Upper Anisian to Lower Carnian magnetostratigraphy from the Northern Calcareous Alps (Austria)

Yves Gallet, Leopold Krystyn, Jean Besse

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 103, NO. B1, PAGES 605-621, JANUARY 10, 1998

Upper Anisian to Lower Carnian magnetostratigraphy from the Northern Calcareous Alps (Austria)

Yves Gallet
Laboratoire de Paléomagnétisme, URA 729, Institut de Physique du Globe de Paris, France

Leopold Krystyn
Institute for Paleontology, Vienna, Austria

Jean Besse
Laboratoire de Paléomagnétisme, URA 729, Institut de Physique du Globe de Paris, France

Abstract. We present a magnetostratigraphic study of three pelagic limestone sections (Gamsstein, Mendlingbach and Mayerling) from the eastern part of the Northern Calcareous Alps. Together these sections, which contain a rich conodont fauna, yield a sedimentary record encompassing the uppermost Anisian, the Ladinian and the Lower Carnian. Thermal demagnetization and isothermal remanent magnetization experiments indicate that the magnetization is essentially carried by a mineral of the magnetite family. The high unblocking temperature components isolated from the three sections provide clear magnetic polarity zonations. Correlations between these results, based on the biostratigraphic data and tephrochronology, allow the construction of a composite magnetic polarity sequence from the Illyrian substage (Upper Anisian) to the Julian 2 zone (Lower Carnian). This sequence contains 17 well-defined polarity reversals, and eight more poorly defined intervals. Correlations can be suggested between the new data and other magnetostratigraphic results previously obtained from marine sections. We estimate that the magnetic reversal frequency was 2.5 to 3.6 reversals per million years during the Ladinian.

Introduction

The Triassic magnetostratigraphy has been recently improved by several studies both on marine and continental sedimentary sections [e.g., *Steiner et al.*, 1989; *Ogg and Steiner*, 1991; *Gallet et al.*, 1992, 1993a, 1994, 1996; *Muttoni and Kent*, 1994; *Muttoni et al.*, 1994, 1995, 1996, 1997; *Kent et al.*, 1995; *Molina-Garza et al.*, 1991, 1993, 1996]. However, these data concentrate on the magnetic reversal chronology during the Late and Early Triassic. For the Middle Triassic, magnetostratigraphic results obtained from marine sediments are available only for the Lower and Middle Anisian [*Muttoni et al.*, 1995, 1996] and from the Uppermost Anisian to the Lower Ladinian [*Muttoni and Kent*, 1994; *Muttoni et al.*, 1994]. Other studies that provide information about Middle Triassic magnetostratigraphy come from the southwestern United States (upper Moenkopi formation [e.g., *Helsley and Steiner*, 1974; *Baag and Helsley*, 1974; *Elston and Purucker*, 1979; *Lienert and Helsley*, 1980; *Purucker et al.*, 1980; *Molina-Garza et al.*, 1991, 1996]) and from Spain [*Turner et al.*, 1989]. These data were obtained from continental sediments (red beds) where biostratigraphic control is generally poor. And because the construction of a reliable composite magnetic polarity sequence from these latter results is problematic, they should be constrained by additional magnetostratigraphic data from well-dated marine sections.

In this study we report the magnetostratigraphy of three pelagic limestone sections from the Northern Calcareous Alps (NCA; Austria). Correlations between these sections based on conodonts and taphrostratigraphy allow the construction of a magnetic polarity sequence from the Uppermost Anisian to the Lower Carnian.

Ladinian Biochronology and Chronostratigraphy

Several recent studies that focused on the Ladinian biochronology [e.g., *Brack and Rieber*, 1993, 1994; *Kovacs et al.*, 1994; *Mietto and Manfrin*, 1995] show differences both in the content and scope of the recognized biostratigraphic zones. Consequently, the Ladinian may either contain six ammonoid zones (with the inclusion of the Reitzi zone [*Kozur*, 1995]), five zones (beginning with the Nevadites zone [*Krystyn*, 1983]) or four zones (beginning with the Curionii zone [*Brack and Rieber*, 1994; *Bucher and Orchard*, 1995]). In this study we will use the second variant which corresponds to possibility B suggested by Brack and Rieber (1994). In this way, the base of the Ladinian is marked by the onset of the *Nevadites secedensis* zone and approximates closely to the appearance of the conodont

Paper number 97JB02155.
0148-0227/98/97JB-02155$09.00

Paragondolella trammeri [see *Krystyn*, 1983; *Nicora and Brack*, 1995; *Muttoni et al.*, 1997]. The Lower Ladinian contains two ammonoid zones (the Fassanian 1 and 2 zones) and the Upper Ladinian three zones (the Longobardian 1 to 3 zones).

The three Ladinian sections analyzed in this study come from the Reifling formation which is apparently devoid of ammonoids but contains rich conodont faunas. The latter have been grouped into six intervals and have been chronostratigraphically fixed by conodont-based correlations with the ammonoid-rich sections of Epidaurus (Greece) and Bagolino (Northern Italy). However, the chronostratigraphy of the Epidaurus section needs to be reconsidered because additional ammonoid and conodont faunal data collected in 1994 provided new stratigraphic constraints (Figure 1) [*Krystyn*, 1983]. The ammonoid zonation is nominaly modified by introducing the Secedensis zone, and also stratigraphically by shifting beds 10 and 11 from the Archelaus zone downwards to the Gredleri zone (Figure 1). The reason for this revision is the discovery of a *Protrachyceras gredleri* specimen in bed 10. Bed 11 lacks diagnostic ammonoids but it has identical lithology and microfacies as the underlying levels 10 and 9. The other changes in conodont faunas concern *Paragondolella excelsa* (Last Occurrence Datum [LOD] in bed 6/3), *P. inclinata* (First Occurrence Datum [FOD] in bed 7), the introduction of *Budurovignathus longobardicus* from beds 13 to 17 and the removal of *Gondolalla cf. bakalovi* (see comment of *Kovacs* [1994]). Within the Upper Fassanian, the former Hungarica zone has been renamed for *P. excelsa* in order to avoid any further confusion with the original scope of this zone [*Kozur*, 1980].

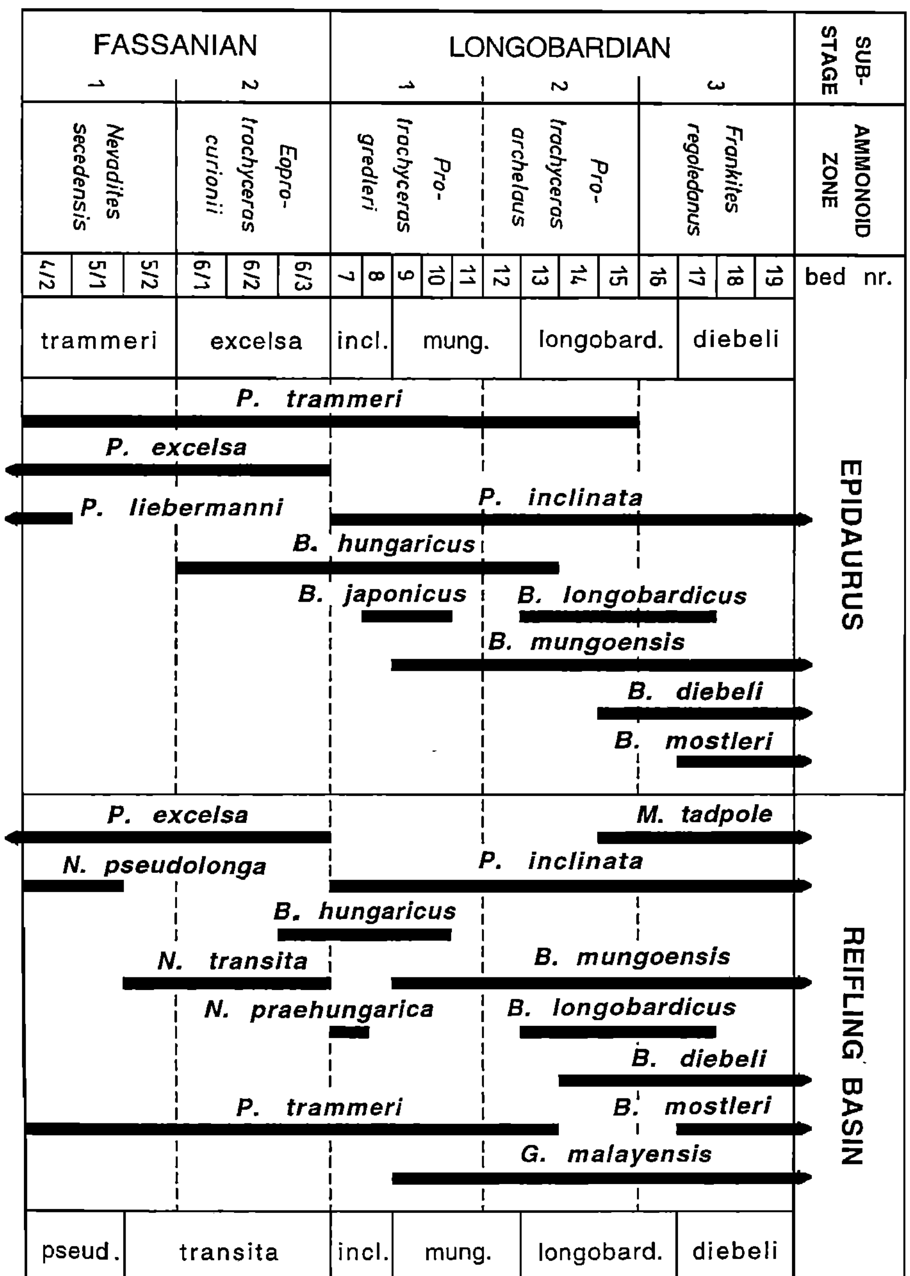


Figure 1. Ladinian biochronology used in this study.

Many sections of the Reifling basin contain three distinct tuffaceous layers with a light grey to greenish primary and yellowish weathering secondary color. These layers probably represent altered pietra verde. They have been numbered as T1, T2 and T3 in our sections and are interpreted as geologically isochronous and therefore chronostratigraphic marker beds. Tephrochronology thus provides an independent tool to constrain the adopted correlations based on conodonts and to establish long-distance time relationships with other tuff-bearing Ladinian sections of the Alpine region. In particular, *Kozur and Mostler* [1971] described a section from the Nemesvamos formation (Koeveskal, Balaton Highland, Hungary) with two distinct tuffaceous intervals at 7.5 and 11.5 m which may correspond to the T2 and T3 layers of the Reifling basin according to the conodont data. The T2 and T3 layers may be also identifiable in Reifling limestones from the Western Calcareous Alps (e.g., from the Martinswand section from Tyrol [*Bechstädt and Mostler*, 1974]). Tephrochronologic correlations with the Buchenstein basin of northern Italy are more difficult because of the large number of tuffaceous layers in this basin. However, grouped on the basis of local frequency peaks, the Buchenstein sequence also shows three major tuffaceous intervals which are located in the well-known Bagolino section at 61 m, between 70 and 75 m and 84-88 m, respectively [*Brack et al.*, 1995]. According to *Nicora and Brack* [1995], these intervals fit closely in age with the three Reifling basin layers.

