GEOLOGICA CARPATHICA, 50, 2, BRATISLAVA, APRIL 1999
125–144

CORRELATION OF MAGNETOSTRATIGRAPHY AND CALPIONELLID BIOSTRATIGRAPHY OF THE JURASSIC/CRETACEOUS BOUNDARY STRATA IN THE WESTERN CARPATHIANS

VÁCLAV HOUŠA, MIROSLAV KRS, OTAKAR MAN, PETR PRUNER and DANIELA VENHODOVÁ

Geological Institute, Academy of Sciences of the Czech Republic, Rozvojová 135, 165 02 Praha 6-Lysolaje, Czech Republic

IUGS UNESCO IGCP
Project No. 362

(Manuscript received February 25, 1998; accepted in revised form September 1, 1998)

Abstract: A short reverse polarity magnetosubzone, herein defined as the Brodno Subzone, was detected in the upper part of the magnetozone M19n at the locality of Brodno near Žilina (Western Carpathians) using high-resolution magnetostratigraphy. An analogous short reverse polarity magnetosubzone, herein defined as the Kysuca Subzone occurs in the middle part of the magnetozone M20n. Both the magnetosubzones are known from marine profiles but have been detected only sporadically and documented insufficiently in continental outcrops. These two subzones have not yet been detected together in one and the same continental section. Their stratigraphic position in the Brodno section is defined and their interpretation in the other studied section at Štramberk is inferred. In the Brodno section, the Kysuca Subzone represents the basal part of the calpionellid Remanei Subzone of the Crassicollaria Standard Zone (early late Tithonian), its base lies at the level of 55 % of the local thickness of the magnetozone M20n. The Brodno Subzone lies within the calpionellid Alpina Subzone of the Calpionella Standard Zone (earliest Berriasian) and its base in the Brodno section lies at the level of 82 % of the local thickness of the magnetozone M19n. In both the studied sections, the Jurassic/Cretaceous boundary based on calpionellids (base of the Calpionella Standard Zone) lies approximately at the end of the lowermost third of the magnetozone M19n (at the level of 34 % of the local thickness of the magnetozone M19n in the Brodno section). Magnetostratigraphic calibration of calpionellid events proved their isochronous character in the localities of Brodno and Štramberk. The interval of ca. ±5000 years, during which a transition occurred from normal (reverse) to reverse (normal) polarity of magnetic field of the co-axial geocentric dipole of the Earth, can be determined from an analysis of paleomagnetic directions inferred from samples with intermediate polarity collected from normally and reversely polarized boundary strata at the locality of Brodno and with respect to the sedimentation rate. This value represents the relative accuracy of possible correlations of the boundaries of the detected magnetosubzones with boundaries of analogous subzones at other localities on the Earth using the above given synchronous global event.

Key words: Jurassic/Cretaceous boundary strata, Tethyan Realm, Brodno and Štramberk sections, high-resolution magnetostratigraphy, two magnetosubzones, calpionellid and magnetostratigraphic correlation.

Introduction

The possibilities of biostratigraphic correlations of chronostratigraphic units of the Jurassic/Cretaceous (J/K) boundary strata between the Tethyan and Boreal realms are very limited due to the practically complete divergence between their fossil associations. This fact hinders the establishment of a J/K boundary acceptable on a global scale, although the biostratigraphic zonation of the J/K boundary strata is elaborated in much detail both in the Tethyan and Boreal realms. Biostratigraphic zones between the Tethyan and Boreal realms unfortunately cannot be correlated directly as they share no common taxa at specific and even generic levels. Consequently, provisional boundaries defined at the boundaries of regional stages are used in both realms, independently of each other. These provisional J/K boundaries in the Tethyan and Boreal realms are not isochronous.

Nevertheless, there are several possibilities to correlate the biostratigraphic scales, and hence also chronostratigraphic units in the two realms using indirect methods. The most precise of these methods is magnetostratigraphy. For the Tethyan Realm, magnetostratigraphic profiles of the J/K boundary strata were worked out for a number of localities, however with imprecise or no correlation with the biostratigraphy of these sections. Only a single magnetostratigraphic profile was published from the Boreal Realm (Ogg et al. 1991), unfortunately containing numerous hiatuses and providing insufficient correlation with the biostratigraphic zonation.

Imprecise and indefinite taxonomic and biostratigraphic interpretations of fossil calpionellid associations recorded in magnetostratigraphically analysed sections in the Tethyan Realm resulted in the placing of the biostratigraphic J/K boundary into different magnetozones by different authors at different localities. The variation was also caused by changes in the general position of the J/K boundary in biostratigraphic scales (see below). Most frequently, the J/K boundary was placed in the M19n (e.g. Channell & Grandesso

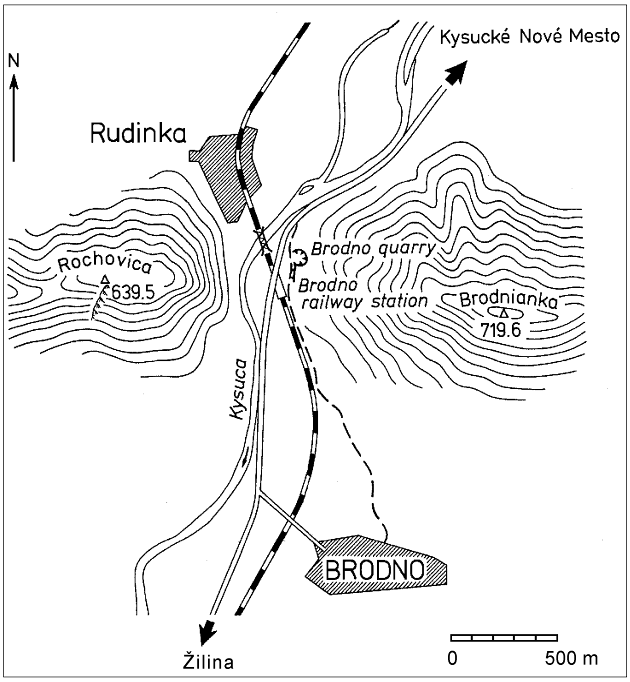


Fig. 1. Location map of the Brodno locality.

1987: Fig. 12), on the base of the M18r (e.g. Lowrie & Ogg 1986, p. 342; Manivit et al. 1986, p. 117; Galbrun et al. 1990: Fig. 8), in the M19r (e.g. Channel & Grandesso 1987: Figs. 4, 17), but also in the M17r (e.g. Cirilli et al. 1984: Fig. 8) or in the M16 (e.g. Márton 1982: Fig. 9) magnetozones.

However, as magnetostratigraphic events represent chronologically very precise correlation horizons, the biostratigraphic events — if expected to have relevant correlation significance — should not occupy different positions relative to magnetostratigraphic events at different localities. J. Kirschvink (in Lowrie & Channell 1984, p. 47) noted that "the marine biological changes were probably not synchronous at the Jurassic-Cretaceous transition". This fact was the main motive of the present authors for an attempt to calibrate the biostratigraphic scales of the J/K boundary strata using magnetostratigraphy, preferably high-resolution magnetostratigraphy, first in the Tethyan Realm and later also in the Boreal Realm. This would allow their precise correlation and test the degree to which isochronous biostratigraphic events are used for chronostratigraphic purposes.

First, it is necessary to define the herein applied biostratigraphic, taxonomic and methodological criteria. The J/K boundary based on ammonites was defined in Lyon–Neuchâtel in 1973 (published in 1975) as the base of the Jacobi-Grandis Zone. This decision was confirmed on all the following meetings of the Working group on J/K boundary (Munich 1982; Moscow 1984; Sümeg 1984 and others) and has recently been universally accepted. However, the precise determination of this boundary by means of ammonites in the whole Tethyan Realm is possible at several localities only. It is due to the presence of stratigraphically significant species of ammonites being strictly limited only to sublittoral facies. Unfortunately, the sublittoral facies are also characterized by frequent hiatuses. Moreover, ammonite faunas do not allow determination of the J/K boundary with the precision required here (down to several centimetres, see below). On sections without ammonites (and in the Tethyan Realm such sections are more than 99 %), the J/K boundary can be determined only if some other group of organisms is used, which, in the majority of cases, are calpionellids. In contradiction to ammonites, calpionellids are common in the J/K boundary strata in the whole Tethyan Realm and their associations occur not only in sublittoral facies but are especially abundant in deeper basinal facies with less frequent hiatuses. The position of the J/K boundary based on calpionellids was agreed upon in Sümeg in 1984 (Remane et al. 1986) as the base of the Calpionella Standard Zone. In sections, the position of this boundary defined on calpionellids can be determined very precisely, usually within several centimetres. Therefore, we use the J/K boundary defined on calpionellids, basic distinguishing characteristics of this boundary along with criteria used for its precise determination were published in detail elsewhere (Houša et al. 1996b, p. 137).

According to Remane et al. (1986, p. 10), the "…boundary at the base of the Jacobi-Grandis Zone is practically identical with the base of the Calpionella Standard Zone". However, Tavera et al. (1994) proved that in the Puerto Escaño section (S Spain), both limits are different and that the ammonite J/K boundary is slightly older than the calpionellid one. In our opinion, the J/K boundary defined by calpionellids is more precise, well determinable and much more universally usable because of the presence of calpionellids in the majority of outcrops, than the boundary defined by a group, which occurs in sufficient composition at only a few localities in the whole Tethyan Realm (ammonites).

With respect to taxonomy, we prefer to use the denomination of the big Tithonian variety of *Calpionella alpina* sensu lato as *Calpionella grandalpina* Nagy 1986 and the prolongated one as *Calpionella elliptalpina* Nagy 1986 (see Houša 1990, p. 362). Below the denomination of *Calpionella alpina* Lorenz 1902 we understand a short, spherical, "middle-size" form only, which is characteristic for the "explosion" of the species on the base of the Calpionella Zone (see Houša 1990, p. 361). This "explosion" must be distinguished from the increase in the abundance of *Calpionella* by the end of the Tithonian (see Houša et al. 1996b, p. 138).

From the methodological point of view, extremely dense sampling was carried out both in paleomagnetic study ("high-resolution magnetostratigraphy") and in biostratigraphic study, particularly in intervals with important boundaries. The positions of magnetostratigraphic boundaries, i.e. horizons of change of the paleomagnetic polarity in rocks, were only provisionally determined through interpolation between two closest samples with different polarity (as is a common practice so far) and localized with maximum possible precision by means of additional sampling of the section (generally 1–2 cm; the boundary was sometimes lying directly in the measured sample showing intermediate polarity of remanence). In sampling, precise mutual positions of biostratigraphic and magnetostratigraphic samples were recorded as well as their exact positions in lithological sections. The sampling points were marked in the sections to allow verification sampling or additional sampling aimed at higher sample density any time in the future. Such precision was applied to magnetostratigraphic study at the locality of Brodno near Žilina (Fig. 1). Magnetostratigraphic study in a similar detail was carried out at the locality of the Bosso Valley, Umbria, central Italy. The present study also refers to magnetostratigraphic profile at the locality of Štramberk, northern Moravia, which was subjected to a synoptic study with no demands for high resolution.

Terminology

In the terminology of magnetostratigraphic polarity units, we follow the International Stratigraphic Guide (Salvador 1994, p. 69–75). For the "classic" magnetostratigraphic units we use common informal numerical designation (e.g. M19; the numbers are given from a certain arbitrary level on the Barremian/Aptian boundary in the order from the youngest unit to the oldest one). Every such numbered "classic" magnetostratigraphic unit has two parts, the older (lower) part with reverse paleomagnetic direction, and the younger (upper) one with normal paleomagnetic direction. For each part we use the term "zone" (we follow the more advanced nomenclature of Quaternary magnetostratigraphic units — see l.c., p. 75, Fig. 12). Magnetostratigraphic polarity zone (magnetozone) is "the basic formal unit in the classification of magnetostratigraphic polarity units" (l.c., p. 71, paragraph C). "Magnetostratigraphic polarity zones may consist of (1) rock bodies with a single polarity of paleomagnetization throughout, (2) an intricate alternation of normal and reverse units (mixed polarity), or (3) an interval of dominantly either normal or reverse polarity, containing minor subdivisions of the opposite polarity. (Thus, a zone of dominantly normal polarity may include lesser-rank units of reverse polarity.)" (l.c., p. 71). Examples of the magnetozones are M19n, or M19r, etc. So, every classic magnetostratigraphic unit has two magnetozones, reverse (older) and normal (younger). If a magnetozone includes a short part with the opposite polarity, we designate it with the term magnetostratigraphic polarity subzone (magnetosubzone, subzone). By "magnetostratigraphic polarity subzone" (magnetosubzone, subzone), we understand a rock body with a single polarity of paleomagnetization throughout and within a magnetozone with dominantly opposite paleomagnetic polarity.

