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# Magnetostratigraphy of the Hettangian Langmoos section (Adnet, Austria): evidence for time-delayed phases of magnetization

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## SUMMARY

Study of the magnetostratigraphy of the earliest Jurassic (mainly Hettangian) section of Langmoos near Adnet in Austria (Northern calcareous Alps) provides a sequence of 10 magnetic polarity intervals. These intervals are often evident in the natural remanent magnetization. However, rather than a true magnetostratigraphic sequence, palaeomagnetic analyses reveal evidence for successive phases of magnetization within the section. Evidence includes (1) changes in lithology associated with changes in magnetic polarity, (2) different combinations of components of both polarities, and (3) largely non-antipodal directions. Considering the palaeomagnetic directions, we suggest that the apparent magnetostratigraphy is the result of two or three phases of magnetization which occurred at different stages of the tectonic emplacement of the Northern Calcareous Alps.

**Key words:** Hettangian, magnetostratigraphy, Northern Calcareous Alps, remagnetization, rotation.

## INTRODUCTION

For the last two decades, magnetostratigraphy has been an attractive method used to solve a large range of problems in biostratigraphy, tectonics and geomagnetism. Recently, considerable effort has been made to expand the reference polarity time scale to the period of time for which there is no sea-floor magnetic anomaly record. Results for the Late–Middle Jurassic (Steiner *et al.* 1986; Steiner, Ogg & Sardoval 1987); Channell *et al.* 1990b), Lower Jurassic (Marton, Marton & Heller, 1980; Horner & Heller 1983; Channell *et al.* 1984; Galbrun, Gabilly & Rasplus 1988; Galbrun *et al.* 1990), Late Triassic (Witte, Kent & Olsén 1991; Molina-Garza *et al.* 1991; Galbrun, Crasquin-Soleau & Jaugéy 1992; Gallet *et al.* 1992, 1993) Lower Triassic (Steiner *et al.* 1989; Ogg & Steiner 1991) and for the Late Permian (Steiner *et al.* 1989; Haag & Heller 1991) have been obtained. These studies, which provide only a discontinuous magnetic sequence back to the Late Permian, could constrain the changes in the magnetic reversal frequency for these periods (see Gallet *et al.* 1992 for a review).

New results are required to complete the Early Mesozoic magnetic sequence and to pursue an analysis of reversal frequency. In particular, no magnetostratigraphic data are

presently available for the Lower Liassic (Hettangian). The results of some previous studies from the Hettangian parastratotype (Ardèche, France) and other sections from southern France and Great Britain (Gallet 1988 and unpublished results) were plagued by a complete recent remagnetization. Recently, Besse & Courtillot (1991) reviewed the available palaeomagnetic poles for the major cratons (Eurasia, North America, Africa and India) for the last 200 million years. Palaeopoles clearly dated by biostratigraphy as Hettangian in age are very rare (e.g. Witte & Kent 1990). Results obtained from the Newark basin (McIntosh *et al.* 1985; Witte & Kent 1990; Witte *et al.* 1991), on continental sediments and volcanic rocks, seem to show a period of normal polarity. In both cases, the lack of complete stratigraphic recovery could invalidate this low reversal rate.

In order to better constrain the magnetic reversal frequency during the Hettangian, we have investigated the Langmoos section in the Northern Calcareous Alps (Austria). The results that we present in this paper, provide an 'apparent' magnetostratigraphy of 10 magnetic intervals. But various palaeomagnetic criteria show that, rather than a true sequence of magnetic reversals, the sequence is probably the combination of remagnetizations in opposite magnetic polarity.

**GEOLOGICAL SETTING AND LITHO-BIOSTRATIGRAPHY**

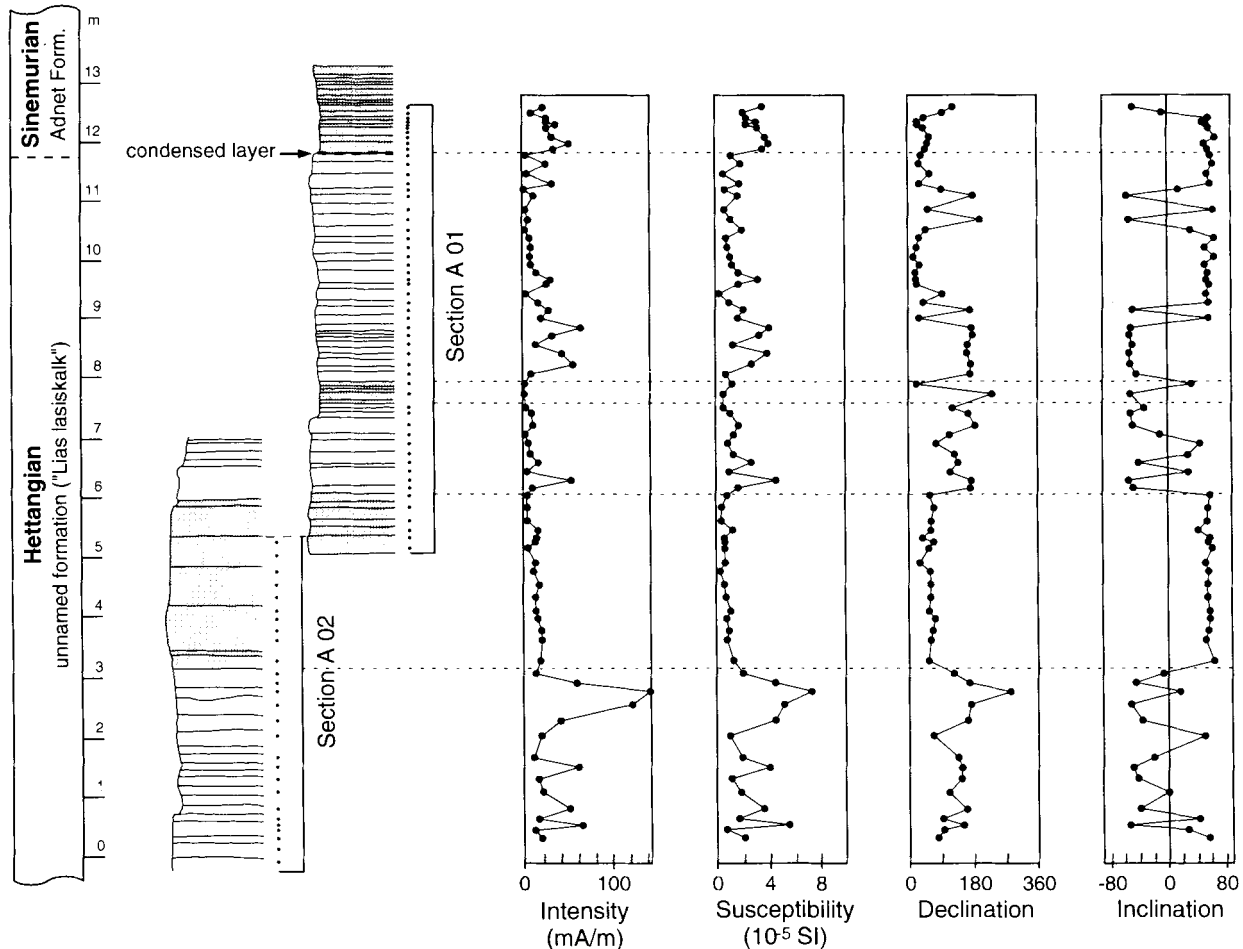
The well-exposed Langmoos section is located in an old quarry also mentioned as 'quarry XVII' by Kieslinger (1964). This outcrop is situated about 750 m east of the small village of Adnet, 10 km south of Salzburg. Tectonically, this area belongs to the Osterhorn syncline of the 'Staufen-Höllengebirge nappe' (Oberhauser 1980) in the Northern calcareous Alps (NCA) classically considered as a part of the southern Tethyan continental margin (Bosselini *et al.* 1980; Weissert & Bernouill 1985), overthrustured during the Alpine orogeny onto the European plate.