Geological Setting, Lithology and Sampling

The studied sections are located in the eastern part of the Northern Calcareous Alps, within the so-called Bajuvaricum mega-unit. This unit consists of a series of north vergent nappes stacked between the Cretaceous and the early Cenozoic [e.g., *Tollmann*, 1976]. Two of the sampling sites, the Mendlingbach and Gamsstein sections, are situated in a local tectonic structure, the "Reiflinger Scholle", intercalated between the Lunz nappe to the north and the Oetscher nappe to the south. This structure, which has a maximum length of approximately 10 km between the village of Göstling and the Enns valley (Figure 2), is itself divided into smaller units called "Schuppen" of which the Gamsstein-Schuppe includes

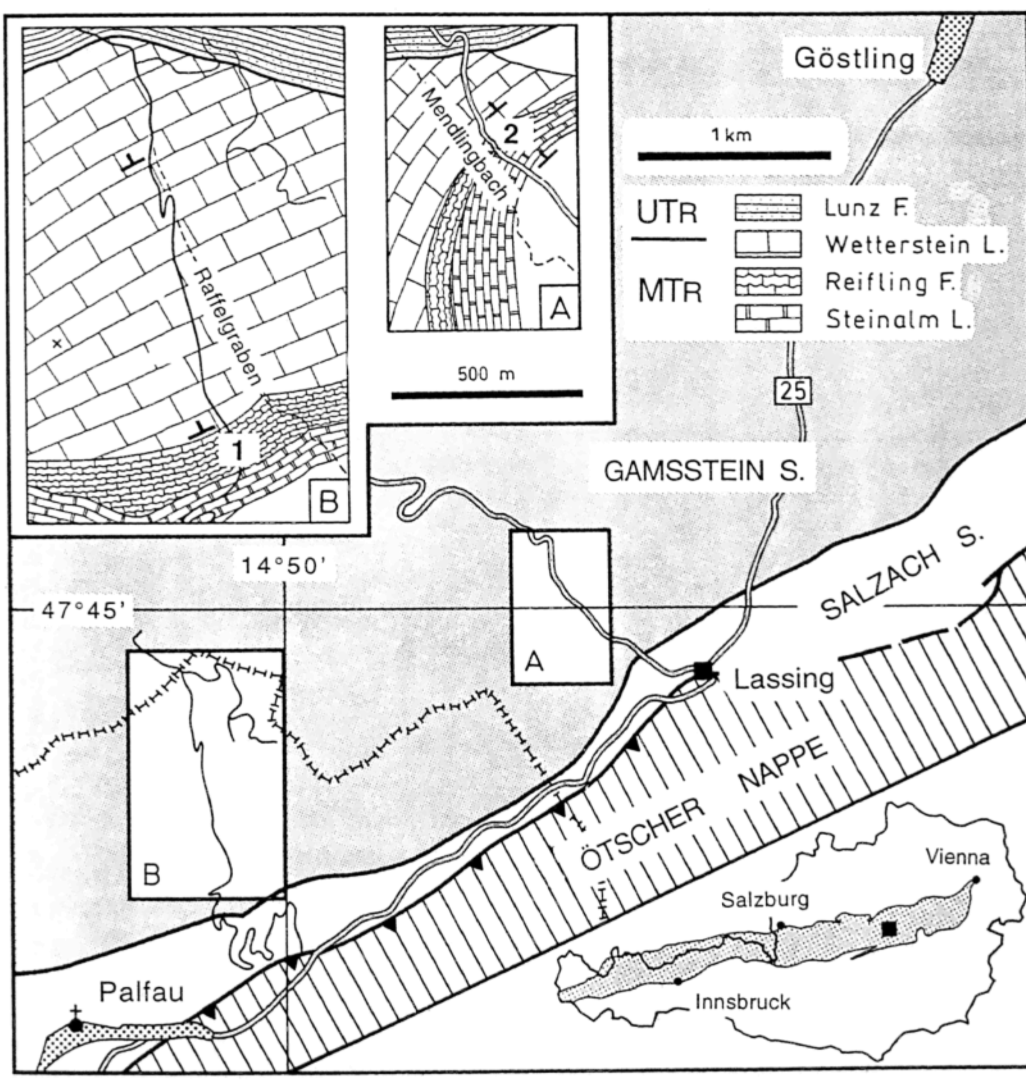


Figure 2. Location map of the Gamsstein (B) and Mendlingbach (A) sections and simplified geologic map of the sampling area.

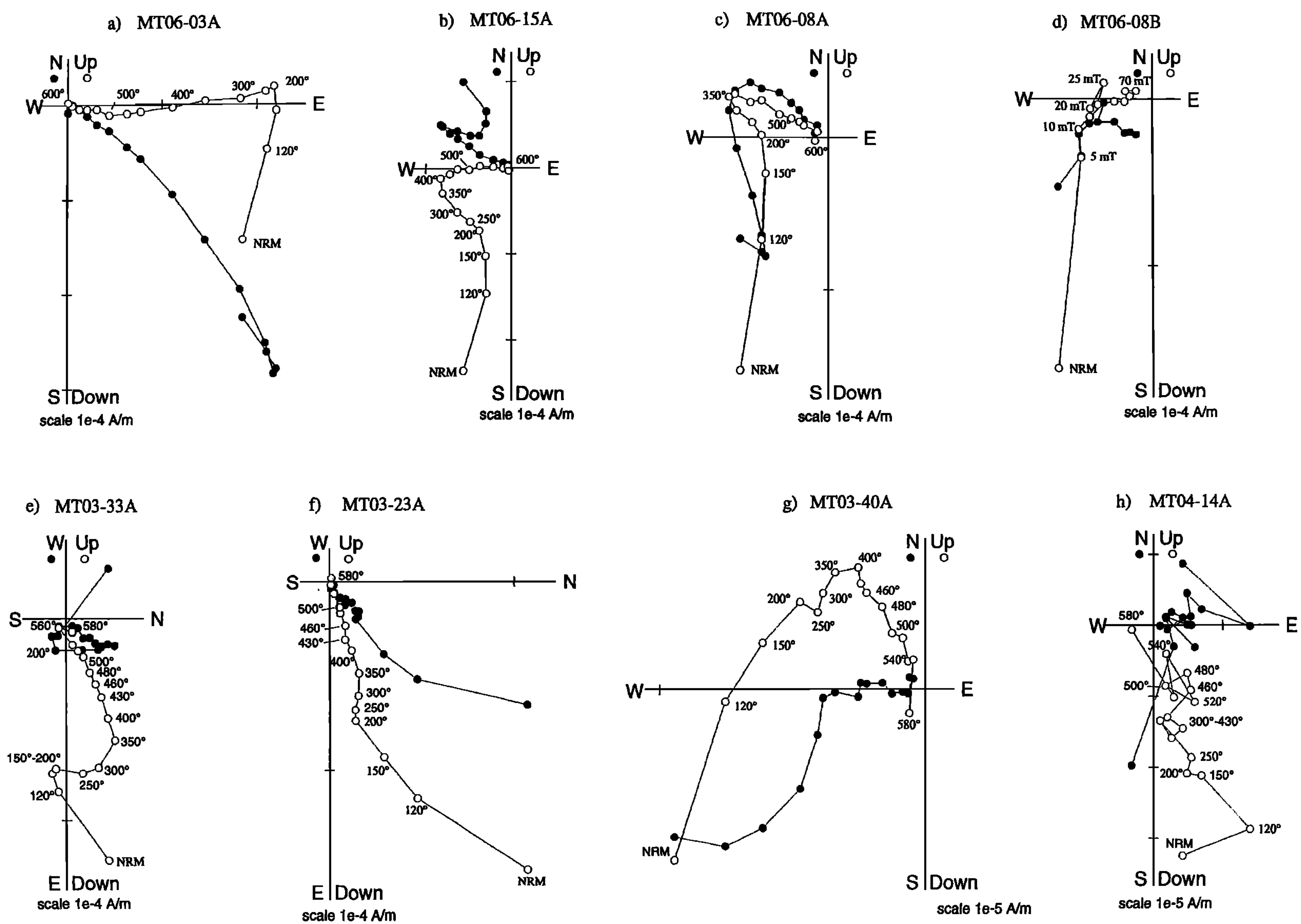


Figure 3. Orthogonal vector diagrams obtained by thermal and AF demagnetization of samples from the (a, b, c, d) Gamsstein section and (e, f, g, h) Mendlingbach sections. The solid (open) symbols refer to the horizontal (vertical) plane. All the diagrams are shown before bedding correction.

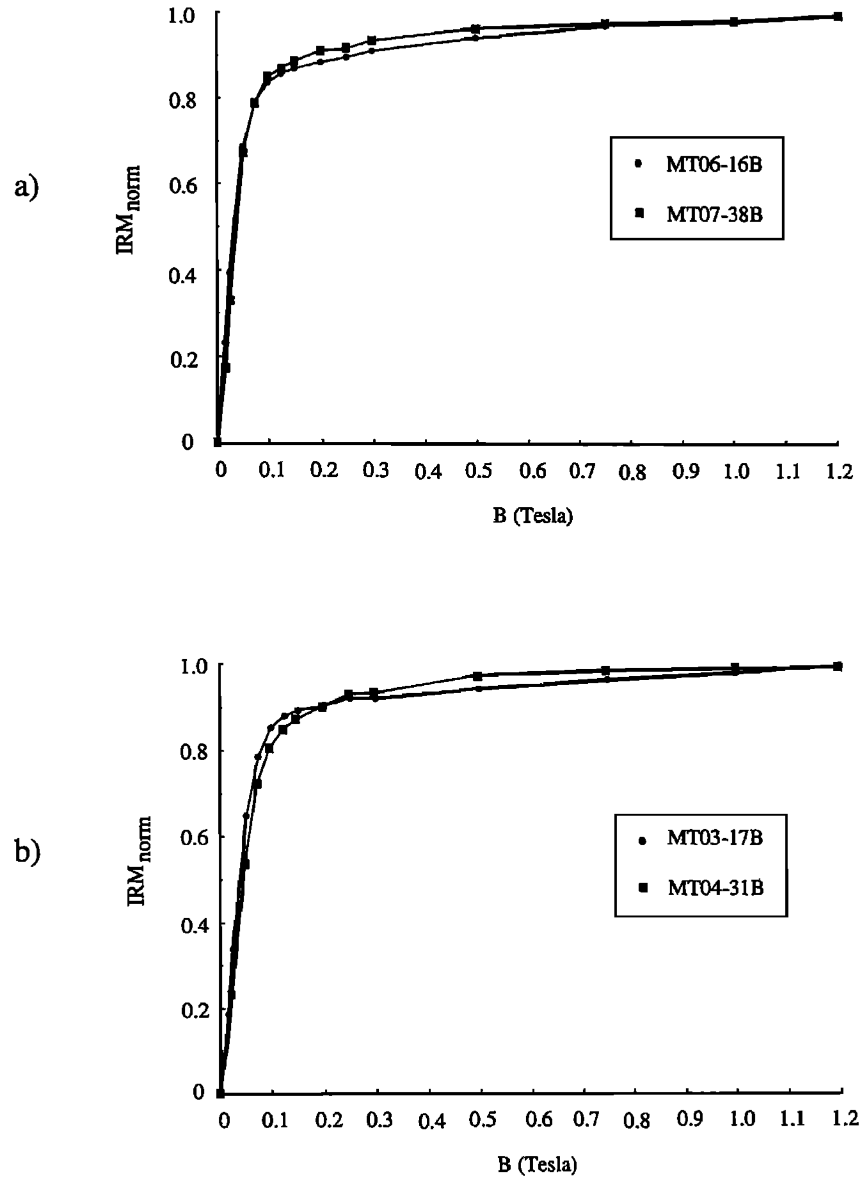


Figure 4. IRM analyses of samples from the (a) Gamsstein and (b) Mendlingbach sections. In both sections the saturation is almost achieved in a 0.3 T field which likely indicates a magnetization dominated by a mineral in the magnetite family. A small fraction of a high-coercivity mineral is also observed.

the two sections (Figure 2). The third section (Mayerling) is located about 100 km to the east of the other two sections, approximately 30 km southwest of Vienna (see *Gallet et al.*, 1994, Figure 1]. A previous study of this section provided a Lower Carnian magnetostratigraphic sequence [*Gallet et al.*, 1994].