Magnetozone or magnetosubzone are terms of magnetostratigraphic classification. In chronostratigraphic terminology every magnetozone (magnetosubzone, respectively) corresponds to a chronozone (subchronozone), in geochronological terminology it corresponds to a chron (subchron), see also Ogg & Lowrie (1986). Chrons and subchrons are time units and their reflection in rocks are zones. Speaking about rock units delimited by their paleomagnetic polarity, we consider it correct to use the terms magnetozone and magnetosubzone, instead of incorrect magnetochron (or magnetosubchron), which must be conserved for designation of the time unit with certain paleomagnetic polarity only.

In the terminology of magnetostratigraphic polarity units during the last 3.5 million years of the Earth's history, every magnetozone and every magnetosubzone is named (see l.c., Fig. 12) in accordance with the general rules for naming stratigraphic units (l.c., section 3.B.3). In Mesozoic magnetozones, we prefer to respect their numerical designation combined with the letter "n" or "r" according to their polarity (e.g. M20n). ("This system is firmly entrenched in the literature and is being usefully employed." — l.c., p.73). However, for naming magnetosubzones (subzones) we prefer to avoid numbers and letters and we use the general rules valid for the naming of stratigraphic units (see l.c., section 7.H, last paragraph) because the numerical designation of magnetosubzones is more complicated and inappropriate for practical use. Short reverse magnetosubzone in M19n was designated by Ogg et al. (1991) M19n-1. The use of this designation e.g. in linguistic expressions is unnecessarily complicated or difficult and it does not solve the denomination of parts of a magnetozone divided by a magnetosubzone. Therefore we propose naming magnetozones with simple geographically derived names as more practical. For this reason, we use the individual geographically derived names with a clearly designated standard (name-bearing standard) for recognition of the unit named.

Standards in magnetostratigraphy fulfil a different role in comparison to standards in chronostratigraphy. Every chronostratigraphic unit is an artificial one, it does not exist in reality, it must be defined (by means of a standard, which is its type section) and delimited (by its boundary stratotypes). This is not the case with magnetostratigraphic polarity units. The pattern of polarity reversals preserved in sea-floor-spreading anomalies or in the sequential record of reversals in rocks everywhere on the continent, reflect the real history of the Earth´s magnetic field. Its units really exist independently of an observer who studies them. If an observer names one such unit, he must only determine exactly which unit he named, nothing more. He can do it simply on an outcrop, where the named unit is preserved, by a permanent artificial marker. Such a stratotype is the standard of the name applied, not the standard of the magnetostratigraphic unit, because the unit needs no stratotype for its exact determination and delimitation.

Magnetostratigraphic studies in the Tethyan Realm

Most of the magnetostratigraphic studies of J/K boundary strata were carried out with the aim of setting out a synoptic scheme of normally and reversely polarized magnetozones or possibly magnetosubzones not aspiring to their detailed delimitation. Synoptic sampling was naturally insufficient for determination of the so-called polarity transition zones where rocks are classified as having intermediate polarity. The J/K boundary was placed at different levels in different magnetostratigraphic studies, ranging between the magnetozones M19 and M17. A synoptic magnetostratigraphic profile of Upper Mesozoic rocks was published from northern Tunisia (Nairn et al. 1981); however, whereas late Jurassic limestones were mostly suitable for paleomagnetic study, Cretaceous rocks generally displayed secondary components of remanence. Magnetostratigraphic studies of the early Cretaceous Maiolica

Fm. pelagic limestones from the Bosso Valley, Umbria, central Italy, resulted in the detection of the magnetozones M20 to M14, and probably to M13 (Lowrie & Channell 1984). In the last mentioned study, the J/K boundary was placed within the lowermost part of the magnetozone M17. Pelagic white limestones rich in ammonites from southern Spain were magnetostratigraphically studied in two sections: in Carcabuey and Sierra Gorda. The detected magnetozones ranging from M15 to M19 were well correlable with magnetic marine M-anomalies and, in a narrower range, also with magnetozones at the locality of Foza, northern Italy. The presence of a reverse subzone was also detected in the normal part of the magnetozone M20 (Ogg et al. 1984). The Umbrian Maiolica Formation was studied by combined biostratigraphic and paleomagnetic methods using samples of white pelagic limestones collected from the locality of Fonte del Giordano (Cirilli et al. 1984). The detected magnetozones were correlated with the magnetic marine M-anomalies M19 to M14 for a lower calpionellid section and — above a hiatus — also for an upper radiolarian section. The critical section around the magnetozone M19 could not be studied due to the occurrence of hiatuses. Determination of the J/K boundary based on the correlation of magnetozones and calpionellid zones was discussed by Márton (1986) who proposed placing this boundary within the magnetozone M17. Lowrie & Channel (1984) placed this boundary close to the base of M17, while the authors of earlier papers placed it above the magnetozone M19. Further magnetostratigraphic studies of pelagic limestones of the Berriasian stratotype in Ardéche, France (Galbrun 1985), and of Berriasian/Valanginian boundary strata in Cehegín, southern Spain, province Murcia (Ogg et al. 1988), also indicate applicability of this method to global correlation. Pelagic limestones in all the above mentioned studies proved to have recorded the paleomagnetic field. However, in other localities of pelagic limestones, paleomagnetic directions could not be determined; samples of Mesozoic limestones displayed syn-tectonic and post-tectonic components of remanence (Villalaín et al. 1996; Parés & Roca 1996; Hoedemaeker et al. 1998). The importance and interpretation aspects of magnetostratigraphy of the J/K boundary interval in the Tethyan and Boreal realms were discussed in the paper of Ogg et al. (1991).

Pilot samples of the Tithonian-Berriasian limestones were magneto-mineralogically and paleomagnetically studied originally at five localities in the Western Carpathians, out of which two lie in northern Moravia and three in western Slovakia. In the first stage, a synoptic magnetostratigraphic study was done at the localities of Štramberk, N. Moravia, and Brodno near Žilina, W. Slovakia (Houša et al. 1996a). A detailed sampling at Brodno followed by paleomagnetic and micropaleontological study resulted in high-resolution magnetostratigraphy (Houša et al. 1996b, 1997). Interpretation of data including the results from samples collected in 1997 are presented in the submitted paper.

Short reverse polarity magnetosubzones

Dense sampling for paleomagnetic studies allowed detection and precise delimitation of two short reverse magnetosubzones in the sections studied. One of them lies in the upper part of the magnetozone M19n, the other one lies immediately above the middle (i.e. in the upper) part of the magnetozone M20n. Both these reverse magnetosubzones were previously known from marine profiles (see Ogg et al. 1991) and one of these magnetosubzones was found in fossil sections in two cases (see Ogg et al. 1984; Lowrie & Channell 1984). However, both of these magnetosubzones have never been found in a single section yet, except in the Brodno section, described in this paper.

Ogg et al. (1991) designate these magnetosubzones with symbols derived from the symbols of the magnetozones in which they are located, such as M19n-1 and M20n-1. This nomenclature is, however, considered impractical by the present authors. Instead, one-word nomenclature is herein proposed for these magnetosubzones, following the guidelines set out by the International Stratigraphic Guide for the nomenclature of stratigraphic units. The reverse magnetosubzone in the upper part of the magnetozone M19n is designated as "Brodno"; the name is derived from the name of a village, in the vicinity of which the thoroughly studied section containing the name-bearing type of this subzone is located (Fig. 2). The reverse magnetosubzone in the middle part of the magnetozone M20n is designated as "Kysuca"; the name is derived from the name of a river in the valley of which the Brodno locality containing the name-bearing type of this magnetosubzone is situated (Fig. 3). A detailed delimitation including the required formal specifications related to the establishment of these names are given in the text below.

The geographical names of "Kysuca" and "Brodno" have already been used by other authors in the past for the designation of lithostratigraphic units: Brodno Member (Scheibner 1967, Aptian–Albian) and Kysuca Member (Scheibner & Scheibnerová 1958, Cenomanian–Turonian). None of these units occur at the stratotype of the described magnetosubzones (Brodno Quarry). With respect to the fact that no other suitable geographical names usable in the international scale are available (i.e. simple names easily pronounced in world languages), both of the above mentioned names are herein used for the designation of a different kind of formal stratigraphic units than those they have been used as there is no risk of any misunderstanding.

The presence of a magnetosubzone in a magnetozone, divides this magnetozone into three parts, i.e. into the magnetosubzone proper and parts of the magnetozone before (below) and after (above) the magnetosubzone. For example, the Kysuca reverse magnetosubzone divides the normal magnetozone M20n into (1) the older (lower) part of the normal zone, (2) the Kysuca reverse magnetosubzone and (3) the younger (upper) part of the normal zone. We prefer to derive the informal designation of both parts of the normal magnetozone from the designation of the reverse magnetosubzone, by prefix "pre-" (for the older part of the normal magnetozone) and "post-" (for the younger part of the normal magnetozone). So, the magnetozone M20n is divided into three parts: the pre-Kysuca part (the older normal part), the Kysuca reverse magnetosubzone and the younger normal post-Kysuca part. Analogically, the M19n magnetozone is divided by presence of the Brodno magnetosubzone into the normal pre-Brodno part, the Brodno reverse magnetosubzone

Fig. 2. The Brodno Subzone, the width of which is marked by two aluminium cylinders (of 1 inch diameter) cemented into the drill holes. The two aluminium cylinders bear the name Brodno.

Fig. 3. The Kysuca Subzone, the width of which is marked by two aluminium cylinders (of 1 inch diameter) cemented into the drill holes. The two aluminium cylinders bear the name Kysuca.

and the normal post-Brodno part. This nomenclature can be effective until both parts of the normal magnetozones receive their individual designations.

Brodno near Žilina, W. Slovakia

Basic information

The locality of Brodno near Žilina (Western Carpathians, NW Slovakia, Fig. 1; — see Michalík et al. 1990; Houša et al. 1996a,b) was selected for a detailed magnetostratigraphic study of the Tithonian-Berriasian limestone strata among five previously considered localities (Houša et al. 1996a; Fig. 1) for its (1) favourable geological setting (relatively continuous sedimentation in a quiet basinal environment, favourable lithology), (2) favourable physical properties of the rocks enabling us to infer primary paleomagnetic directions with a high degree of reliability, using multi-component remanence analysis combined with fold tests, and (3) rich calpionellid associations. With respect to the relatively low sedimentation rate of the limestones, the original collecting of orientated samples was realized with short sampling intervals and the inferred data were related to limestone strata numbered by Michalík et al. (1990). The inferred magnetozones M21r to M17r could be correlated with analogous sections in the Tethyan Realm (Foza, Bosso, Štramberk) and with marine M (Mesozoic) anomalies. A narrow subzone with reverse polarity was first detected in the upper part of the magnetozone M19n. This state of knowledge has been published by Houša et al. (1996a). Later, the Brodno section was labelled with new, more detailed numbering in order to detect another expected reverse subzone within the magnetozone M20n and to meet the needs of high-resolution magnetostratigraphy, particularly to specify more exactly the positions of the determined magnetostratigraphic and biostratigraphic boundaries (Houša et al. 1996b). The older, synoptic numbering was also preserved.

In 1996 and 1997, very dense (locally even continuous) collecting of orientated paleomagnetic samples was performed in several consecutive phases at this locality. Therefore, the profile can be characterized as a high-resolution one. Relatively extensive laboratory paleomagnetic, petromagnetic and micropaleontological analyses were realized due to the financial support of the Grant Agency of the Academy of Sciences of the CR in Prague and of the Dionýz Štúr Geological Institute in Bratislava. Detailed sampling of the section (averaging 20 to 35 orientated samples per 1 m of true thickness) allowed a more precise identification of boundaries of the individual magnetozones and of both reverse subzones within the magnetozones M19 and M20 (Houša et al. 1997). In 1997, collection of additional samples was aimed primarily at identification of the boundaries of both reverse polarity subzones. In consequence, these subzones are defined with a high precision today. A new procedure in magnetozone and subzone interpretation was also proposed during the detailed processing of magnetostratigraphic data from the Brodno locality: it is based on analysis of the angle deviation of the separated fossil component of remanence from the most probable paleomagnetic direction considered for the whole studied section. A procedure providing estimated mean values as well as standard deviations of the smoothed interpolated course of the given quantities was also applied.

Magnetostratigraphy

Altogether 360 orientated hand samples were collected for the construction of a high-resolution profile with the maximum sampling density between the base of the magnetozone M21r and the base of the magnetozone M18r. In geological cross-section, this interval represents only 10 metres of the true thickness of strata.