The Langmoos section, which is about 13 m thick, is monoclinal, gently dipping to the west (N36°E, 11°NW). Owing to the orientation of the bedding, we drilled this section in two places, the upper one (site A01) at the western end and the lower one (site A02) at the eastern end of the quarry. Correlation between these two sites was possible along a bedding plane that we traced throughout the quarry. Changes in the bed thicknesses, due to individual thinning and partitioning of the beds, are observed in the zone of overlap between the two sites (Fig. 1).

The lithology consists of mostly thin (5–15 cm, rarely

40–50 cm) and well-bedded multicoloured limestones (Fig. 1). A very distinct yellowish-reddish 3–5 cm thick hard-ground layer (Enzesfeld limestone, also called 'Brandschichte') occurs 1 m below the top of the section (Figs 1 and 2). It marks the boundary between the basal Adnet formation, constituted by brownish to reddish, slightly marly and platy limestones, and a sequence of 12 m of variously grey to yellowish, sometimes also red to violet coloured wackestones and packstones. This lower formation which is known from different places within the Adnet area, has not yet received a clear name, but local workers call it the 'Rot-Grau-Schnöll-Marmor' (or 'Unnamed Formation', Fig. 2). The Adnet formation consists of highly oxidized pelagic carbonates formed well below wave base with a fauna dominated by ammonites. For the 'Rot-Grau-Schnöll-Marmor', a shallower environment (probably around 50 m), close to the storm wave base, is indicated by the presence of crinoid coquina layers (packstones) and the dominance of brachiopods in the megafauna.

A detailed biostratigraphic zonation is not available from the Langmoos section and in general, from the Adnet Liassic formation. Although ammonites have been described as early as 1850 (see Wendt 1971), no modern biostratigraphic analysis of the region has been performed. Another problem results from the discontinuous ammonite



**Figure 1.** Lithostratigraphy of the Langmoos section and magnetic results obtained at the NRM step. In the lithostratigraphic log, shaded levels correspond to reddish or brownish wackestones. We show the changes in magnetic intensity, susceptibility and directions within the section. The magnetic susceptibilities fit quite well with the magnetic intensities and the directions define magnetic intervals of both polarities.

		Triassic Palaeogeography		
		Basin	Slope	Platform
Lower Sinemurian	Semi-Costatum	Adnet Formation		
	Bucklandi	?		
Hettangian	Angulata	Enzesfeld L. ("Brandschichte")		
	Liasicus	Kendlbach F.	Unnamed Formation ("Rot-Grau-Schnöll-Marmor")	
	Planorbis			
Rhaetian		Kössen F.	Oberhät Limestone	

**Figure 2.** Lower Liassic (Earliest Jurassic) stratigraphy in the Adnet area. Hachures indicate gaps in sedimentation. The distribution of facies strongly depends on the former Triassic relief. The studied section contains the 'unnamed' Hettangian formation and lowest part of the Adnet formation of Sinemurian age.

faunal record over the sequence, with large non-fossiliferous parts and occasional ammonite-rich layers that often represent stratigraphically condensed deposits. There are no age diagnostic megafossils in the basal Adnet formation from the Langmoos section; however, ammonites of Upper Sinemurian age of the genera *Asteroceras*, *Oxyntoceras* and *Arnioceras* have been found by us in a nearby quarry (quarry XII) between 2 and 3 m above the base of the formation. The same genera are known from several other places in the Adnet area as well as from outcrops within the Osterhorn syncline (Blind 1963). In contrast, the lack of distinct lower Sinemurian ammonites, such as *Coroniceras* or *Agassiceras*, indicates a major regional break in sedimentation during the Lower Sinemurian, as suggested by Bloos (1988).

The 'Rot-Grau-Schnöll-Marmor', or unnamed formation of the Langmoos section, is stratigraphically determined by two ammonite horizons, one at the base and the other at the top. The lower horizon is located outside the quarry but is stratigraphically directly below the studied section. It contains *Parapsiloceras naumanni*, equivalent to the Johnstoni level in the Upper Planorbis zone (Fig. 2). The upper condensed fossil bed (Enzesfeld L.) contains *Kammerkaroceras emmrichi*, *Alsatites sp.*, *Storhoceras cf calcimontanum* and *Angulaticeras marmoreum*, indicating a Middle Hettangian age (upper? Angulata zone, Fig. 2). Therefore, the studied section probably has an age encompassing the Middle and Upper Hettangian. This is in agreement with the biostratigraphic data obtained from the equivalent thinner section from quarry XXXI (Böhm 1992), located about 150 m from the Langmoos section.

The rock colour is largely varying within the Langmoos section. These changes from grey to yellow and red are a conspicuous feature of the formation. An oxidizing environment during sediment deposition is indicated by strong bioturbation as well as by the presence of autochthonous benthic fauna. Since the change in colour is

mostly irregular and crosses the bedding planes, widescale diagenetic alteration of the rocks and hence of the magnetic mineralogy must be considered. In some limestone beds, a 'primary' magnetic mineralogy is illustrated by sharply delimited mm size grey ichnofossil burrowings within a pure red matrix. However, a more general problem is the late diagenetic reoxidation of many beds from grey back to red as can be observed on large outcrops in nearby quarry XXXI (Böhm 1992) from the same formation. All this makes the question of the primary rock colour and the nature of the primary magnetic minerals difficult to answer before any palaeomagnetic study has been performed.

## PALAEOMAGNETIC ANALYSIS

A total of 81 stratigraphic levels were sampled with a regular spacing of about 15 cm, using a portable gasoline-powered drill. Magnetic measurements of the samples were performed with a cryogenic CTF three-axis magnetometer in the shielded palaeomagnetic Laboratory of Scripps Institution of Oceanography (La Jolla, USA).

### Natural remanence magnetization

Figure 1 summarizes the results obtained after measurement of the natural remanence magnetization (NRM). The magnetic intensities have an arithmetic mean of  $2.3 \cdot 10^{-3} \text{ A m}^{-1} \pm 17$  per cent. The mean intensity of the grey wackestones is notably higher than the intensity of the red wackestones,  $2.6 \cdot 10^{-3} \text{ A m}^{-1} \pm 17$  per cent and  $1.0 \cdot 10^{-3} \text{ A m}^{-1} \pm 14$  per cent respectively. The stratigraphy of these intensities reveals some homogeneous zones (between 3 and 7.5 m and between 9.5 and 10.5 m; Fig. 1). This zonation fits quite well with that given by magnetic susceptibility. The values of susceptibility are very weak and range from about 1 to  $7 \times 10^{-5}$  SI units.