Ladinian strata crop out widely within the NCA. They can be broadly grouped in two main sedimentary environments: (1) large shallow-water carbonate platforms of the Wetterstein formation and (2) deeper basins filled with hemipelagic limestones of the Reifling formation. The latter usually consists of dark grey, chert-rich, thin-bedded filament and radiolarian-bearing wackestones. Although belonging to the Reifling formation, our sections show some facial differences as they are composed of light colored (grey to yellowish) limestones of various thicknesses with less chert. The microfauna is also more diverse, containing foraminifera and relatively abundant conodonts. The intercalations of redeposited shallow-water debris in Mayerling and the close proximity of platform carbonates in Gamsstein and Mendlingbach suggest a specific oceanographic environment for these sections.

Gamsstein Section

This section is located about 1 km northeast of the village of Palfau, and approximately 2 km southwest of Mendlingbach (Figure 2, site B). The section outcrops at an altitude of 1010 m, along a forest road leading from the Bundesstrasse 25 to the Gamsstein plateau, at the western side of the deeply incised Raffel grabben. The section was divided into two subsections about 25 m from each other. The first site (Gamsstein 1) consists of 27 m of Upper Ladinian sediments from which we collected 88 paleomagnetic samples. Twenty five samples

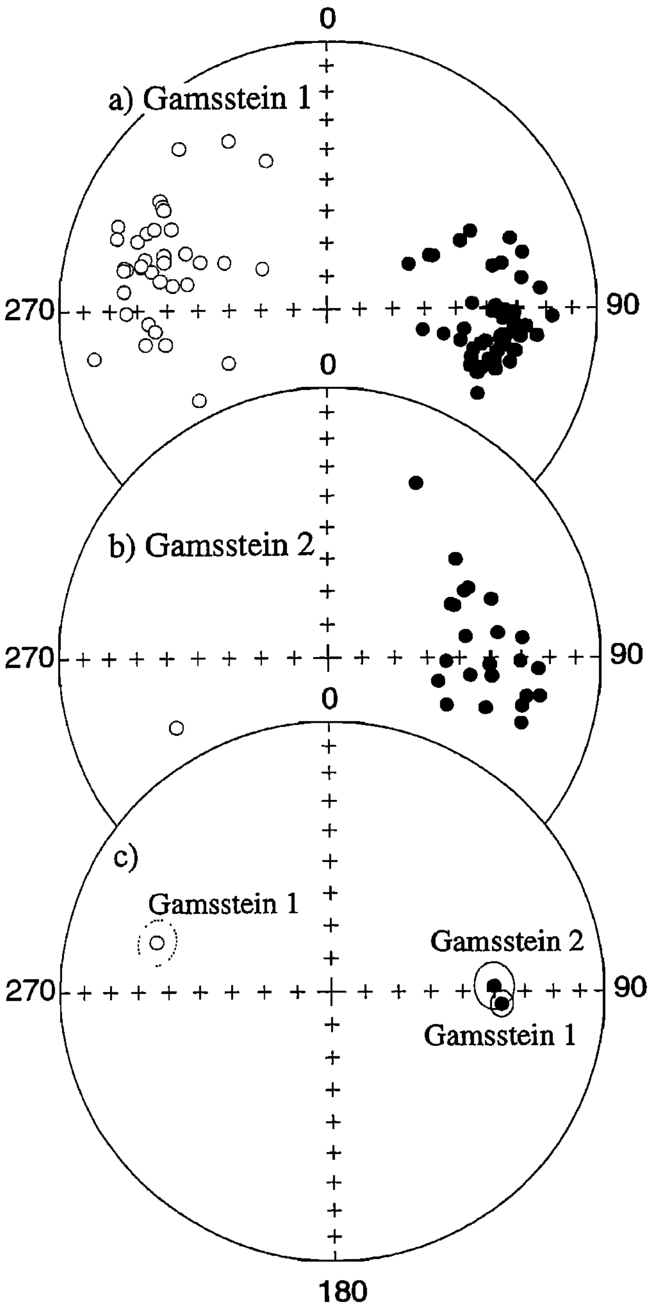


Figure 5. Equal-area projection of directions of the high-unblocking temperature component obtained from the (a) Gamsstein 1 and (b) Gamsstein 2 subsections. Solid (open) symbols refer to directions in the lower (upper) hemisphere. (c) The mean normal and reversed polarity directions.

were drilled from the second (Gamsstein 2), which is stratigraphically thinner (5 m) with an age ranging from the Upper Anisian to the Lowermost Ladinian. Approximately 50 conodont samples were obtained from these two subsections.

Mendlingbach Sections

Two sections were sampled near the small village of Lassing (Figure 2). The first, called Mendlingbach-East, is exposed along a road at the eastern side of a valley, about 1 km north of Lassing. It has a thickness of about 30 m. The second, called Mendlingbach-West section, is located along the western side of the same valley where a forest road was recently built. This latter section is important because it includes a 13-m-thick interval that is missing in Mendlingbach-West due to faulting. Fifty five conodont samples were collected from the whole sequence, and the related data indicate an age from the Lower to the Upper Ladinian. Over 100 paleomagnetic samples were drilled in the Mendlingbach-East section and 40 in the Mendlingbach-West section.

Mayerling Section

This section is exposed along a railway cutting, 1 km northwest of the village of Weissenbach (see *Gallet et al.*, 1994, Figure 1]. A new stratigraphic interval of approximately 40 m was sampled. This sequence differs lithologically from typical Reifling limestones because of thicker bedding, lack of chert bands, and by the presence of stromatactis-like calcite cavities up to 5 cm in length and 2 cm in height. Twentv-five conodont samples provided a faunal record from the Longobardian 2 to the Longobardian 3 zones (Upper Ladinian). Forty samples were collected for paleomagnetic analysis.

Chronostratigraphy and Biostratigraphy of the Reifling Sections

The Upper Anisian (Illyrian substage) is very thin in the investigated sections (approximately 1.5 m) and starts with a distinct erosional surface. Accumulations of cephalopod shell fragments and the microfacies (echinoderm and glauconite bearing packstones) indicate bottom current activity with possible erosion and/or nondeposition of sediments. The upper half of this stratigraphic interval is dated by ammonoids. *Aplococeras ? sp.*, *"Ceratites"* cf. *lenis*, *Parakellnerites rothpletzi*, *P. zonianensis*, *Hungarites* ? cf. *plicatus*, *Flexoptychites acutus*, *F. noricus*, *F. gibbus* and *Ptychites arthaberi* were found in Gamsstein (bed M1). Following *Brack and Rieber* [1994], this fauna clearly characterizes the Reitzi zone and is probably located close to the base of the Nevadites recte Secedensis zone sensu *Brack and Rieber* [1994]. The rich conodont fauna of M1 includes *Neogondolella constricta/cornuta*, *Paragondolella liebermanni* and *P. excelsa*. The FOD of *N. pseudolonga* is located three beds above M1 (about 60 cm), less than 10 cm below the tuffaceous layer T1. For practical reason, the Anisian-Ladinian boundary is drawn here at the base of T1, 20 cm below the FOD of *P. trammeri*. Following *Nicora and Brack* [1995] who have found *N. transita* from the Chiesense level (top of the Secedensis zone) of Bagolino, the Fassanian 1 to 2 boundary has to be placed within the Transita zone (Figure 1).

The boundary between the Lower and Upper Ladinian coincides with the FOD of *P. inclinata* as documented from ammonoid-dated rocks from Epidaurus. Within the Upper Ladinian, no corresponding boundaries between ammonoid and conodont zones could be established. The adopted Longobardian 1/2 boundary results from a tephrochronologic correlation of the Reifling T3 layer with the 84-88 m tuffaceous interval of the Bagolino section. The latter horizon is included into the lower Longobardian 2 zone on the basis of ammonoids and daonellids by *Brack et al.* [1995]. Conodonts support the above postulated correlation because *Budurovignathus mungoensis* is observed in these tuffaceous

Table 1. Mean Directions of the Characteristic Magnetic Components Obtained From the Gamsstein Subsections

	Component	N	Declination, deg	Inclination, deg	Declination, deg	Inclination, deg	a_{95}	K
			Before Tilt Correction		After Tilt Correction			
Gamsstein 1	Normal	47	121.9	15.5	94.8	35.6	3.7	33.1
	Reversed	36	306.5	-7.5	285.6	-35.0	6.2	15.9
	General	83	123.9	12.2	99.4	35.5	3.4	21.5
Gamsstein 2	Normal	22	122.4	21.0	88.2	40.1	6.4	24.5
	Reversed	1	296.5	-41.3	245.7	-38.1	--	--
	General	23	122.1	23.3	87.2	40.1	6.2	24.6
General	General	106	123.3	16.2	96.6	36.7	3.1	21.6

levels from both sections. The boundary between Longobardian 2 and 3 cannot be well constrained by conodonts and it might be located somewhere in the upper part of the Longobardicus zone. Finally, the Ladinian/Carnian boundary is datable by the FOD of *Paragondolella polygnathiformis*, a datum already used in our earlier magnetostratigraphic studies [*Gallet et al.*, 1993a, 1994].

The ranges of platform conodont species in the Gamsstein, Mendlingbach and Mayerling sections are shown in Figure 1. *N. pseudolonga*, *N. transita*, *P. excelsa*, *P. trammeri* and *Gladigondolella tethydis* are the most abundant species found in the Lower Ladinian, and *P. inclinata*, *B. mungoensis* and *G. malayensis* are the most abundant species found in the Upper Ladinian. We paid special attention to the fact that some stratigraphic guide forms have more limited ranges in the Reifling intraplatform basin than in the eupelagic to miopelagic settings of Epidaurus or of the Balaton region [*Kovacs*, 1994]. Indeed, some species common in the Reifling basin (e.g., *N. pseudolonga*, *N. transita* and *Metapolygnathus tadpole*) are missing in Epidaurus. Some others (*N. praehungarica*, *P. trammeri* and *B. hungaricus*) have more limited ranges in the Reifling limestones. Therefore the detailed vertical distribution of all species has been primarily established and used for correlation of the sections sampled for magnetostratigraphy. Future studies may decide on its applicability as a local reference scale for Ladinian intraplatform basins of the Alpine region.

