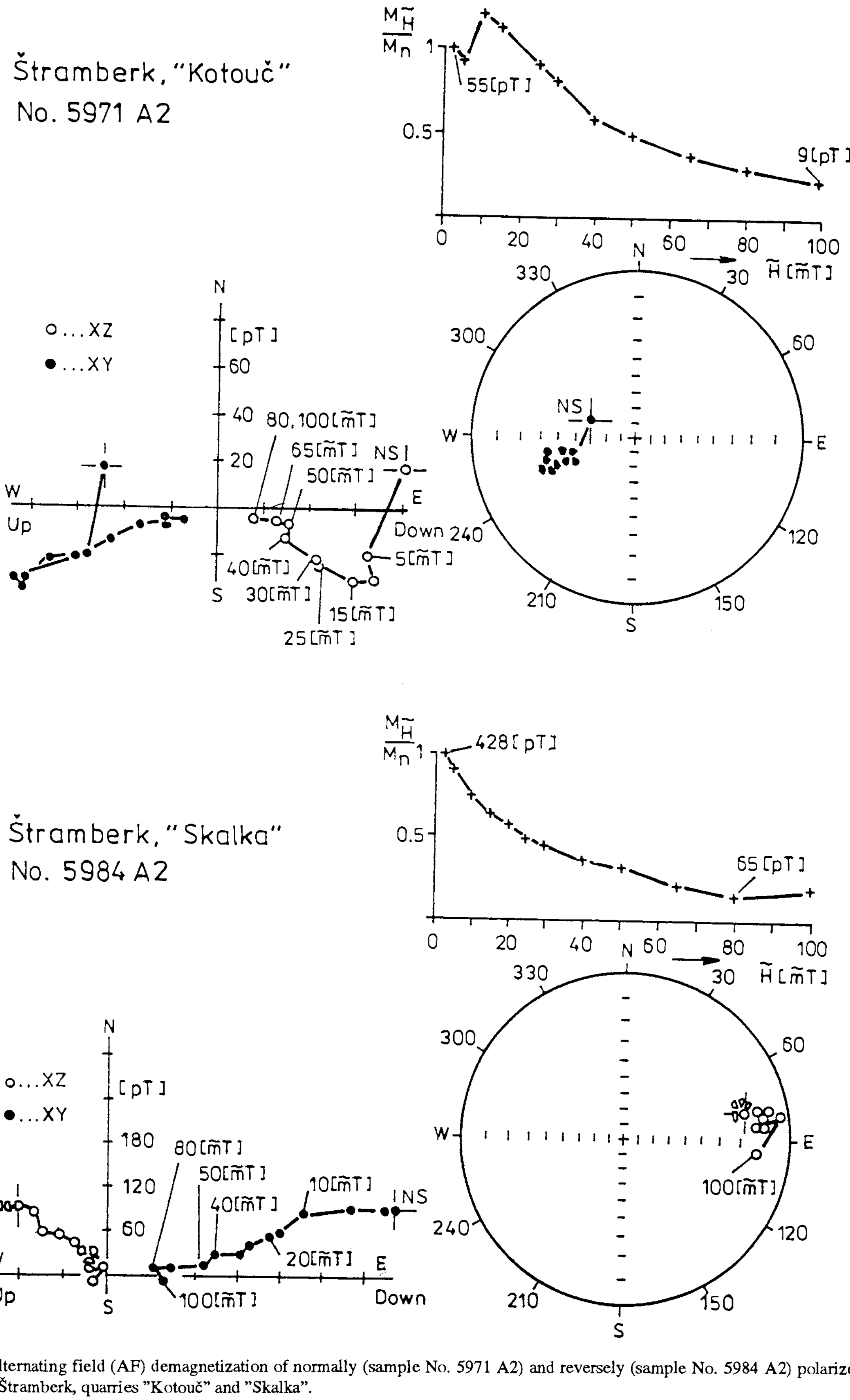

Fig. 4. Alternating field (AF) demagnetization of normally (sample No. 5971 A2) and reversely (sample No. 5984 A2) polarized limestone samples, Štramberk, quarries "Kotouč" and "Skalka".

Štramberk, quarries "Kotouč" and "Skalka". The Zijderveld diagrams and stereographic projection of remanence directions of samples in natural state (NS) and after demagnetization in alternating field were constructed for each sample. M_H denotes the remanent magnetic moment of the sample demagnetized at the alternating field (in mT); M_n denotes the sample moment in natural state. From the figures and all other results of AF demagnetization it is evident that application of AF demagnetization is possible, but not very effective.

Demagnetization by means of the thermal demagnetizer MAVACS was much more effective. Moreover, unblocking temperatures were automatically derived for all samples. This way, data were obtained defining the carriers of magnetization and paleomagnetization in relation to the separated remanence components. Fig. 5 shows results for typical samples from Štramberk, quarry "Kotouč", the 6th level, Fig. 6 from Štramberk, quarry "Skalka", Fig. 7 from Brodno, near Žilina, Fig. 8 from Střážovce and Fig. 9 from Hĺboč near Smolenice. Again, as in the case of AF demagnetization, the Zijderveld diagrams and stereographic projections of remanence directions of samples in natural state (NS) and after thermal demagnetization at respective temperature t (°C) are given. M_t means the remanent magnetic moment of the sample demagnetized at the temperature t (°C), M_n means the sample moment in natural state. Due to phase changes of ferrimagnetic minerals at higher temperatures, temperature dependences of normalized values of $\kappa_t/\kappa_n = f(t)$ were also investigated for each sample. The symbol κ_t stands for the volume magnetic susceptibility of the sample after thermal treatment at temperature t (°C), κ_n stands for susceptibility of the sample in natural state.