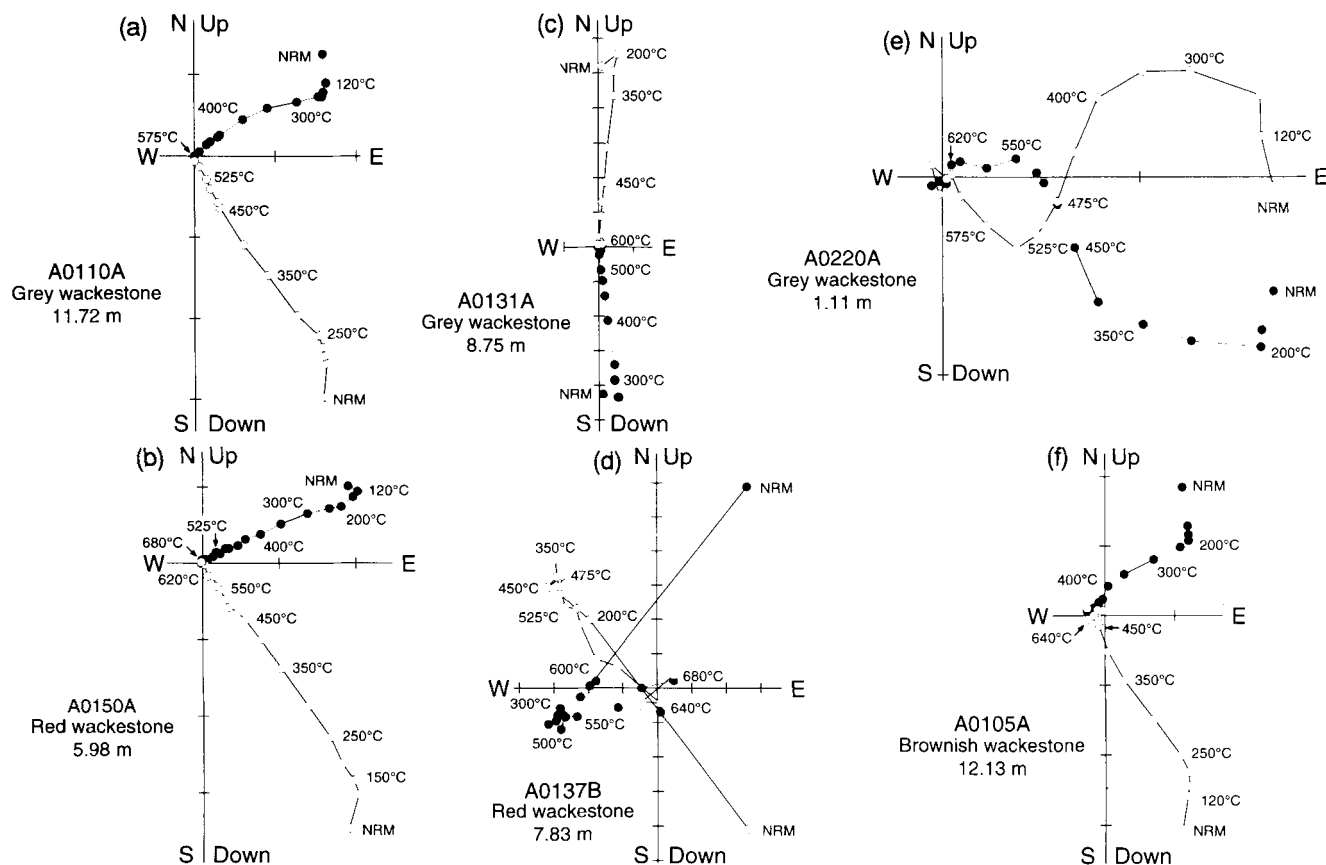
The NRM measurements already reveal, prior to any demagnetization, normal and reversed polarity directions (Fig. 1). Indeed, several intervals of normal and reversed polarity are observed, well defined both in declination and inclination. Some directions are intermediate, especially at the bottom of the section corresponding to a zone where the intensities and susceptibilities are more scattered (Fig. 1).

### Thermal demagnetization

For all samples, thermal demagnetization (in air) was carried out in about 15–19 steps beginning at 120 °C and up to 680 °C for some red samples. After each step, measurements of the magnetic susceptibility allowed us to judge the stability of the magnetic mineralogy of the samples during the treatment.

Large increases in susceptibility are often observed above 400 °C. Depending on the relative importance of mineralogical changes, a new unstable magnetic phase sometimes prevents the determination of a clear end of demagnetization. The alteration could be due to a progressive oxidation of sulfides to magnetite or haematite during the thermal treatment in air (e.g. Lowrie & Heller 1982; Dekkers 1990).

Different kinds of behaviour during thermal demagnetization can be observed on vectorial diagrams (Zijderveld 1967; Fig. 3). The first two examples of normal polarity



**Figure 3.** Examples of orthogonal projections of the different behaviours observed during the thermal demagnetization. (a, b) Samples which have a final component of normal polarity. (c, d) Samples which have a final component of reversed polarity. (e) One sample in grey wackestones which presents an intermediate component of reversed polarity. (f) Example of demagnetization paths observed in the brownish wackestones at the top of the section. Solid symbols are in horizontal plane, and open symbols in vertical plane. Numbers adjacent to data points indicate temperatures (degrees Celsius).

directions show a very favourable palaeomagnetic behaviour (Figs 3a and b). A soft component, in the present field direction, can be first isolated between 0 and about 200°C. This component is followed by a normal component with an easterly declination. This component has an unblocking range from 250°C to about 350–400°C. Finally, a component with a more or less easterly declination, depending on the samples, is observed for the highest steps until 600°C for the grey wackestones (Fig. 3a) and about 620–660°C for the red wackestones (Fig. 3b).

Many samples in the grey wackestones reveal a very well-defined single magnetic component of reversed polarity between 200°C and the end of demagnetization at about 600°C (Fig. 3c). In contrast, the reversed polarity direction of two red samples, at about 8 m (Fig. 1), appears more noisy (one example is shown in Fig. 3d). Demagnetization until 680°C does not isolate a clear component which decays to the origin.

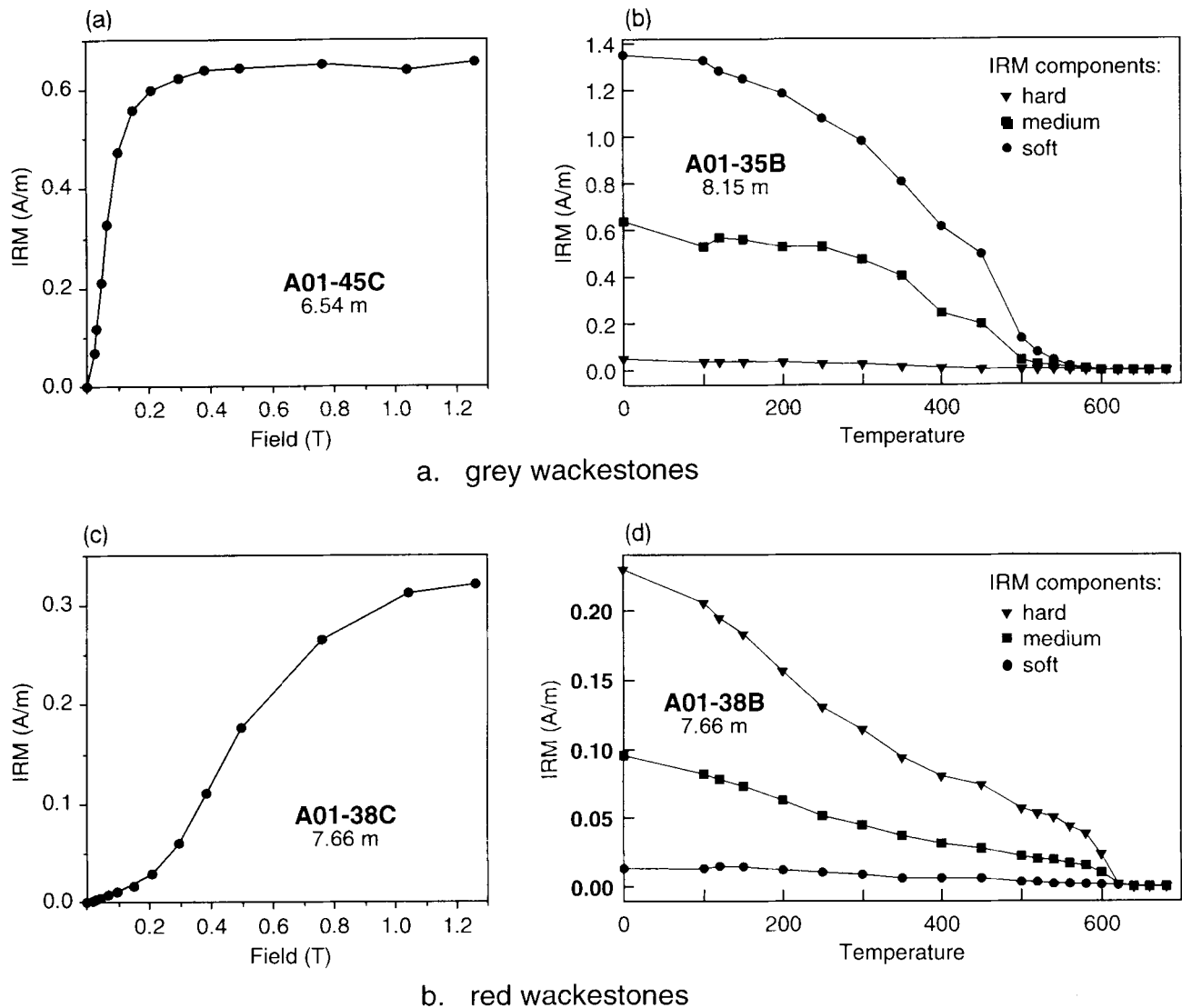
In Fig. 3(e), we show one example of behaviour that appears only in the grey samples. In this behaviour, a component of reversed polarity exists between a low unblocking temperature component of normal polarity, roughly parallel to the present field direction, and a high unblocking temperature component again of normal polarity. But this last component with highest unblocking temperature cannot be completely isolated. Many cases,

intermediate between these two examples (Fig. 3c and e), occur in the grey wackestones within the section.