The discriminated zones are all defined by the FOD of their nominate species except for the Diebeli zone. In our sections, *N. pseudolonga* replaces *N. cornuta* or *N. constricta cornuta* sensu *Kovacs* [1994] in the bed just below T1. *P. trammeri* used by *Krystyn* [1983] as a marker for defining the base of the Ladinian in the pelagic facies, appears directly below T1 in the Mendlingbach-East section and slightly higher (0.2 m) in the Gamsstein section with rare juvenile individuals but becomes common above. *P. excelsa* and *G. tethydis* range throughout the Pseudolonga zone. The sudden increase in frequency of the latter species could be used as an additional lower zonal boundary indicator. *N. transita* which may be a synonym of *N. excentrica* (see also comments by *Kovacs* [1994]) occurs together with *G. tethydis*, *P. excelsa* and *P. trammeri* throughout the Transita zone. *B. hungaricus* appears with rare specimens in the upper half of this zone. Within the Inclinata zone, *P. inclinata*, *G. tethydis*, *B. hungaricus* and *P. trammeri* are common. In contrast, *N. praehungarica* is relatively rare and restricted to the Gamsstein section. A single but diagnostic specimen of *B. japonicus* was helpful to define the Fassanian-Longobardian boundary within the *Paragondolella*-free interval of the Mendlingbach-West section. *B. mungoensis*, *G. tethydis*, *P. trammeri*, *P. inclinata* and *G. malayensis* range throughout the Mungoensis zone. *B. hungaricus*, which is long ranging in the Epidaurus section, is restricted to the lower half of this zone. The index form of the Longobardicus zone is common in Mendlingbach but relatively rare in the Gamsstein and Mayerling sections. *G. malayensis*, *P. inclinata* and *P. mungoensis* range throughout this zone in all sections. *P. fueloepi* (sensu holotype *Kovacs* [1994]) and *P. trammeri* occur sporadically in Gamsstein and Mayerling, the latter of which disappears within the zone. The FOD of *Metapolygnathus tadpole* occurs low within the Longobardicus zone in the Mendlingbach-East section. As *B. diebeli* has a very long range, here we define the base of the

Diebeli zone by the FOD of *B. mostleri*. This boundary is recognized only in the Mayerling section, as time equivalents have not been sampled in the other sections. Throughout the Diebeli zone, the faunal composition is quite uniform and dominated by *P. inclinata*, *G. malayensis* and *B. mostleri* . *B. mungoensis* and *B. diebeli* are less frequent and *B. longobardicus* is present only in the lowermost part of this zone. Although missing in the Mayerling section, *M. tadpole* is known from many time-equivalent sections of the Reifling basin. The upper limit of the Diebeli zone has been modified by *Krystyn* [1983] to coincide with the FOD of *Metapolygnathus polygnathiformis*.

Paleomagnetic Results

Paleomagnetic analyses were carried out with a three-axis CTF SQUID magnetometer in the magnetically shielded room at the Institut de Physique du Globe. Samples were thermally demagnetized in approximately 15 steps using a laboratory-built furnace. For comparison, several samples were also demagnetized by alternating fields (AF) with a GSD1 Schönstedt demagnetizer. The paleomagnetic directions were determined by least squares analysis [*Kirschvink*, 1980], and the statistical methods of *Fisher* [1953] and *McFadden and McElhinny* [1988] were used to compute the mean directions.

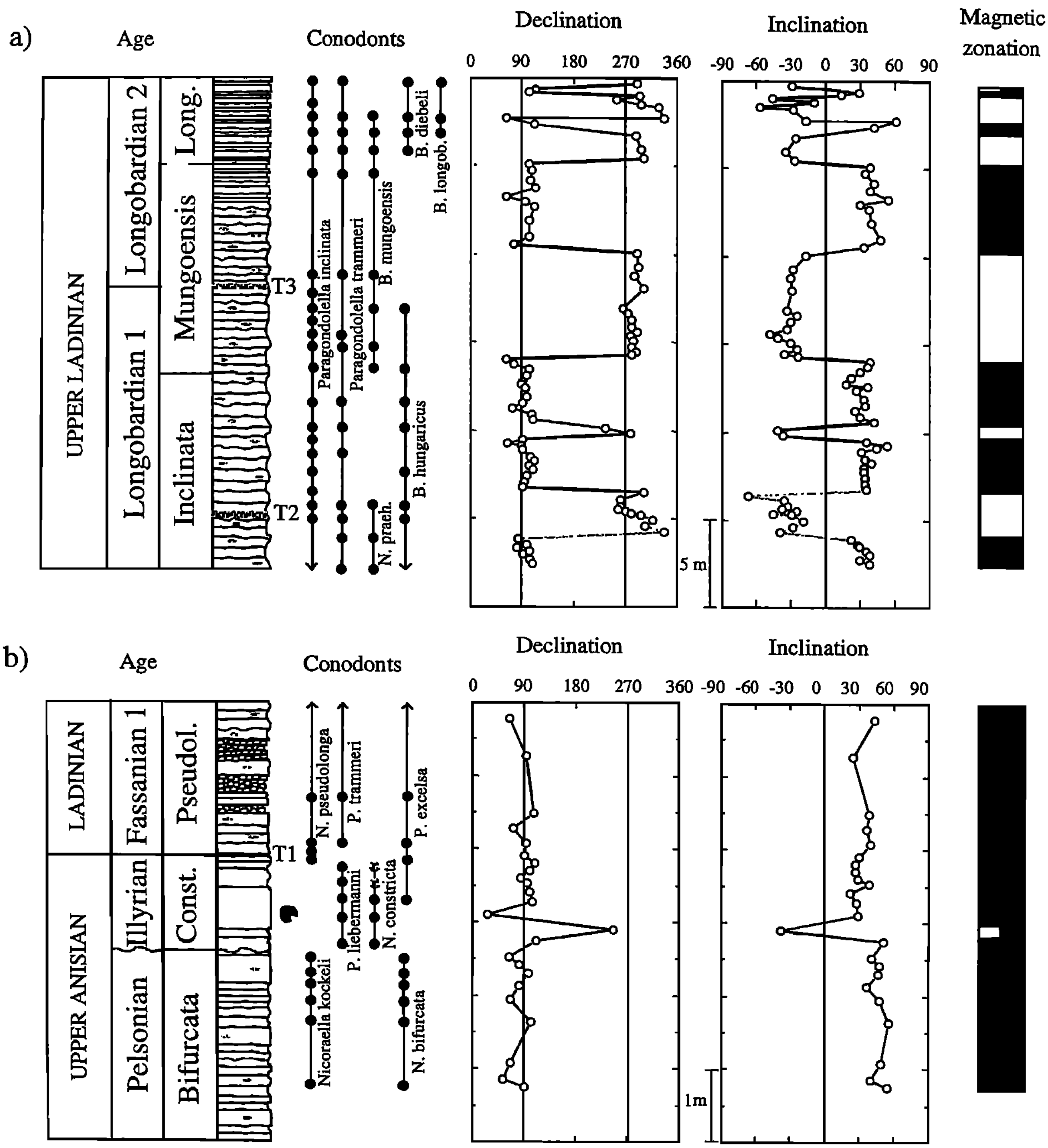


Figure 6. Magnetic stratigraphy obtained from the (a) Gamsstein 1 and (b) 2 subsections. The age zonation is established from conodonts. T1, T2 and T3 indicate the location of three tuffaceous layers. A sequence of 11 magnetic polarity intervals is obtained from Gamsstein 1, one of them being poorly defined by a single sample in the topmost part of the subsection. Another poorly defined magnetic interval is observed during the Illyrian stage from the Gamsstein 2 subsection.

Gamsstein and Mendlingbach Sections

Except for the samples from the upper part of the Mendlingbach-East section, the bulk susceptibility measured after each demagnetization step remains stable during progressive thermal demagnetization. This indicates that no noticeable change in magnetic mineralogy occurs during the heating-cooling process. A similar paleomagnetic behavior is observed both in Gamsstein and Mendlingbach. Examples of demagnetization diagrams are shown in Figure 3 before bedding correction. They indicate the presence of three magnetic components. A first component of normal polarity is removed between the NRM and approximately 200°C. Before bedding correction, the directions obtained for this component are close to the direction of the present Earth's magnetic field. An intermediate component is removed next between 200°C and about 450°C. Although this component is present in many samples (e.g., Figures 3b and 3e), its direction can never be precisely determined because of significant overlap of its temperature spectrum. However, this component has clearly a reversed magnetic polarity before bedding correction. Finally, a high unblocking temperature (or characteristic) component with the two polarity states is isolated between about 500°C and 580°-600°C (normal polarity, Figures 3a, 3e and 3h; reversed polarity, Figures 3b, 3c, 3d and 3g).

The magnetic behavior is more complex in samples from the upper part of the Mendlingbach-East section. That difference is illustrated by large changes in bulk susceptibility above 450°C. This clearly shows the occurrence of mineralogic transformations in these samples, which sometimes prevents the determination of a reliable high unblocking temperature component. However, the magnetic polarity of these samples appears unambiguous (Figure 3h).