The measured remanence data were subjected to the multicomponent analysis (Kirschvink 1980). Similar results, as presented in Figs. 5 to 9, were obtained on the next samples used for a systematic magnetostratigraphic investigation. All samples, almost without exception, exhibit high proportions of secondary magnetization, (viscous magnetization and chemo-remanent magnetization conditioned by weathering). The weathering effect was observed especially in those samples coming from cross-sections in Brodno, Strážovce and partly from Hĺboč near Smolenice as well. In all the samples investigated, the unblocking temperatures vary within the limits of 540-560 °C, particularly within 520° (even 500°) -580 °C. These data indicate that the paleomagnetization carrier is magnetite, evidently fine-grained magnetite which is in accordance with results from other localities in the Tethyan realm and generally with results obtained in samples of marine shallow-water carbonates. Some samples collected from surface outcrops exhibit unblocking temperatures below 680 °C, due to small admixtures of hematite. In a few samples, a share of admixtures of minerals of very low unblocking temperature was also found showing a presence of hydro-oxides of Fe as a result of the weathering effect. But without exception, the magnetite as the principal paleomagnetization carrier was proved in all samples analyzed, out of a total of 524. The studied limestone samples generally show broad spectra of micro-coercive forces, as can be interpreted from graphs showing isothermal remanent magnetization (IRM) in dependence on direct magnetizing field (in mT) and graphs of AF (alternating field in mT) demagnetization of normalized values of saturated remanent magnetization. Typical examples are demonstrated in Fig. 10 for limestone samples from Štramberk, quarry "Kotouč". The limestone samples reach the state of saturation at high intensities of the magnetizing field.

X-ray and magnetomineralogical verification of magnetite content in the limestone samples

The fine grained magnetite contained in the limestone samples from both the localities Brodno and Štramberk required independent verification by means of X-ray analysis. This was carried out in collaboration with the Mineralogical Department of the Institute for Raw Materials in Kutná Hora (F. Novák, J. Jansa). The contents and dimensions of ferrimagnetics in the limestone were so small that they could not be studied in polished sections. Consequently, large limestone sample charges were prepared for dissolution in acids. To avoid undesirable phase changes or even contamination of respective concentrate fractions during the preparation of the final concentrate, a procedure was selected based on magnetomineralogical identification of ferrimagnetics in the original natural limestone samples, in the progressively prepared sludge samples, and finally in the concentrate subjected to X-ray analysis.

For the preparation of the concentrate samples, the original limestone samples were first washed, then dried and crushed down to the grain fractions less than 5 mm. Two ways of dissolving the limestone samples were used: *1* — dissolution in vinegar acid of the 10 % concentration for 2-3 days, *2* — dissolution in HCl acid of the 10 % concentration for 2-3 hours.

The principal carrier of ferrimagnetic properties in the limestone samples from Brodno and Štramberk is fine-grained magnetite. In both cases it is accompanied by hematite and hydro-oxides of Fe. Hydro-oxides of Fe originated most probably from pyrite and also partly from hematite and magnetite.

In the sample from Štramberk, the content of magnetite after treatment in the HCl acid is about 0.3 g/t. In the sample from Brodno, some minor contents of minute crystals of pyrite, partly limonized, were also found. In the sample from Brodno the content of the magnetite after treatment in the vinegar acid was found to be higher (8.9 g/t) than after treatment in HCl (2.2 g/t). The grain sizes of the magnetite in the Brodno sample are smaller (3-10 μm) than in the Štramberk sample (10-20 μm). In both the samples, fine spherolites of magnetite were also found (cf. F. Novák and J. Jansa in Houša et al. 1993a).

The unblocking temperature in the interval between 540 and 560 °C, corresponding to that in the original natural limestone samples from both the localities of Štramberk and Brodno, was also established for all progressively prepared concentrate fractions (from sludge samples) and for the final concentrate, which was X-ray analyzed. In this way, the presence of magnetite was verified during the course of the preparation of the magnetic concentrate from the originally exceptionally weak magnetic limestone samples.

Magnetostratigraphic profile

Originally, the basic magnetostratigraphic profile at Brodno near Žilina across the Tithonian-Berriasian limestone boundary strata was derived on oriented hand samples collected from two tectonically mutually separated rock blocks comprising strata labelled with numbers from 0 to 15, and from 13 to 43, respectively (cf. reports by Houša et al. 1992; 1993a, b). In 1994, another portion of the profile was sampled comprising strata numbered from 6 to 13 and continuing into stratigraphic overlayinig strata without tectonic interruption. In this way, more precise data were derived, which are presented in this paper. The next works were focused on a detailization of previously