Finally, the brownish-reddish wackestones from the top of the section (basal Adnet formation) display a very characteristic demagnetization path, which successively follows the present field direction, a normal polarity component and a component of reversed polarity, which cannot be completely isolated (Fig. 3f).

### Rock magnetism

To characterize better the magnetic carriers in both lithologies (grey and red wackestones), several rock magnetic experiments were performed. Isothermal remanent magnetization (IRM) acquisition curves up to 1.3 Tesla (T) indicate that the magnetic mineralogy is not the same in these two lithologies. A low coercivity mineral, probably magnetite, seems to be the dominant magnetic mineral in the grey wackestones, the saturation being reached around 0.2T (Fig. 4a), whereas a high coercivity mineral, probably haematite, is dominant in the red wackestones (Fig. 4c). Thermal demagnetization up to 680°C of a composite IRM (0.12, 0.4 and 2.3 T in three perpendicular directions, as described by Lowrie 1990) confirms these characteristics. Examples given for samples in grey wackestones (Fig. 4b) show a magnetization mainly



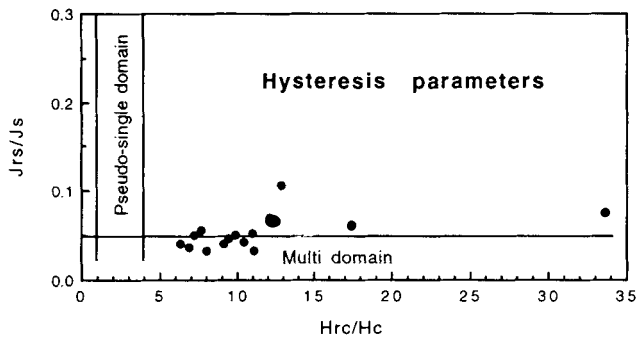
**Figure 4.** Acquisition of a monodirectional isothermal remanent magnetization (IRM) in grey (a) and red wackestones (c). Magnetite is the dominant magnetic carrier in the first lithology while haematite is dominant in the second. We also show examples of thermal demagnetization of a triaxial differential IRM (method described in Lowrie 1990) in grey (b) and red (d) wackestones. The magnetization in the grey wackestones is carried by a magnetite of low coercivity. Haematite is recognized in the red wackestones.

carried by magnetite with low coercivity and an unblocking temperature of approximately 560 °C. No high coercivity mineral (sulfides or haematite) is recognized in this lithology. We can suggest that the large increase in magnetic susceptibility observed during thermal demagnetization is due to progressive oxidation of pyrite. Similar behaviour is obtained for one sample in brownish-reddish wackestones from the top of the section (Adnet formation). In contrast, haematite is the main magnetic carrier in the reddish wackestones from the lower part of the Langmoos section (Fig. 4d). The more or less regular decrease of the hard component (IRM at 2.3T) during the demagnetization shows that this haematite has a large spectrum of unblocking temperature. No evidence for goethite is recognized in sample A0138B and in most of the reddish samples. But, a fraction of this mineral cannot be excluded from the sample A0137B (Fig. 3d). Finally, from the examination of the thermal demagnetization of the medium coercivity curve

(Fig. 4d), a mixture of both magnetite and haematite appears to be unlikely in the reddish wackestones.

The difference in magnetic mineralogy, related to difference in lithology, is probably reflected by the values of magnetic susceptibility. We noticed that the susceptibility is slightly higher in grey layers (with a mean of  $2.1 \cdot 10^{-6}$  SI) than in the reddish layers (mean of  $0.7 \cdot 10^{-6}$  SI).

We also investigated the grain size of the remanence carriers in the grey wackestones by measuring hysteresis properties (e.g. Day, Fuller & Schmidt 1977). These measurements for 17 different stratigraphic levels were performed using the alternating gradient force magnetometer (AGFM, Princeton Measurements Corporation Micromag 2900) at Scripps. In all cases, a diamagnetic component is present and must be subtracted to isolate the 'characteristic' behaviour. The hysteresis measurements show that the grains of magnetite are fairly large. If we except one sample, the ratios of saturation remanence to



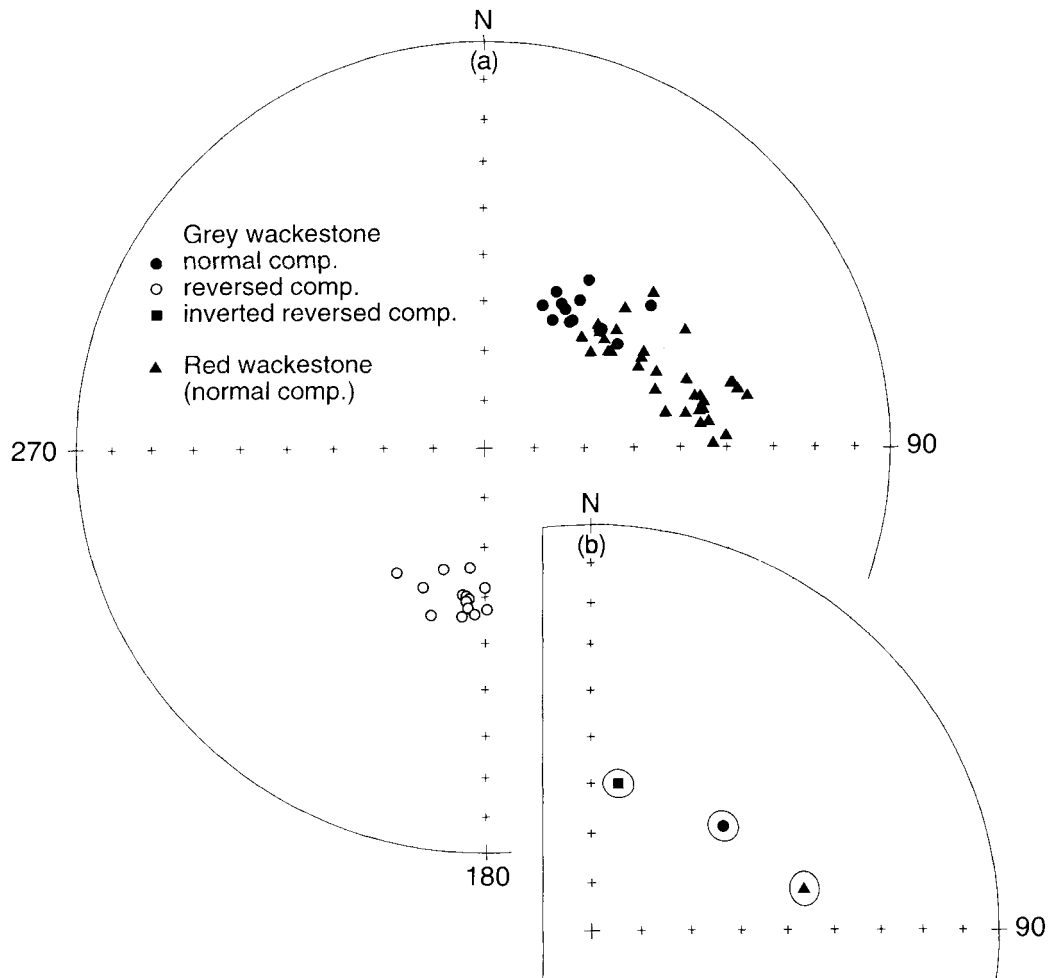
**Figure 5.** Hysteresis ratios obtained from samples in the grey lithology. The ratios are given after the diamagnetic correction and compared with the domain-state proposed by Day *et al.* (1977).

saturation magnetization ( $J_{rs}/J_s$ ) are similar and close to 0.05 (Fig. 5). For the magnetite (open dots), this value is, in the Day *et al.* (1977) diagram, in between the pseudo-single domain and multidomain range (Fig. 5). However, the ratios of remanent coercivity to bulk coercivity ( $H_{rc}/H_c$ ) are only in agreement with the multidomain range. In some cases, the hysteresis behaviour is characterized by very

slightly ‘wasp-waisted’ loops which could indicate a bimodal coercivity distribution (e.g. Nagata & Carleton 1987). From these experiments, we can conclude that the remanence in the grey wackestones resides in coarse (multidomain) grained magnetite with perhaps a very small fraction of pseudo-single domain magnetite.

