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High-resolution magnetostratigraphic and lithostratigraphic correlations in Middle Triassic pelagic carbonates from the Dolomites (northern Italy)

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Abstract

New magnetostratigraphic and lithostratigraphic data are reported from the Pedraces and Belvedere limestone sections from the Dolomites region of northern Italy. These sections are comprised of the Buchenstein Beds of Late Anisian to Ladinian (Middle Triassic) age. The results from Pedraces and Belvedere are compared with data from the biostratigraphically and isotopically constrained Frötschbach and Seceda sections from the literature. A satisfactory magnetostratigraphic correlation is obtained on laterally traceable limestone and volcaniclastic intervals. These marker beds are then used to extend lithostratigraphic correlations to additional key sections from a palaeogeographically coherent area of around 500 km^2. The aim of this study is to unravel the spatial and temporal evolution of the Buchenstein basin and the surrounding carbonate platforms. Platforms in the northwestern Dolomites show an early stage of aggradation followed by progradation, whereas in the central Dolomites the Cernera platform, after fast initial aggradation, drowned and became a pelagic seamount. In the intervening Buchenstein basin, the differential subsidence between the northwestern and central Dolomites is manifested by the lateral increase of thickness of "Lower Pietra Verde" volcaniclastic sediments. Accumulation of volcaniclastic material reworked from adjacent carbonate platform slopes characterised the more subsiding and unstable central Dolomites. In the pelagic carbonate intervals, the persistence over tens of kilometres of bedding patterns suggests that carbonate material presumably washed out from the surrounding, still active carbonate platforms was volumetrically small and homogeneously distributed throughout the uniformly subsiding Buchenstein basin. A Milankovitch precessional origin for the platform interior cycles at Latemar as suggested elsewhere implies a net accumulation rate of 2 m/Ma or less for the correlative interval of pelagic Buchenstein Beds. This value differs significantly from the average value of around 10 m/Ma as calculated using high-resolution isotopic age data for the Buchenstein Beds.

Keywords: correlations; Dolomites; lithostratigraphy; magnetostratigraphy; Middle Triassic; Southern Alps

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1. Introduction

The Dolomites of northern Italy (Fig. 1) is an ideal area to study the evolution of ancient pelagic basins surrounded by carbonate platforms. Basinal sediments of the upper Anisian to lower Ladinian (Middle Triassic) Buchenstein Beds and coeval platform carbonates are exposed with well-preserved geometries (e.g. Bosellini, 1984). In the northwestern Dolomites, the correlation between the Schlern/Rosengarten and Latemar platforms, and the basinal Buchenstein Beds was firmly established by means of geometrical, biostratigraphical and sedimentological studies (e.g. Bosellini, 1984; Bosellini and Stefani, 1991; Brack et al., 1996; Maurer, 1999). Platforms in this area are characterised by an early stage of predominant aggradation followed by significant progradation. In the central Dolomites, the Cernera platform instead underwent an initial phase of fast aggradation followed by inbuilding and early drowning possibly related to a local increase of subsidence (Blendinger et al., 1984; Brack and Rieber, 1993). Large portions of the Buchenstein basin lying in between the platforms of the northwestern and central Dolomites lack detailed correlations and age. Magnetostratigraphic data were recently obtained from the Frötschbach section from the northwestern Dolomites (Muttoni et al., 1996a, 1997). The Buchenstein Beds at Frötschbach were correlated to the biostratigraphically and isotopically dated Seceda section located nearby (Brack and Rieber, 1993; Brack et al., 1996; Mundil et al., 1996). New magnetostratigraphic data from Pedraces and Belvedere in the northwestern and central Dolomites, respectively, are presented here and compared with data from Frötschbach. Lithostratigraphic marker beds, whose isochroneity is supported by magnetostratigraphic correlations at Frötschbach, Pedraces and