Isothermal remanent magnetization (IRM) experiments show that most of the magnetization is saturated in a 0.3 T field, but a small fraction of high-coercivity minerals is also observed (Figures 4a and 4b). Together with maximum unblocking temperatures close to 580°C-600°C (Figure 3), these characteristics indicate that the magnetization is

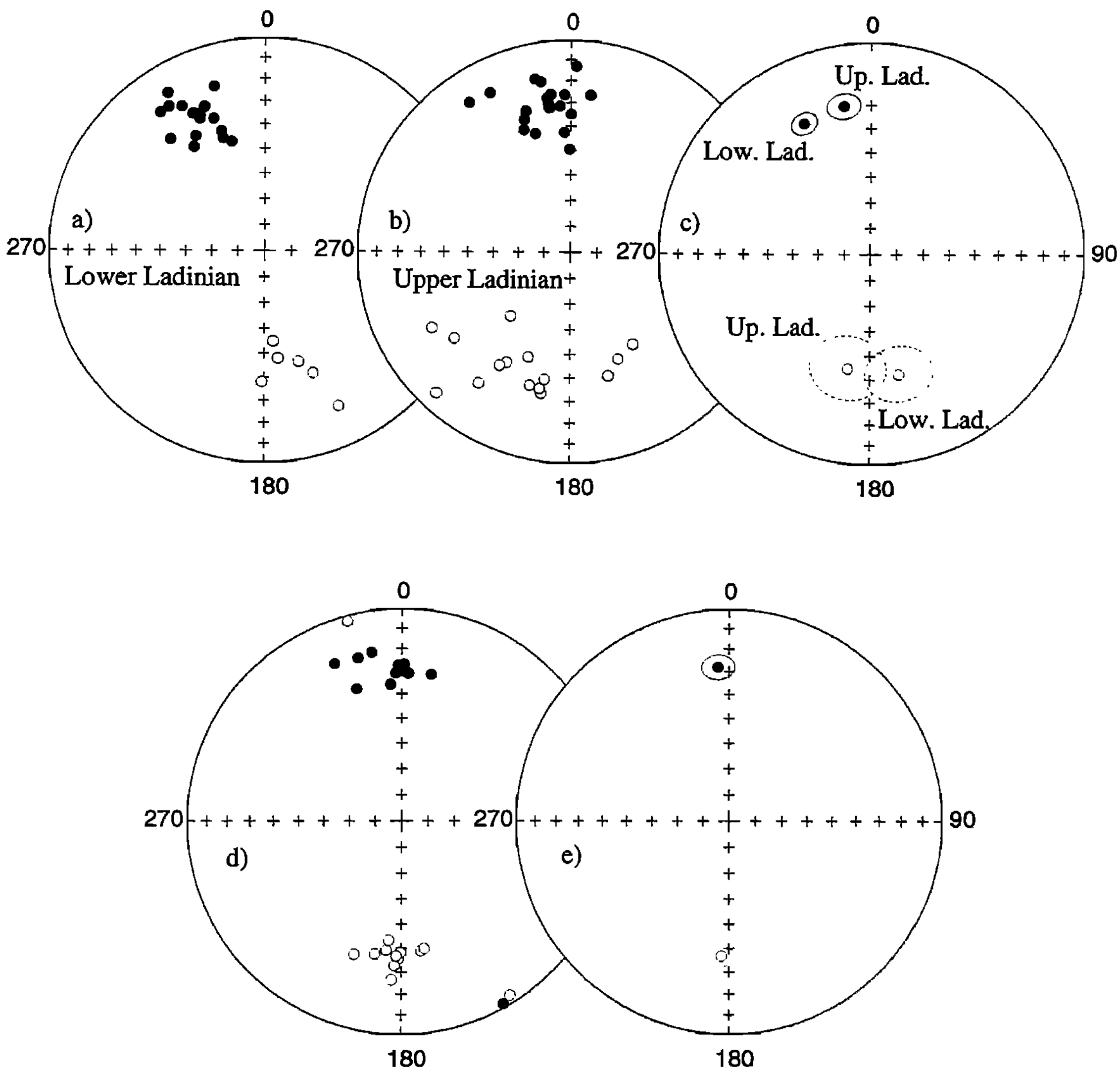


Figure 7. Equal-area projections of directions of the high-unblocking temperature component isolated throughout the (a, b, c) Mendlingbach-East and (d, e) Mendlingbach-West sections. Same convention as in Figure 5. Although a large scatter is observed in directions for the Upper Ladinian from the Mendlingbach-East section (Figure 7b), a rotation of approximately 20° is observed betwen the Lower and Upper Ladinian from this section (Figure 7c).

essentially carried by a mineral of the magnetite family. The small fraction of high-coercivity minerals may correspond to the presence of hematite or iron sulfides. In particular, the presence of pyrrhotite may explain the changes in magnetic mineralogy observed during thermal demagnetization of samples from the upper part of the Mendlingbach-East section. Further confirmation of high coercivity minerals is also obtained from alternating field (AF) demagnetization up to 70 mT of samples from the Gamsstein section (Figure 3d). In these samples a component of reversed polarity before bedding correction is clearly not demagnetized. We suggest that this latter component is equivalent to the intermediate component isolated by thermal demagnetization.

The directions of the high unblocking temperature component isolated throughout the two Gamsstein subsections are shown in Figure 5. Both normal and reversed polarity directions are observed. The mean normal and reversed directions are not exactly antipodal (Table 1; γ=10.0°, γc=6.8°) [*McFadden and McElhinny*, 1990]. This is probably due to the presence of the poorly defined intermediate magnetic component which may introduce a bias in the determination of the high-unblocking temperature component. Nevertheless a clear magnetic zonation is obtained from both subsections (Figures 6a and 6b). Two intervals, probably of short duration, are defined by single samples, one during the uppermost Longobardian 2 zone (Gamsstein 1; Figure 6a) and the second during the Illyrian (Gamsstein 2; Figure 6b).

The directions isolated from the Mendlingbach sections are shown in Figure 7. Two equal area projections are presented for the Mendlingbach-East section, separating data of the lower and upper Ladinian, from each side of a fault. Although a large scatter is observed for the Upper Ladinian (Figure 7b), which is likely due to the alteration of the magnetic mineralogy during thermal demagnetization, two statistically different mean directions are observed (Figure 7c), showing a relative rotation of 20.2° +/- 8.1° between the two parts of this section (Table 2). In contrast, the directions obtained for the Lower Ladinian from the Mendlingbach-East section and from Mendlingbach-West section are better clustered. But as in Gamsstein, the mean normal and reversed polarity directions are not exactly antipodal: Mendlingbach-East: γ=14.6°, γc=10.0°; Mendlinbach-West: γ=5.5°, γc=5.3° [*McFadden and McElhinny*, 1990]. A sequence of 10 magnetic polarity intervals is obtained from the Mendlingbach-East section (Figure 8a). An interval of normal polarity within the Longobardian 1 zone is poorly defined, one sample showing an intermediate direction. The location of the fault at the Lower-Upper Ladinian boundary coincides with a change in magnetic polarity, confirming a sedimentary gap at this level. The Mendlingbach-West section yields a sequence of eight additional polarity zones, but two of them are again poorly defined by single samples (Figure 8b).

Mayerling Section

The paleomagnetic behavior of these samples is identical to the one previously observed in the Lower Carnian part of this section [*Gallet et al.*, 1994]. A description of this behavior can thus be found in this previous study. The directions isolated for the high unblocking temperature component are reported in Figure 9a. The mean direction computed for the Upper Ladinian is statistically similar to the direction

Table 2. Mean Directions of the Characteristic Magnetic Components Obtained Throughout the Mendlingbach Sections

	Component	N	Declination, deg (Before Tilt Correction)	Inclination, deg (Before Tilt Correction)	Declination, deg (After Tilt Correction)	Inclination, deg (After Tilt Correction)	a_{95}	K
Mendlingbach-East, Lower Ladinian	Normal	18	68.0	66.3	333.1	31.2	4.7	55.6
	Reversed	6	254.4	-55.6	166.6	-41.0	11.9	32.9
	General	24	70.0	63.7	336.2	33.8	4.8	38.3
Mendlingbach-East, Upper Ladinian	Normal	19	64.6	61.7	349.7	29.4	5.6	36.4
	Reversed	11	256.7	-43.4	190.0	-39.9	10.8	18.7
	General	30	70.3	55.1	356.4	33.6	6.0	20.4
Mendlingbach-West	Normal	19	57.5	46.1	356.2	31.4	4.1	66.8
	Reversed	17	245.0	-42.9	181.6	-34.5	3.4	109.3
	General	36	63.1	44.4	358.7	32.9	2.7	76.6

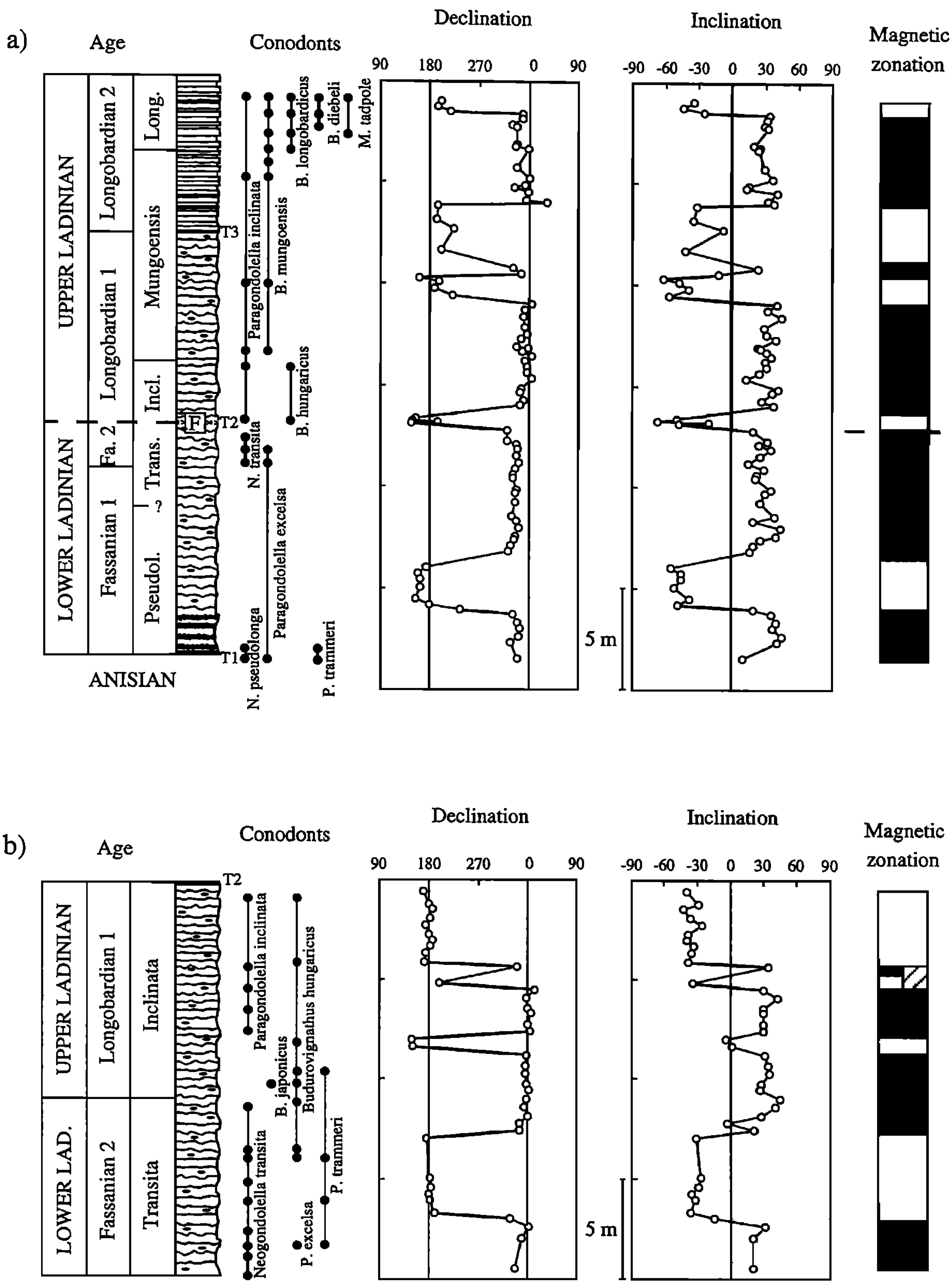


Figure 8. Magnetic stratigraphy obtained from the Mendlingbach-East and Mendlingbach-West sections. In both sections the age zonation is established from conodonts. (a) A magnetic sequence of 10 intervals is obtained from Mendlingbach-East. F indicates the location of a fault between the Lower and Upper Ladinian. (b) Eight magnetic intervals are obtained from the Mendlingbach-West section, but two of them, during the Longobardian 1, are poorly defined.