**PALAEOMAGNETIC DIRECTIONS**

The palaeomagnetic analysis reveals large differences in magnetic behaviour within the section. When the final directions determined using principal component analysis (PCA; Kirschvink 1980) are reported on an equal-area projection (Fig. 6), a strongly elongated distribution in declination can be observed. This elongation, which reaches approximately 90°, clearly indicate different timings in the magnetization of the Langmoos section. In particular, we note that the change of lithology between about 3 and 6 m (Fig. 1), with the occurrence of red wackestones, corresponds exactly to a change of magnetic polarity. This lithologic dependence, together with the palaeomagnetic results, can be understood if they result from successive magnetization phases.



**Figure 6.** Normal and reversed polarity characteristic directions observed within the Langmoos section before tilt correction. (a) Equal-area projection of these directions. The open (closed) symbols indicate the reversed (normal) polarity components obtained in the grey (dots) and in the red (triangles) wackestones. (b) Mean directions estimated from the grey wackestones (square: inverted reversed polarity direction; dot: normal polarity direction) and from the reddish wackestones (triangle). The distribution shows a strong elongation in declination between the directions of reversed and normal polarity observed in grey wackestones, and the directions of easterly declination observed in the red wackestones.

### Evidence for a reversed polarity remagnetization

A well-defined component of reversed polarity is observed in about 20 grey samples (Fig. 3c and e). In some cases (Fig. 3c), this component can be isolated at low-temperature steps of demagnetization, around 200 °C. In geographic coordinates (i.e. before the tilt correction), this component has a declination close to 180°, quite similar to the intermediate (medium temperature) reversed component in the sample shown in Fig. 3(e). Considering this different combination of the reversed component and the different unblocking temperature range of the reversed component in sample A0131A (Fig. 3c), we propose the hypothesis of selective remagnetization in a reversed magnetic field. This remagnetization would be slightly overprinted later by a very recent remagnetization in the present field direction as observed in many samples (Fig. 3). Following this hypothesis, samples of reversed polarity would be completely remagnetized. When the degree of this remagnetization is weaker, we observe the paths of demagnetization shown in Fig. 3(e). In these cases, the reversed component is only an intermediate direction which is followed by a small final component of normal polarity at higher temperatures.

A reversed magnetic component is also observed in two reddish samples at the middle of the section (about 8 m, Fig. 1). However, the direction seems different, more westerly, to that obtained in the grey wackestones, although their behaviour during thermal demagnetization is noisy. The demagnetization path shown in Fig. 3(d) presents a curvature in declination which could be interpreted as a combination of two overlapping reversed components of different declinations. The first demagnetized reversed component might be the same obtained in the grey wackestones. But, this kind of demagnetization path, observed only in two samples, cannot provide a definitive answer.

For the samples showing a reversed polarity component (as a final or an intermediate component), we have estimated two mean directions. First, a low-stability component is isolated in the two or three first steps (below 250 °C). The mean direction which is obtained ( $D = -0.7^\circ$ ,  $I = 61.0^\circ$  and  $\alpha_{95} = 10.5^\circ$  before tilt correction) is roughly parallel to the present day field direction ( $D = 1.0^\circ$ ,  $I = 63.5^\circ$ ). Depending on the samples, the magnetic directions shift directly to the well-defined reversed component (e.g. Fig. 3c) or define a great circle which reaches this reversed direction (evident from Fig. 3e).

Excluding the two westerly directions given by the red wackestones, a well-defined reversed mean direction is obtained (Table 1).

### Normal polarity magnetization

Excluding the low-stability component in the present earth field direction, two consistent normal polarity characteristic directions are observed within the 13 m of the Langmoos section. These directions, which have significantly different declinations, are clearly related to the lithology (Fig. 6). A group of about 12 samples in the grey wackestones, principally from the upper part of the section, shows a final component of moderate easterly declination (see also Fig. 3a; Table 1). A second group, mainly represented by the red wackestones, shows a more easterly declination (see Fig. 3b; Table 1). We also observe that this final direction can be compared with the intermediate component observed both in the grey samples of normal polarity and in the brownish-reddish samples from the Adnet formation (Fig. 3f; Table 1).

We could consider and discuss separately the two normal directions given by the grey wackestones. However, some arguments show that the difference in the normal directions may result from differential overlapping between two components of opposite polarity. Two processes are proposed.

#### 1 Bias by an 'underlying' reversed component

As previously pointed out, the different behaviour of the few brownish-reddish samples from the basal Adnet formation can be explained by an underlying reversed polarity component which can be never well isolated (Fig. 3f). In terms of combination of magnetic components, the demagnetization path obtained for these samples is quite similar to the path observed in Fig. 3(a). The difference could be attributed to a difference in proportion of the reversed final component. In Fig. 3(a), this component would be very weak and could be seen only by the curvature in the declination path. Following this explanation, the magnetic component of moderate easterly declination observed in grey samples from the upper part of the section would be the result of an overlap between a normal component with an easterly declination and an 'unknown' reversed final component. From the hysteresis measurements, we could also suggest that the normal magnetic component is carried by the multidomain magnetite

**Table 1.** Mean palaeomagnetic directions before and after tilt correction obtained within the Langmoos section.

Lithology	Component	Magnetic Polarity	N samples	Decl. before tilt correction	Incl. before tilt correction	Decl. after tilt correction	Incl. after tilt correction	$\alpha_{95}$	K
Grey	Intermediate and final	Reversed	14	190.2°	-59.5°	176.3°	-52.2°	3.0°	181.6
	Intermediate	Normal	13	75.9	44.6°	65.8°	50.7°	4.2°	98.1
	Final		12	51.0°	55.8°	34.5°	57.0°	3.1°	198.9
Red	Final	Normal	15	78.5°	45.7°	68.3°	52.2°	3.2°	147.3



observed and the reversed underlying component by a small fraction of pseudo-single domain magnetite.

## 2 Bias by the reversed component of remagnetization

From the behaviour displayed by the sample A0220A (Fig. 3e), we can postulate the reversed polarity remagnetization (intermediate component) may shift the declinations eastward. Indeed, we observe in some samples a slight curvature in declination in the range of medium temperatures (Fig. 3a). The great circles, which can be determined on three or four points (Hall 1976; McFadden & McElhinny 1988), show that these directions evolve along a great circle which roughly contains the previously defined reversed direction. In this case, only a weak remagnetization of reversed polarity would be thus noticeable and the similarity between the directions observed in the red wackestones and the medium temperature normal component obtained in the grey samples would be only fortuitous.

Examples of demagnetization diagrams of greyish samples can provide some arguments to consider either one of the two processes. In the first case, we should consider only one normal polarity component within the Lagmoos section with an easterly declination; in the second case, we should distinguish two components related to the lithology, significantly different in declination.