The volume magnetic susceptibility k and the remanent magnetization J of samples were measured by means of the KLY-2 A.C. bridge and the JR-5 spinner magnetometer (Jelínek 1973, 1966), respectively. A part of the set of samples was subjected to demagnetization by alternating field using the Schonstedt GSD-1 apparatus. Demagnetization in thermal fields generally proved to be more effective; consequently, each sample of the whole set was subjected to progressive thermal demagnetization up to 590 °C in eleven to thirteen thermal fields on average using the MAVACS apparatus (Příhoda et al. 1989). The measured values of remanent magnetization of thermally demagnetized samples were subjected to multi-component analysis of remanence following the method of Kirschvink (1980), paleomagnetic directions were subjected to fold tests and, after correction for dip of strata, used for construction of the magnetostratigraphic profile. In addition, diagrams of normalized values of M_t/M_n vs. demagnetizing temperature t [°C] were constructed for all samples, M_t being the modulus of the moment of remanent magnetization of the thermally treated sample after cooling, M_n being the modulus of the moment of remanent magnetization of the sample in its natural state. These diagrams were used for estimation of the values of unblocking temperatures in all samples from the given set. A more precise determination of unblocking temperatures was derived on pilot samples following the methods described in Houša et al. (1996a, p. 186–188). All the samples, with no exception, displayed large components of secondary magnetization, corresponding to the viscous component and to chemo-remanent magnetization conditioned by weathering. The stable component of remanence was separated with an unblocking temperature of 520 to 580 °C linked with the content of magnetite as a carrier of the primary paleomagnetic directions. These results are in accordance with the results of combined magneto-mineralogical and X-ray diffraction analyses of the pilot samples. Diagrams showing the correlation of normalized values of volume magnetic susceptibility k_t/k_n vs. temperature were constructed for all the studied samples to assess the influence of possible phase changes of magnetically active minerals during thermal treatment of the samples (Krs & Pruner 1997).

The studied limestones are ranked among medium to weakly magnetic rocks. The scatter of J_n and k_n values is relatively wide, with a marked decrease in magnetization from older to younger rocks. Statistics for the quantities J_n and k_n for both medium magnetic late Tithonian and weakly magnetic early Berriasian limestones are given in Table 1. The table also implies that the paleomagnetic polarity of the samples is not reflected in the changes of basic magnetic parameters.

The magnetostratigraphic profile shows the values of moduli of natural remanent magnetization J_n in [10^{-6}A/m] units, the values of volume magnetic susceptibility of samples in natural state k_n in [10^{-6} SI] units, paleomagnetic declination D_p and inclination I_p in degrees and the so-called discrimination function first introduced into the interpretation of magnetostratigraphic data (Figs. 5 and 9).

A newly proposed procedure for evaluating magnetostratigraphic data

An innovation to the hitherto used method of data processing and graphic presentation of results (cf. Houša et al. 1996a, 1997) was applied to the herein submitted processing of magnetostratigraphic data from the locality of Brodno near Žilina. This innovation (by O.M.) employed some of the procedures described in the monograph of Fisher et al. (1987).

The essential purpose of magnetostratigraphy is to continuously, if possible, subdivide the studied stratigraphic section into intervals corresponding to normal (**N**) and reverse (**R**) polarity of the paleomagnetic field. Accordingly, data processing comprises two steps: the first step is the construction of a discrimination function, the direction of remanent magnetization being its independent variable. On the basis of the discrimination function, the detected direction can be classified, i.e. placed into one of two classes — **N** or **R**. The second step includes the interpolation and smoothing of the detected directions, and the constructed discrimination function as well, along the magnetostratigraphic profile. The applied procedure provides continuous estimates of both the mean value and standard deviation of a studied quantity thereby providing the required subdivision of the section or, where appropriate, the designation of intervals where the quality of input data does not allow a reliable classification. Both these steps will be discussed separately in the two paragraphs below.

Table l: Brodno near Žilina, basic magnetic parameters of limestone samples.

Age	Number of samples	Normal (N) Reverse (R) magnetozone	Modulus of natural remanent magnetization J_n [10^{-6} A/m]		Volume magnetic susceptibility k_n [10^{-6} SI]	
			Mean value	Standard deviation	Mean value	Standard deviation
Early	50	N	678	343	9.8	4.2
Berriasian	71	R	452	386	5.5	8.9
Late	159	N	1068	474	19.5	8.7
Tithonian	88	R	1274	791	22.0	10.0

Construction of the discrimination function

The directions

$$\mathbf{s}_i\,,\quad i = 1, ..., n \tag{1}$$

of remanent magnetization of all the samples from the magnetostratigraphic profile are plotted using the Lambert equal-area projection in Fig. 4. This sample of directions corresponds to a hitherto unknown distribution, which should be (in an ideal case only the paleomagnetic component of remanent magnetization, which originated at the time of sedimentation is involved):

1) bimodal, with modes corresponding to opposite directions, a normal mode and a reverse mode, herein referred to as s_{normal}, and $s_{reverse}$,

2) isotropic with respect to the axis intersecting both modes.

The above idea may be confronted with the qualitative features of the data set (1), enhanced by non-parametric estimate of the true probability density $f(\mathbf{s})$ giving rise to the data. The estimate, being a modification of Parzen estimate (Parzen 1962), has the form (Fisher et al. 1987):

$$\hat{f}(\mathbf{s}) = \sum_{i=1}^{n} W(\mathbf{s}_i, \mathbf{s})\,, \tag{2}$$

where

$$W(\mathbf{s}_i\,, \mathbf{s}) = C_n / (4\pi n \sinh(C_n) \exp(C_n \cos(\mathbf{s}_i\,, \mathbf{s})) \tag{3}$$

and C_n is a parameter, whose value $C_n = 28.5$ was found using the maximum probability method. The estimated density, being displayed in Fig. 4, is not in evident contradiction to the presumed properties of the distribution. The estimate implies the values of $\mathbf{s}_{normal}$ (inclination 37°, declination 263°) and $\mathbf{s}_{reverse}$ (inclination –41°, declination 65°), which are in a rather good agreement with each other.

Although the decision on the assignment of a direction to the class **N** or **R** may be based immediately on the quantities of *declination* and *inclination*, such an approach is not the best one. In order to avoid ambiguity, the classification should be based on a single scalar quantity — *discrimination function* $d(\mathbf{s}_i)$. Providing that the distribution has the above given properties, an optimum choice for this function is the angle between directions $\mathbf{s}_i$ and $\mathbf{s}_{normal}$. Then, inequality $d(\mathbf{s}_i) < \pi/2$ or $d(\mathbf{s}_i) > \pi/2$ implies the classification of direction $\mathbf{s}_i$ to class **N** or **R**, respectively.

After the classification, polarity in the class **R** may be reversed and the two classes may be grouped together again to estimate the mean direction of magnetization regardless of its polarity. In this way, mean direction $\mathbf{s}_{mean}$ (inclination 38.7°, declination 250.9°) was found. Providing that the distribution has the above given properties, this direction can be regarded as a better approximation of $\mathbf{s}_{normal}$ than that previously derived from the estimate of probability density.

The graphic presentation of results includes the diagrams of declination and inclination of the paleomagnetic directions for the individual samples. The values $\mathbf{s}_{normal}$, and $\mathbf{s}_{reverse}$ may be seen in the diagrams, too. The values of the discrimination function computed for individual samples are also plotted.

Interpolation and smoothing

The samples are obviously not distributed continuously along the section. Besides, the paleomagnetic directions of remanent magnetization show a relatively high dispersion even in the same stratum. This is understandable as the studied component of remanent magnetization is usually very low if compared with natural remanent magnetization, the values of which are typically of the order of 1 mA/m. These two reasons suggest a need for interpolation and smoothing of the detected direction or the discrimination function derived from it. Several approaches to the solution of this problem were tested, mostly mentioned in the monograph of Fisher et al. (1987), such as the use of smoothing splines (Reinsch 1967). Among these, a relatively simple technique of moving average seems to be the most advantageous. The algorithm is described below.

Each sample is characterized by the coordinate t_i, corresponding to its position normal to stratification or to the time of sedimentation, and by the direction described by a unit vector $\mathbf{s}_i$.

i) A weight function $w(t)$, e.g.,

$$w(t) = \begin{cases} 1 \text{ for } |t| \leq ½\,, \\ 0 \text{ for } |t| > ½ \end{cases} \tag{4}$$

or

$$w(t) = \exp(-½\, t^2) \text{ for arbitrary real } t, \tag{5}$$

an integer value constant c, e.g. $c = 6$, and a real parameter *step* are chosen.

ii) The following operations are performed for a chosen coordinate $t = t_0$: the weights

$w_i = w((t_i - t_0)/h),\ i = 1,.., n,$

where the parameter h is chosen so as to meet the condition

$$\sum_{i=1}^{n} w_i = c\,, \tag{6}$$

are assigned to individual samples. Then the weighted mean direction $\mathbf{s}_0$ is calculated using the formulas

$$\mathbf{r} = \sum_{i=1}^{n} w_i\, \mathbf{s}_i\,,\quad r = |\,\mathbf{r}\,|,\quad \mathbf{s}_0 = \mathbf{r}/r\,, \tag{7}$$

and so is the angular standard deviation of direction

$$\delta_0 = \text{arrccos}\,(r / c)\,. \tag{8}$$

The quantities $\mathbf{s}_0$ and δ_0 are assigned to the coordinate t_0.

iii) The coordinate t_0 is substituted by t_0 + *step* and the process is repeated from step ii).

The essence of the algorithm can be described very simply. A window whose shape, position, and width are given by the function $w(t)$, the coordinate t_0, and the parameter h, respec-

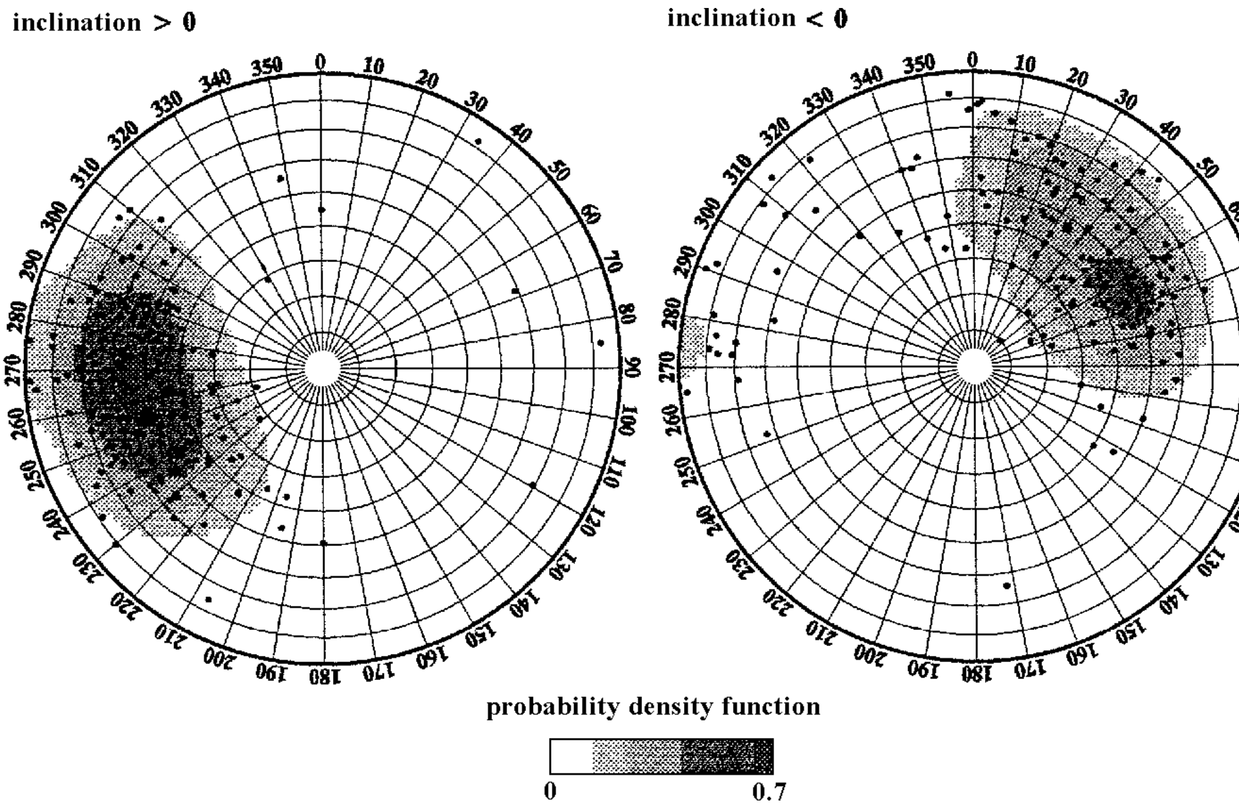


Fig. 4. Brodno locality. Paleomagnetic directions and hence derived probability density function, Lambert equal-area projection.