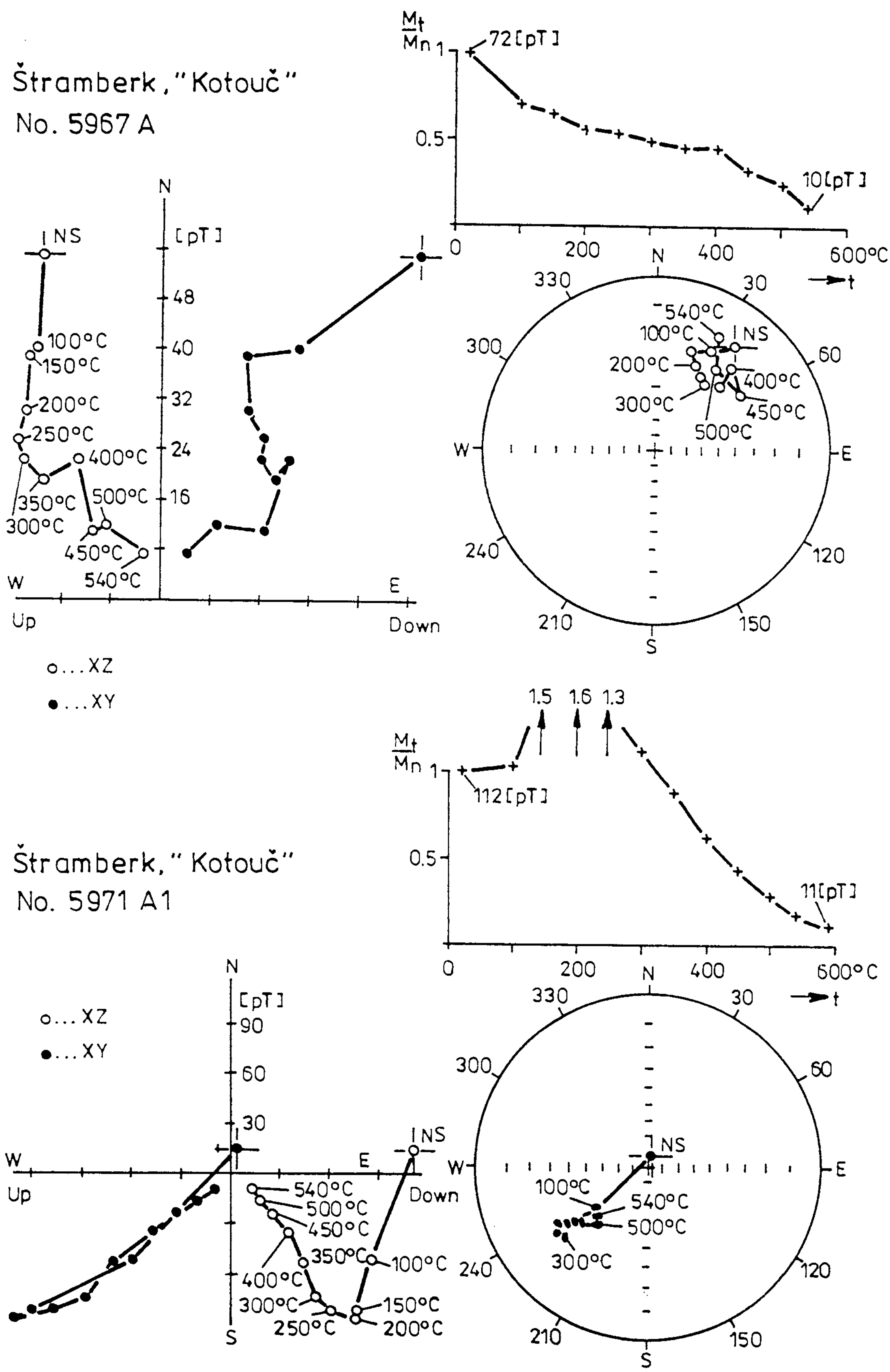

Fig. 5. Thermal demagnetization of reversely (sample No. 5967 A) and normally (sample No. 5971 A1) polarized limestone samples, Štramberk, quarry "Kotouč".