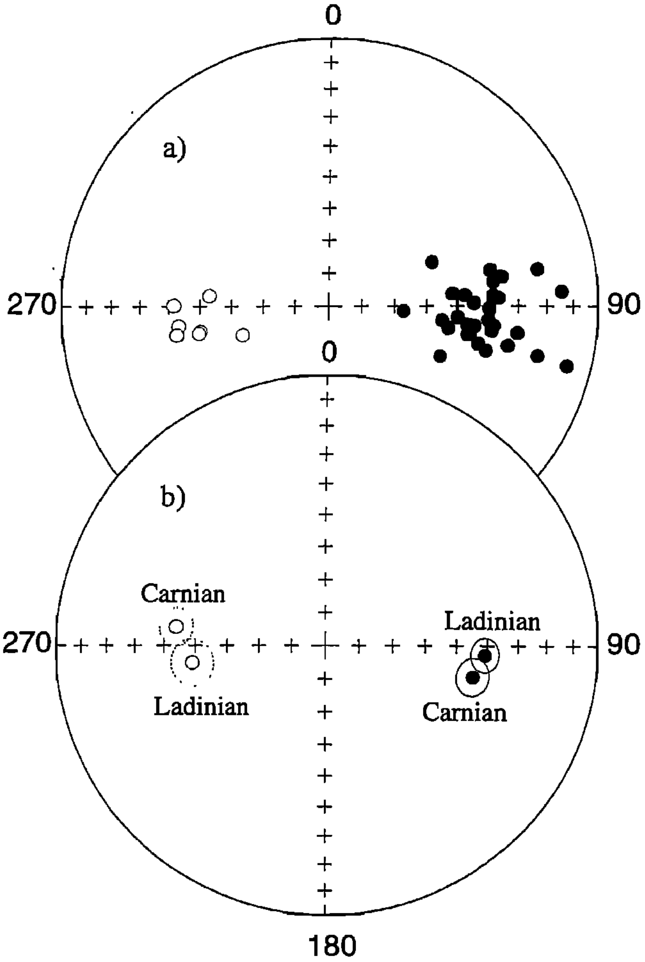


Figure 9. (a) Equal-area projection of the directions isolated for the characteristic component from the Upper Ladinian part of the Mayerling section. (b) A comparison between the Upper Ladinian and the Lower Carnian mean normal and reversed polarity directions.

obtained for the Lower Carnian (Table 3 and Figure 9b). Six additional magnetic intervals are obtained, yielding a complete sequence of 14 intervals including the Lower Carnian (Figure 10).

Discussion

The easterly directions found in Gamsstein and Mayerling are very similar to directions previously obtained from early Jurassic sections from the NCA [e.g., *Mauritsch and Frisch*, 1978, 1980; *Channell et al.*, 1992]. A large difference in declination is observed between the Mendlingbach and Gamsstein sections, although both sections belong to the same tectonic unit. But local and large rotations have already been reported from the NCA [e.g., *Gallet et al.*, 1996]. Moreover, the data obtained from the Mendlingbach-East section show a more complex tectonic history with the occurrence of a rotation of approximately 20° between the Lower and Upper Ladinian (Figure 11). The mean directions obtained from the different sections can thus be compared

Table 3. Mean Directions of the Characteristic Magnetic Components Obtained for the Upper Ladinian and Lower Carnian from the Mayerling Section

	Component	N	Declination, deg (Before Tilt Correction)	Inclination, deg (Before Tilt Correction)	Declination, deg (After Tilt Correction)	Inclination, deg (After Tilt Correction)	a_{95}	K
Mayerling, Upper Ladinian	Normal	30	32.5	51.6	93.4	40.7	4.7	31.9
	Reversed	7	198.2	-46.3	262.7	-48.7	6.7	81.9
	General	37	28.7	50.0	91.6	42.3	4.2	33.1
Mayerling, Lower Carnian	General	63	38.6	65.7	100.0	43.6	3.8	23.5

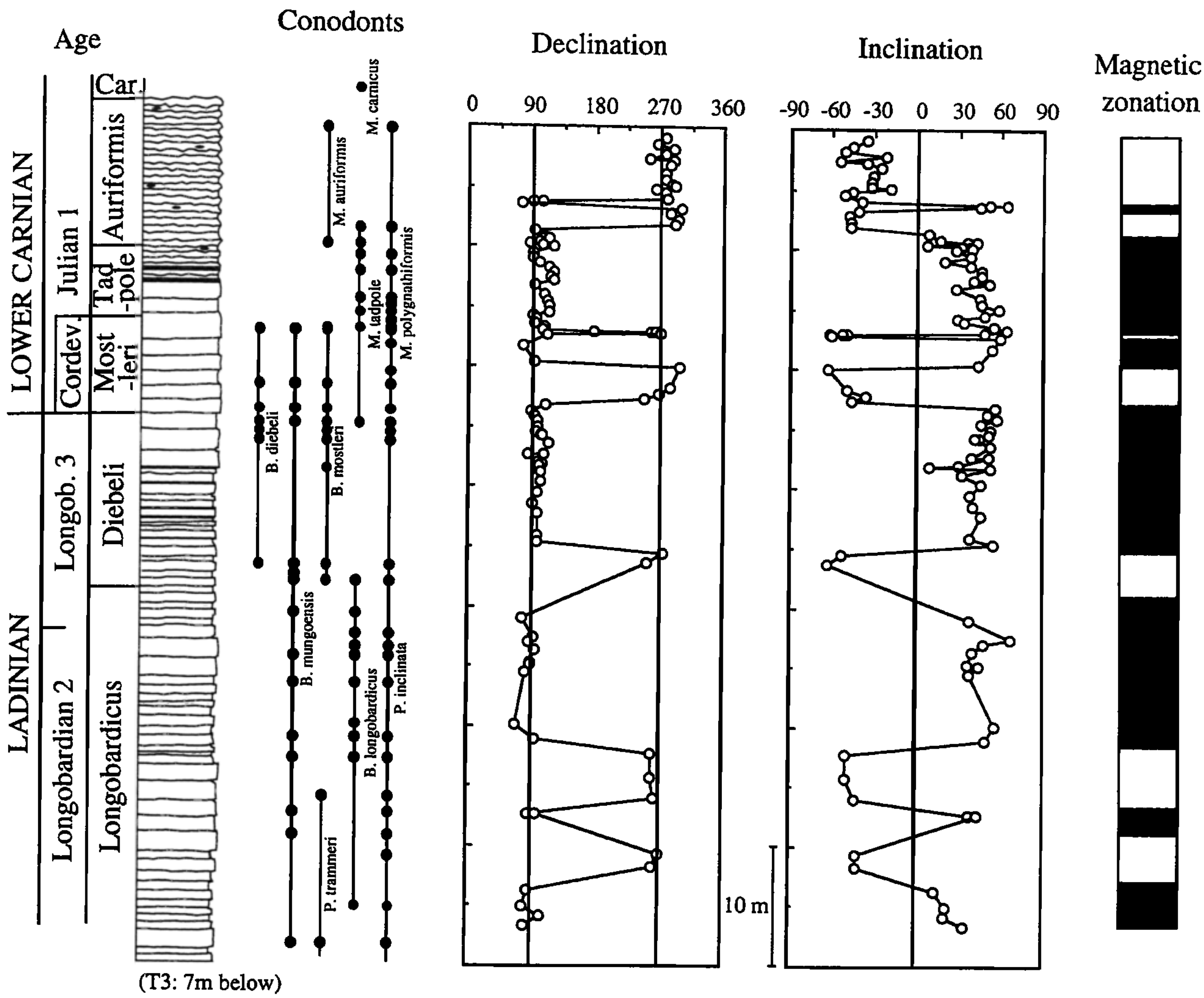


Figure 10. Upper Ladinian to Lower Carnian magnetostratigraphy from the Mayerling section. A sequence of 14 magnetic intervals is observed. Black bars within the lithostratigraphic column represent Partnach marl intercalations.

