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Middle Triassic magnetostratigraphy and biostratigraphy from the Dolomites and Greece

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Abstract

Magnetostratigrapic and biostratigraphic data across the Anisian/Ladinian (Middle Triassic) boundary were obtained from the Frötschbach/Seceda section from the Dolomites region of northern Italy, and the Vlichos section from the Greek island of Hydra, where the Aghia Triada published section was also resampled. The Frötschbach/Seceda section includes two radiometrically dated (U–Pb) tuff levels and covers two of the three chief candidates for the position of the base of the Ladinian, namely at the base of the Secedensis Zone or the subsequent Curionii Zone. The Aghia Triada section yields biochronological evidence for the base of the Secedensis Zone, whose significance is, however, critically discussed in the light of the magnetostratigraphic correlation with Frötschbach/Seceda. The Vlichos section can be correlated with Aghia Triada and Frötschbach/Seceda by means of magnetic polarity stratigraphy and sparse fossil occurrences. The satisfactory correlation of the magnetozones allows us to construct a composite geomagnetic polarity sequence tied to Tethyan ammonoid and conodont biostratigraphy for about a 2.4 Myr interval across the Anisian/Ladinian boundary.

Keywords: biostratigraphy; Hellenic Arc; Dolomites; magnetostratigraphy; Anisian; Ladinian

1. Introduction

Triassic magnetostratigraphy and biostratigraphy in the Tethyan marine domain has received considerable attention in recent years (e.g., [1–4]). These studies are aimed at correlating the widely recognized biozonation in the Tethyan Triassic realm to the geomagnetic polarity sequence of reversals for the construction of a standard Tethyan Triassic time scale.

Precise dates have recently become available for the Anisian/Ladinian (Middle Triassic) boundary interval at the Frötschbach/Seceda section located in the Dolomites region of northern Italy [5,6]. This gave us the opportunity for placing them in a magnetic polarity context which can be tested by means of correlation with the coeval Aghia Triada section of [2], located on the Greek island of Hydra and containing one of the best magnetostratigraphic and biostratigraphic records across the Anisian/Ladinian boundary. In order to confirm and also extend downward the data from Frötschbach/Seceda, we refined sampling at Aghia Triada and also studied the Vlichos section, located a few kilometres to the south-

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west of Aghia Triada. The final result is a well constrained composite geomagnetic polarity time scale tied to ammonoids, conodonts and radiometric ages across the Anisian/Ladinian boundary, which is among the most widely studied in the Tethyan Triassic [2,7–12].

2. Frötschbach / Seceda

2.1. Stratigraphy and age constraints

Exposures along the Frötschbach stream and on the Seceda peak in the western Dolomites (Fig. 1a) provide a classic section of Middle Triassic Tethyan stratigraphy (e.g., [8,13,14]). The Dolomites are a portion of the Southern Alps that have experienced significant tectonic deformation since the Triassic. The polyphase deformation was not intense enough, however, to obliterate the original stratigraphic patterns, and the western Dolomites have some of the best preserved Paleozoic and Mesozoic rocks in the Southern Alps.

The Frötschbach and Seceda sections are comprised of the Buchenstein Beds and are subdivided into two units: the Lower Plattenkalke and the Knollenkalke (Fig. 2a,b). The Lower Plattenkalke is a succession of evenly bedded, black siliceous and

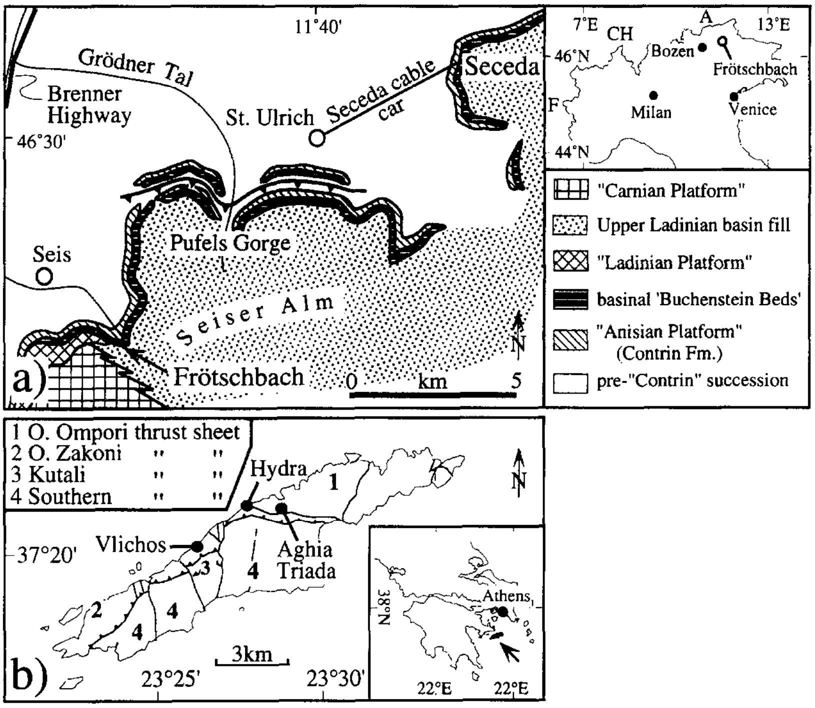
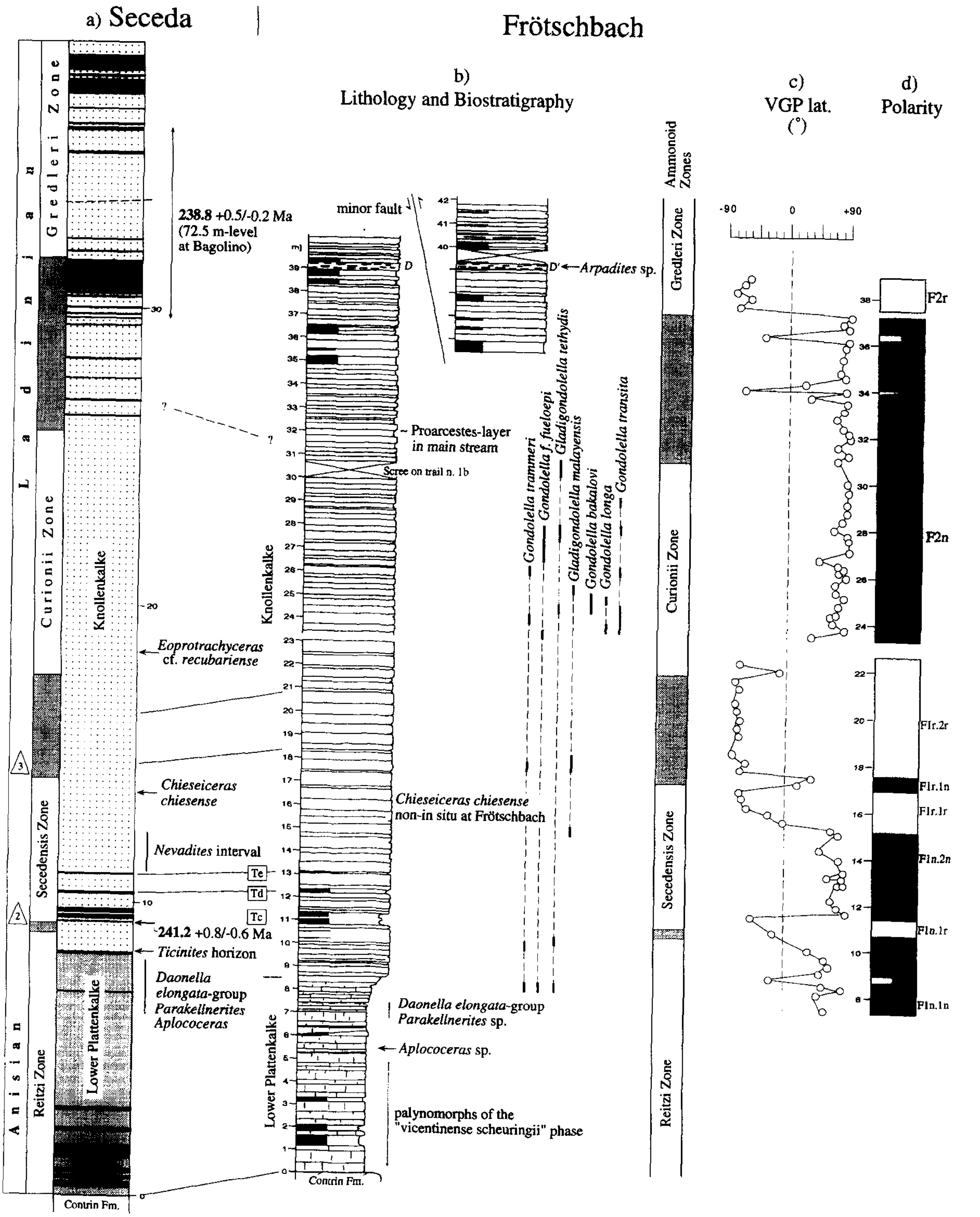