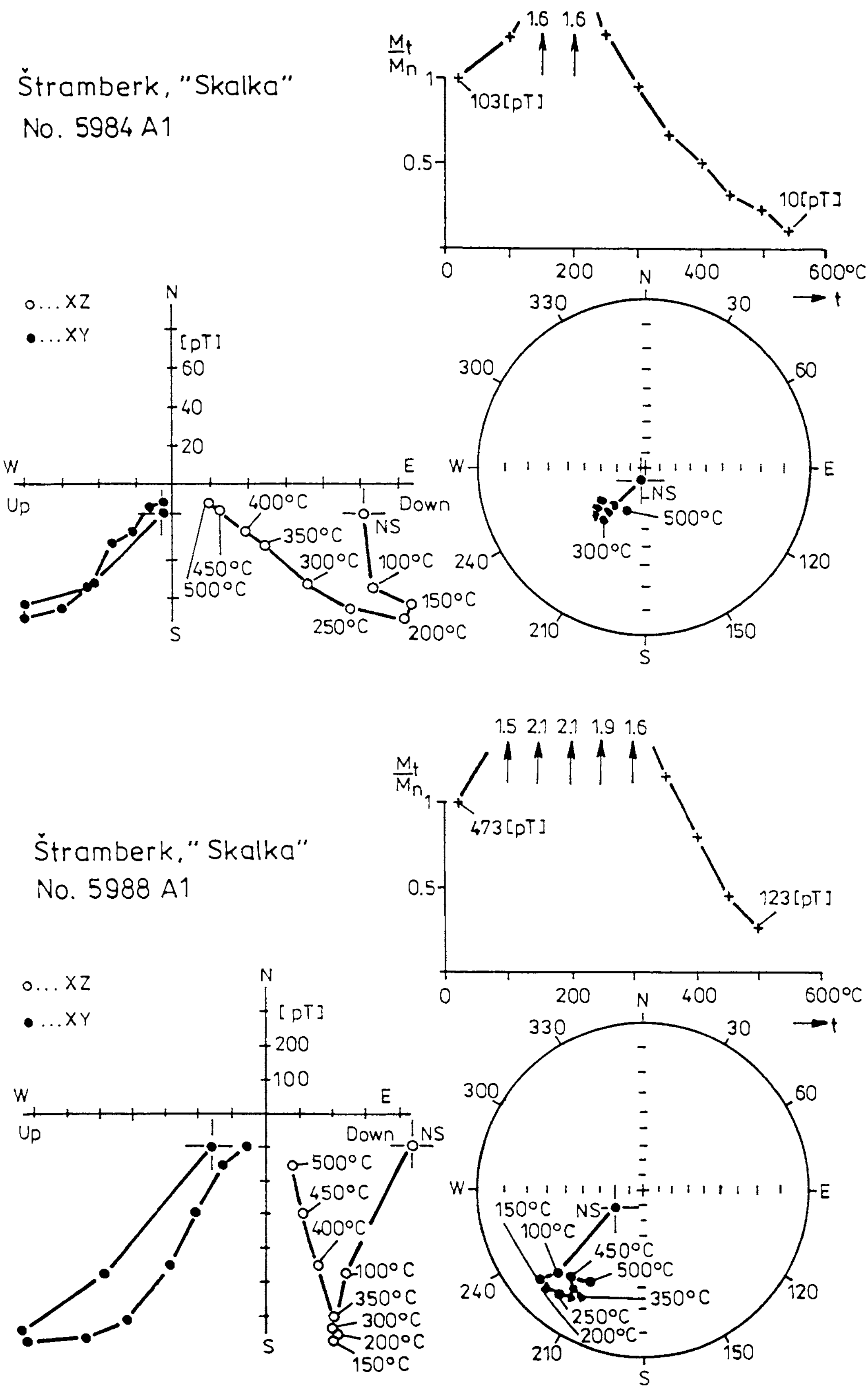

Fig. 6. Thermal demagnetization of normally polarized limestone samples, Štramberk, quarry "Skalka".

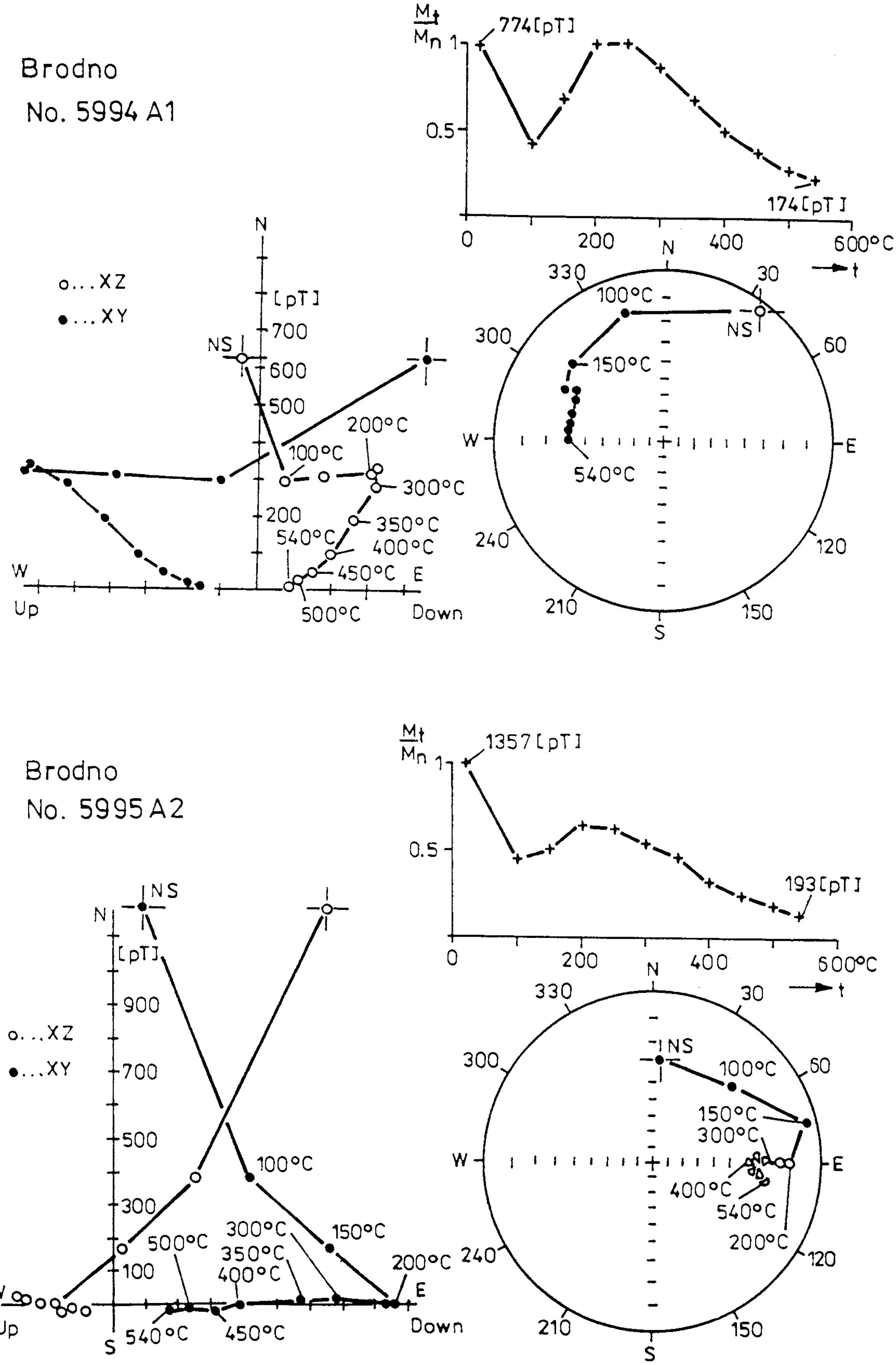

Fig. 7. Thermal demagnetization of normally (sample No. 5994 A1) and reversely (sample No. 5995 A2) polarized limestone samples, Brodno near Žilina.