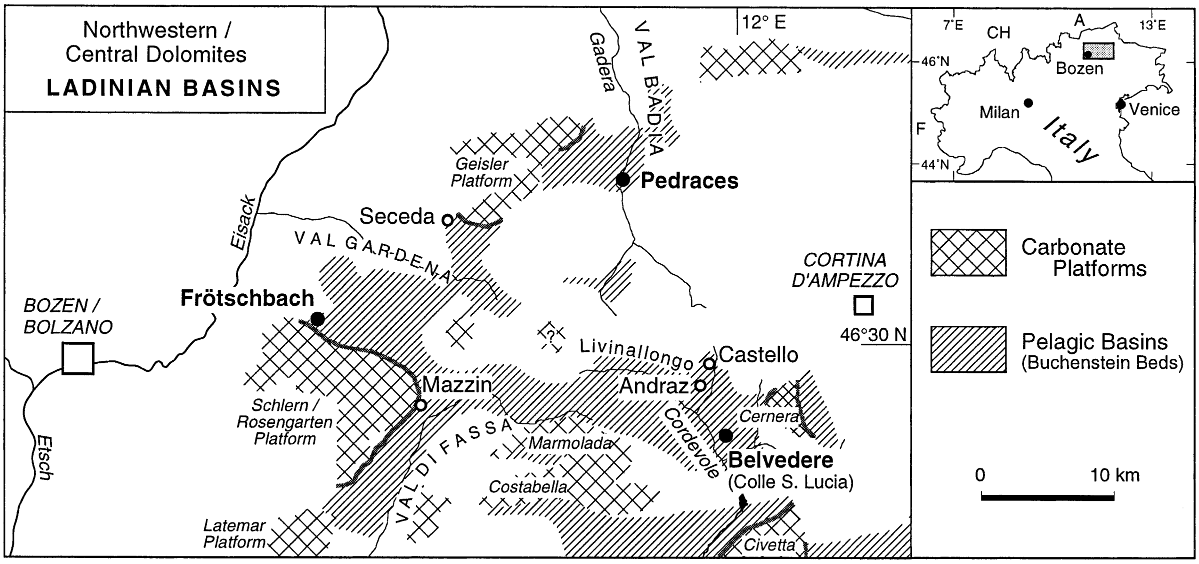


Fig. 1. Distribution of carbonate platforms and pelagic basins in the Dolomites during the Early Ladinian. Black dots mark sections with both magnetostratigraphy and lithostratigraphy (Frötschbach, Pedraces and Belvedere). Circles indicate additional sections with lithostratigraphic control (Seceda, Mazzin, Andraz, Castello). The Seceda section is located near St. Ulrich/Ortisei, whereas Frötschbach lies near Seis/Siusi, both close to Val Gardena (see Brack and Rieber, 1993). The Mazzin section is in Val di Fassa, about 1.5 km north of the village of Mazzin at 1950 m altitude east of Calvidoi. The Pedraces section is in Val Badia, along the main road at a large bend 2 km north of the village of Pedraces. The Belvedere section is in the Upper Cordevole Valley, along and below the road connecting Rucava to Villagrande (Colle S. Lucia), close to a tunnel to the northwest of the Belvedere sightseeing point. The Andraz section is in the Upper Cordevole Valley, along a steep cliff between 1630 and 1680 m altitude west of the village of Andraz. The Castello section is about 1.5 km north of Andraz, again along a cliff.

Belvedere, are then used to extend correlations to additional key sections from a palaeogeographically coherent basinal area of around 500 km^2. The aim of this study is to date and analyse, by means of high-resolution correlations, the vertical and spatial evolution of the Buchenstein basin and relate this to the coeval evolution of the surrounding carbonate platforms. The implications of our correlations for a Milankovitchan origin of the stratal patterns in the Buchenstein Beds and in platform carbonates at Latemar are also briefly discussed.

2. Stratigraphical setting of the Buchenstein Beds

The Buchenstein Beds consist mainly of pelagic carbonates, layers with platform-derived material and subordinate intercalations of volcaniclastic sediments referred to in the literature as "Pietra Verde".

2.1. The carbonate fraction

A generalised lithological succession of the Buchenstein Beds comprises the following, mainly carbonatic members, from bottom to top (see Brack and Rieber, 1993, for further information).

1. The "Lower Plattenkalke" (middle/upper Reitzi ammonoid Zone). This member overlies Upper Anisian platform carbonates of the Contrin Formation or equivalent shallow basinal deposits, and consists of locally up to 20 m of commonly laminated limestones and shales rich in organic matter. Bedding surfaces are planar to undulate. The limestone beds are siliceous and contain abundant thin shells of pelagic bivalves and sometimes well-preserved radiolarians. The "Lower Plattenkalke" member is overlain with a sharp contact by the "Knollenkalke" described later. This contact coincides with a switch from partly anoxic ("Lower Plattenkalke") to fully oxygenated ("Knollenkalke") sea-bottom conditions.

2. The "Knollenkalke" (uppermost Reitzi to Gredleri Zones). This member is 20–40 m thick and consists of centimetre to decimetre thick siliceous nodular muddy pelagic limestone beds characterised by traces of burrowing organisms. Chert is either spread out or concentrates in centimetric to decimetric nodules and bands. "Knollenkalke" limestone beds and, in particular, a stack of six marker beds hereafter labelled from 1 to 6, maintain similar morphological and sedimentological characteristics over >30 km between Frötschbach in the northwestern Dolomites, and Andraz and Belvedere in the central Dolomites (Fig. 2). Limestone beds 1–6 are each 10–30 cm thick and consist of compact micritic limestone, and are separated by centimetre-thick intervals of nodular limestone/marl less resistant to surface weathering.

3. The "Bänderkalke" (Gredleri to Archelaus Zones). This member consists mainly of evenly bedded turbiditic calcarenites and breccias with platform-derived debris. The comparably minor pelagic fraction, rich in carbonate mud and shale, is present between the turbidites. The "Bänderkalke" member is often intensively dolomitised. Its thickness varies depending on the palaeogeographical position with respect to active carbonate platforms.

2.2. The volcaniclastic fraction

Layers of variable thickness of sandy-silty, rusty weathered to greenish acidic volcaniclastic material referred to as "Pietra Verde" are also present within the Buchenstein Beds. These volcaniclastics are related to a phase of Middle Triassic explosive volcanism whose source areas are not precisely known but were located outside of the Dolomites. Apart from graded bedding, few sedimentological features are usually recognised in "Pietra Verde" layers. The "Pietra Verde" volcaniclastics and, in particular, individual layers that are correlated over large distances between different basins from the Dolomites to southern Switzerland (Brack and Rieber, 1993, fig. 11) were originally airborne deposits. Multiple layers may be the result of successive eruptions or due to the instantaneous reworking of unconsolidated volcaniclastic material.

In complete Buchenstein successions, "Pietra Verde" layers of variable thickness are mainly concentrated at three stratigraphic intervals:

1. The "Lower Pietra Verde" occurs in the lowermost portion of the Buchenstein Beds, i.e.

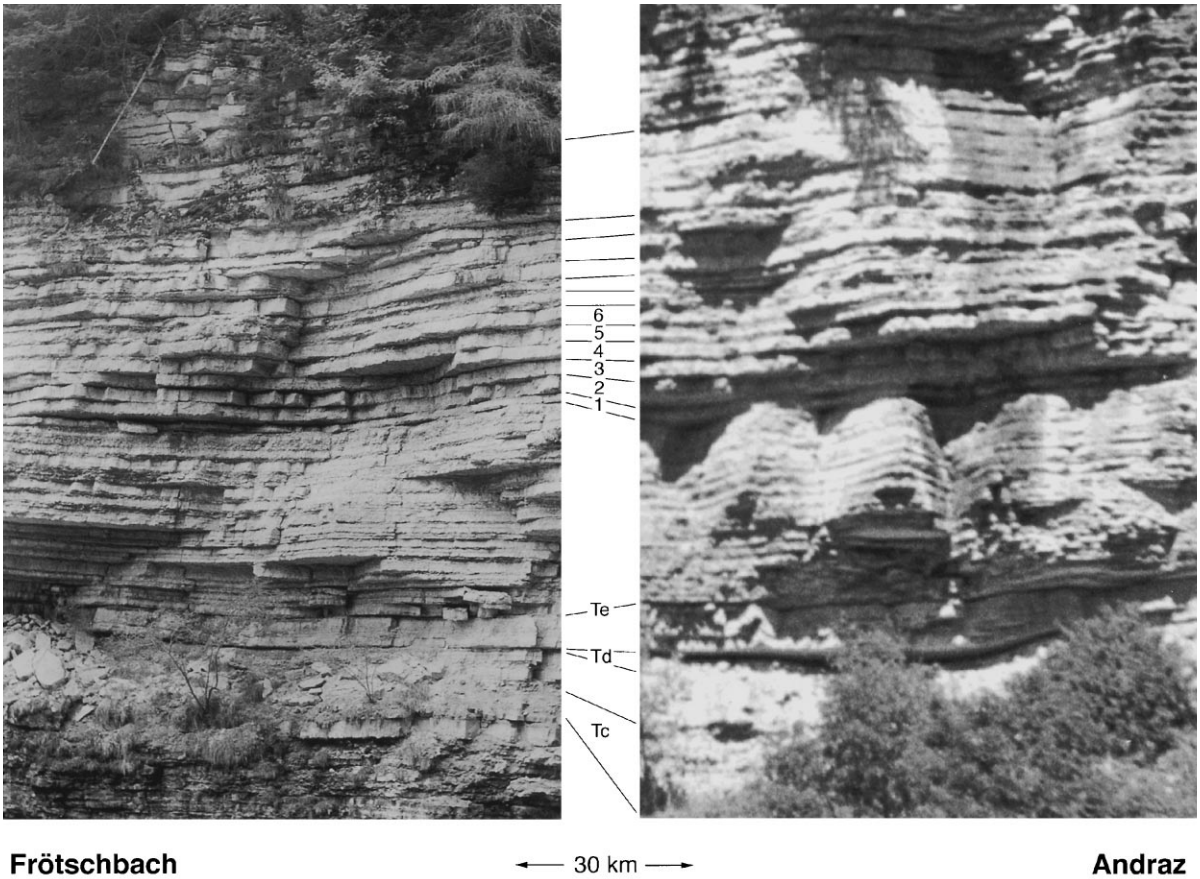


Fig. 2. Visual comparison of the stratal pattern in the lower Buchenstein Beds between the northwestern Dolomites (Frötschbach) and the central Dolomites (Andraz, as seen from a distant viewpoint to the east, along the main road to Caprile). Stratigraphic thickness is about 22 m at both sections. "Tc", "Td", "Te" are characteristic tuff beds.

throughout the "Lower Plattenkalke" member up to three tuff beds referred to as "Tc", "Td" and "Te" (Brack and Rieber, 1993) located in the lowermost part of the "Knollenkalke". In the northwestern Dolomites, these tuff intervals are a few centimetres thick and laterally homogeneous (Fig. 3), whereas towards the central Dolomites they show an apparent significant increase in thickness (Fig. 2; see also fig. 5 in Cros and Houel, 1983).

2. The "Middle Pietra Verde" is an interval of abundant volcaniclastic layers usually located in the middle/upper portion of the "Knollenkalke". A distinct marker bed with accretionary lapilli occurs in several sections throughout the northwestern and central Dolomites including Seceda (Brack et al., 1997) and Belvedere. This marker bed is also known in Buchenstein sections at Rosengarten (Maurer, 1999) and in the Marmolada/Costabella area in the northwestern and central Dolomites (e.g. Gianolla, 1991).
3. The "Upper Pietra Verde" is a distinct interval with frequent volcaniclastic layers present in the "Bänderkalke" member at complete Buchenstein sections in the northwestern Dolomites (e.g. Seceda), or in the uppermost "Knollenkalke" member in the Giudicarie Alps and Lombardy (e.g. Bagolino; see fig. 7 in Brack and Rieber, 1993). Because of a significant increase in "Pietra Verde" thickness towards the eastern Dolomites, the unambiguous dis-