Fig. 1. (a) Simplified geological map of the Frötschbach section area. The section is located southeast of the village of Seis am Schlern, a half an hour walk from Bad Ratzes, on the trail heading to Seiser Alm. The Seceda section is about 13 km to the northeast on the western flank of Mount Seceda. (b) Simplified tectonic map of the island of Hydra. The Aghia Triada section is located west of the Aghia Triada monastery, about 1 hour walk heading southeast from the village of Hydra. The Vlichos section crops out in the first ravine west of the village of Vlichos, along the western flank of the mountain due south of the village.

Fig. 2. The Anisian/Ladinian boundary Seceda and Frötschbach sections. (a) Age, ammonoid zonation and lithologic subdivision at Seceda; some fossils of biochronological importance and radiometrically dated levels are indicated. (b) Lithology and biostratigraphy of the Frötschbach section ([14], simplified). (c) VGP relative latitudes of the characteristic component plotted as function of stratigraphic thickness at Frötschbach and (d) corresponding polarity interpretation where magnetic polarity zones are shown by filled bars for normal polarity and open bars for reversed polarity.



a) Seceda
Frötschbach
b)
Lithology and Biostratigraphy
c)
VGP lat.
(°)
d)
Polarity
L a d i n i a n
A n i s i a n
Gredleri Zone
Curionii Zone
Secedensis Zone
Reitzi Zone
Knollenkalke
Lower Plattenkalke
Contrin Fm.
238.8 +0.5/-0.2 Ma
(72.5 m-level
at Bagolino)
Eoprotrachyceras
cf. recubariense
Chieseiceras
chiesense
Nevadites interval
Te
Td
Tc
241.2 +0.8/-0.6 Ma
Ticinites horizon
Daonella
elongata-group
Parakellnerites
Aplococeras
minor fault
D
D'
Arpadites sp.
Proarcestes-layer
in main stream
Scree on trail n. 1b
Chieseiceras chiesense
non-in situ at Frötschbach
Daonella elongata-group
Parakellnerites sp.
Aplococeras sp.
palynomorphs of the
"vicentinense scheuringii" phase
Gondolella trammeri
Gondolella f. fueloepi
Gladigondolella tethydis
Gladigondolella malayensis
Gondolella bakalovi
Gondolella longa
Gondolella transita
Ammonoid
Zones
-90
0
+90
F2r
F2n
F1r.2r
F1r.1n
F1r.1r
F1n.2n
F1n.1r
F1n.1n

calcareous mudstones (8–9 m thick) resting with a sharp basal contact on an Upper Anisian carbonate platform (Contrin Formation). The Knollenkalke consist of 30–35 m of calcareous mudstones arranged in decimeter thick, wavy to nodular beds with abundant chert nodules in the lower part, which grades into more evenly bedded, light dolomitic limestones and dolomites, which have a partly turbiditic origin. Carbonate breccias and basaltic layers of the Wengen Group follow on top. Volcaniclastic levels (Pietra Verde) occur throughout the Buchenstein Beds as silty to sandy layers up to 70 cm thick.

A characteristic set of three volcaniclastic levels (T_c, T_d and T_e) occurs in the lower part of the Frötschbach section (Fig. 2b). These layers, in conjunction with other lithostratigraphic markers, allow us to correlate with a bed-by-bed resolution the basal two-thirds of the Frötschbach section with meters 0–35 at Seceda (Fig. 2a,b; see also figure 6 in [8]). On the basis of the vertical distribution of volcaniclastic layers and fossils, the Seceda section is, in turn, closely tied to other well studied Anisian/Ladinian boundary sections in the Southern Alps, such as Bagolino and Monte San Giorgio [8].

New high resolution U–Pb radiometric ages were obtained on zircons from Seceda, Bagolino and Monte San Giorgio [5,6]. The base of the volcaniclastic T_c layer at Seceda, which was also identified at Frötschbach (Fig. 2a,b), yielded a mean age of 241.2 (+0.8/−0.6) Ma. A tuff layer located at the 72.5 m level at Bagolino gave a mean age of 238.8 (+0.5/−0.2) Ma; this level can be correlated via Seceda to the 35–40 m interval of the Frötschbach section. At Frötschbach the duration of the stratigraphic interval bracketed by the radiometrically dated levels can thus be evaluated as a minimum of 1.3 and a maximum of 3.4 Myr, and the mean duration of 2.4 Myr gives a sedimentation rate of 11 m/Myr.

A few palynomorphs, ammonoids, conodonts and daonellas of biochronological significance were found at Frötschbach (Fig. 2b) and are extensively discussed in [14]. On the basis on these fossil occurrences and correlations with Seceda and other localities in the Southern Alps, the base of the Frötschbach section is assigned to the Reitzi Zone and the top of the section to the Gredleri Zone. Frötschbach therefore fully covers two of the three chief candidates for the stratigraphic position of the Anisian/Ladinian boundary; namely, the base of the (*Nevadites*) Secedensis or the base of the Curionii Zone. The base of the Secedensis Zone is placed immediately below the volcaniclastic layer T_c, and is constrained by the first occurrence of *Nevadites* at this level in the Giudicarie Alps [11,15]. This conclusion is also supported by the first occurrence of the conodont *Gondolella trammeri* at about meter 8 at Frötschbach, a bio-event that is considered a proxy for the base of the Secedensis Zone (e.g., [10,12]). The base of the Curionii Zone is constrained by the occurrence of the ammonoid species *Chieseiceras chiesense* and *Eoprotrachyceras* at Seceda. At Frötschbach this boundary most probably falls in an interval between 4 and 8 m above the volcaniclastic T_e layer.