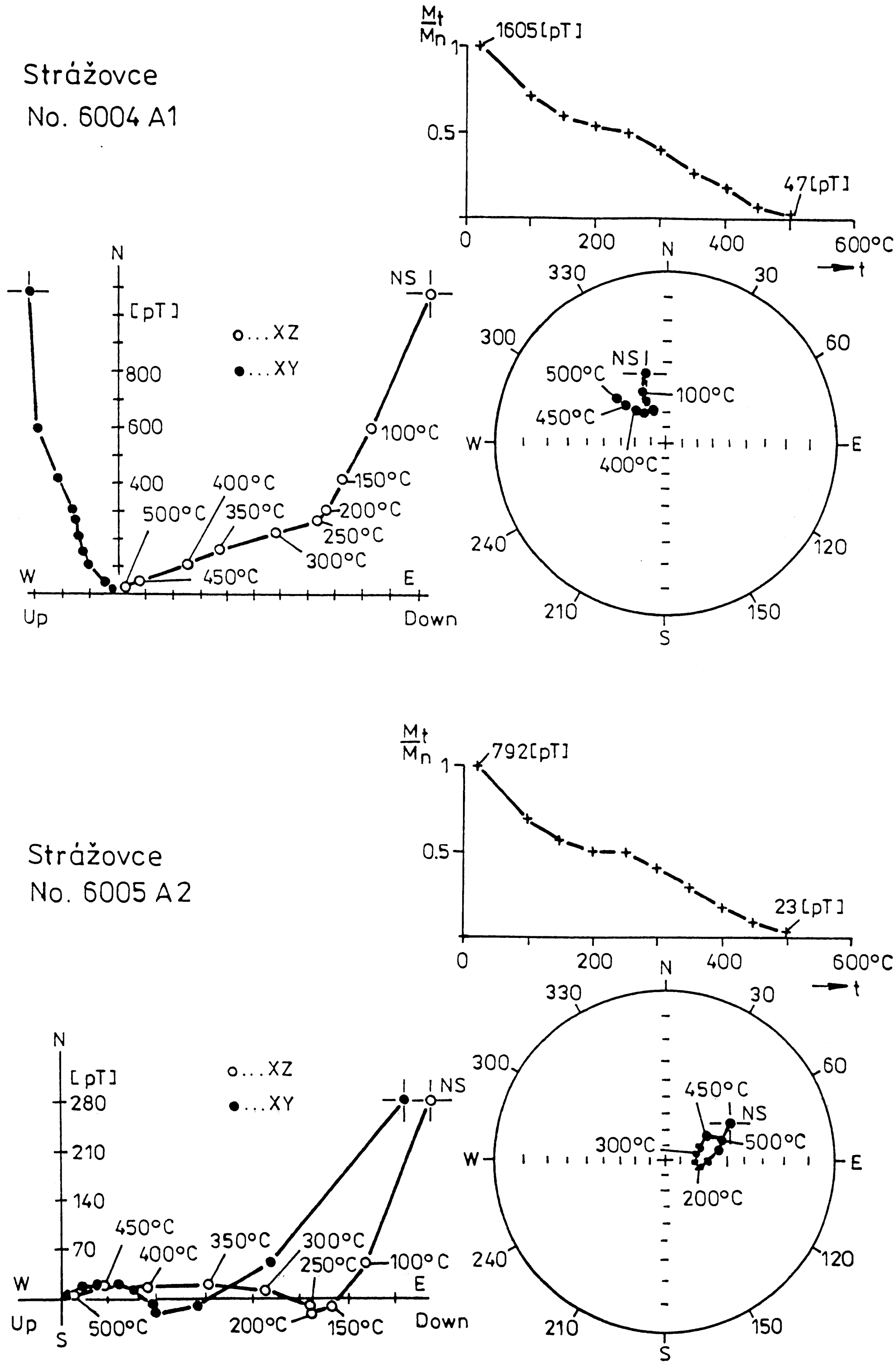

Fig. 8. Thermal demagnetization of normally polarized limestone samples, Strážovce.