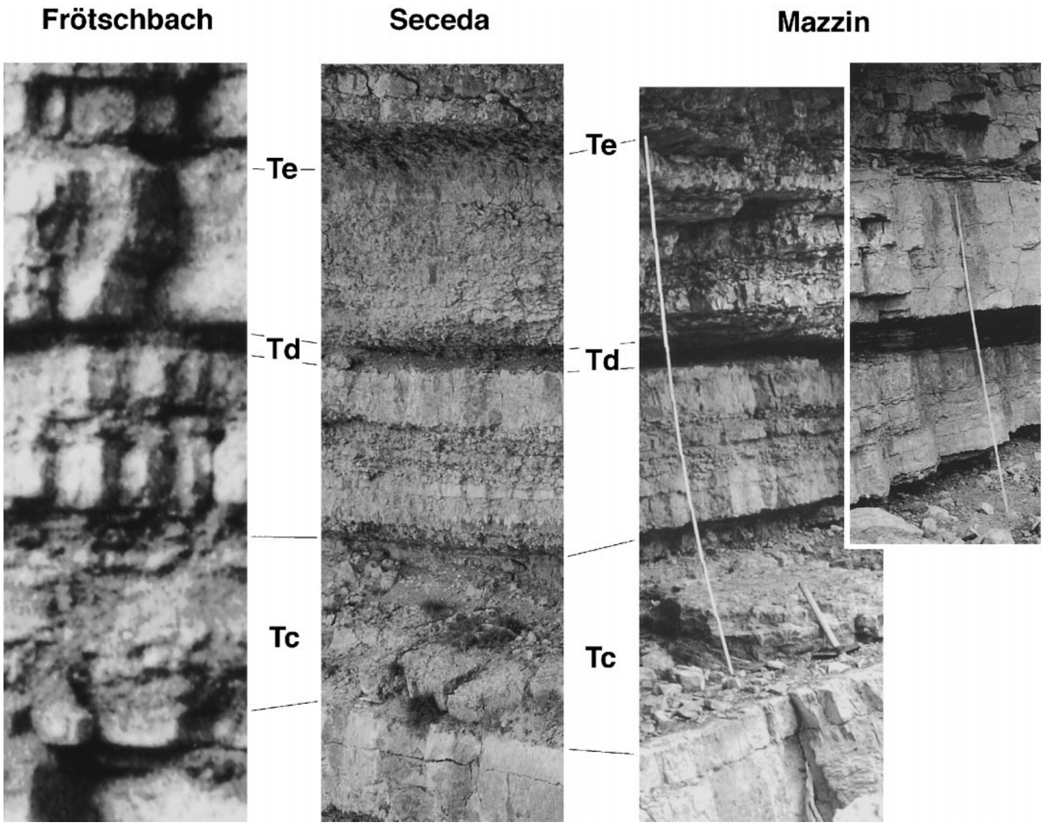


Fig. 3. Detailed correlation of a thin sediment interval with tuff beds "Tc", "Td", "Te" in the northwestern Dolomites. Note how thickness and the pattern of pelagic limestone beds are laterally reproducible. Scale bars at Mazzin are 2 m long.

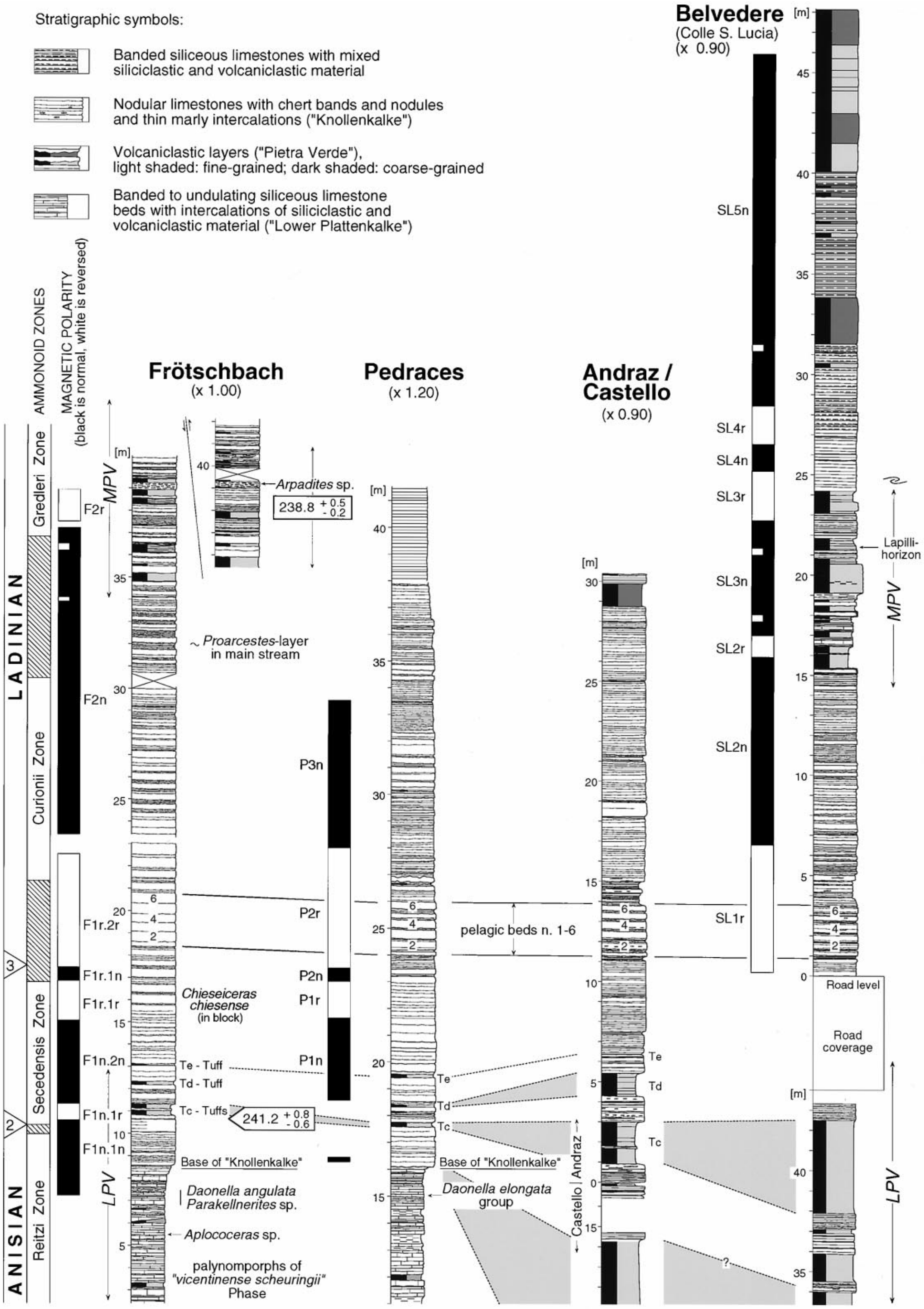
tinction between "Middle Pietra Verde" and "Upper Pietra Verde" is difficult, especially in the eastern part of the Buchenstein basin [note that Cros and Houel (1983) combine both intervals in their "Upper Pietra Verde"].