2.2. Paleomagnetism

Frötschbach was sampled with a sampling interval of 2–4 samples per meter, yielding a total of 92 samples for statistical analysis. The steep outcrop at Seceda could not be sampled with a portable drill but this section may eventually be recovered by scientific drilling.

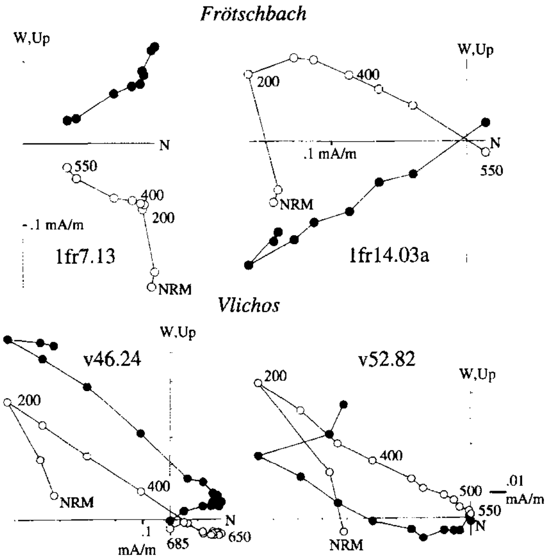


Fig. 3. Zijderveld diagrams of thermal demagnetization of NRM of representative Frötschbach and Vlichos samples. ● = projections onto the horizontal plane; ○ = projections onto the vertical plane. Temperatures are expressed in degrees Celsius. All diagrams are in geographic coordinates.

Standard 11 cm^3 oriented samples were subjected to progressive thermal demagnetization, and remanence measurements were performed on a 2G 3-axis cryogenic magnetometer. The median intensity of the natural remanent magnetization (NRM) at room temperature is 0.11 mA/m, whereas the initial susceptibility has a median value of 2×10^{-5} SI and it is stable over the heating procedure. Samples typically show an initial steeply inclined component which, in geographic coordinates, is consistent with the present-day field direction (Fig. 3). A bipolar NW-down (SE-up) characteristic component, obtained by least-squares analysis on vector end point demagnetograms [16], was successively unblocked between about 200°C and 500°C with a maximum of 575°C. Thermal demagnetization of orthogonal-axes IRM [17] indicates the presence of a dominant soft component with a maximum unblocking temperature of 575°C (e.g., Fig. 4a), interpreted as magnetite, which is the main carrier of the magnetization.

The characteristic component directions do not appreciably change in orientation after correction for bedding tilt (Fig. 5a; Table 1) because bedding planes are gently inclined to the southeast; no fold test is therefore available at Frötschbach. The mean normal and reversed characteristic directions, calculated by standard Fisher statistics, depart from antipodality by 20° ± 19° (tilt-corrected coordinates), which may be attributed to contamination of the characteristic magnetizations by the present-day field component.

A virtual geomagnetic pole (VGP) has been calculated for each of the characteristic component directions (Fig. 2c). Assuming that the Dolomites were north of the equator during the Middle Triassic and that the characteristic component was acquired before deformation, northerly and down directions correspond to normal polarity. The latitude of the sample VGP relative to the north pole of the paleomagnetic axis was used for interpreting the polarity stratigraphy. Relative VGP latitudes that are positive and ideally approach +90° are interpreted as recording normal polarity, and those that are negative and ideally approach −90° as recording reversed polarity (Fig. 2c). For identification of polarity magnetozones which are defined by at least two samples, we adapt the nomenclature used for the Late Triassic/earliest Jurassic Newark geomagnetic polarity sequence [18]. The data from Frötschbach define four main magnetozones, namely F1n, F1r, F2n and F2r, with two short polarity intervals within F1n and F1r (Fig. 2d). This sequence of eight magnetozones is considered to represent a ca. 2.4 Myr record of Middle Triassic geomagnetic field reversals, biochronologically bracketed between the upper part of the Reitzi Zone

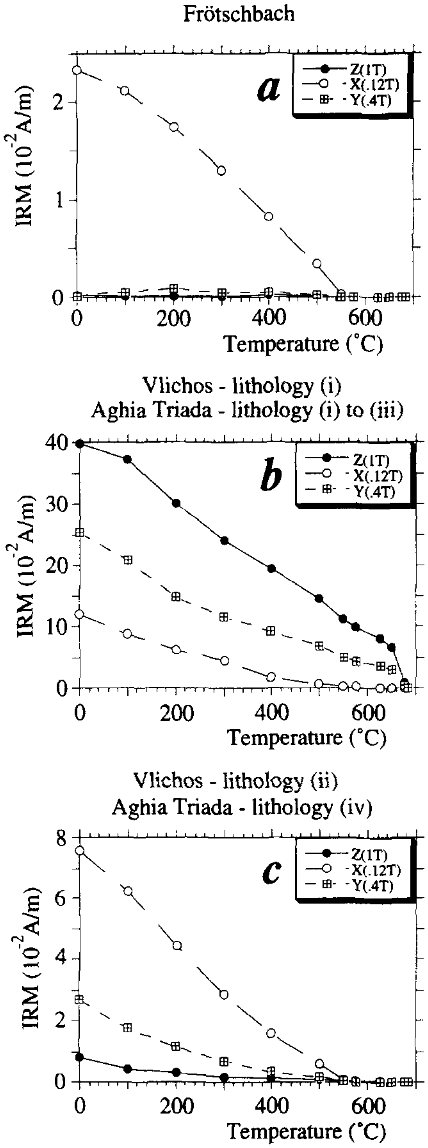


Fig. 4. Thermal demagnetization curves of orthogonal-axes IRM for representative samples from grey limestone at: (a) Frötschbach; (b) lower pink to grey limestone at Vlichos (i.e., unit (i)); and (c) overlying mostly grey limestone at Vlichos (i.e., unit (ii)).