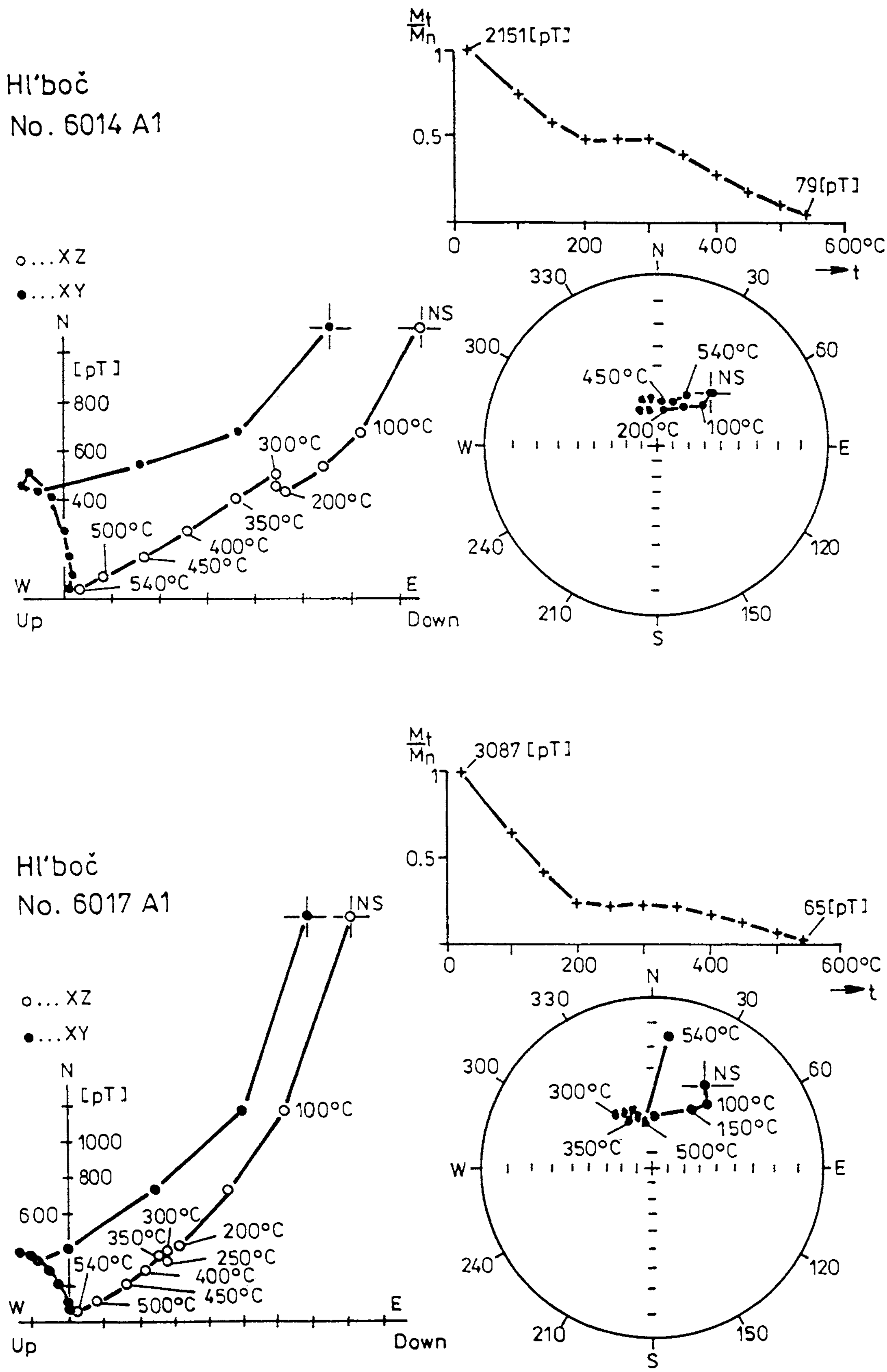

Fig. 9. Thermal demagnetization of normally polarized limestone samples, Hlboč near Smolenice.

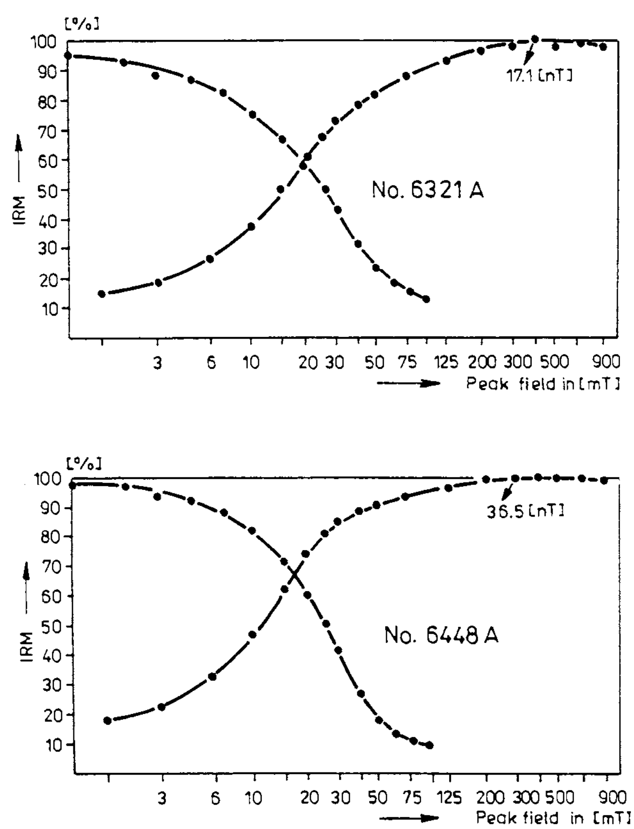

Fig. 10. Data for interpretation of micro-coercivity spectra of natural limestone samples, Štramberk, quarry "Kotouč". The ascending curve shows progressive acquisition of isothermal remanent magnetization (IRM) in a direct field (in mT); the descending curve shows demagnetization of IRM in the alternating field (AF, in mT).

determined polarity magnetozones, e.g. on the reverse magnetozone M 19, and on verification of a very narrow magnetozone (sub-magnetozone) expected to be detected in the younger part of the normal magnetozone M 19. Detection of very narrow magnetozones, so far derived from the marine magnetic anomalies and not verified on continental profiles, required collection of a continuous column of oriented samples. This was especially true for a condensed sedimentation at the Brodno profile. Narrow reverse magnetozone in the normal parts of the zones M 19 and M 20, derived from marine magnetic anomalies see e.g. in (Ogg et al. 1984, 1988, 1991; Butler 1991; Soffel 1991 etc.).

During the initial stage of magnetostratigraphic investigations at Brodno, samples were collected at a bigger step, ca. 3 to 4 samples per 1 m, in order to derive basic patterns of polarity magnetozones. In the following period of investigations, the samples were collected at a higher density, so that even narrow magnetozones were documented by at least 5 to 7 samples. For the continuous sequence of strata numbered from 6 to 43 (the same numbers are also indicated on respective strata in the field), the basic values of J_n, κ_n, D_p and I_p were derived. The fossil components of remanence were separated by means of multi-component analysis (Kirschvink 1980). Fig. 11 shows the measured and interpreted data, the magnetozones with normal polarity are denoted by dark field and with reverse polarity by vacant field. The symbol J_n stands for the modulus of remanent magnetization in units 10^{-4} [A/m], κ_n stands for volume magnetic susceptibility in units of 10^{-6} [SI], and D_p, I_p stand for paleomagnetic declination, inclination [in degrees].

The values of magnetic susceptibility do not correlate in any way with the pattern of normally and reversely polarized magnetozones, which is in agreement with the local to regional origin of susceptibility values and with the global origin of reversals of the main geomagnetic dipole field. To get data for elaboration of high-fidelity magnetostratigraphy, the documentation of collection of oriented geophysical and of paleontological samples should be adequate. Fig. 12 shows an example used in our investigation programme. Moreover, we compiled complete catalogues of primary magnetic and paleomagnetic data for eventual additional studies (Houša et al. 1993 a, b, c; Krs et al. 1993b).