2.3. Rates of sediment accumulation

High-resolution U–Pb isotopic age data were recently obtained on single zircon crystals from volcaniclastic layers from the Buchenstein and equivalent beds in the Dolomites, Lombardy and southern Switzerland (Mundil et al., 1996). These data suggest that the pelagic sedimentation rate in the Buchenstein Beds increased upsection, from the "Knollenkalke" to the "Bänderkalke" (Brack et al., 1996), probably due to dilution of pelagic material with platform-derived debris from the rapidly advancing carbonate platforms. For the non-diluted "Knollenkalke" facies in the Dolomites, we assume average sedimentation rates in the order of 10 m/Ma (non-decompacted), with a lower limit of 7.5 and an upper limit of 23 m/Ma as deduced by maximising the uncertainties associated with isotopic age data (Fig. 4). The interval of time represented by the "Pietra Verde" volcaniclastic layers is very short as individual beds presumably resulted from single fallout events.

3. Stratigraphic range of Buchenstein sections

The following sections were considered in this study: Seceda as the lithostratigraphic and biostratigraphic reference section, Frötschbach as the magnetostratigraphic reference section, Mazzin



Stratigraphic symbols:
Banded siliceous limestones with mixed siliciclastic and volcaniclastic material
Nodular limestones with chert bands and nodules and thin marly intercalations ("Knollenkalke")
Volcaniclastic layers ("Pietra Verde"), light shaded: fine-grained; dark shaded: coarse-grained
Banded to undulating siliceous limestone beds with intercalations of siliciclastic and volcaniclastic material ("Lower Plattenkalke")
AMMONOID ZONES
MAGNETIC POLARITY (black is normal, white is reversed)
LADINIAN
ANISIAN
Gredleri Zone
Curionii Zone
Secedensis Zone
Reitzi Zone
Frötschbach (x 1.00)
Pedraces (x 1.20)
Andraz / Castello (x 0.90)
Belvedere (Colle S. Lucia) (x 0.90)
F2r
F2n
F1r.2r
F1r.1n
F1r.1r
F1n.2n
F1n.1r
F1n.1n
MPV
LPV
Arpadites sp.
238.8 +0.5 -0.2
Proarcestes-layer in main stream
Chieseiceras chiesense (in block)
Te - Tuff
Td - Tuff
Tc - Tuffs
241.2 +0.8 -0.6
Base of "Knollenkalke"
Daonella angulata
Parakellnerites sp.
Aplococeras sp.
palynomporphs of "vicentinense scheuringii" Phase
P3n
P2r
P2n
P1r
P1n
Daonella elongata group
pelagic beds n. 1-6
Castello | Andraz
SL5n
SL4r
SL4n
SL3r
SL3n
SL2r
SL2n
SL1r
Lapilli-horizon
Road level
Road coverage

and Pedraces, all from the northwestern Dolomites. Belvedere (Colle S. Lucia) and Andraz/Castello from the Livinallongo/Upper Cordevole Valley area of the central Dolomites (Fig. 1, with information on location of sections).

3.1. Seceda

The stratigraphically most complete Buchenstein Beds section is exposed at Seceda in Val Gardena. Seceda yields the majority of the age-diagnostic macrofossils (ammonoids and thin-shelled bivalves of the genus *Daonella*) known from the Buchenstein Beds of the Dolomites. The section consists of a complete sequence of Buchenstein members and associated "Pietra Verde" intervals as outlined above. See Brack and Rieber (1993, figs. 4–7) for a detailed description of the Seceda section.

3.2. Frötschbach

The lithostratigraphy and magnetostratigraphy of the Frötschbach section in Val Gardena (Fig. 4, with a general outlook in Fig. 2) were described by Muttoni et al., 1996a, 1997. The section spans the stratigraphic interval from the base of the Buchenstein Beds to a level within the "Middle Pietra Verde".

3.3. Mazzin

The Mazzin section in Val di Fassa, details of which are shown in Fig. 3, lies at the eastern toe-of-slope of the Rosengarten carbonate platform. Particularly well exposed is the "Knollenkalke" member from its base upwards. An interval characterised by thin volcaniclastic layers represents the "Middle Pietra Verde" and is overlain by the "Bänderkalke" member. The section is capped by the outermost carbonate wedge of the Rosengarten platform and by volcanic and clastic rocks of the Wengen Group.

3.4. Pedraces

The Pedraces section in Val Badia (Figs. 4 and 5) was briefly illustrated by Cros and Houel (1983) who also proposed a possible correlation with other Buchenstein Beds sections (e.g. from the Cordevole Valley). The undisturbed part of the steeply dipping stratigraphic succession spans the base of the Buchenstein Beds to the lower part of the "Middle Pietra Verde". The first 7 m of the Pedraces section (i.e. the portion of the "Lower Plattenkalke" located below the base of the section reported in Figs. 4 and 5) were considered as part of the Moena Formation by Masetti and Neri (1998, fig. 21).