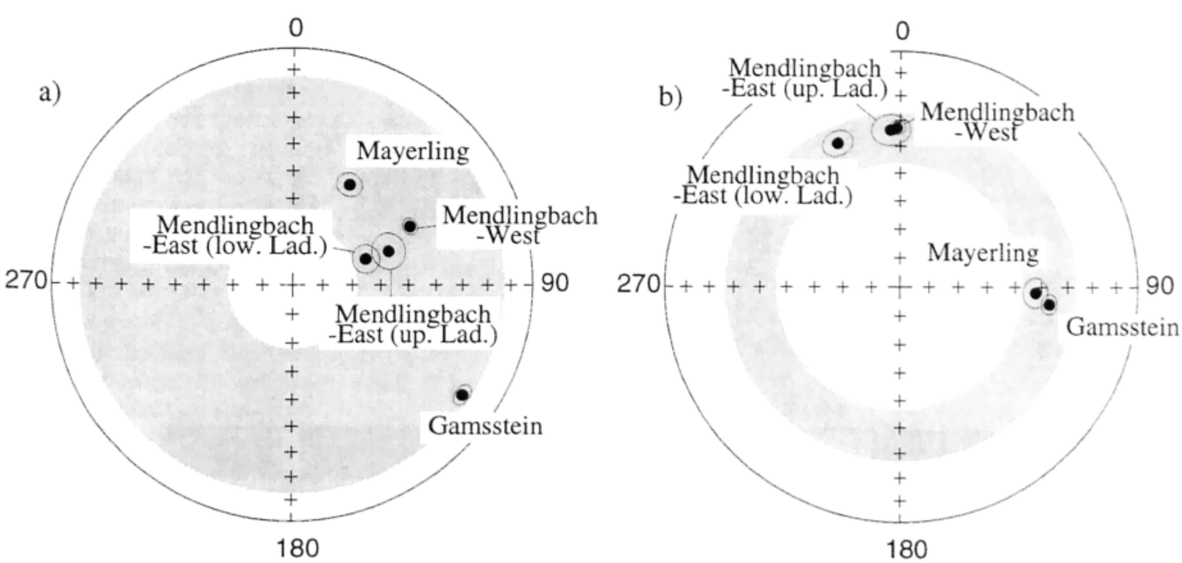
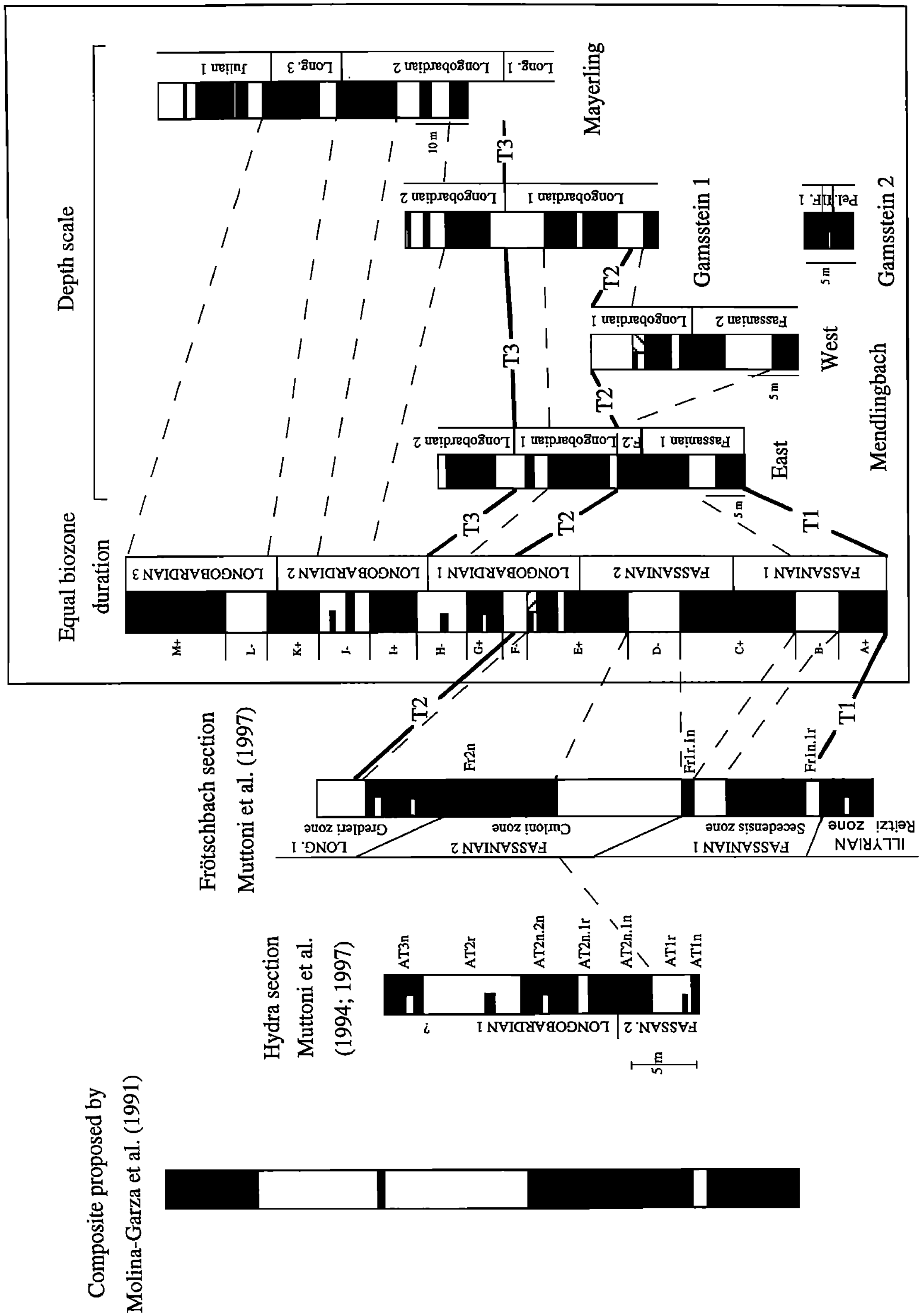


Figure 11. Equal-area projection of the mean directions obtained from the Gamsstein, Mendlingbach and Mayerling sections (a) before and (b) after bedding correction. The dispersion of the inclinations notably decreases after bedding correction.



Depth scale
Equal biozone duration
Mayerling
Julian 1
Long. 3
Longobardian 2
Long. 1
10 m
Gamsstein 1
Longobardian 1
Gamsstein 2
Pel. F. 1
5 m
Mendlingbach
West
Fassanian 2
East
Fassanian 1
LONGOBARDIAN 3
LONGOBARDIAN 2
LONGOBARDIAN 1
FASSANIAN 2
FASSANIAN 1
T1
T2
T3
Frötschbach section
Muttoni et al. (1997)
Fr2n
Fr1r.1n
Fr1n.1r
LONG. 1
Gredleri zone
Curioni zone
Secedensis zone
Reitzi zone
ILLYRIAN
Hydra section
Muttoni et al.
(1994; 1997)
AT3n
AT2r
AT2n.2n
AT2n.1r
AT2n.1n
AT1r
AT1n
FASSAN. 2
Composite proposed by
Molina-Garza et al. (1991)

considering only the inclinations. The bedding correction clearly decreases the dispersion of the inclinations (Figure 11; in situ: I_{mean}=53.3°, α_{95}=13.3°, K=48.6, N=5; tilt corrected: I_{mean}=36.0°, α_{95}=8.2°, K=126.4, N=5 [*McFadden and Reid*, 1982]). The better consistency in inclination after bedding correction, together with a magnetization essentially carried by magnetite and the presence of normal and reversed polarity directions in all sections, indicate that the high-unblocking temperature components isolated from the three localities were acquired during sediment deposition. In addition to this primary component, our study shows evidence for a remagnetization phase in a reversed polarity field. Because of overlaps with other components, no reliable paleomagnetic direction can be estimated for this component. A similar case was recently observed from middle Triassic (Anisian) limestones from Albania [*Muttoni et al.*, 1996]. Furthermore, a reversed polarity component of remagnetization was also observed from the Langmoos section (close to Adnet; central NCA [*Gallet et al.*, 1993b]). In this latter study we suggested a remagnetization occurring during the last deformation phase of the NCA (i.e., during the late Eocene [*Tollmann*, 1987; *Channell et al.*, 1992]), although a very recent remagnetization possibly during the Matuyama magnetic period was not excluded.

This study provides several magnetic polarity sequences which together document the Upper Anisian, the Ladinian and the Lower Carnian magnetostratigraphy. A comparison between these sequences is shown in Figure 12. The correlations that we propose (dashed lines) are based on the conodont zonation and tephrochronology. A good agreement is obtained between the results, although three thin, likely short, magnetic intervals are not confirmed within the overlapping zones (they are indicated by half bars in the composite sequence). We consider that this is likely due to the sampling (in fact, an effect resulting from the sampling density, the duration of the magnetic intervals and the stratigraphic completeness of the sections). Three other intervals are poorly defined by single samples (two in the Mendlingbach-West section and one in Gamsstein 2). We propose a Ladinian composite magnetic polarity sequence which contains 25 intervals, or 17 if the uncertain intervals are excluded (Figure 12). This composite sequence is shown considering an equal duration for the biostratigraphic zones which should be modified when data on the relative duration of the Triassic biostratigraphic zones will become available. Of course, these changes will not modify the number and the age calibration of the magnetic intervals, but only their relative duration within the Ladinian. The Carnian sequence obtained from the Mayerling section has already been discussed by *Gallet et al.* [1994]. We recall the very good agreement observed between this sequence and the one previously obtained from Bolücektasi Tepe (southwestern Turkey [*Gallet et al.*, 1992]), although the sampling resolution in Mayerling is twice the one of Bolücektasi Tepe.

In Figure 12 we also report the magnetostratigraphic results which are presently available for the Upper Anisian and the Ladinian. From their compilation, *Molina-Garza et al.* [1991] suggested a Ladinian composite magnetic sequence which mostly depends on the magnetostratigraphy obtained from a red bed section from Iberian Cordillera in eastern Spain [*Turner et al.*, 1989]. This Ladinian composite contains seven magnetic polarity intervals with a predominantly normal magnetic polarity during the Lower Ladinian and a predominantly reversed polarity during the Upper Ladinian. A rough agreement can be suggested for the Lower Ladinian, but no correlation is observed for the Upper Ladinian. Upper Anisian and Ladinian magnetostratigraphic results were also obtained by *Muttoni et al.* [1994, 1997] from the marine sedimentary section of Aghia Triada (Hydra Island, Greece; Figure 12). Considering the new time calibration considered by *Muttoni et al.* [1997], together with additional unpublished biostratigraphic data (L. Krystyn, 1996), a very satisfactory correlation is found for the Fassanian 2 and the lower part of the Longobardian 1 (Figure 12). Age determinations are much more difficult in the upper part of the Aghia Triadia section (Pantokrator limestones), and the magnetostratigraphic correlation with the Austrian composite sequence is poorly constrained. *Muttoni et al.* [1997] also recently proposed an upper Anisian to Ladinian magnetostratigraphy from the Frötschbach section (northern Italy; Figure 12). A coherent magnetostratigraphic correlation can be suggested between these latter results, the Aghia Triadia sequence and the Austrian data (dashed lines; Figure 12). The correlation of the interval Fr1r.1n from Frötschbach with the interval C+ from the Austrian sequence is supported by field evidence in Frötschbach of a more reduced sedimentation rate close to the Fassanian 1/2 boundary. Only the interval Fr1n.1r, at the base of the Ladinian, cannot be correlated with the Austrian sequence. But we remark that this short interval may be missing in Austria due to the slow sedimentation rate across the Anisian-Ladinian boundary.

Finally, it is possible to roughly estimate the magnetic reversal frequency during the Ladinian. Using the timescale suggested by *Gradstein et al.* [1994] who proposed a duration of 6.9 m.y. for the Ladinian, a frequency of 3.6 reversals per million years is obtained if all the magnetic intervals are considered and 2.5 reversals per million years if the uncertain intervals are excluded. These mean values are similar to the estimates we previously obtained for the Norian [*Gallet et al.*, 1993a], but they are lower than the ones we computed from the Carnian (between about 4.0 and 4.8 reversals per million years also considering Gradstein et al.'s timescale [*Gallet et al.*, 1994]).

Acknowledgments. We thank H. Théveniaut for his help during the field work. We also thank S. Gilder, H. Bucher and J. Guex for comments. L.K. was financially supported by Hochschuljubiläumsstiftung der Stadt Wien (H-00234/94). This is IPGP contribution 1490 and DBT "Terre profonde" contribution 91.

Figure 12. Comparison between the magnetostratigraphic sequences obtained from Gamsstein, Mendlingbach and Mayerling. Correlations between these sections are based on conodonts and tephrochronology (dashed lines). T1, T2 and T3 indicate the location of three tuffaceous layers. A composite Ladinian magnetic polarity sequence is shown considering an equal duration for the biostratigraphic zones. Half bars correspond to poorly defined magnetic intervals. We also show for comparison the previous Ladinian composite sequence suggested by *Molina-Garza et al.* [1991] and the magnetostratigraphic results obtained from the pelagic limestone Aghia Triada and Frötschbach sections [*Muttoni et al.*, 1994, 1997].

References

Baag, C., and C.E. Helsley, Evidence for penecontemporaneous magnetization of the Moenkopi formation, *J. Geophys. Res.*, *79*, 3308-3320, 1974.

Bechstädt, T., and H. Mostler, Mikrofacies und Mikrofauna mitteltriadischer beckensedimente der Nördlichen Kalkalpen Tirols, *Geol. Paläontolog. Mitt. Innsbruck*, *4*, 1-74, 1974.

Brack, P., and H. Rieber, Towards a better definition of the Anisian/ladinian boundary: New biostratigraphic data and correlations of boundary sections from the southern Alps, *Eclogae Geol. Helv.*, *86*, 415-527, 1993.