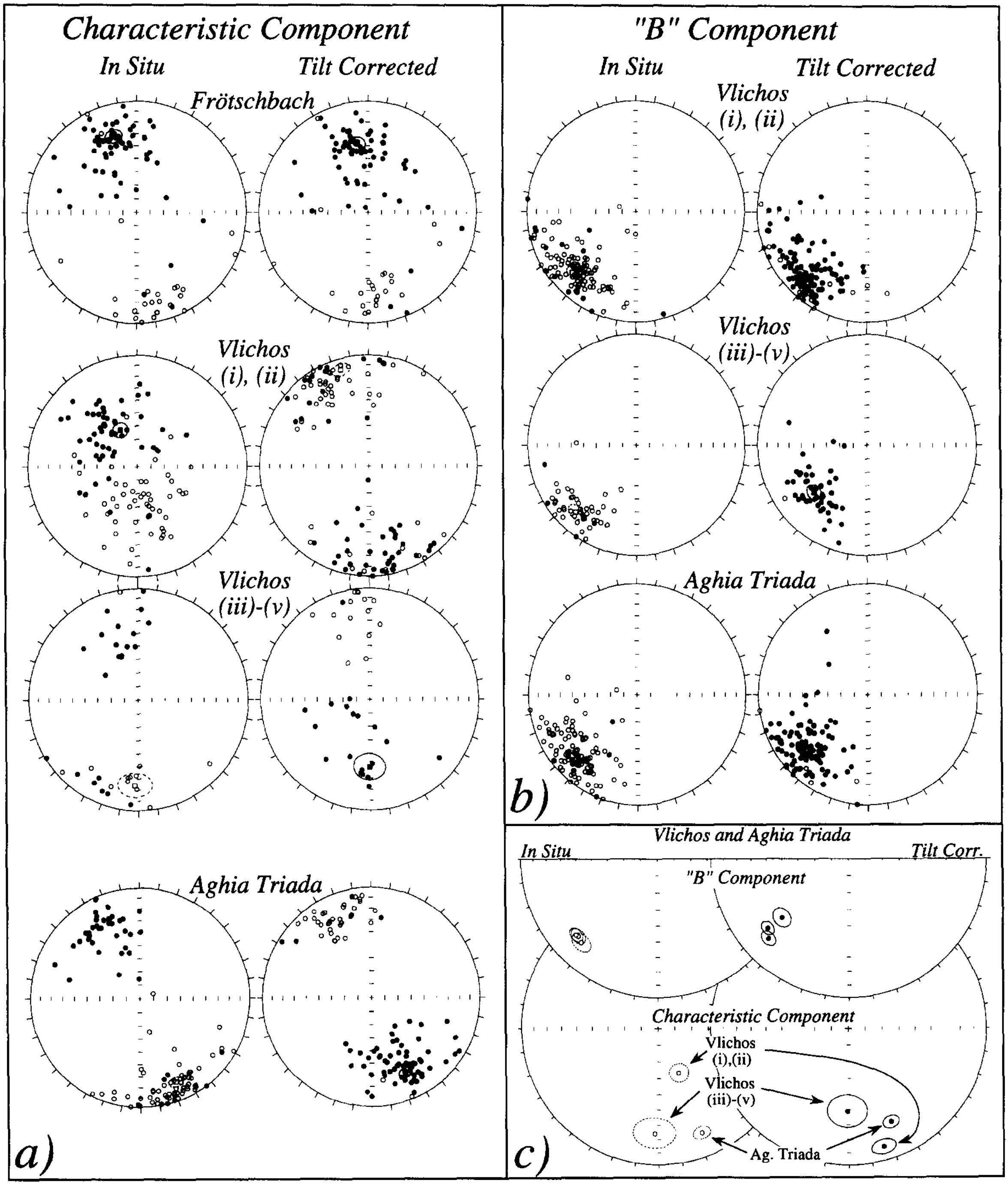


Fig. 5. Equal-area projections before and after bedding tilt correction of: (a) the characteristic component directions from Frötschbach, Aghia Triada and Vlichos lithology (i)–(ii) and (iii)–(v); (b) the "B" component directions from Aghia Triada and Vlichos lithology (i)–(ii) and (iii)–(v); and (c) the overall "B" and characteristic component directions from Aghia Triada and Vlichos lithology (i)–(ii) and (iii)–(v). ● = lower hemisphere; ○ = upper hemisphere.

Table 1
Paleomagnetic directions from Frötschbach, Aghia Triada and Vlichos

Site		Comp.	N_1/N_2	In situ				Tilt corrected				Lat./Long.	dp/dm	Plat.
				Dec. (°)	Inc. (°)	k	a95 (°)	Dec. (°)	Inc. (°)	k	a95 (°)	(°N/°E)	(°)	(°N)
1	Frötschbach	C	102/092	343.3	29.3	8	5.5	350.8	38.0	8	5.7	63.9/211.0	4.0/6.7	21.3
2a	Aghia Triada	B	165/113	226.4	−20.7	11	4.2	225.6	19.3	11	4.1			
2b	Aghia Triada	C	165/105	157.8	−18.5	11	4.4	155.8	26.1	11	4.3	−34.2/052.1	2.5/4.6	13.8
3a	Vlichos (i), (ii)	B	136/110	227.6	−20.2	13	3.8	229.8	23.8	13	3.8			
3b	Vlichos (iii)–(v)	B	052/046	223.0	−19.0	16	5.4	229.0	35.6	16	5.4			
3c	Vlichos (i),(ii)	C	136/102	155.2	−60.5	7	5.6	163.7	10.8	7	5.6	−44.7/046.5	2.9/5.7	05.5
3d	Vlichos (iii)–(v)	C	052/034	182.5	−24.1	6	10.7	180.9	39.1	6	10.7	−30.9/022.3	7.6/12.8	22.1
Overall sites 2a, 3a, 3b		B	3	225.7	−20.0	1131	3.7	228.1	26.2	88	13.2	41.0/134.5	2.0/3.8	10.3
Overall sites 2b, 3c, 3d		C	3	166.8	−34.8	10	41.5	166.0	25.7	20	28.0	−37.6/040.5	16.3/30.2	13.5

Comp. = component designation; N_1 = number of 11 cm^3 specimens thermally demagnetized; N_2 = number of 11 cm^3 specimens used for statistical analysis; Dec., Inc. = declination and inclination; k = precision parameter; a95 = radius of cone of 95% confidence about the mean direction; Lat., Long. = latitude and longitude of north paleomagnetic pole; dm/dm = semi-axes of the a95 confidence oval about the paleomagnetic pole; Plat. = paleolatitude.

and the Gredleri Zone and with an estimated frequency of about three reversals per million years.

3. Vlichos and Aghia Triada

3.1. Geology and stratigraphy

The Vlichos and Aghia Triada sections are located on the island of Hydra, which lies off the coast of the Argolis peninsula in Greece (Fig. 1b). As described in more detail elsewhere ([2,19] and references therein), Hydra is part of the Subpelagonian zone of mainland Greece and exhibits a Permian to Jurassic passive continental margin succession deposited on the western part of the Pelagonian terrane. The Pelagonian terrane is though to have separated from the northern margin of Africa sometime in the Triassic. The Argolis peninsula was affected by nappe emplacement during the Late Jurassic and Late Eocene/Early Oligocene but on Hydra it is difficult to separate the contribution of the Late Jurassic and Cenozoic deformation phases.

The 60 m thick Vlichos section (Fig. 6a) approximately corresponds to the Han-Bulog Limestone and the basal Pantokrator Limestone of litho-biostratigraphic section "B" of Angiolini et al. [19] [1] and can be subdivided into five units: (i) 11.5 m of pink nodular limestone with red marls; (ii) 29.5 m of decimeter thick grey limestone beds rich in pelagic bivalves, associated with less abundant red marls; (iii) 3.5 m of centimetre thick beds of red limestone with abundant red chert nodules, this unit is tectonically dismembered and shows lateral variations in thickness; (iv) 2 m of grey nodular limestone beds with red marls; (v) 8.5 m of decimeter thick resedimented grey limestone beds of the Pantokrator Limestone, which continues on top but becomes difficult to access. We now suspect, contrary to earlier studies [19], that the tectonic disturbance in unit (iii) is such that the upper part of the section (unit (iv) and above) is not in stratigraphic continuity with the lower part.