Principal results

Results of the magnetostratigraphic profile across the Tithonian-Berriasian boundary strata at Brodno near Žilina presented in Fig. 11 are self-explanatory to a great extent. The values of J_n (natural remanent magnetization) and of κ_n (volume magnetic susceptibility of samples in natural state) are plotted as well, with the aim of demonstrating the magnetism of individual limestone strata and to indicate petrophysical boundaries of local to semi-regional significance. Magnetozones with normal polarity (N) and reverse polarity (R) clearly indicated by values of D_p, I_p (paleomagnetic declination, inclination) represent a fossil record of global events, of normally and reversely polarized intensity of the main (geocentric, co-axial, dipole) geomagnetic field. The paleomagnetic record was derived from rocks sedimented in a quiet basin, the normal and reverse polarity magnetozones are clearly documented. However, there are some points which should be stressed or discussed:

1 — The pattern of normal and reverse polarity magnetozones correlates well with similar data derived in the regions of Foza (north Italy), Bosso Valley (Umbria, central Italy) and with marine M (Mesozoic) anomalies.

2 — Additional detailed sampling carried out in the normal part of the magnetozone M 19 revealed a very narrow reverse sub-zone, for the first time proved in a continental profile. This sub-zone is correlated with a narrow reverse sub-zone derived from marine magnetic M anomalies.

3 — Another narrow reverse sub-zone is expected to be found in the upper part of the normal magnetozone M 20. The next detailed sampling will be carried out with the aim of verifing its existence on the Brodno profile.

4 — Optimum results of progressive demagnetization were obtained by means of the MAVACS apparatus securing creation of high magnetic vacuum during thermal treatment of samples. Fossil components of remanence were reliably separated at higher temperature intervals of approximately 300–450 °C (up to 540 °C).

5 — Unblocking temperatures derived from thermal demagnetization data of samples of natural rocks (predominantly limestone) and of isothermaly saturated samples, clearly revealed that the magnetite is the principal carrier of paleomagnetization. The magnetite was also confirmed by X-ray analysis in combination with magnetomineralogy in magnetic concentrate samples prepared from bigger charges of weakly magnetic natural limestone samples. Minerals — paleomagnetization carriers — with similar unblocking temperatures were found in other

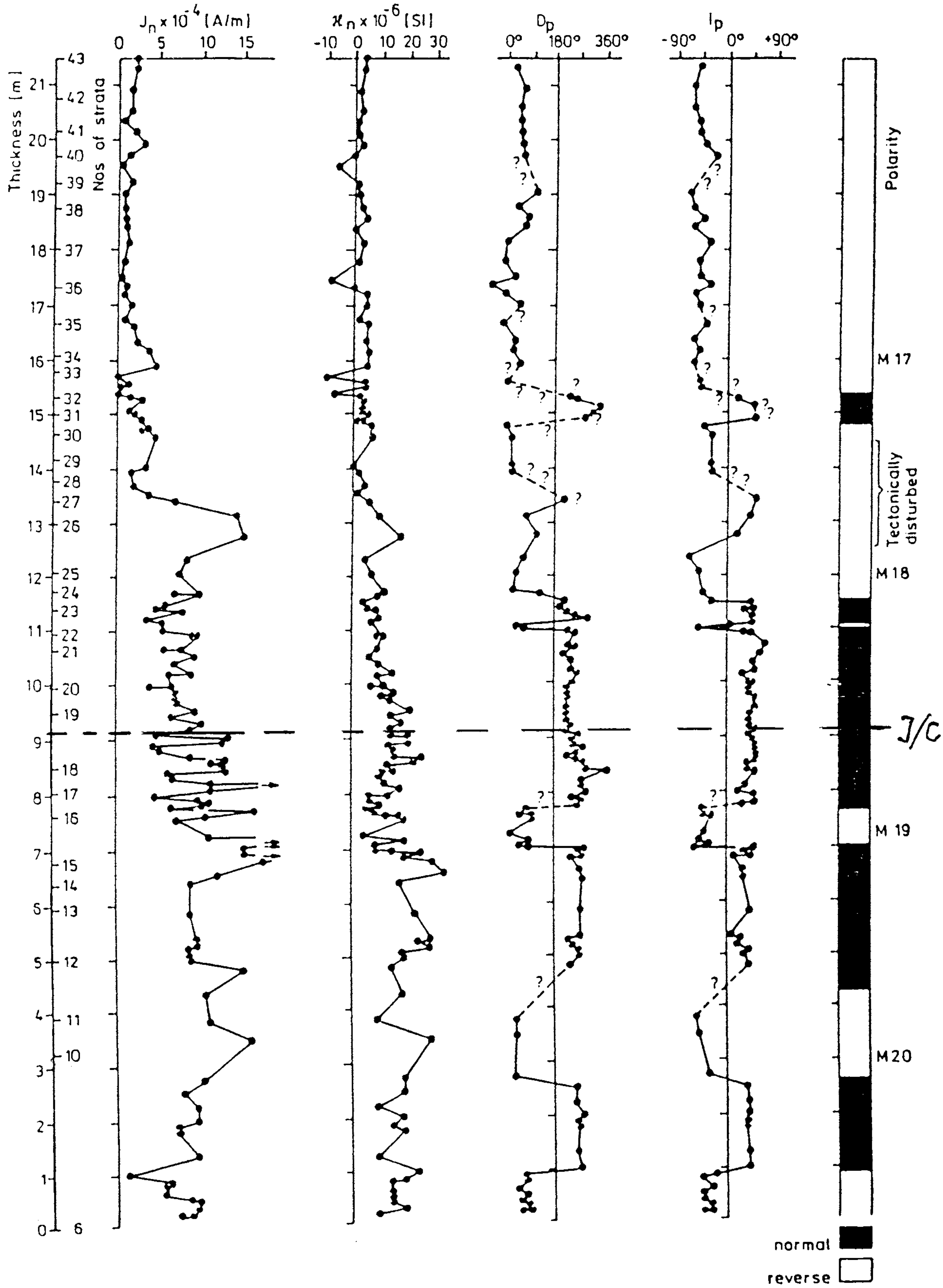

Fig. 11. Magnetic and magnetostratigraphic data along a profile of the Tithonian-Berriasian boundary strata, Brodno near Žilina.