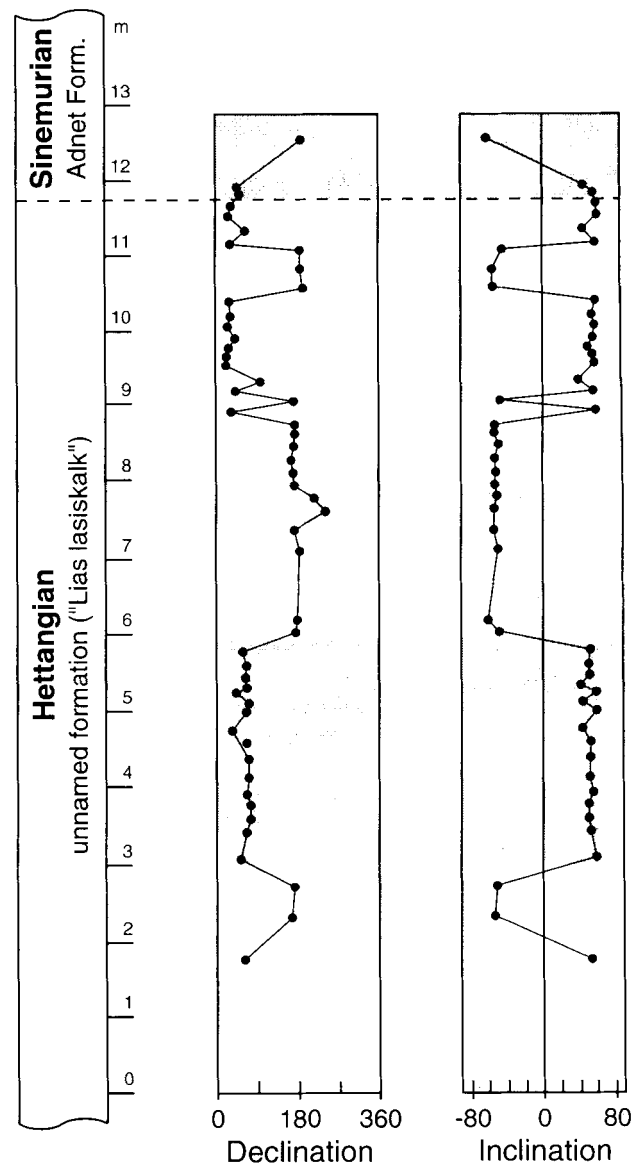
## DISCUSSION

### Apparent Hettangian magnetostratigraphy

The apparent Hettangian magnetostratigraphy of the Langmoos section, defined only by the samples which clearly contain a final component going to the origin (52 samples), provides a sequence of 10 polarity intervals (Fig. 7). Due to this selection, four of them are represented by a single sample. This sequence could be considered as an additional reference section for the establishment of the pre-oceanic reversal magnetic time scale. In this case, we ought to discuss the lack in our results of predominantly normal polarity during the Hettangian (McIntosh, Hargraves & West 1985; Witte & Kent 1990). Unfortunately, our magnetostratigraphic goal is clearly thwarted by remagnetizations probably linked with the tectonic emplacement of the Northern Calcareous Alps. In our section, evidence for selective remagnetizations includes, (1) largely non-antipodal directions, (2) observation that a change in lithology corresponds exactly to a change in magnetic polarity, (3) different chronologies of magnetic components in the samples. Only the samples from the basal Adnet formation (Lower Sinemurian) likely contain a characteristic reversed component. We could also suggest a reversed magnetic polarity during the Late Hettangian and a normal polarity during the lower part of Hettangian but a definitive answer cannot be reached.

### Mechanism of acquisition and age of magnetization

One of the major problems in our study is to determine the age of the magnetization both in the grey and in the reddish wackestones. In these two lithologies, we observe magnetic directions of normal and reversed polarity. However, in the



**Figure 7.** Apparent magnetostratigraphy of 10 polarity intervals obtained from the well-defined directions (i.e. which go through the origin during the demagnetization). Shaded levels correspond to reddish or brownish wackestones.

grey wackestone, it is clear that the reversed and normal components are not antipodal and have probably been acquired at two different periods. In the reddish wackestones, the normal and reversed polarity directions, although only two reversed directions are obtained, could be antiparallel (see Fig. 6). In these beds, the growth of a haematite in an early diagenetic process is questionable.

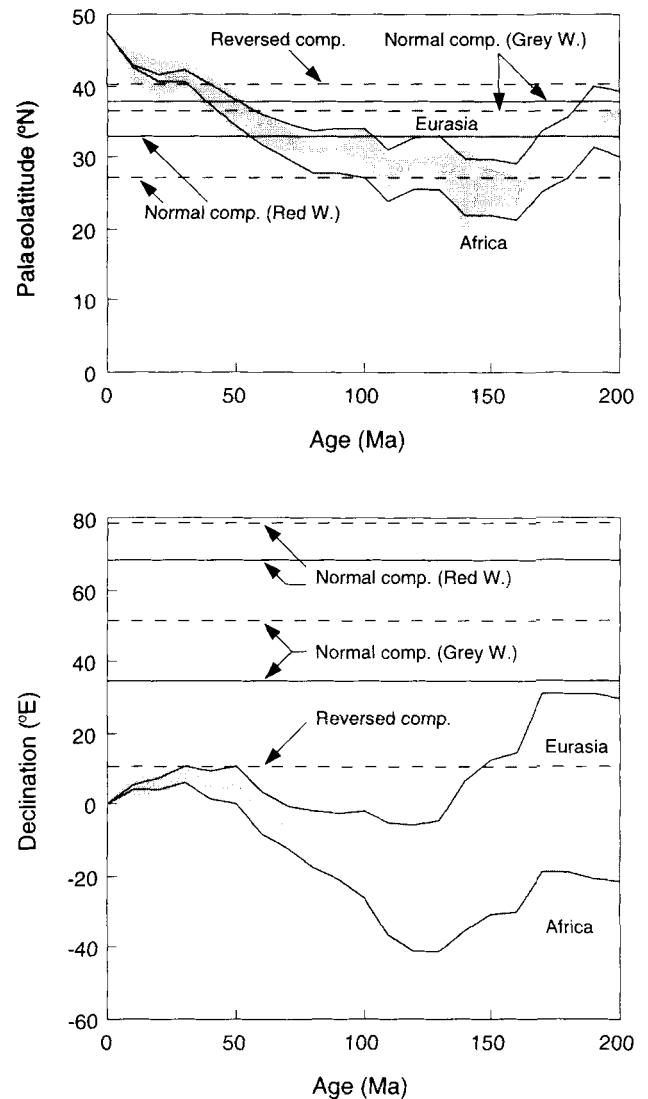
In a recent paper, Tarduno *et al.* (1992) underline the problem of timing of magnetization carried by haematite from a magnetostratigraphic study in Albian Contessa (Italy). The growth of haematite from a goethite precursor has been documented in different well-documented studies (e.g. Channell *et al.* 1982). Appearance of goethite and then of haematite in oxidizing conditions seems to be clearly related to a low sedimentation rate leading to oxidation of organic matter. In Ammonitico rosso facies, it has been

demonstrated that the diagenetic nucleation of haematite could be precocious enough to record accurately a magnetitic polarity sequence. In our study, the antipodal directions carried by haematite could argue for a similar early diagenetic process and then, we could consider the magnetic direction given by the reddish wackestones as 'primary'. However, Tarduno *et al.* (1992) found evidence in many studies for a late diagenetic precipitation of haematite during fluid migration. Possibility for fluid migration would be not surprising in the tectonic context of emplacement of the Northern Calcareous Alps and has already been observed in the field (along fractures or along 'alteration channels' intersecting the bedding planes as in quarry XXXI). In this case, which is for us more likely, the remagnetization proceeded long enough to encompass at least one change of polarity.