Two distinct levels containing ammonoids were observed in the Vlichos section, although the hardness of the rock did not allow us to assemble a satisfactory collection of fossils from this locality. The base of unit (i) contains Fe–Mn oxide-coated Arcestidae and Ceratitidae, whereas the base of unit (iv) yielded badly preserved ammonoids with no Fe–Mn coatings. Renz ([20] and references therein) reported an ammonoid fauna from the Han-Bulog Limestone cropping out some 300 m to the west at Aghia Irene. This fauna was restudied by Balini [21], who recognized that it represents two distinct stratigraphic levels. We suggest that Fe–Mn oxide-coated specimens of *Asseretoceras camunum*, *Megacer-*

[1] The correct thickness of section "B" is approximately double that reported in [19], due to typographic error.

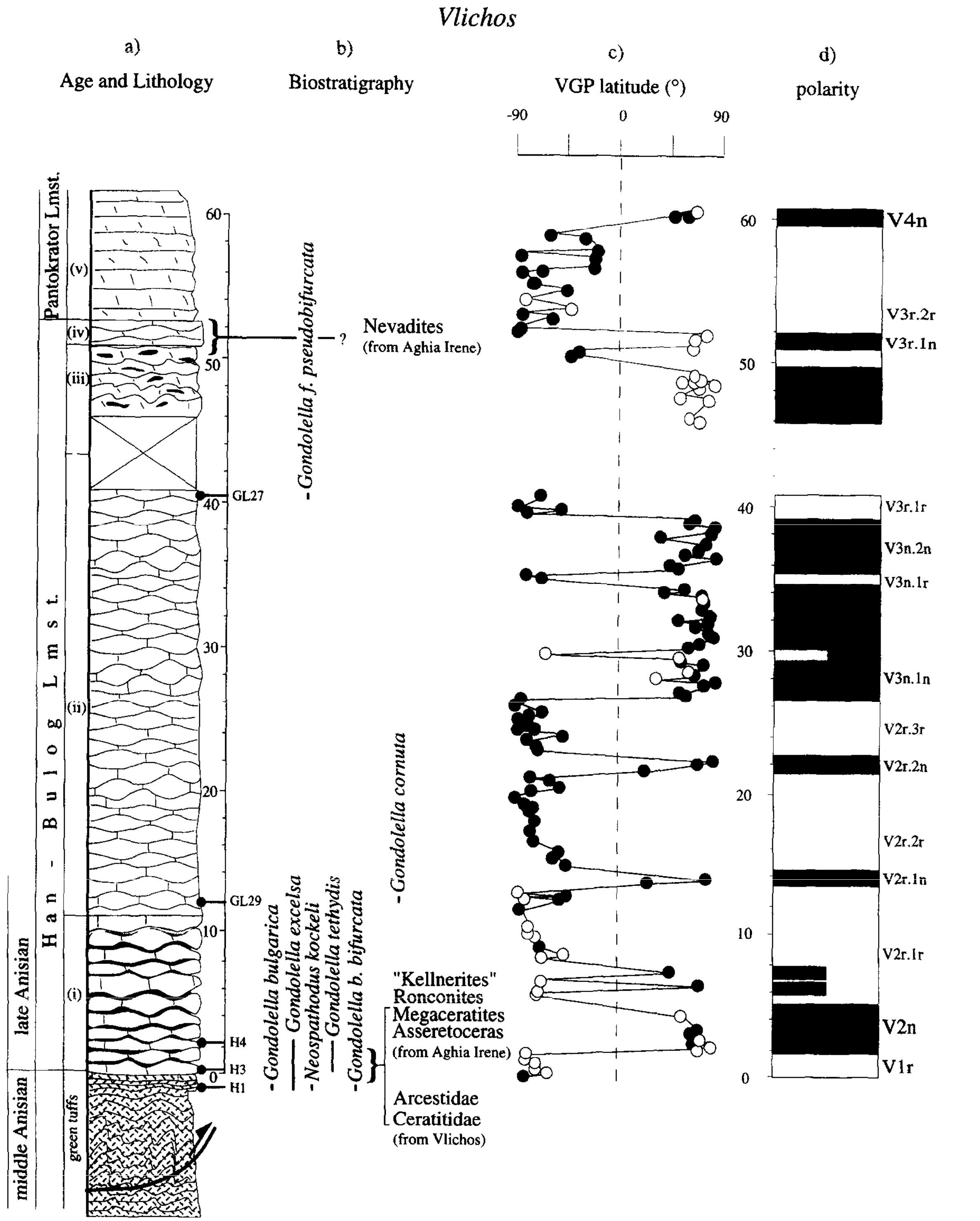


Fig. 6. The middle/late Anisian Vlichos section. For column descriptions see Fig. 2. Conodont biostratigraphy is from [19]. In the VGP latitude column, ○ = mainly hematite, ● = mainly magnetite is the magnetic carrier of the characteristic remanence.

atites aff. *fallax*, *Ronconites* sp. n. A and '*Kellnerites*' sp. ind., described by [21] from Rentz's collection can be referred to an older stratigraphic level at Aghia Irene, which can most probably be correlated with the level found at the base of unit (i) at Vlichos, whereas a single specimen of *Nevadites* sp. ind. with no Fe–Mn coating can be attributed to a younger level at Aghia Irene, which can be projected to the base of unit (iv) at Vlichos. The base of unit (i) at Vlichos would thus correspond to the late Anisian Trinodosus to Reitzi Zone, whereas the base of unit (iv) may be attributed to the Secedensis Zone (Fig. 6b). The conodont biostratigraphy at Vlichos [19] shows that the middle Anisian fauna was found at the very base of the section, and precisely in the uppermost portion of the green tuffs (sample H1, Fig. 6a,b), whereas conodonts of late Anisian age were collected in the overlying unit (i) (samples H3, H4 and GL29), in agreement with the inferred ammonoid biostratigraphy.