Brack, P., and H. Rieber, The Anisian/Ladinian boundary: Retrospective and new constraints, *Albertiana*, *13*, 25-36, 1994.

Brack, P., H. Rieber, and R. Mundil, The Anisian/Ladinian boundary interval at Bagolino (Southern Alps, Italy): I. Summary and new results on ammonoid horizons and radiometric age dating, *Albertiana*, *15*, 45-46, 1995.

Bucher, H., and M. Orchard, Intercalibrated ammonoid and conodont succession, Upper Anisian-Lower Ladinian of Nevada, *Albertiana*, *15*, 66-71, 1995.

Channell, J.E.T., R. Brandner, A. Spieler, and J.S. Stoner, Paleomagnetism and paleogeography of the Northern Calcareous Alps (Austria), *Tectonics*, *11*, 792-810, 1992.

Elston, D.P., and M.E. Purucker, Detrital magnetization in red beds of the Moenkopi formation (Triassic), Gray Mountain, Arizona, *J. Geophys. Res.*, *84*, 1653-1665, 1979.

Fisher, R.A., Dispersion on a sphere, *Proc. R. Soc. London*, *A217*, 295-305, 1953.

Gallet, Y., J. Besse, L. Krystyn, J. Marcoux, and H. Théveniaut, Magnetostratigraphy of the late Triassic Bolücektasi Tepe section (southwestern Turkey): Implications for changes in magnetic reversal frequency, *Phys. Earth Planet. Int.*, *73*, 85-108, 1992.

Gallet, Y., J. Besse, L. Krystyn, H. Théveniaut, and J. Marcoux, Magnetostratigraphy of the Kavur Tepe section (southwestern Turkey): Establishment of a Norian magnetic polarity time scale, *Earth Planet. Sci. Lett.*, *117*, 443-456, 1993a.

Gallet, Y., D. Vandamme, and L. Krystyn, Magnetostratigraphy of the Hettangian Langmoos section (Adnet, Austria): Evidence for time-delayed phases of magnetization, *Geophys. J. Int.*, *115*, 575-585, 1993b.

Gallet, Y., J. Besse, L. Krystyn, H. Théveniaut, and J. Marcoux, Magnetostratigraphy of the Mayerling (Austria) and Erenkolu Mezarlik (Turkey) sections: Improvement of the Carnian (Late Triassic) magnetic polarity time scale, *Earth Planet. Sci. Lett.*, *125*, 173-191, 1994.

Gallet, Y., J. Besse, L. Krystyn, and J. Marcoux, Norian magnetostratigraphy from the Scheibkogel section, Austria: Constraint on the origin of the Antalya Nappes, Turkey, *Earth Planet. Sci. Lett.*, *140*, 113-122, 1996.

Gradstein, F., F. Agterberg, J. Ogg, J. Hardenbol, P. Van Veen, J. Thierry, and Z. Huang, A Mesozoic time scale, *J. Geophys. Res.*, *99*, 24051-24074, 1994.

Helsley, C.E., and M.B. Steiner, Paleomagnetism of the Lower Triassic Moenkopi formation, *Geol. Soc. Am. Bull.*, *85*, 457-464, 1974.

Kent, D.W., W.K. Witte, and P.E. Olsen, High-resolution Late Triassic-Early Jurassic geomagnetic polarity sequence from drill-cores in the Newark rift basin, eastern North America, *J. Geophys. Res.*, *100*, 14965-14998, 1995.

Kirschvink, J.L., The least squares line and plane and the analysis of paleomagnetic data, *Geophys. J. R. Astron. Soc.*, *62*, 699-718, 1980.

Kovacs, S., Conodont biostratigraphy of the Anisian/Ladinian boundary interval in the Balaton Highland, Hungary and its significance in the definition of the boundary (preliminary report), *Acta Geol. Hung.*, *36*, 39-57, 1993.

Kovacs, S., Conodonts of stratigraphic importance from the Anisian/Ladinian boundary interval of the Balaton Highland, Hungary, *Riv. Ital. Paleontolog. Stratigr.*, *99*, 473-514, 1994.

Kovacs, S., L. Dosztaly, F. Goczan, A. Oravecz-Scheffer, and T. Budai, The Anisian/Ladinian boundary problem in the Balaton Highland, Hungary: A complex microbiostratigraphic approach, *Albertiana*, *14*, 53-64, 1994.

Kozur, H., Revision der Conodontenzonierung der Mittel- und Obertrias des Tethyalen Faunenreich, *Geol. Paläontolog. Mitt. Innsbruck*, *10*, 79-172, 1980.

Kozur, H., The position of the Anisian-Ladinian boundary and the development of the radiolarian faunas in this level, *Zb. Rad. Kroat. Geol. Kongr. 1st.*, *1*, 311-314, 1995.

Kozur, H., and H. Mostler, Holothurienskelerite und Conodonten aus der Mittel und obertrias von Köveskal (balatonhochland, Ungary), *Geol. Paläontolog. Mitt. Innsbruck*, *1*, 1-36, 1971.

Krystyn, L., Das Epidaurus-Profil (Griechenland) -Ein Betrag zur Conodonten-Standardzonierung des tethyalen Ladin und Unterkarn, *Schriftenr. Edwiss. Komm. Osterr. Akad. Wiss.*, *5*, 231-258, 1983.

Lienert, B.R., and C.E. Helsley, Magnetostratigraphy of the Moenkopi formation at Bears Ears, Utah, *J. Geophys. Res.*, *85*, 1475-1480, 1980.

Mauritsch, H., and W. Frisch, Palaeomagnetic data from the central part of the Northern Calcareous Alps, Austria, *J. Geophys.*, *44*, 623-637, 1978.

Mauritsch, H., and W. Frisch, Paleomagnetic results from the Eastern Alps and their comparison with data from the Southern Alps and the Carpathians, *Mitt. Oesterr. Geol. Ges.*, *73*, 5-13, 1980.

McFadden, P.L., and A. Reid, Analysis of paleomagnetic inclination data, *Geophys. J. R. Astron. Soc.*, *69*, 307-319, 1982.

McFadden, P.L., and M.W. McElhinny, The combined analysis of remagnetization circles and direct observations in palaeomagnetism, *Earth Planet. Sci. Lett.*, *87*, 161-172, 1988.

McFadden, P.L., and M.W. McElhinny, Classification of reversal test in paleomagnetism, *Geophys. J. Int.*, *103*, 725-729, 1990.

Mietto, P., and S. Manfrin, A high resolution middle Triassic ammonoid standard scale in the Tethys realm. A preliminary report, *Bull. Soc. Géol. Fr.*, *166*, 539-563, 1995.

Molina-Garza, R., J. Geissman, R. Van der Voo, S. Lucas, and S. Hayden, Paleomagnetism of the Moenkopi and Chinle formations in central New Mexico: Implications for the North American apparent polar wander path and Triassic magnetostratigraphy, *J. Geophys. Res.*, *96*, 14239-14262, 1991.

Molina-Garza, R., J. Geissman, and S. Lucas, Late Carnian-Early Norian magnetostratigraphy from nonmarine strata, Chinle group, New Mexico. Contribution to the Triassic magnetic polarity time scale and the correlation of nonmarine and marine Triassic faunas, in *The nonmarine Triassic* edited by S. Lucas and M. Morales, *N. M. Mus. Nat. Hist. Sci. Bull.*, *3*, 345-352, 1993.

Molina-Garza, R., J. Geissman, S. Lucas, and R. Van der Voo, Palaeomagnetism and magnetostratigraphy of Triassic strata in the Sangre de Cristo Mountains and Tucumcari Basin, New Mexico, *Geophys. J. Int.*, *124*, 935-953, 1996.

Muttoni, G., and D. Kent, Paleomagnetism of latest Anisian (middle Triassic) sections of Prezzo limestone and Buchenstein formation, southern Alps, Italy, *Earth Planet. Sci. Lett.*, *122*, 1-18, 1994.

Muttoni, G., J. Channell, A. Nicora, and R. Rettori, Magnetostratigraphy and biostratigraphy of an Anisian-Ladinian (middle Triassic) boundary section from Hydra (Greece), *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, *111*, 249-262, 1994.

Muttoni, G., D. Kent, and M. Gaetani, Magnetostratigraphy of a lower-middle Triassic boundary section from Chios (Greece), *Earth Planet. Sci. Lett.*, *92*, 245-260, 1995.

Muttoni, G., D. Kent, S. Meço, A. Nicora, M. Gaetani, M. Balini, D. Germani, and R. Rettori, Magneto-biostratigraphyof the Spathian to Anisian (Lower to Middle Triassic) Kçira section, Albania, *Geophys. J. Int.*, *127*, 503-514, 1996.

Muttoni, G., D. Kent, P. Brack, A. Nicora, and M. Balini, Middle Triassic magnetostratigraphy and biostratigraphy from the Dolomites and Greece, *Earth Planet. Sci. Lett.*, *146*, 107-120, 1997.

Nicora, A., and P. Brack, The Anisian/Ladinian boundary at Bagolino (southern Alps, Italy), II, The distribution of conodonts, *Albertiana*, *15*, 57-71, 1995.

Ogg, J.G., and M.B. Steiner, Early Triassic magnetic polarity time scale -integration of magnetostratigraphy, ammonite zonation and sequence stratigraphy from stratotype sections (Canadian Arctic Archipelago), *Earth Planet. Sci. Lett.*, *107*, 69-89, 1991.

Purucker, M.E., D.P. Elston, and E.M. Shoemaker, Early acquisition of characteristic magnetization in red beds of the Moenkopi formation (Triassic), Gray Mountain, Arizona, *J. Geophys. Res.*, *85*, 997-1012, 1980.

Steiner, M.B., J.G. Ogg, Z. Zhang, and S. Sun, The Late Permian/Early Triassic magnetic polarity time scale and plate motions of South China, *J. Geophys. Res.*, *94*, 7343-7363, 1989.

Tollmann, A., *Der Bau der Nördlichen Kalkapen. Orogenese, Stellung und regionale Tektonik*, Deuticke, Vienna, 1976.

Tollmann, A., Geodynamic concepts of the evolution of the Eastern Alps, in *Geodynamics of the Eastern Alps*, edited by H.W. Flügel and P. Faupl, pp. 361-378, Deuticke, Vienna, 1987.

Turner, P., A. Turner, A. Ramos, and A. Sopena, Paleomagnetism of Permo-Triassic rocks in the Iberian Cordillera, Spain: Acquisition of secondary and characteristic remanence, *J. Geol. Soc. London*, *146*, 61-76, 1989.

J. Besse and Y. Gallet, Laboratoire de Paléomagnétisme, URA 729, Insitut de Physique du Globe de Paris, 4, Place Jussieu, 75252 Paris cedex 05, France. (e-mail: gallet@ipgp.jussieu.fr)

L. Krystyn, Institute for Paleontology, üniversitätsstrasse 7, A1010, Wien, Austria

(Received March 11, 1997; revised July 15, 1997; accepted July 29, 1997.)