The magnetic direction obtained in the reddish wackestones must be compared with the available palaeomagnetic data already obtained in the Northern Calcareous Alps (Mauritsch & Frisch 1978, 1980; Channell *et al.* 1990a, 1992). Recently, Channell *et al.* (1990a, 1992) suggested from a palaeomagnetic investigation in Austria, a large-scale clockwise rotation model for the NCA. Following their suggestion, that during the Lower Jurassic the NCA was a tectonic entity, independent from Eurasia, the Southern Calcareous Alps and Apulia. From palaeomagnetic sites well distributed in the NCA, a consistent easterly declination is found. In particular, we notice that a palaeomagnetic mean direction has been obtained from the Lower Jurassic Adnet formation ( $D = 79.4^\circ$ ,  $I = 47.5^\circ$  before tilt correction with  $K = 149.2$ ,  $\alpha_{95} = 10.1^\circ$  and  $N = 3$ ;  $D = 80.0^\circ$ ,  $I = 57.1^\circ$  after tilt correction with  $K = 63.9$  and  $\alpha_{95} = 15.5^\circ$ ; Channell *et al.* 1990a). We are not able to discuss the primary origin of magnetization in these results but it is remarkable that this direction is, in geographic coordinates, very similar to the direction obtained in the Langmoos reddish wackestones, also in geographic coordinates. Although the precise timing of magnetization of the Langmoos reddish wackestones remains uncertain, it seems that the magnetization of these levels has been acquired before the large-scale clockwise rotation of the NCA during the Late Cretaceous and Tertiary (Channell *et al.* 1990a, 1992).

The late acquisition of the reversed magnetic component in the grey wackestones is less questionable. When compared to the expected Eurasian direction at our site since the Lower Jurassic (Figs 8a and b), we observe that this direction has probably been obtained between say Eocene and the present. Although a very recent remagnetization, for example in the Matuyama field, cannot be excluded, we can suggest that this remagnetization may have been linked with the Late Eocene phase of deformation of the NCA (e.g. Tollmann 1987; Channell *et al.* 1992). This study from one site, initially performed with a magnetostratigraphic goal, does not provide a shorter time interval for the occurrence of this remagnetization event. However, the tectonic history of the NCA makes possible the chronologic discrimination between two successive phases of magnetization of opposite polarity.

The compared timing of acquisition of the normal magnetization in the grey and red wackestones is also interesting. Depending on the interpretation of the final normal polarity direction of moderate easterly declination



**Figure 8.** Comparison between the directions observed within the Langmoos section and the expected Eurasian and African directions at our site for the last 200 millions years (derived from Besse & Courtillot 1991). Shaded areas correspond to error bars of the expected palaeolatitudes and declinations. The directions are shown by horizontal solid and dashed lines (without the error bars to simplify the figure), respectively in stratigraphic and geographic coordinates. The large difference observed in declination between the different components allows us to propose a chronology of at least two, maybe three, different phases of magnetization in both polarities during the tectonic history of the NCA.

observed in the grey wackestones, two alternative solutions may be proposed. The first one, considering a bias by an 'underlying' component of reversed polarity (clearly observed in the samples of the basal Adnet formation; Fig. 3f), would favour the hypothesis of a single normal polarity component both present in the grey (as an intermediate component) and reddish wackestones (as a final component). In this case, although the magnetization process is different between the two lithologies, the age and duration of these two magnetization phases would be close enough to have allowed the same magnetic direction to be recorded (prior the tectonic rotation of the NCA). Rather than a

viscous remanent magnetization, recent studies from eastern North America have shown that secondary (chemical) magnetite may carry the magnetization in some remagnetized sediments (McCabe *et al.* 1983; McCabe, Sassen & Saffer 1987; Jackson *et al.* 1988; Jackson 1990). The magnetite authigenesis could be caused by alteration and replacement of framboidal pyrite (Suk, Peacor & Van der Voo 1990; Suk, Van der Voo & Peacor 1993). We might suggest with caution a similar remagnetization process for the grey wackestones where multidomain magnetite and pyrite have been evidenced from the palaeomagnetic analyses.

The second hypothesis explaining the two normal magnetic components in the grey wackestones is the bias of the secondary component (with an easterly declination) by the locally very well-defined recent reversed component. In this case, we should consider the final direction of moderate declination as different of the direction carried by the red wackestones and thus, we could suggest two successive phases of magnetization at two different periods. The duration in between these two phases would be underlined by the difference in declination (about 30°). Considering the model of large clockwise rotation of the NCA (Channell *et al.* 1990a, 1992), the magnetization of the grey wackestones in the normal field would occur after the magnetization of the red wackestones, probably during the rotation of the NCA. Finally, following this case, we could establish a chronology of three magnetization phases within the Langmoos section (excluding the low stability component in the present day field): (1) magnetization of the red wackestones probably before the rotation of NCA, (2) magnetization of the grey wackestones during the rotation of NCA, and (3) selective remagnetization of the grey wackestones in a reversed field after the rotation.

## CONCLUSION

This study provides an example of an apparently well-defined magnetostratigraphy which results from successive magnetization phases. Some non-palaeomagnetists could be disconcerted by such a result and might begin to have doubts about other magnetostratigraphic data. Fortunately, the methods developed for the analysis of palaeomagnetic data are probably sufficient to detect the 'anomalies'. In our study, criteria such as a change in lithology associated with change of magnetic polarity and different combinations of magnetic components, allow us to avoid an erroneous interpretation of this magnetic sequence.

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## REFERENCES

Besse, J. & Courtillot, V., 1991. Revised and synthetic apparent polar wander paths of the African, Eurasian, North American

- and Indian Plates, and True Polar wander since 200 Ma, *J. geophys. Res.*, **96**, 4029–4050.
- Blind, W., 1963. Die Ammoniten des Las Alpha aus Schwaben, vom Fonsjoch und Breitenberg (Alpen) und ihre Entwicklung, *Paleontographica*, Abt. A, **121**, 38–131.
- Bloos, G., 1988. Ammonites marmoreus OPPEL (Schlotheimiidae) im Unteren Lias (Angulata zone, depressa subzone) von Württemberg (Südwest Deutschland), *Stuttgarter Beitr. Natur., Ser. B*, **141**.
- Böhm, C., 1992. Mikrofazies und Ablagerungsmilieu des Lias und Dogger der Nordöstlichen Kalalpen, *Erlanger Geol. Abh.*, in press.
- Bosselini, A., Lobitzer, H., Brandner, R., Resch W. & Castellarin, A., 1980. The complex basins of the Calcareous Alps and paleomargins, *Abhandlungen der Geologischen Bundesanstalt*, **34**, 287–325.
- Channell, J. E. T., Brandner, R., Spieler, A. & Stoner, J. S., 1992. Paleomagnetism and paleogeography of the Northern Calcareous Alps (Austria), *Tectonics*, **11**, 792–810.
- Channell, J. E. T., Brandner, R., Spieler, A. & Smathers, N., 1990a. Mesozoic palaeogeography of the Northern Calcareous Alps-evidence from palaeomagnetism and facies analysis, *Geology*, **18**, 828–831.
- Channell, J. E. T., Freeman, R., Heller, F. & Lowrie, W., 1982. Timing of diagenetic haematite growth in red pelagic limestones from Gubbio (Italy), *Earth planet. Sci. Lett.*, **85**, 153–166.
- Channell, J. E. T., Lowrie, W., Piali, P. & Venturi, F., 1984. Jurassic magnetic stratigraphy from Umbria (Italian) land sections, *Earth planet. Sci. Lett.*, **68**, 309–325.
- Channell, J. E. T., Massari, F., Benetti, A. & Pezzoni, N., 1990b. Magnetostratigraphy and biostratigraphy of Callovian–Oxfordian limestones from the Trento plateau (Monti Lessini, northern Italy), *Palaeogeog., Palaeoclimat., Palaeoecol.*, **79**, 289–303.
- Day, R., Fuller, M. D. & Schmidt, V. A., 1977. Magnetic hysteresis properties of synthetic titanomagnetites, *J. geophys. Res.*, **81**, 873–880.
- Dekkers, M. J., 1990. Magnetic monitoring of pyrrhotite alteration during thermal treatment, *Geophys. Res. Lett.*, **17**, 779–782.
- Galbrun, B., Crasquin-Soleau, S. & Jauguey, J. M., 1992. Magnetostratigraphie des sédiments triasiques des sites 759 et 760, ODP Let 122, Plateau de Wombat, Nord-Ouest de l'Australie, *Mar. Geol.*, **107**, 293–198.
- Galbrun, B., Gabilly, J. & Rasplus, L., 1988. Magnetostratigraphy of the Toarcian stratotype sections at Thouars and Airvault (Deux-Sèvres, France), *Earth planet. Sci. Lett.*, **87**, 453–462.
- Galbrun, B., Baudin, F., Fourcade, E. & Rivas, P., 1990. Magnetostratigraphy of the Toarcian ammonitico rosso limestone at Iznalloz, Spain, *Geophys. Res. Lett.*, **17**, 2441–2444.
- Gallet, Y., 1988. La magnetostratigraphie: aspects fondamentaux et appliqués, *PhD thesis*, University of Paris VII.
- Gallet, Y., Besse, J., Krystyn, L., Marcoux, J. & Théveniaut, H., 1992. Magnetostratigraphy of the Late Triassic Bolucektasi Tepe (south-western Turkey) and implications for changes in reversal frequency, *Phys. Earth planet. Inter.*, **73**, 85–108.
- Gallet, Y., Besse, J., Krystyn, L., Théveniaut, H. & Marcoux, J., 1993. Magnetostratigraphy of the Kavur Tepe section (southwestern Turkey): A magnetic polarity time scale for the Norian, *Earth planet. Sci. Lett.*, **117**, 443–456.
- Hall, H. C., 1976. A least-squares method to find a remanence direction from converging remagnetization circles, *Geophys. J. R. astr. Soc.*, **45**, 297–304.
- Haag, M. & Heller, F., 1991. Late Permian to Early Triassic magnetostratigraphy, *Earth planet. Sci. Lett.*, **107**, 42–57.
- Horner, F. & Heller, F., 1983. Lower Jurassic magnetostratigraphy at the Breggia Gorge (Ticino, Switzerland) and Alpe Turati (Como, Italy), *Geophys. J. R. astr. Soc.*, **73**, 705–718.