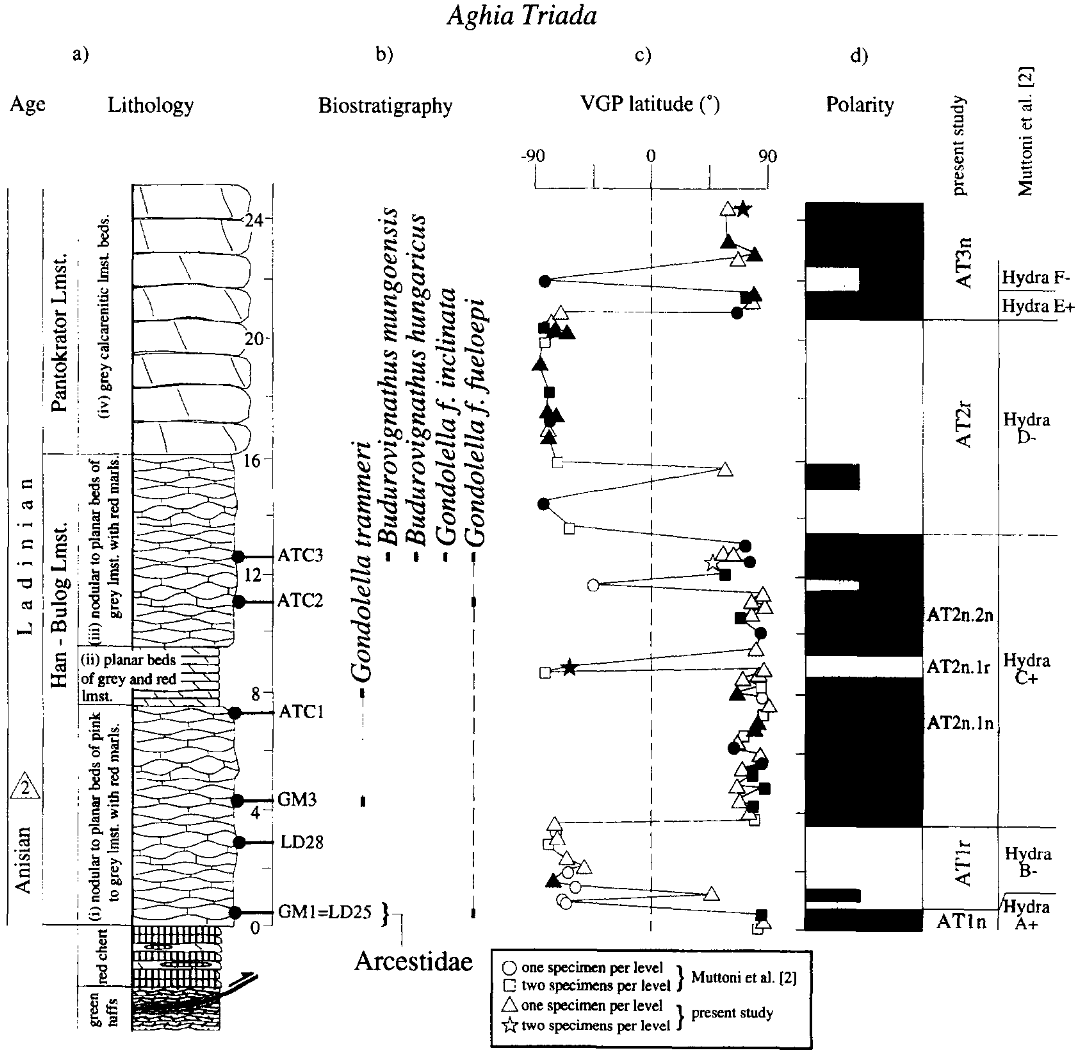


Fig. 7. The Anisian/Ladinian boundary Aghia Triada section. For column descriptions see Fig. 2. Lithostratigraphy is slightly modified from [2]. Conodont biostratigraphy and paleomagnetic data are from [2] integrated with data from the present study (see legend at foot of column c). In the VGP latitude column open symbols = mainly hematite and solid symbols = mainly magnetite is the magnetic carrier of the remanence.

The lithostratigraphy, biostratigraphy and paleomagnetism of the 24.4 m thick Aghia Triada section (Fig. 7a) have been described previously [2]. For placement of new paleomagnetic and biostratigraphic samples the section was remeasured, but thickness differences with the earlier study are generally within 10 cm. The base of the Ladinian was placed at the first occurrence of the conodont *Gondolella trammeri*, which we now have found about 4 m below the occurrence proposed previously [2]; that is, at the 4.3 m level in sample GM3 (Fig. 7a,b). The first occurrence of *G. trammeri* approximates the base of the Secedensis ammonoid zone (e.g., [10,12]). Conodonts from meter 13.2 (sample ATC3) indicate a late Ladinian age [2]. The section should thus represent a time interval comprised between the latest Anisian and the late Ladinian [2]. Note that the position for the base of the Ladinian at Aghia Triada (i.e., at the approximated base of the Secedensis Zone) differs from that proposed by Brack and Rieber [8,9] for the Frötschbach/Seceda section (i.e., at the base of the Curionii Zone). Some specimens of Arcestidae, a pelagic ammonoid of little biochronological value, have also now been observed at the base of unit (i) (Fig. 7a,b).

3.2. Paleomagnetism

For the Vlichos and Aghia Triada sections we used paleomagnetic techniques similar to those described for Frötschbach. At both sections, 3 or 4 samples were taken per stratigraphic meter. Vlichos yielded a total of 136 standard 11 cm^3 specimens for paleomagnetic analysis and Aghia Triada 105 (56 of them are from [2]). Vector end-point demagnetograms for the Vlichos section (Fig. 3) show a similar component structure to that described for Aghia Trada [2]. There is an initial component which coincides with the present-day field direction, a southwest directed "B" component of single polarity unblocked between about 200°C and 420–450°C, and a bipolar SE/NW characteristic component unblocked from about 450°C to 575°C in the grey limestone or 685°C in the pink limestone.

The initial NRM intensity at Vlichos is weak (median value of 0.26 mA/m) and the magnetic susceptibility is also very low, near the sensitivity limit of the measuring instrument, even after heating procedures. Thermal demagnetization of orthogonal-axes IRM for samples collected at Vlichos in the basal pink and grey nodular limestone [unit (i)] shows the co-existence of soft and hard components, with a maximum unblocking temperature compatible with magnetite (575°C) and hematite (685°C), respectively (Fig. 4b). In the overlying, mostly grey, limestone [unit (ii)], the soft 575°C component dominates (Fig. 4c). The reported rock magnetic properties of the Han-Bulog Limestone at Aghia Triada [2] are consistent with data for similar lithologies at Vlichos. For example, the initial NRM (median value of 0.17 mA/m) and susceptibility are of a similar magnitude at both sections. The pink and grey nodular limestone at Aghia Triada [units (i) to (iii)] yielded evidence for the co-existence of hematite and magnetite, whereas the overlying grey limestone [unit (iv)] was found to contain predominantly magnetite [2].

The presence at Vlichos of a tectonic discontinuity within unit (iii) and a related variation in bedding attitude from 354°/72° to 14°/64° (azimuth of the dip/dip) suggested to us that the paleomagnetic directions from units (i)–(ii) and (iii)–(v) should be calculated separately. The single-polarity "B" component overprint from the two Vlichos subsections and from Aghia Triada (Fig. 5b) yield well defined site-mean directions which are undistinguishable in geographic coordinates (at the 99% level of confidence, [22]) but diverge significantly when corrections for bedding tilt are applied (Fig. 5c; Table 1). We can now more confidently conclude that the "B" component was acquired after deformation, even though it is still difficult to date because of the poor age constraint on the tectonic evolution of Hydra. In the previous study of Aghia Triada [2], this overprint was tentatively associated with nappe emplacement that affected Hydra and the Argolis peninsula in the Late Jurassic.