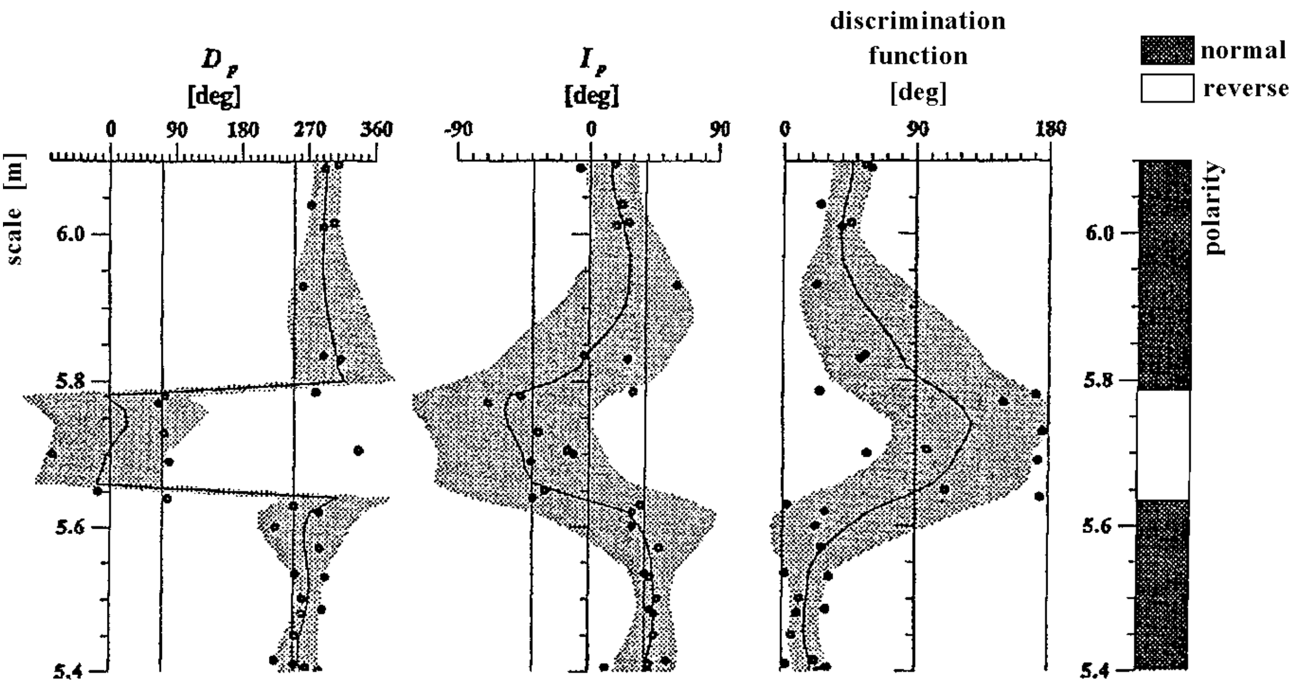


Fig. 5. Brodno locality. Kysuca Reverse Polarity Subzone. D_p — paleomagnetic declination; I_p — paleomagnetic inclination; discrimination function expressing total angular deviation of paleomagnetic direction; normal, reverse — normal (N), reverse (R) polarity of paleomagnetic direction for respective parts of the magnetozone or magnetosubzone.

tively, is moving along the magnetostratigraphic profile assigning a weight w_i to the individual samples. While its shape is kept firm, its width varies according to the local density of samples, so that the sum of all weights is constant. The weighted mean direction and its angular standard deviation are found for each window position. The discriminating function introduced in the preceding paragraph may be treated in a similar way.

In the graphic presentation, the diagram of a studied quantity, e.g. declination, inclination, or discriminating function, shows both the estimate of its mean value (depicted by full line) and the zone

mean value ± standard deviation

(see Figs. 5 and 9). For declination, the standard deviation is defined by expression $\delta/\cos(inclination)$.

Definition of the Kysuca and Brodno magnetosubzones

The Kysuca reverse magnetosubzone is situated above the middle of the normal magnetozone M20n. The reverse paleomagnetic direction of this magnetosubzone at locality Brodno is represented by limestone bed No. 99, only 15 cm in total true thickness, i.e. 6 % of the total thickness of the normal zone M20n (2.37 m, covering the pre- and post-Kysuca normal parts as well as the Kysuca reverse magnetosubzone), see Figs. 5 and 6. The base of the Kysuca reverse magnetosubzone in Brodno lies at a level of 55 % of the local thickness of the magnetozone M20n. Samples collected from the Kysuca magnetosubzone were subjected to progressive thermal demagnetization in the fields of 100°, 150°, 200°, 250°, 300°, 350°, 400°, 450°, 500°, (520°), (540°) up to 590 °C. Figures 7 and 8 show Zijderveld diagrams of samples from the Kysuca magnetosubzone indicating moduli of natural remanent magnetization (NRM) and of remanent magnetization after the final step of thermal demagnetization (RM). Graphs showing dependence of k_t/k_n vs. temperature of demagnetization field are drawn below the Zijderveld diagrams. Symbols N or R indicated with each of the Zijderveld diagrams denote normal (N) or reverse (R) polarity of the primary paleomagnetic component of remanence. This component was inferred using multi-component analysis (Kirschvink 1980) and subjected to combination with fold test. The proportion of the intensity of secondary components is high in all samples, reaching from 80 to 90 % of J_n. Unblocking temperature of minerals — carriers of primary components of remanence — vary between 560° and 590 °C thus indicating the presence of magnetite. The results of the multi-component analysis have proved that J_n consists of three components: The A-component of remanence was inferred in the temperature interval of 20−100 °C, undoubtedly being of viscous origin; the B-component of secondary origin was inferred in the temperature interval of ca. 100−350 °C, whereas the C-component corresponding to the primary (paleomagnetic) component of remanence was determined in the temperature interval of ca. 300 °C (350 °C) to 500 °C (590 °C), cf. Houša et al. (1996a). The results of thermal demagnetization are presented in this paper as examples only for some samples on the basis of which the Kysuca reverse subzone was interpreted. In sample No. 7550, the C-component displays both normal polarity (in the temperature interval of 350−500 °C) and reverse polarity (in the temperature interval of 520−590 °C). This sample comes from the boundary interval separating the uppermost part of the Kysuca reverse subzone from the post-Kysuca part of the magnetozone M20n. With respect to the thickness of the sample (2 cm) having two polarities of primary components of remanence and to the presumed low value of the sedimentation rate of the boundary interval claystones, it can be concluded that the transition from reverse to normal polarity of the geocentric co-axial magnetic dipole of the Earth occurred within a time span of ca. ±5000 years (cf. also Butler 1992, p. 191). The boundary sample No. 7554 seems to display intermediate polarity direction.

The Brodno reverse magnetosubzone was detected in the upper (late) part of the normal magnetozone M19n and constitutes the uppermost part (8 cm) of the bed 24A, the whole bed 24B and also the whole overlying bed 24C. Its complete thickness is 24 cm. The Brodno reverse magnetosubzone represents only 8 % of the total thickness of the normal magnetozone M19n (3.13 m, covering the pre- and post-Brodno normal parts as well as the Brodno reverse magnetosubzone), see Figs. 9 and 10. The base of the Brodno reverse magnetosubzone in Brodno lies at a level of 82 % of the local thickness of the magnetozone M19n. This subzone was defined on the basis of an analysis of paleomagnetic parameters carried out in the same manner as for the preceding subzone. Analogically, J_n consists of three components of remanence, the C-component corresponding to the primary (paleomagnetic) component of remanence was determined in temperature interval of ca. 300 °C (400 °C) to 500 °C (540 °C) in the process of progressive laboratory thermal demagnetization. The results of thermal demagnetization of only 12 samples from the Brodno magnetosubzone and its vicinity are shown as examples in Figs. 11 and 12, out of which six have normal (N) paleomagnetic polarity and six have reverse (R) paleomagnetic polarity. The high proportion of secondary components of remanent magnetization frequently reaching 90 % of J_n is visible in figures again. A transition between reverse (normal) and normal (reverse) polarity of the magnetic field of the dipole of the Earth was not detected in this subzone.

Correlation of paleomagnetic events and calpionellid biostratigraphy

The oldest calpionellids, i.e. the first species of genus *Chitinoidella* (*Ch. slovenica* Borza, *Ch. colomi* Borza, *Ch. dobeni* Borza) characterizing the oldest calpionellid Dobeni Subzone of the Chitinoidella Zone, were found in high numbers in the late part of the magnetozone M20r. The first representatives of these species appear in the bed 84 and the last ones were recorded in the uppermost part of the bed 86, i.e. at the very base of the overlying magnetozone M20n.

The base of the pre-Kysuca part of the magnetozone M20n lies in the upper part of the bed 86. The earliest portion of the pre-Kysuca part still belongs to the calpionellid Dobeni

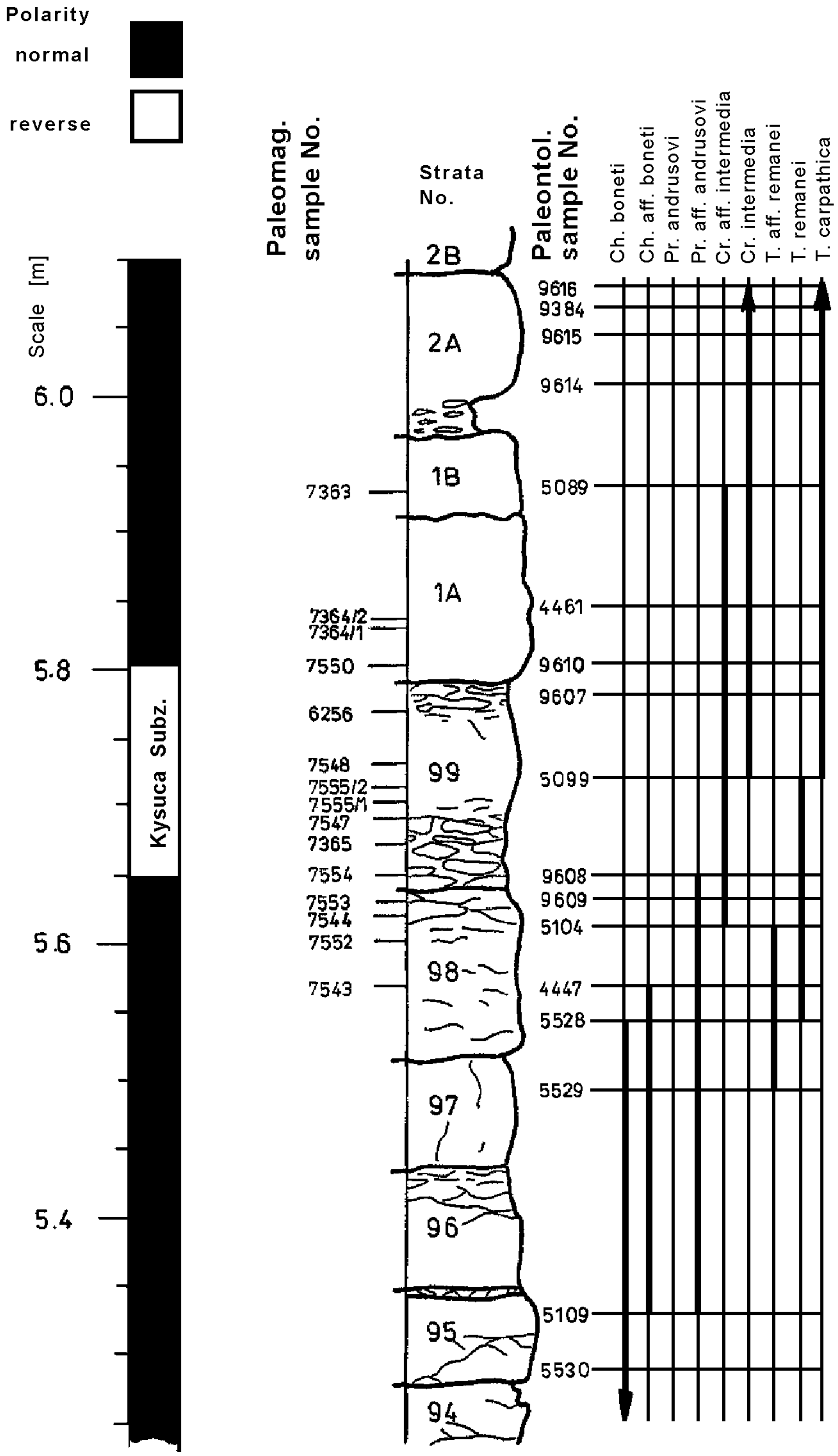


Fig. 6. Brodno locality. Kysuca Reverse Polarity Subzone. Paleomagnetic sample Nos, strata Nos and palentological sample Nos. Ch. — Chitinoidella; Pr. — Praetintinnopsella; Cr. — Crassicollaria; T. — Tintinnopsella.