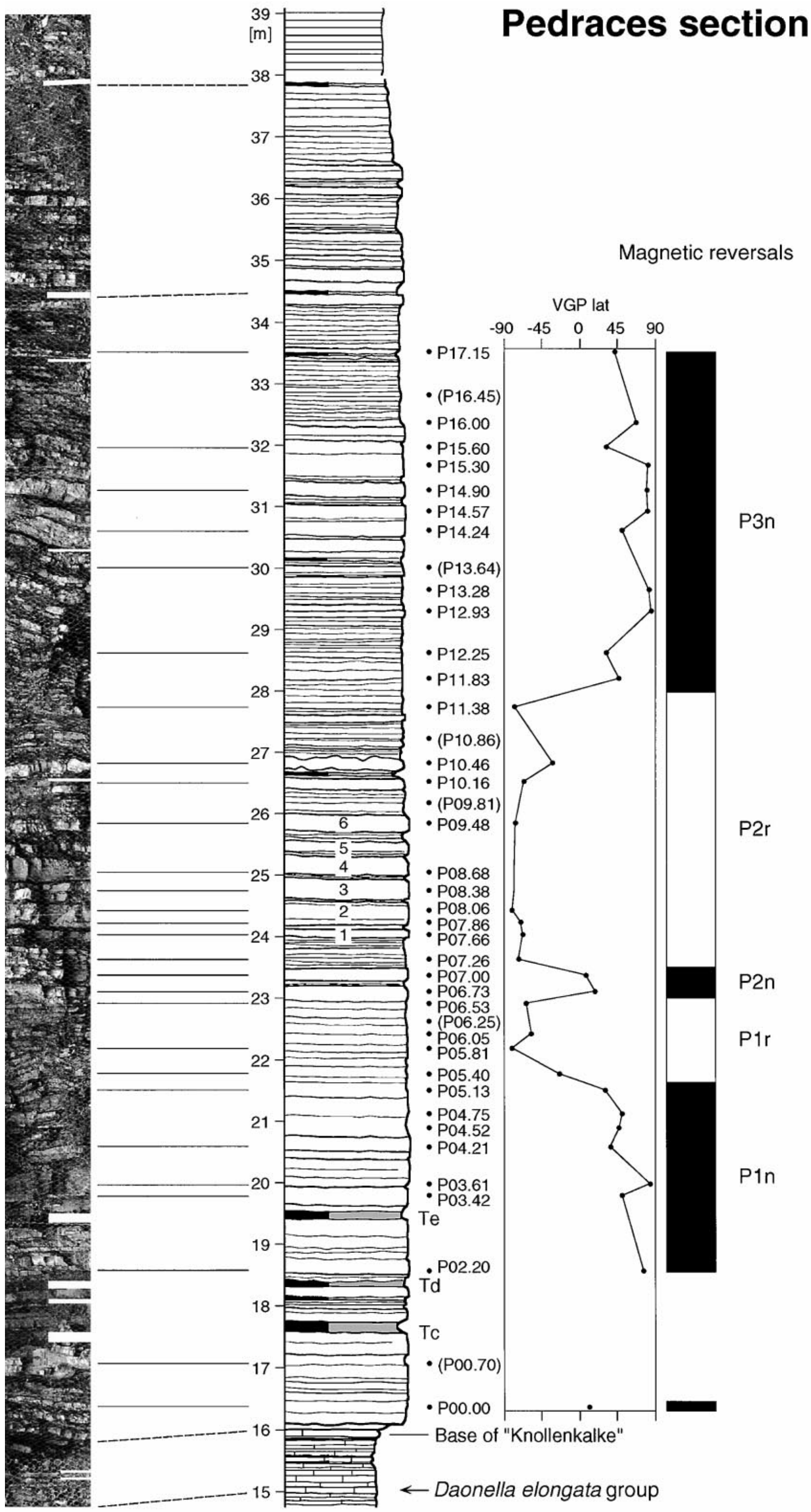
3.5. Andraz/Castello

The Andraz section in the Upper Cordevole Valley (Fig. 4, with a general outlook in Fig. 2) starts with the "Knollenkalke" just below the "Tc" tuff bed. Higher up follow thick but partly covered "Pietra Verde" layers probably comprising the "Middle Pietra Verde" interval. At the nearby Castello section, a "Pietra Verde" interval more than 10 m thick is visible within the lowermost part of the "Knollenkalke" member below the "Tc" tuff bed. The overlying succession of "Knollenkalke" and "Pietra Verde" is virtually identical to that at Andraz.

3.6. Belvedere (Colle S. Lucia)

The Belvedere section in the Upper Cordevole Valley (Figs. 4 and 6) corresponds to the reference section of Bacelle and Sacerdoti (1965) (sometimes

Fig. 4. General lithostratigraphic and magnetostratigraphic correlation of Buchenstein sections in the northwestern and central Dolomites. See Muttoni et al. (1996a) for details on biostratigraphy, based mainly on ammonoids from Seceda (Brack and Rieber, 1993). The position of the Anisian/Ladinian boundary is still under discussion. Current candidates are the base of the Reitzi, Secedensis (2) or Curionii Zones (3). Isotopic age values are imported on to Frötschbach stratigraphy via correlation of corresponding tuff layers and sediment intervals from Seceda and Bagolino (Brack et al., 1996; Mundil et al., 1996). LPV, "Lower Pietra Verde"; MPV, "Middle Pietra Verde".



Pedraces section
Magnetic reversals
VGP lat
-90 -45 0 45 90
39 [m]
38
37
36
35
34
33
32
31
30
29
28
27
26
25
24
23
22
21
20
19
18
17
16
15
P17.15
(P16.45)
P16.00
P15.60
P15.30
P14.90
P14.57
P14.24
(P13.64)
P13.28
P12.93
P12.25
P11.83
P11.38
(P10.86)
P10.46
P10.16
(P09.81)
P09.48
P08.68
P08.38
P08.06
P07.86
P07.66
P07.26
P07.00
P06.73
P06.53
(P06.25)
P06.05
P05.81
P05.40
P05.13
P04.75
P04.52
P04.21
P03.61
P03.42
P02.20
(P00.70)
P00.00
6
5
4
3
2
1
Te
Td
Tc
Base of "Knollenkalke"
Daonella elongata group
P3n
P2r
P2n
P1r
P1n

referred to as the type section of the Livinallongo Formation/Buchenstein Beds). Additional versions of this section were also illustrated in Bacelle Scudeler (1972), Viel (1979, fig. 6), Cros and Houel (1983, Villagrande section, figs. 3 and 5) and Gianolla et al. (1998, Colle S. Lucia section, fig. 9). The road level divides the Belvedere section in two portions. The lower half is located below the road level and is around 44 m thick. It comprises the "Lower Plattenkalke" and includes several thick "Pietra Verde" layers close to the "Lower Plattenkalke"/"Knollenkalke" boundary (only the uppermost part of the lower half of the section is shown in Fig. 4). The upper half (Figs. 4 and 6) is exposed along the road-cut and spans a stratigraphic interval between the lower "Knollenkalke" and a succession of siliceous banded limestones with thick volcaniclastic layers located above the "Middle Pietra Verde". Gianolla et al. (1998) ascribe the uppermost part of the Belvedere section to the Zoppè Sandstones. In contrast to sections in the northwestern Dolomites (Seceda, Frötschbach, Mazzin and Pedraces), the Belvedere section is characterised by much thicker "Pietra Verde" layers.