The dual polarity characteristic component (Fig. 5a) gives site-mean directions which show some degree of convergence after correction for bedding tilt (Fig. 5c; Table 1). This suggests that the characteristic remanence was acquired before the main phase of deformation. However, the limited difference in bedding attitudes makes the fold test statistically inconclusive in this case; that is, the precision parameter progressively increases to only a factor of

2 with full (100%) tilt correction. The mean normal and reversed directions are not very antipodal, because they are offset by 18° ± 11° and 39° ± 17.5° at Vlichos units (i)–(ii) and (iii)–(v), respectively, and 13.5° ± 8° at Aghia Triada.

The general departure from antipodality may be due to residual contamination of the characteristic magnetizations by the "B" component. We assume that the contamination influences both the normal and reversed directions, whose averaging by inverting to common polarity should minimize the biassing effect in determining an overall mean direction.

For interpretation of the magnetostratigraphy, the polarity option chosen for the characteristic remanence (i.e., tilt-corrected southerly and down directions represent normal polarity) assumes that Hydra

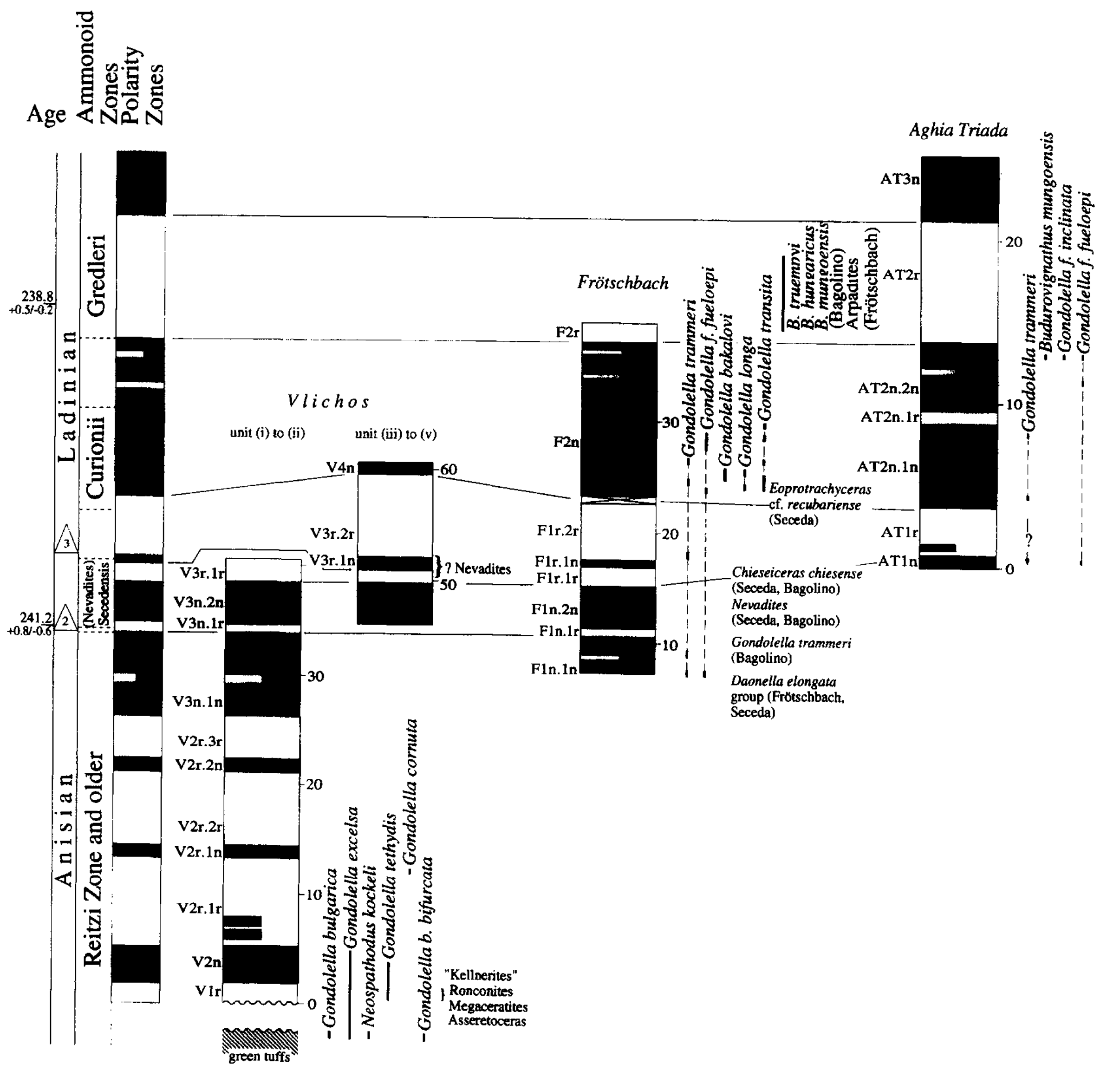


Fig. 8. Comparison of magnetic polarity sequences from the Vlichos, Aghia Triada and Frötschbach/Seceda sections and, on the left, a geochronologically calibrated composite magnetostratigraphic and biostratigraphic sequence across the Anisian/Ladinian boundary interval. The two alternative (younger) options for the position of the base of the Ladinian are indicated (*2* = base of the Secedensis Zone, *3* = base of the Curionii Zone). The magnetozones are reported in thicknesses.

was located north of the equator during the Middle Triassic; this implies that large-magnitude rotations affected the thrust sheets of Hydra in post-Middle Triassic times, as previously suggested [2]. A sequence of six main magnetozones are recognized at Vlichos: V1r, V2n, V2r, V3n, V3r and V4n, in which four short intervals are embedded (Fig. 6c,d). The presence of a tectonic discontinuity within unit (iii), however, suggests that the sequence of reversals from here upwards may be in part repeated. At Aghia Triada, five main magnetozones are recognized (AT1n to AT3n) interrupted by one short reversed interval within AT2n (Fig. 7c,d). These magnetozones were renamed from the earlier study because the polarity identification originally adopted (e.g., 'Hydra A + ' [2]) is considered less descriptive than that used here (e.g., AT1n). The resulting polarity stratigraphy essentially confirms the pattern published earlier [2], the main difference being a better definition of the magnetozones AT1n and AT2n.1r ('Hydra A + ' and unnamed, respectively, in [2]), but also that the top of the section is now characterized by an interval of normal polarity, interrupted by a single sample-based reversal (named 'Hydra F − ' by [2]). There is no obvious correlation between magnetic mineralogy variations and polarity stratigraphy in the Hydra sections (Fig. 6cFig. 7c).

4. Correlation of Anisian/Ladinian boundary sections

We have constructed a composite magnetostratigraphy and biostratigraphy across the Anisian/Ladinian boundary based on a proposed correlation of magnetozones from the Frötschbach/Seceda, Aghia and Vlichos sections (Fig. 8). The key magnetozones that are common to the three sections consist of a predominantly normal polarity (F1n, AT1n and V3n), reversed polarity (F1r, AT1r and V3r) and normal polarity (F2n, AT2n and V4n) magnetozone sequence. The Vlichos and Aghia Triada sections extend this key sequence around the Anisian/Ladinian boundary to older and younger intervals, respectively.