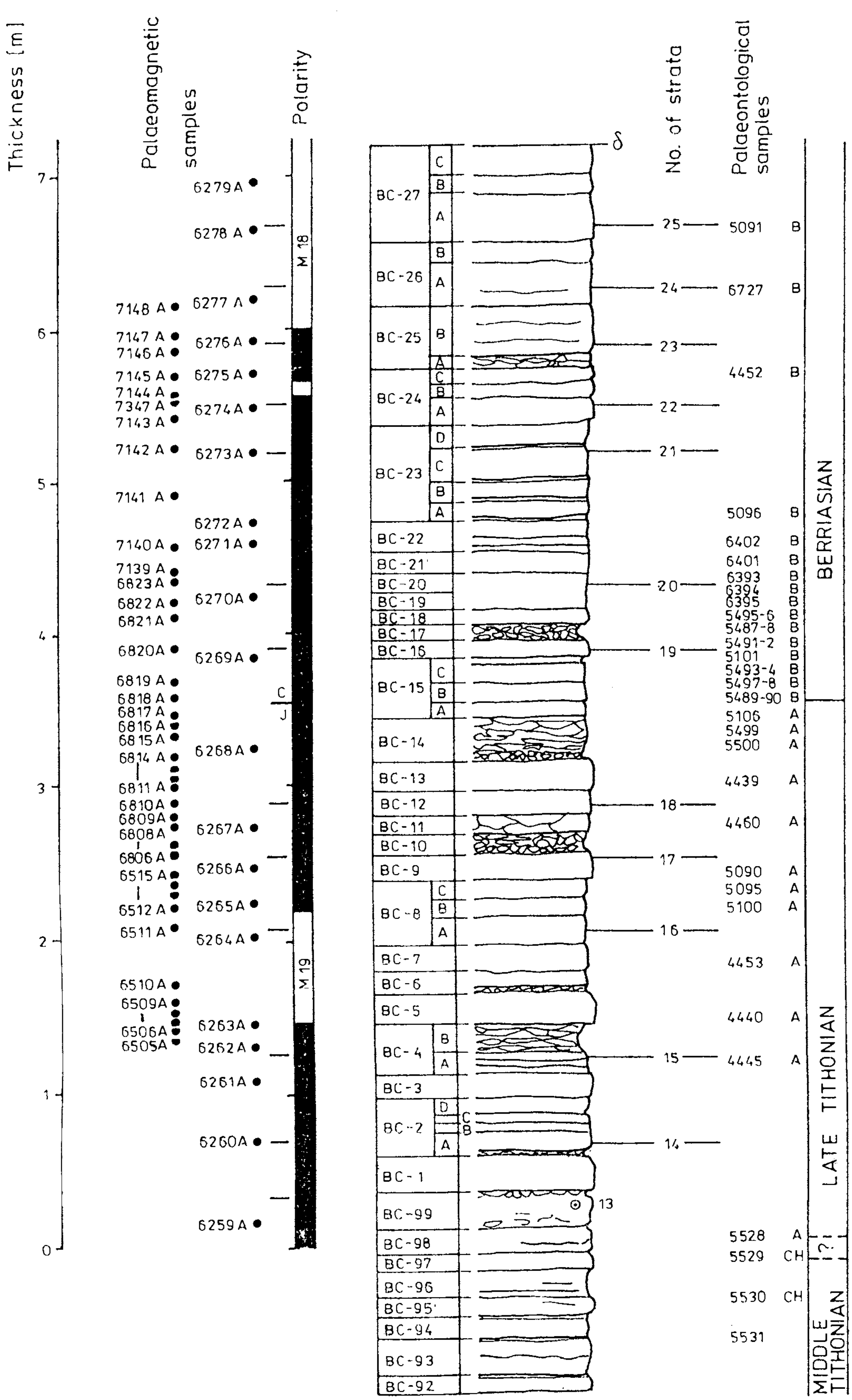

Fig. 12. An example of documentation of magnetostratigraphic and paleontological samples. A section of the Late Tithonian and the Early Berriasian boundary, Brodno near Žilina.

localities of Jurassic and Cretaceous limestones in the Tethyan and Boreal realms. Physical properties of limestone samples indicate that the biogenic magnetite is most probably the principal carrier of paleomagnetization.

6 — The section at the Brodno locality is very suitable for the study of changes in the calpionellid associations at the Jurassic/Cretaceous boundary. The information on the occurrence of brecciated intervals was not confirmed by the present authors nor were any signs of washouts in the Jurassic/Cretaceous boundary interval. This is also supported by homogeneity of paleomagnetic data, no significant deviations of paleomagnetic directions were found for the respective oriented samples. According to our preliminary results, sedimentation in this interval was absolutely continuous. Clayey intercalations between individual limestone beds originated due to either the decrease in the sedimentation rate of calcareous nannoplankton remains, or the increase in clay material influx. The first possibility would probably express climatic cyclicity and the beds would be valuable in stratigraphic correlations. The second possibility would indicate a local influence and the impossibility of correlation between beds at farther distances. These assumptions are planned to be tested in our future research. In any case, no signs of gaps in sedimentation were found in the clayey horizons.

7 — Concerning the correlation of the individual important biostratigraphical boundaries with the individual magnetozones, only the base of the standard intermedia Subzone and the base of the magnetozone M-19r lie at the same level (basal part of bed BC-5 in the studied section) - see Fig. 2. The base of the standard Calpionella Zone, i.e. the Jurassic/Cretaceous boundary, lies in the younger part of the older half of the magnetozone M-19n. The base of the standard Crassicollaria Zone lies approximately in the middle of the magnetozone M-20n in the studied section.

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