Subzone; the Boneti Subzone starts in the bed 87 (i.e. in approx. one tenth of the local thickness of the pre-Kysuca part). The acme of the species *Ch. boneti* Doben was recorded in the late portion of the pre-Kysuca part. The top of the Boneti Subzone, hence also the top of the Chitinoidella Zone, is defined by the first appearance of small *Tintinnopsella* (Remane et al. 1986) first recorded at Brodno in the bed 98, i.e. below the Kysuca magnetosubzone. Thus, the pre-Kysuca part of M20n comprises the late portion of the calpionellid Dobeni Subzone, the whole calpionellid Boneti Subzone and the earliest portion of the Remanei Subzone of the Crassicollaria Standard Zone (the bed 98).

In terms of calpionellid biostratigraphy, the Kysuca Polarity Subzone is situated in the section at Brodno at the very base of the Crassicollaria Standard Zone. The lowermost subzone of the Crassicollaria Standard Zone, i.e. the calpionellid Remanei Subzone, in the Brodno section has a thickness of 100 cm, stretching from the topmost bed of the pre-Kysuca part (the bed 98) across the Kysuca magnetosubzone (i.e. the bed 99) and almost the whole overlying post-Kysuca part (except for its latest portion — the bed 4B; bed numbers see Houša et al. 1996b: Fig. 12). The top of the Remanei Subzone is marked by a major event representing the base of the overlying calpionellid Intermedia Subzone. This event is the appearance of species *Calpionella grandalpina* Nagy. The first (oldest) representatives of this species in the Brodno section were recorded in the middle of the limestone bed 4B, i.e. immediately below the top of the post-Kysuca part (lying between the beds 4B and 5 and in fact representing the boundary between the magnetozones M20n and M19r). Thus the base of the calpionellid Intermedia Subzone coincides with the latest portion of the post-Kysuca part.

The whole magnetozone M19r is constituted by the calpionellid Intermedia Subzone. This subzone also extends to the overlying magnetozone M19n. Here, its top is defined as the base of the Calpionella Standard Zone, herein considered as the J/K boundary. In the studied section, the J/K boundary lies at the level of 40 % of the thickness of the pre-Brodno part, i.e. at approx. 35 % of thickness of the whole magnetozone M19n. The last Tithonian calpionellid Intermedia Subzone therefore starts in the topmost part of the post-Kysuca part and corresponds to the whole magnetozone M19r and approximately the lowermost one-third of the magnetozone M19n; the rest of the magnetozone M19n is included into the Calpionella Standard Zone, i.e. the basal part of the Berriasian.

This implies that the boundary between the Crassicollaria and Calpionella Standard Zones (i.e. the J/K boundary in the present concept as recognized in the sections studied) lies within the pre-Brodno part of the magnetozone M19n. No magnetoevents lie in the immediate proximity of this boundary.

There is another event important for the verification of the position of the J/K boundary based on calpionellids: a short acme of species *Cr. parvula* Remane lying in the earliest part of the Calpionella Zone. This acme is well defined in the section at Brodno, being confined to the beds 20 and 21. This calpionellid event also lies within the pre-Brodno part, at approx. one half of the interval between the J/K boundary and the base of the Brodno reverse magnetosubzone.

The whole Brodno magnetosubzone lies within the Calpionella Standard Zone (Alpina Subzone). The interval occupied by this magnetosubzone in the section at Brodno is included in the monotonous part of the calpionellid Alpina Subzone and so is the whole overlying post-Brodno part. The boundary between the magnetozones M19n and M18r lies between the limestone beds 25B and 26A. In the opinion of Michalík et al. (1990), this level corresponds to the top of the calpionellid Alpina Subzone (i.e. the base of the calpionellid Cadischiana Subzone), but it has not proved possible for the present authors to confirm this with the required degree of accuracy. Accordingly, the whole magnetozone M18r should be included in the calpionellid Cadischiana Subzone.

Definition of the Jurassic/Cretaceous boundary according to calpionellids

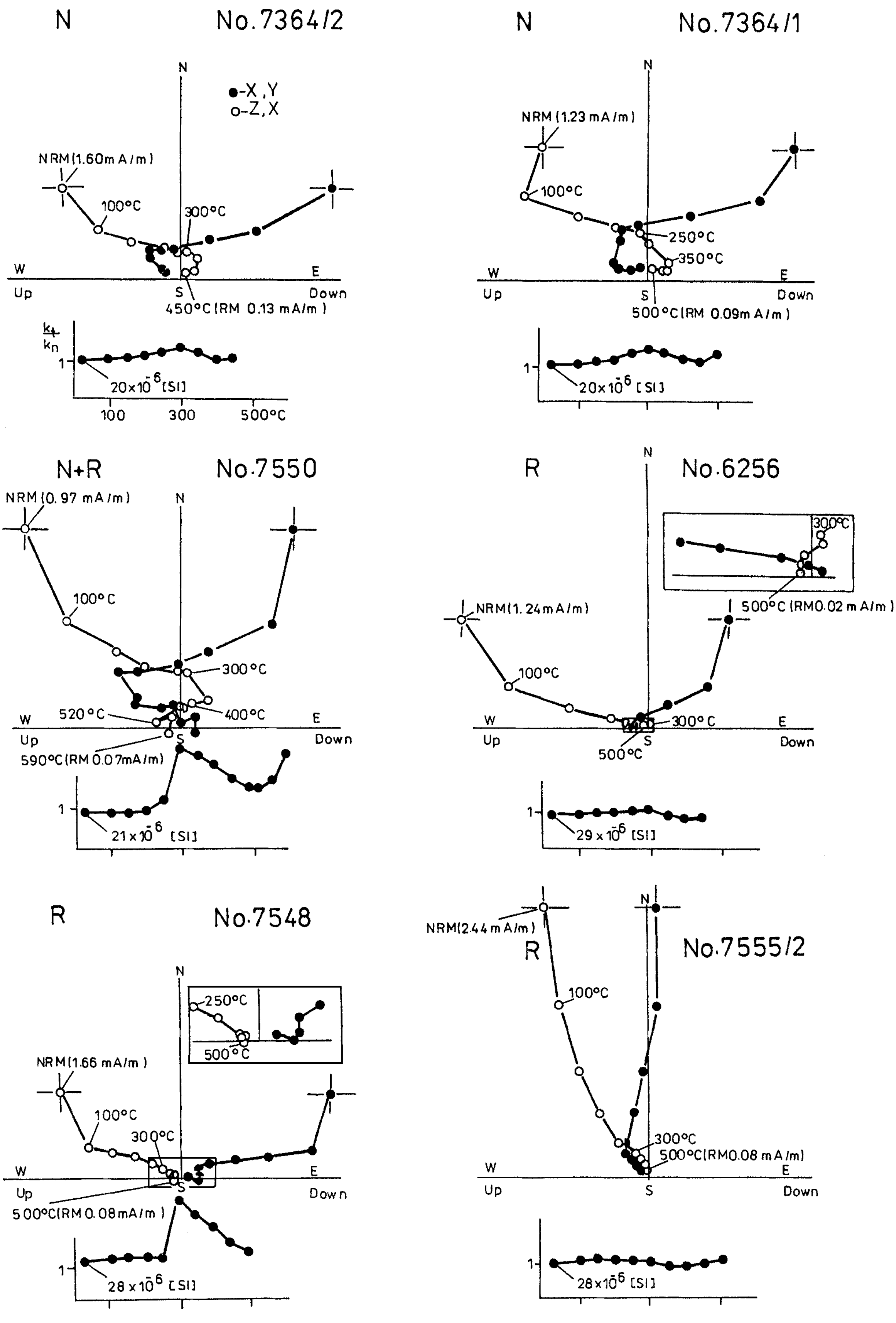
According to calpionellids, the J/K boundary (i.e. the Tithonian/Berriasian boundary) is placed at the base of the Calpionella Standard Zone as defined by Remane et al. (1986). The basic diagnostic features for the identification of the base of the calpionellid zone Calpionella were already defined by Remane (1964). The problem of the position of J/K boundary in the Brodno section was discussed in more detail by Houša et al. (1996b, p. 137–139) who placed this boundary in the Brodno section between the beds 15A (the latest Tithonian) and 15B (the earliest Berriasian). The reasons for the erroneous placement of this boundary in the Brodno section at a different level by other authors (to a stratigraphically lower level — approx. to the level of the upper portion of the bed 8 in the present, more detailed numbering) were also explained.

The base of the Calpionella Standard Zone represents one of the most prominent events in the relatively short history of calpionellid evolution. A great advantage of the Brodno section is that no hiatuses, slumps or washouts occur either at the level of this event or in its close proximity. According to all indicators, the limestone sedimentation at this horizon and in its close proximity at Brodno was quiet, relatively slow and continuous, and characterized by conditions very favourable for the fossilization of calpionellid loricae. Gradual changes associated with this event can be, therefore, studied in considerable detail (see Houša et al. 1996b; Fig. 6).

Štramberk, northern Moravia

Basic information

The Štramberk Limestone represents a complex of peri-reef accumulations of fine or coarser organic debris with an almost complete absence of terrigenous admixture. In some intervals, grain-sized particles disappear and the rock passes into finer varieties, to micritic limestones. This fact probably reflects sea-level fluctuations but may also result from the position of the given site of sedimentation with respect to the main axes of detrital material transport in a debris talus around Tithonian-Berriasian reefs. Sedimentation rates in the Štramberk peri-reef accumulation must have been variable in space and in time as


N
No.7364/2
•-X,Y
o-Z,X
NRM (1.60 mA/m)
100°C
300°C
450°C (RM 0.13 mA/m)
W
E
Up
Down
S
N
kt/kn
1
20x10^-6 [SI]
100
300
500°C
N
No.7364/1
NRM (1.23 mA/m)
100°C
250°C
350°C
500°C (RM 0.09 mA/m)
20x10^-6 [SI]
N+R
No.7550
NRM (0.97 mA/m)
100°C
300°C
400°C
520°C
590°C (RM 0.07 mA/m)
21x10^-6 [SI]
R
No.6256
NRM (1.24 mA/m)
100°C
300°C
500°C
500°C (RM 0.02 mA/m)
29x10^-6 [SI]
R
No.7548
NRM (1.66 mA/m)
100°C
300°C
250°C
500°C
500°C (RM 0.08 mA/m)
28x10^-6 [SI]
R
No.7555/2
NRM (2.44 mA/m)
100°C
300°C
500°C (RM 0.08 mA/m)
28x10^-6 [SI]

well. The occurrence of washouts must also be considered probable in such shallow-water depositional environments. Larger blocks of limestones (several metres in size), represent olistoliths in detrital material, they are probably derived from eroded reef bodies emerged during temporary eustatic sea-level falls.

The studied section was therefore chosen outside the coarse to blocky facies, in a deeper part of the original peri-reef accumulation farther from the source of materials, where a lower incidence of hiatuses, washouts or secondary olistoliths can be anticipated. The section was situated on the 6th level of the Kotouč Quarry where rather finer varieties of biofragmental limestones occur in a suitable position, at some levels passing into micritic limestones several metres thick.

The studied section begins at the edge of the limestone body of the Homole Hill and stretches along the 6th level northern wall to the central part of the Kotouč Quarry, where it ends on the opposite side of the body of the Homole Hill (close to the Mendocino Fault). The section is 620 m long, being intersected by no major fault. Stratigraphically, it covers approximately the same time interval (between the magnetozones M21n and M18n) as the above discussed part of the Brodno section, which is only 11 m thick (extending between the magnetozones M21r and M18r).

Magnetostratigraphy

Magnetostratigraphic study of the J/K boundary limestone strata at the locality of Štramberk was started in 1992 in two sections. Priority was given to the section on the 6th level of the Kotouč Quarry. Altogether 342 orientated drill samples were collected from the northern wall of the 6th level. The limestone samples are exceptionally weakly magnetic with moduli of J_n ranging between several tens to several hundred $[10^{-6}$ A/m]. The values of k_n are mostly negative, diamagnetism of the limestone mass prevails over weak paramagnetism and ferrimagnetism. Tithonian limestones were measured from 94 samples in the first stage. The mean value of 78.1 μA/m and standard deviation 72.4 μA/m were obtained for J_n of samples with normal polarity, while the mean value of 56.0 μA/m and standard deviation 45.2 μA/m were obtained for J_n of samples with reverse polarity. The mean value of -12.7×10^{-6} SI and standard deviation 2.6×10^{-6} SI were obtained for k_n (Houša et al. 1992, 1993). The procedure described for the Brodno locality was used for the precise determination of unblocking temperatures and for the X-ray diffraction determination of ferrimagnetic minerals in exceptionally weakly magnetic limestones. Unblocking temperatures of 540–560 °C corresponding to magnetite were determined. Analogous unblocking temperatures were determined in all samples used for construction of the magnetostratigraphic profile. Magnetite content determined in pilot samples is approx. 0.3 $g.t^{-1}$. Irregular, less commonly isometric and spherolitic magnetite particles range between 3 and 20 μm in size.