- Jackson, M., 1990. Diagenetic sources of stable remanence in remagnetized paleozoic cratonic carbonates: a rock magnetic study, *J. geophys. Res.*, **95**, 2753–2761.
- Jackson, M., McCabe, C., Ballard, M. & Van der Voo, R., 1988. Magnetite authigenesis and diagenetic paleotemperatures across the northern Appalachian basin, *Geology*, **16**, 592–595.
- Kieslinger, A., 1964. *Die nutzbaren gesteine Salzburgs*, Bergland, Salzburg Austria.
- Kirschvink, J. L., 1980. The least-squares line and plane and the analysis of palaeomagnetic data, *Geophys. J. R. astr. Soc.*, **62**, 699–718.
- Lowrie, W., 1990. Identification of ferromagnetic minerals in a rock by coercivity and unblocking temperature properties, *Geophys. Res. Lett.*, **17**, 159–162.
- Lowrie, W. & Heller, F., 1982. Magnetic properties of marine limestones, *Rev. Geophys. Space Phys.*, **20**, 171–192.
- Marton, E., Marton, P. & Heller, F., 1980. Remanent magnetization of a Pliensbachian limestone sequence at Bakonycsernye (Hungary), *Earth planet. Sci. Lett.*, **57**, 182–190.
- Mauritsch, H. & Frisch, W., 1978. Palaeomagnetic data from the central part of the Northern Calcareous Alps, Austria, *J. Geophys.*, **44**, 623–637.
- Mauritsch, H. & Frisch, W., 1980. Palaeomagnetic results from the Eastern Alps and their comparison with data from the Southern alps and the Carpathians, *Mitt. österr. geol. Ges.*, **73**, 5–13.
- McCabe, C., Sassen, R. & Saffer, B., 1987. Occurrence of secondary magnetite within biodegraded oil, *Geology*, **15**, 7–10.
- McCabe, C., Van der Voo, R., Peacor, D., Scotese, C. & Freeman, R., 1983. Diagenetic magnetite carries ancient yet secondary remanence in some Paleozoic sedimentary carbonates, *Geology*, **11**, 221–223.
- McFadden, P. L. & McElhinny, M., 1988. The combined analysis of remagnetization circles and direct observations in palaeomagnetism, *Earth planet. Sci. Lett.*, **87**, 161–172.
- McIntosh, W. C., Hargraves, B. & West, L., 1985. Paleomagnetism and oxide mineralogy of Upper Triassic to Lower Jurassic red beds and basalts in the Newark Basin, *Geol. Soc. Am. Bull.*, **96**, 463–480.
- Molina-Garza, R., Geissman, J., Van der Voo, R., Lucas, S. & Hayden, S., 1991. 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.
- Nagata, T. & Carleton, B. J., 1987. Magnetic remanence coercivity of rocks, *J. Geomagn. Geoelect.*, **39**, 447–461.
- Oberhauser, R., 1980. *Der geologische Aufbau Österreichs*, Springer, Vienna, Austria.
- Ogg, J. G. & Steiner, M. B., 1991. Early Triassic magnetic time scale-integration of magnetostratigraphy, ammonite zonation and sequence stratigraphy from statotype sections (Canadian Arctic Archipelago), *Earth planet. Sci. Lett.*, **107**, 69–89.
- Steiner, M. B., Ogg, J. G. & Sandoval, J., 1987. Jurassic magnetostratigraphy, 3. Bathonian–Bajocian of Carcabuey, Sierra Harana and Campillo de Aranas (Subbetic Cordillera, southern Spain), *Earth planet. Sci. Lett.*, **82**, 357–372.
- Steiner, M. B., Ogg, J. G., Melendez, G. & Sequeiros, L., 1986. Jurassic magnetostratigraphy, 2. Middle–Late Oxfordian of Aguilon, Iberian Cordillera, northern Spain, *Earth planet. Sci. Lett.*, **76**, 151–166.
- Steiner, M. B., Ogg, J. G., Zhang, Z. & Sun, S., 1989. The Late Permian/Early Triassic magnetic polarity time scale and plate motions of South China, *J. geophys. Res.*, **94**, 7343–7363.
- Suk, D., Peacor, D. R. & Van der Voo, R., 1990. Replacement of pyrite framboids by magnetite in limestone and implications for palaeomagnetism, *Nature*, **345**, 611–613.
- Suk, D., Van der Voo, R. & Peacor, D. R., 1993. Origin of magnetite responsible for remagnetization of early Paleozoic limestones of New York, *J. geophys. Res.*, **98**, 419–434.
- Tarduno, J., Lowrie, W., Sliter, W., Bralower, T. & Heller, F., 1992. Reversed polarity characteristic magnetizations in the Albian contessa section, Umbrian Apennines, Italy: implications for the existence of a mid-Cretaceous mixed polarity interval, *J. geophys. Res.*, **97**, 241–271.
- Tollmann, A., 1987. Geodynamic concepts of the evolution of the Eastern Alps, in *Geodynamics of the Eastern Alps*, pp. 361–378, eds Flügel, H. W. & Faupl, P. Deuticke, Vienna, Austria.
- Weissert, H. & Bernoulli, D., 1985. A transform margin in the Mesozoic Tethys: evidences from the Swiss Alps, *Geologische Rundschau*, **74**, 665–679.
- Wendt, J., 1971. Die Typlokalität der Adneter Schichten (Lias, Österreich), *Ann. Inst. Geol. Publ. Hung.*, **54**, 105–116.
- Witte, W. K. & Kent, D. V., 1990. The paleomagnetism of red beds and basalts of the Hettangian extrusive zone, Newark Basin, New Jersey, *J. geophys. Res.*, **95**, 17533–17545.
- Witte, W. K., Kent, D. V. & Olsen, P. E., 1991. Magnetostratigraphy and paleomagnetic poles from Late Triassic–Earliest Jurassic strata of the Newark basin, *Geol. Soc. Am. Bull.*, **103**, 1648–1662.
- Zijderveld, J. D. A., 1967. AC demagnetization of rocks, analysis of results, in *Methods in Palaeomagnetism*, pp. 254–286, eds Collinson, D. W., Creer, K. M. & Runcorn, S. K., Elsevier, Amsterdam.