4. Palaeomagnetism at Pedraces and Belvedere

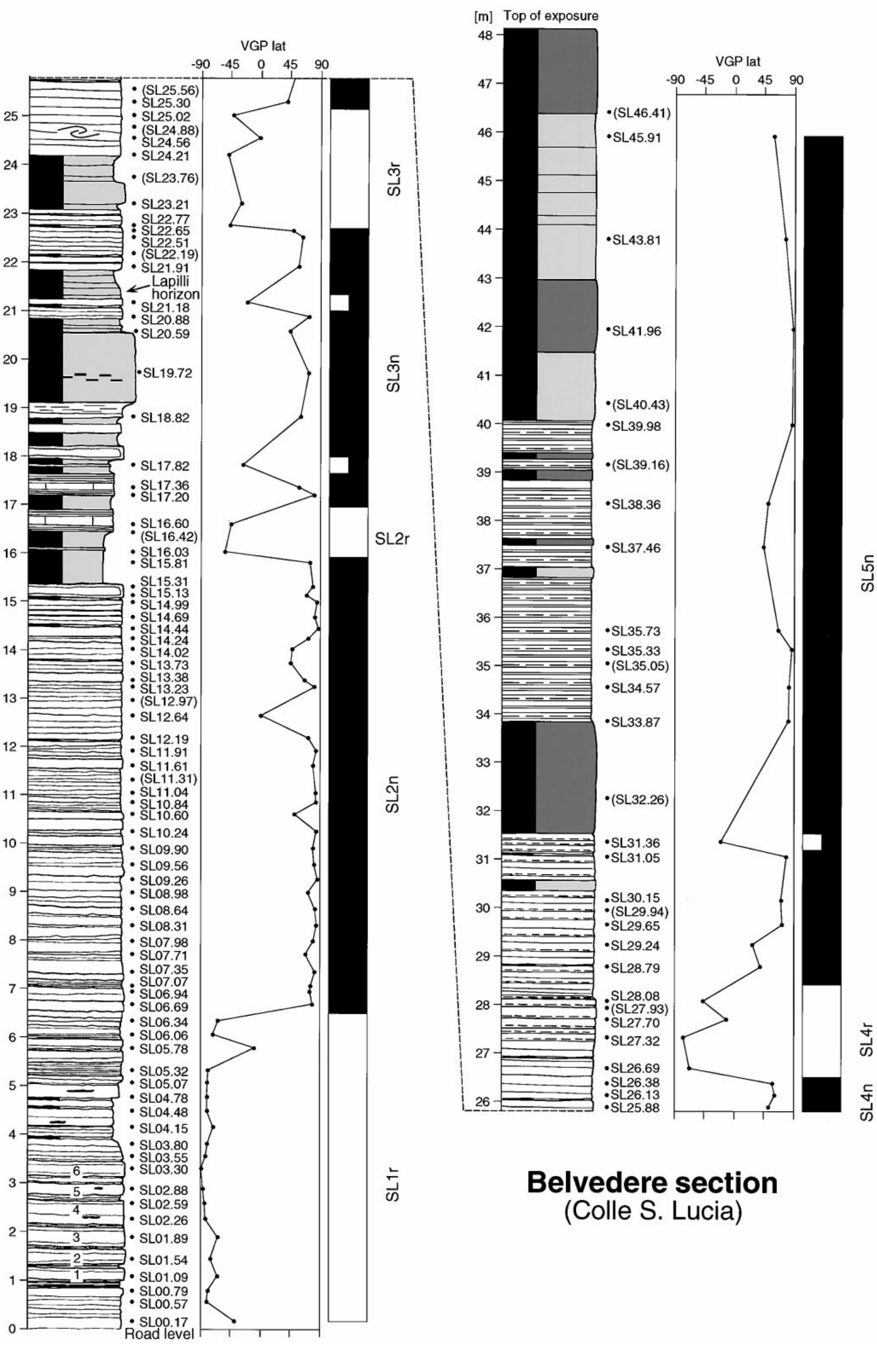
At Pedraces, core samples for palaeomagnetism were taken from the "Knollenkalke" member (Fig. 5), whereas the interval sampled at Belvedere corresponds to the upper half of the section along the road-cut as outlined above (Fig. 6). At both sections, 2–4 samples per metre were taken, yielding a total of 41 (Pedraces) and 106 (Belvedere) samples for analysis. Standard 11.4 cm^3 oriented samples were subjected to progressive thermal demagnetisation, and remanence measurements were performed on a 2G three-axis cryogenic magnetometer with DC SQUID sensors at the palaeomagnetics laboratory of ETH Zürich.