All samples collected were subjected to progressive thermal demagnetization using the MAVACS apparatus. The results clearly demonstrate that, in spite of the very weak magnetization of the limestones studied and a higher proportion of secondary components of remanence, the samples are suitable for inferring paleomagnetic directions (see Houša et al. 1996a,b). A magnetostratigraphic profile constructed on the basis of samples collected in 1992, indicated the basic positions of magnetozones, but proved to be rather complicated in some intervals due to tectonic deformations and the generally dynamic sedimentation of limestones deposited in the peri-reef zone. In 1993 and 1994, additional sampling was carried out to reach a sampling point density of ca. 3 samples per 10 m of true thickness and — in other intervals — of ca. 8 samples per 10 m. Documentation of paleomagnetic samples is included in the report of Houša et al. (1994) as well as a magnetostratigraphic profile with values of J_n , k_n , D_p , I_p and with interpreted normal and reverse magnetozones and magnetosubzones.

In the submitted study, the essential results from the Štramberk section are shown only in the form of a comparative scheme of hitherto studied magnetostratigraphic profiles for the localities of Brodno and Štramberk in Fig. 13. The basic magnetozones were proved in the Štramberk section, however, the reverse magnetozone M19r and the Kysuca reverse magnetosubzone were indicated with a lesser degree of conclusiveness. Two reverse subzones were recorded in the late part of the normal magnetozone M19n at the level of the Brodno reverse subzone. The above mentioned shortcomings of the magnetostratigraphic profile at Štramberk may be caused by the complicated tectonic setting and possibly also by the extremely dynamic sedimentation. This section should, therefore, be regarded as an orientational one, not reaching the accuracy and reliability of the section at the Brodno locality.

◀

Fig. 7. Brodno locality. Kysuca Reverse Polarity Subzone. Results of progressive thermal demagnetization of samples by means of the MAVACS apparatus. Only selected samples are demonstrated to show typical examples, see Fig. 6. R (reverse), N (normal) polarity of the paleomagnetic remanence component derived by multi-component analysis is indicated for respective samples. The Zijderveld diagrams represent orthogonal projection onto the horizontal X,Y plane (full circles) and the vertical X,Z plane (empty circles). NRM — natural remanent magnetization. Beneath the Zijderveld diagrams, the normalized values of k_t / k_n in relation to temperature t [°C] are plotted; k_t is the volume magnetic susceptibility of the sample demagnetized at temperature t and cooled to room temperature; k_n is the volume magnetic susceptibility of the sample in its natural state (prior to thermal treatment).

Calpionellid associations

Considering the character of sedimentation in a peri-reef talus of calcareous detritus and its close vicinity (see above), the preservation of calpionellid associations itself in the Štramberk Limestone is remarkable. Loricae of calpionellids were most probably transported by water flow into interstices among detrital particles of calcareous organic remains along with other allochthonous material forming the matrix of the rock. Calpionellids are generally less abundant in bio-

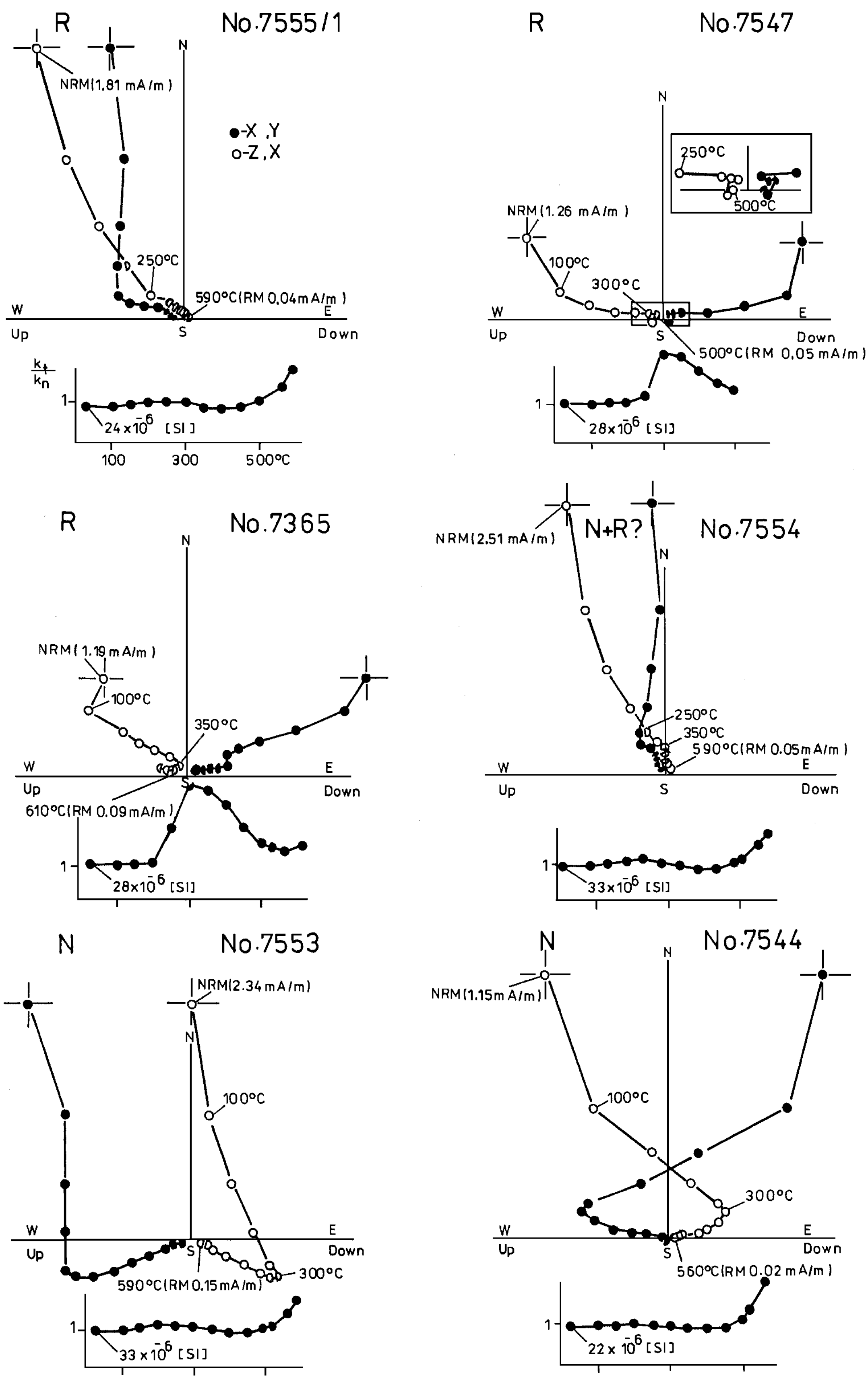


Fig. 8. Brodno locality. Kysuca Reverse Polarity Subzone. See caption to Fig. 7.

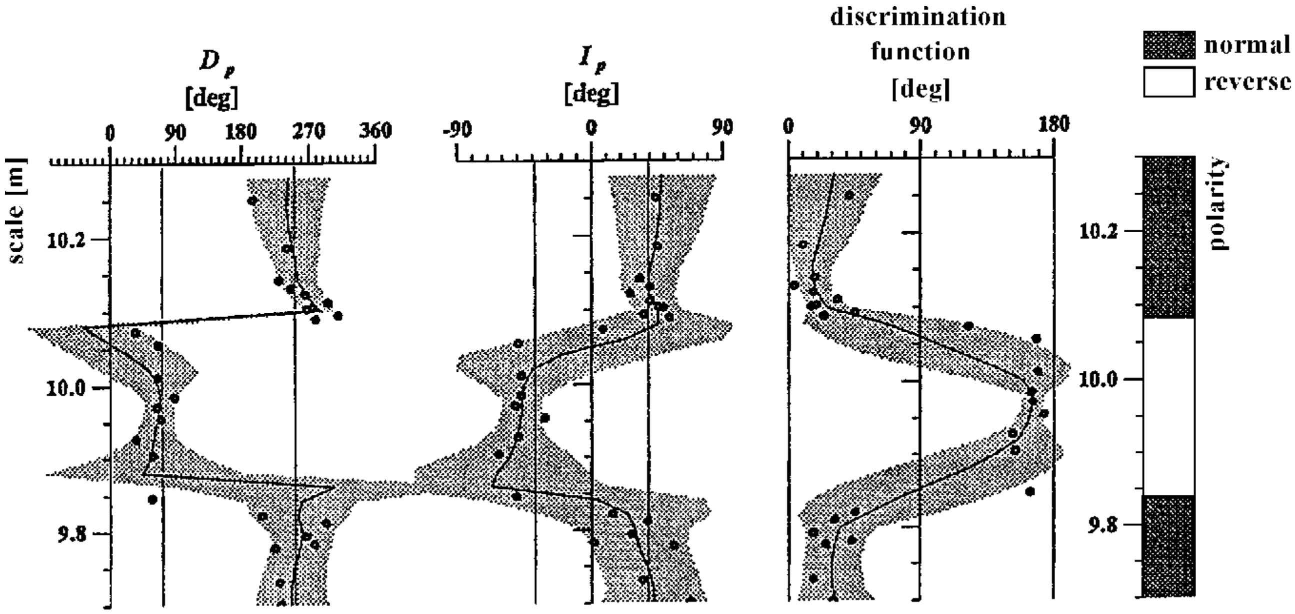


Fig. 9. Brodno locality. Brodno Reverse Polarity Subzone. See caption to Fig. 5.

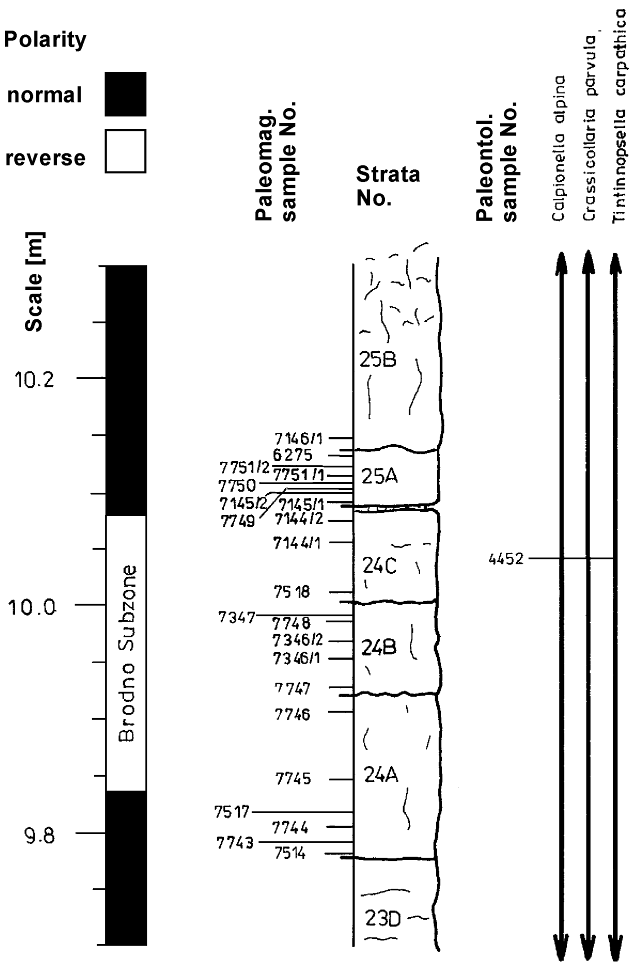


Fig. 10. Brodno locality. Brodno Reverse Polarity Subzone. See caption to Fig. 6.

fragmental varieties of the Štramberk-type limestones, which most probably originated close to the source of the biofragmental material, i.e. probably in shallow marine conditions not far from the reefs as such. In contrast, calpionellids are more abundant in finer, micritic Štramberk-type limestones, which probably represent a more distal, deeper-water environment possibly originating during periods of sea-level rise. The abundance of calpionellids in the Štramberk Limestone is generally low and only exceptionally (e.g., in thin sections of micrite fills of ammonite shells) comparable with the calpionellid abundances in limestones from basinal localities (such as Brodno).