Three alternative positions for the base of the Ladinian using Western Tethys ammonoid zones have been proposed [7,10,23]: (1) at the base of the Reitzi Zone sensu [9,11]; (2) at the base of the Secedensis Zone sensu [9,11]; and (3) at the base of the Curionii Zone. The base of the Reitzi Zone is not well defined in any of the sections we have studied. The Frötschbach/Seceda section contains evidence for the base of both the Secedensis and Curionii Zones, the former being placed at around magnetozone F1n.1r and the latter in the lower part of F1r (Fig. 8). At Aghia Triada, the base of the Secedensis Zone was approximated by the first occurrence of *Gondolella trammeri*, which was found towards the base of polarity zone AT2n. The base of the Secedensis Zone at Frötschbach/Seceda and Aghia Triada therefore do not fall at the same position with respect to magnetic polarity stratigraphy. This is interpreted as due to discontinuous recovery of fossils at Aghia Triada, which would make the first occurrence of *G. trammeri* a poor proxy of its first appearance. This limitation becomes less disturbing up-section, where the richer conodont fauna of late Ladinian age found at the very top of magnetozone AT2n (Hydra C + in [2]) is in general agreement with a fauna of similar age found at Frötschbach/Seceda at the base of F2r.

The correlation of the Vlichos section with respect to Frötschbach/Seceda and Aghia Triada largely relies on magnetic stratigraphy as constrained by only sparse occurrences of fossils of biochronological significance. The uppermost portion of the green tuffs at the base of the Vlichos section contains a middle Anisian conodont fauna, whereas the immediately overlying unit (i) yields a late Anisian conodont and ammonoid fauna (within V1r and the top of V2r). A hiatus may therefore be present between the green tuffs and the base of unit (i), which is nevertheless regarded as being older as a whole than the base of the Frötschbach/Seceda and Aghia Triada sections. The age of the top of the Vlichos section is less well constrained. Further research is required to verify whether *Nevadites* sp. ind. collected at Aghia Irene by Renz [20,21] does in fact come from the upper ammonoid-bearing level, which, at Vlichos, is most probably located towards the base of magnetozone V3r (i.e., the base of unit (iv)). If so, the upper part of the Vlichos section would match better the lower parts of the Frötschbach/Seceda and Aghia Triada sections, which belong to the Secedensis Zone, and would thus imply that the tectonic discontinuity within unit (iii) at Vlichos acted as a reverse fault (Fig. 8).

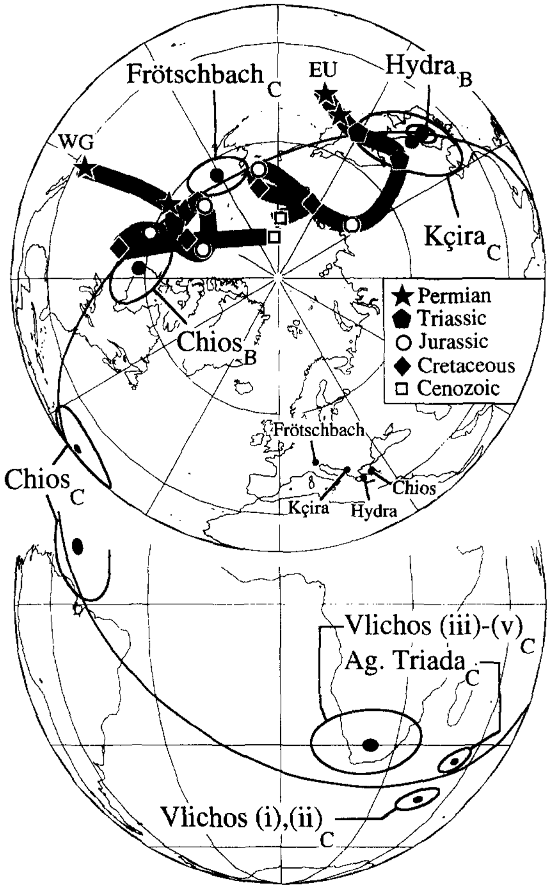


Fig. 9. The paleomagnetic poles from Frötschbach and Hydra (Table 1) and from other regions in the Mediterranean (Chios, Greece, and Kçira, Albania) compared with the West Gondwana (*WG*, in northwest Africa coordinates) and Europe (*EU*) apparent polar wander paths [27]. The suffix attached to the pole designation refers to the magnetization component used for pole calculation: C = the characteristic component, B = a secondary component (note that $Hydra_B$ is the mean of $Vlichos_B$ and Aghia $Triada_B$). The solid line is a small circle centered on the eastern Mediterranean (28°E, 36°N) whose radius of 78° is approximately the average paleoco-latitude of the Frötschbach and Hydra characteristic and ancient overprint magnetizations, illustrating that vertical axis rotations can account for the dispersion of these paleopoles.

5. Conclusions

The satisfactory correlation of the magnetozones across the Anisian/Ladinian boundary interval implies that the characteristic remanence was acquired when these sections were all located in the same hemisphere. The reported successful magnetostratigraphic correlations between the Lower Triassic Werfen Formation from the Dolomites [24] and the composite polarity sequence of the Canadian Arctic [25] suggest that the Dolomites (and hence Hydra) were most probably in the northern hemisphere in the Middle Triassic, in agreement with the most recent paleogeographic reconstructions of Pangea (e.g., [26]). A northern hemisphere location since the Middle Triassic would also imply that the post-folding "B" component overprint in the Aghia Triada and Vlichos sections was acquired during a period of reversed polarity.

The north paleomagnetic pole corresponding to the characteristic component from Frötschbach (Table 1) falls near Middle Triassic paleopoles from other regions in the Southern Alps which have West Gondwana affinity [26]. Indeed, data from the Southern Alps, and particularly the Frötschbach pole, were used [26] to refine the APWP of West Gondwana [27]. On the other hand, the characteristic components from the Vlichos and Aghia Triada sections give north paleopoles that fall near South Africa, well removed from both the West Gondwana and Europe APWPs [27] (Fig. 9). If the paleopoles from Hydra were instead regarded as south poles, this would imply that Hydra was in the southern hemisphere and the polarity correlations with Frötschbach would no longer match. However, the large rotations required by our preferred interpretation as north paleopoles are suggested by other results from the eastern Mediterranean. For example, the Triassic paleopoles from Chios [3] and Kçira [4] fall in a similar co-latitude band as those from Hydra and are all rotated with respect to the Frötschbach pole. Within this pattern falls also the post-folding "B" component paleopole from Hydra and a syn-folding "B" component paleopole from Chios [3]. These data, however sparse, suggest that large-magnitude vertical-axis rotations in opposite senses have occurred since the Triassic in the eastern Mediterranean, to the east of the parautochthonous regions of Adria (e.g., the Southern Alps). Part of these rotations, which are larger than those generally observed in Neogene rocks from the Aegean region (e.g., [28]), occurred before the acquisition of the "B" component overprint, whose age is most probably pre-Cenozoic, because the directions tend to be shallower than predicted from Cenozoic reference poles for West Gondwana or Europe (Fig. 9).

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