No material sufficient for the definition of the oldest calpionellid Dobeni Subzone was obtained anywhere at Štramberk. Occasional finds of species of the Dobeni Subzone association are absolutely insufficient for delimitation of the Subzone. On the contrary, the following calpionellid Boneti Subzone was recorded in all larger bodies of the Štramberk-type limestones. The occurrence of the species *Chitinoidella boneti* Doben in the Štramberk Limestone in fact corresponds to the interval of its maximum abundance (acme). In the studied section, this species was found in samples from the late portion of the pre-Kysuca part of the magnetozone M20n. *Ch. boneti* thus occurs at the same stratigraphic position here as does the acme of this species at Brodno. The last occurrence of *Ch. boneti* at Štramberk coincides with the first appearance of calpionellids with hyaline lorica walls. This event lies immediately below the top of the pre-Kysuca part in the studied section.

The pre-Kysuca part in the section at Štramberk is 62 m thick (sic!, only 90 cm at Brodno) and the interval of occurrence of *Ch. boneti* is 20 m thick here (acme of this species is restricted to ca. 50 cm at Brodno).

The base of the Crassicollaria Standard Zone in the studied section was localized at the very top of the pre-Kysuca part.

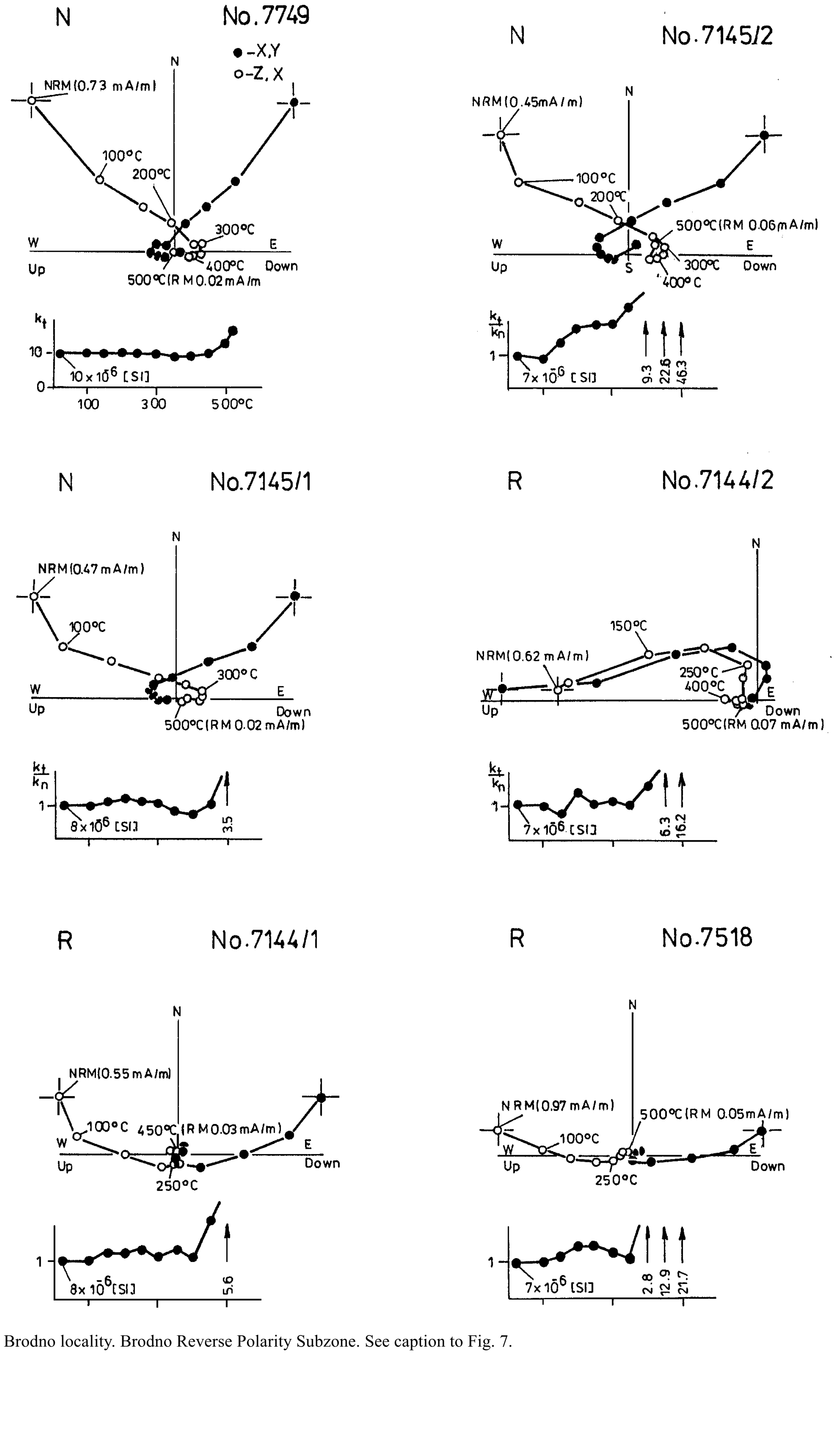


Fig. 11. Brodno locality. Brodno Reverse Polarity Subzone. See caption to Fig. 7.

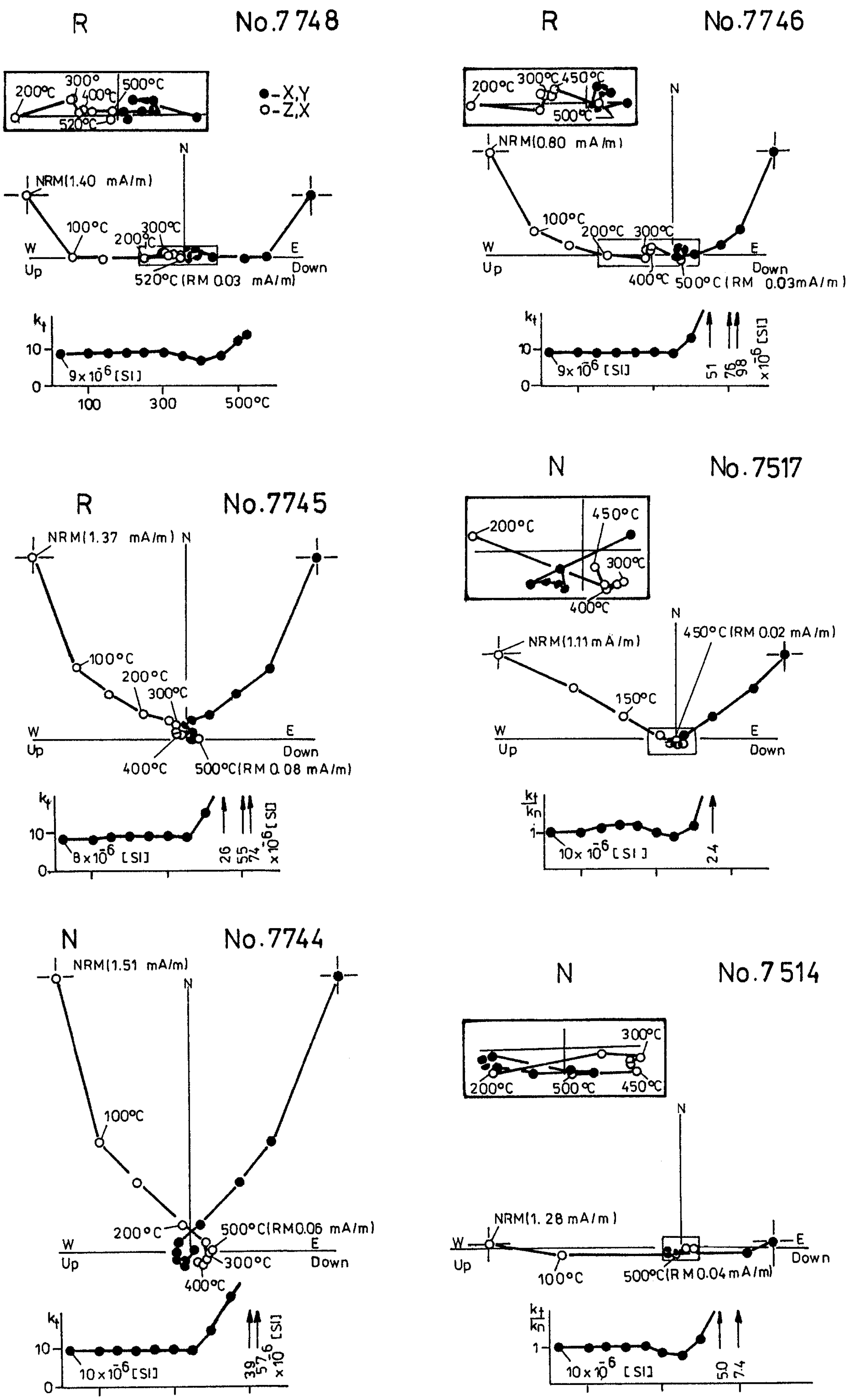


Fig. 12. Brodno locality. Brodno Reverse Polarity Subzone. See caption to Fig. 7.

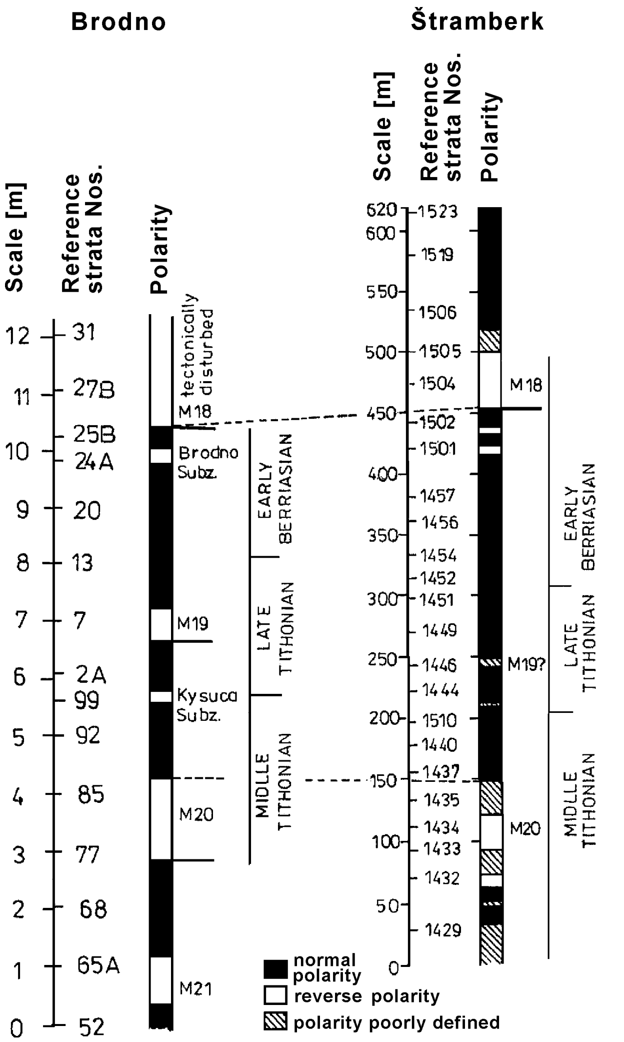


Fig. 13. Resultant magnetostratigraphic profiles across the Tithonian/Berriasian boundary strata at Brodno and Štramberk.

This situation exactly corresponds to that at Brodno. The Crassicollaria Zone (its lowermost calpionellid Remanei Subzone) also includes the overlying Kysuca magnetosubzone, the thickness of which is still difficult to assess precisely (a thickness of 3 m can be estimated from interpolation). The above given lowermost subzone of the Crassicollaria Standard Zone also includes the overlying post-Kysuca part having a thickness of some 30 m here (as opposed to 90 cm at Brodno). The base of the calpionellid Intermedia Subzone should coincide with the base of the magnetozone M19r, however, this magnetozone is only insufficiently documented up to now. Its thickness was assessed at only 3.5 m by interpolation, which may be caused by primary reduction of sedimentary record at this level. Datable calpionellid samples from this level are also missing up to now and, consequently, the first specimens of *Calpionella grandalpina* Nagy (base of the Intermedia Subzone) are known from the earliest part of the magnetozone M19n.

The most important calpionellid event — the base of the Calpionella Standard Zone (i.e. the J/K boundary) is well defined in the Štramberk section and its position was determined more precisely on the basis of a denser sampling. It lies within the magnetozone M19n, 22 m above its base, i.e. approximately at 30 % of the local thickness of the whole magnetozone (at 35 % at Brodno). This implies that the last Tithonian calpionellid subzone — Intermedia Subzone — also corresponds here approximately to the lowermost one-third of the magnetozone M19n (the pertinence of the magnetozone M19r to this calpionellid subzone in Štramberk has still not been shown by any fossiliferous sample).

An interesting point about the Štramberk section is the presence of two reverse magnetosubzones in the late part of the magnetozone M19n. The Brodno magnetosubzone correlates either to one or to both of them. This cannot be decided on the basis of biostratigraphic criteria, as the Brodno magnetosubzone lies in the monotonous part of the Alpina Subzone of the Calpionella Standard Zone. The position of the short acme of species *Cr. parvula* has still not been determined more precisely within the Štramberk section, due to sparse sampling.

Discussion of results

The positions of the Kysuca and Brodno magnetosubzones are also confirmed by our preliminary results obtained from the section at Bosso (Italy). Lowrie & Channell (1984, p. 45) have speculated that "A single reversed sample at the base of the section in the top of the more slowly deposited Calcari Diasprigni may represent the short reversed interval between M19 and M20", i.e. the herein described Kysuca Subzone. This occurrence of reverse magnetization was not confirmed by detailed sampling at the level of 304.15 m or in its vicinity. The equivalent of the Kysuca Subzone itself was recorded in the Bosso section rather at the level of 299.2 to 299.55 m, i.e. 4.5 m lower. It is represented by bed 28 in our numbering. Calpionellids are unfortunately completely absent from this basal interval of the Bosso section.

The only equivalent of the magnetosubzones in M19n, i.e. the Brodno Subzone, in the Bosso section corresponds to the level of 318.90–319.55 m (it is represented by the beds 100–103 of our numbering). Its base lies at the level of 80 % and its top at the level of 85 % of the local thickness of the magnetozone M19n. As at Brodno, it lies within the monotonous part of the calpionellid Alpina Subzone of the Calpionella Standard Zone.

From the geophysical point of view, the magnetostratigraphic profile at the locality of Brodno near Žilina can be considered absolutely unique among all the hitherto studied sections across the J/K boundary strata in the Tethyan Realm. This is the first section on the continent, where two reverse subzones were very precisely detected within the magnetozones M20n and M19n at positions corresponding to marine M (Mesozoic) anomalies. Although the paleomagnetic components of remanence are very low in comparison with natural remanence, they were easily inferred with the use of progressive thermal demagnetization by the MAVACS apparatus and subsequent multi-component analysis of remanence. Samples with intermediate polarity were detected at the boundaries of the Kysuca Subzone localized within the magnetozone M20n in the zones of transition from N to R and R to N polarities. Time interval within the limits of ca. ±5000 years can be assumed for a transition from normal (reverse) to reverse (normal) polarity of magnetic field of the coaxial geocentric dipole of the Earth with respect to the thickness of the samples (2 cm) and the assumed sedimentation rate (ca. 2 mm/ka). This figure depends on the estimation of the sedimentation rate of the studied pelagic sediments, but is in agreement with data obtained from other localities (Butler 1992). A similar sedimentation rate (2.27 mm/ka) may be obtained from the Brodno profile if the magnetozones of total thickness from the base of M21 to the base of M18 (10 m) and the corresponding time interval (4.4 Ma) are considered. An analogous figure was also obtained from the Miocene sediments of the Sokolov Basin, western Bohemia (Krs et al. 1991).

Ackowledgements: The authors wish to thank Dr. J. Michalík, Dr. D. Reháková and two anonymous referees for reviewing the paper and some helpful suggestions.

References

Butler R.F., 1992: Paleomagnetism: Magnetic Domains to Geologic Terranes. *Blackwell Sci. Publ.*, Oxford, 1–319.

Colloque sur la limite Jurassique-Crétacé, Lyon, Neuchâtel, septembre 1973. *Mém. B.R.G.M.*, 86, 393.

Channell J.E.T. & Grandesso P., 1987: A revised correlation of Mesozoic polarity chrons and calpionellid zones. *Earth Planet. Sci. Lett.,* 85, 222–240.

Cirilli S., Márton P. & Vigli L., 1984: Implications of a combined biostratigraphic and palaeomagnetic study of the Umbrian Maiolica Formation. *Earth Planet. Sci. Lett.,* 69, 203–214.

Fisher N.I., Lewis T. & Embleton B.J.J., 1987: Statistical analysis of spherical data. *Cambridge University Press*, Cambridge, 1–329.

Galbrun B., 1985: Magnetostratigraphy of the Berriasian stratotype section (Berrias, France). *Earth Planet. Sci. Lett.*, 74, 130–136.

Galbrun B., Berthou P.Y., Moussin C. & Azéma J., 1990: Magnétostratigraphie de la limite Jurassique-Crétacé en facies de la plate-forme carbonatée: la coupe de Bias do Norte (Algarve, Portugal*). Bull. Soc. Géol. France*, 1990, 8, VI, 1, 133–143.

Hoedemaeker Ph.J., Krs M., Man O., Parés J.M., Pruner P. & Venhodová D., 1998: The Neogene remagnetization and petromagnetic study of the Early Cretaceous limestone beds from the Río Argos, Province Murcia, SE Spain. *Geol. Carpathica,* 49, 1, 15–32.

Houša V., 1990: Ecological aspects of the evolution of calpionellids (Calpionellidae; Proyozoa inc. sed.). In: Pallini G. (Ed.): *Atti II. Conv. Int. F. E. A. Pergola*, 87, 357–363.

Houša V., Krs M., Krsová M., Man O., Pruner P. & Venhodová D., 1997: High-resolution magnetostratigraphy across the Jurassic-Cretaceous boundary strata at Brodno near Žilina, Western Slovakia. *Miner. slovaca*, 4–5/29, 312–314.

Houša V., Krs M., Krsová M. & Pruner P., 1996a: Magnetostratigraphy of Jurassic-Cretaceous limestones in the Western Carpathians. In: Morris A. & Tarling D.H. (Eds.): *Paleomagnetism and Tectonics of the Mediterranean Region. Spec. Publ. (Geol. Soc. London), 105*, 185–194.

Houša V., Krs M., Krsová M. & Pruner P., 1996b: Magnetostratigraphic and micropalaeontological investigations along the Jurassic-Cretaceous boundary strata, Brodno near Žilina (Western Slovakia). *Geol. Carpathica*, 47, 3, 135–151.

Houša V., Krs M. & Pruner P., 1992: Influence of Earth's magnetic field inversions on organisms and their possible reflection in fossil record. *Geol. Inst. Acad. Sci. Czech Rep.*, Prague, unpublished Internal Report (in Czech).

Houša V., Krs M. & Pruner P., 1993: Magnetostratigraphic investigations of two profiles of Jurassic-Cretaceous boundary strata at Štramberk (Czech Republic) and Brodno (Slovakia). *1st General Meeting IGCP Project 362*, Coimbra, Portugal 1993, 28–29.

Houša V., Krs M. & Pruner P., 1994: Influence of Earth's magnetic field inversions on organisms and their possible reflection in fossil record. Stage 1994. *Geol. Inst. Acad. Sci. Czech Rep.,* Prague, unpublished Internal Report (in Czech).

Jelínek V., 1966: A high sensitivity spinner magnetometer. *Stud. Geophys. Geodaet.*, 10, 58–78.

Jelínek V., 1973: Precision A.C. bridge set for measuring magnetic susceptibility and its anisotropy. *Stud. Geophys. Geodaet.*, 17, 36–48.

Kirschvink J.L., 1980: The least-squares line and plane and the analysis of palaeomagnetic data. *Geophys. J. Royal Astronom. Soc.*, 62, 699–718.

Krs M., Krsová M., Pruner P. & Kouklíková L., 1991: On the detailed magnetostratigraphy of greigite- (smythite) mineralization, Sokolov Brown-coal Basin, Bohemia. *Stud. Geophys. Geodaet.*, 35, 267–284.

Krs M. & Pruner P., 1997: Petromagnetic and palaeomagnetic investigations of Jurassic-Cretaceous limestones aimed at magnetostratigraphy in the Mediterranean area. *Miner. slovaca*, 4–5/29, 324–325.

Lowrie W. & Channell J.E.T., 1984: Magnetostratigraphy of the Jurassic-Cretaceous boundary in the Maiolica limestone (Umbria, Italy). *Geology*, 12, 44–47.

Lowrie W. & Ogg J.G., 1986: A magnetic polarity time scale for the Early Cretaceous and Late Jurassic. *Earth Planet. Sci. Lett.*, 76, 341–349.

Manivit H., Azéma J., Galbrun G. & De Wever P., 1986: Biostratigraphic study of calpionellids and nannofossils in the Tethyan Realm (Spain, Sicily, SE France) in Late Jurassic and Berriasian time: a correlation with magnetostratigraphic results. *Acta Geol. Hung.*, 29, 1–2, 105–123.

Márton E., 1982: Late Jurassic/Early Cretaceous magnetic stratigraphy from the Suemeg section, Hungary. *Earth Planet. Sci. Lett.*, 57, 182–190.

Márton E., 1986: The problems of correlation between magnetozones and calpionellid zones in Late Jurassic-Early Cretaceous sections. *Acta Geol. Hung.*, 29, 1–2, 125–131.

Michalík J., Reháková D. & Peterčáková M., 1990: To the stratigraphy of Jurassic-Cretaceous boundary beds in the Kysuca sequence of the West Carpathian Klippen belt, Brodno section near Žilina. *Knihovnička ZPN*, 9 b, 57–71 (in Slovak with English abstract).

Nairn A.E.M., Schmitt T.J. & Smithwick M.E., 1981: A palaeomagnetic study of the Upper Mesozoic succesion in Northern Tunisia. *Geophys. J. Royal Astronom. Soc.*, 65, 1–18.

Ogg J.G., Hasenyager R.W., Wimbledon W.A., Channell J.E.T. & Bralower T.J., 1991: Magnetostratigraphy of the Jurassic-Cretaceous boundary interval — Tethyan and English faunal realms. *Cretaceous Research,* 12, 455–482.

Ogg J.G. & Lowrie W., 1986: Magnetostratigraphy of the Jurassic-Cretaceous boundary. *Geology*, 14, 547–550.

Ogg J.G., Steiner M.B., Company M. & Tavera J.M., 1988: Magnetostratigraphy across the Berriasian-Valanginian stage boundary (Early Cretaceous), at Cehegín (Murcia Province, southern Spain). *Earth Planet. Sci. Lett.*, 87, 205–215.

Ogg J.G., Steiner M.B., Oloriz F. & Tavera J.M., 1984: Jurassic magnetostratigraphy, 1. Kimmeridgian-Tithonian of Sierra Gorda and Carcabuey, southern Spain. *Earth Planet. Sci.*

Lett., 71, 147–162.

Parés J.M. & Roca E., 1996: The significance of tectonic-related Tertiary remagnetization along the margins of the Valencia through. *J. Geodynamics*, 22, 207–227.

Parzen E., 1962: An estimation of probability density function and mode. *Ann. Math. Stat*., 33, 1065–1076.

Příhoda K., Krs M., Pešina B. & Bláha J., 1989: MAVACS – a new system creating a non-magnetic environment for paleomagnetic studies. *Cuad. Geol. Ibér.,* 1988–1989, Universidad Complutense de Madrid, 12, 223–250.

Reinsch C.H., 1967: Smoothing by spline functions. *Numer. Math.*, 10, 177–183.

Remane J., 1964: Untersuchungen der Systematik und Stratigraphie der Calpionellen in der Jura-Kreide-Grenzschichten des Vocontischen Troges. *Paleontographica*, *Abt. A*, 123, 1–57.

Remane J., Bakalova-Ivanova D., Borza K., Knauer J., Nagy I. & Pop G., 1986: Agreement on the subdivision of the standard calpionellid zones defined at the 2nd planctonic conference, Roma 1970. *Acta Geol. Hung*., 29, 5–14.

Salvador A. (Ed.), 1994: International stratigraphic guide., 2nd ed.- IUGS & *Geol. Soc. Amer.*, xix + 214.

Scheibner E., 1967: Carpathian klippen zone. In: Buday T. et al. (Eds.): *Region. Geol. ČSSR, díl II - Západ. Karpaty*, 2, (in Slovak).

Scheibner E. & Scheibnerová V., 1958: Kysuca and Snežnica beds — new Cretaceous members of the Pieniny clan in the Kysuca development. *Geol. Sbor. Slov. Akad. Vied.,* 9, 178–181 (in Slovak).

Tavera J.M., Aguado R., Company M. & Oloriz F., 1994: Integrated biostratigraphy of the Durangites and Jacobi Zones (J/K boundary) at the Puerto Escaño section in Southern Spain (Province of Córdoba). *Geobios*, M.S. 17, 469–476.

Villalaín J.J., Osete M.L., Vegas R., García-Duenas V. & Heller F., 1996: The Neogene remagnetization in the western Betics: a brief comment on the reliability of palaeomagnetic directions. In: Morris A. & Tarling D.H. (Eds.): *Palaeomagnetism and Tectonics of the Mediterranean Region. Spec. Publ. (Geol. Soc. London),* 105, 33–41.