4.1. Palaeomagnetic properties

The magnetic properties of the Buchenstein Beds at Pedraces and Belvedere are similar to those at Frötschbach (Muttoni et al., 1997). The mean intensity of the natural remanent magnetisation (NRM) of the pelagic limestone beds is 0.1 and 0.2 mA/m at Pedraces and Belvedere, respectively, whereas the volcaniclastic rich upper part of the Belvedere section has a mean NRM intensity of 20 mA/m. The mean value of the initial susceptibility of the pelagic limestone beds is 8×10^{-6} and 4×10^{-5} SI at Pedraces and Belvedere, respectively, and reaches a mean value of 5×10^{-4} SI in the upper part of the Belvedere section. The initial susceptibility is usually stable over the heating procedure. Acquisition curves of isothermal remanent magnetisation (IRM) performed on limestone samples show the presence of a soft magnetic component which tends to saturate at ca. 150 mT fields. Alternating field (AF) decay curves show that this saturation IRM is half-destroyed by ca. 30–40 mT fields (e.g. Fig. 7a). Thermal demagnetisation of orthogonal-axes IRM (Lowrie, 1990) indicates that this dominant soft magnetic phase has a maximum unblocking temperature of 575°C (Fig. 7b). These bulk rock-magnetic properties indicate that magnetite is the main carrier of the remanence at both sections.

Least-squares analysis (Kirschvink, 1980) on vector end-point demagnetograms (Zijderveld, 1967) was applied to calculate magnetic component directions. Samples in in situ (geographic) coordinates typically show the presence of an initial steeply inclined component which is consistent with the present-day field direction (Fig. 8). A generally bipolar southeasterly and down (northwesterly and up) characteristic component was successively unblocked between about 200°C and 500°C to 575°C in 88% of the specimens at Belvedere (Fig. 8a; see also Fig. 9a). At Pedraces, a bipolar southerly and up (northerly and down)

Fig. 5. Lithological column and magnetic polarity stratigraphy of the steeply dipping "Knollenkalke" member of the Buchenstein Beds at Pedraces. Tuff beds "Tc" and "Te", and pelagic limestone beds 1–6 are reported. Black bars on the lithology column and white bars on the photograph indicate the position of tuff beds. Magnetic reversals: black is normal, white is reversed. See Fig. 4 for lithological symbols. Sample numbers are indicated to the right of the lithology column.


VGP lat
-90 -45 0 45 90
(SL25.56)
SL25.30
SL25.02
(SL24.88)
SL24.56
SL24.21
(SL23.76)
SL23.21
SL22.77
SL22.65
SL22.51
(SL22.19)
SL21.91
Lapilli horizon
SL21.18
SL20.88
SL20.59
SL19.72
SL18.82
SL17.82
SL17.36
SL17.20
SL16.60
(SL16.42)
SL16.03
SL15.81
SL15.31
SL15.13
SL14.99
SL14.69
SL14.44
SL14.24
SL14.02
SL13.73
SL13.38
SL13.23
(SL12.97)
SL12.64
SL12.19
SL11.91
SL11.61
(SL11.31)
SL11.04
SL10.84
SL10.60
SL10.24
SL09.90
SL09.56
SL09.26
SL08.98
SL08.64
SL08.31
SL07.98
SL07.71
SL07.35
SL07.07
SL06.94
SL06.69
SL06.34
SL06.06
SL05.78
SL05.32
SL05.07
SL04.78
SL04.48
SL04.15
SL03.80
SL03.55
SL03.30
SL02.88
SL02.59
SL02.26
SL01.89
SL01.54
SL01.09
SL00.79
SL00.57
SL00.17
Road level
SL3r
SL3n
SL2r
SL2n
SL1r
[m] Top of exposure
(SL46.41)
SL45.91
SL43.81
SL41.96
(SL40.43)
SL39.98
(SL39.16)
SL38.36
SL37.46
SL35.73
SL35.33
(SL35.05)
SL34.57
SL33.87
(SL32.26)
SL31.36
SL31.05
SL30.15
(SL29.94)
SL29.65
SL29.24
SL28.79
SL28.08
(SL27.93)
SL27.70
SL27.32
SL26.69
SL26.38
SL26.13
SL25.88
SL5n
SL4r
SL4n
Belvedere section
(Colle S. Lucia)

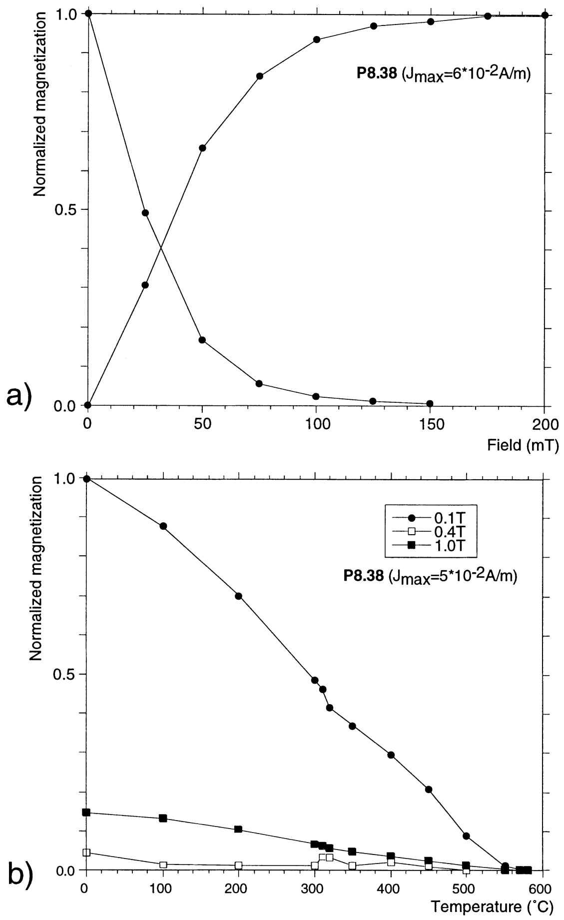


Fig. 7. (a) Acquisition and AF decay curves of isothermal remanent magnetisation (IRM) and (b) the thermal unblocking characteristics of orthogonal-axes IRM (Lowrie, 1990) of a representative Buchenstein Beds limestone sample from Pedraces.

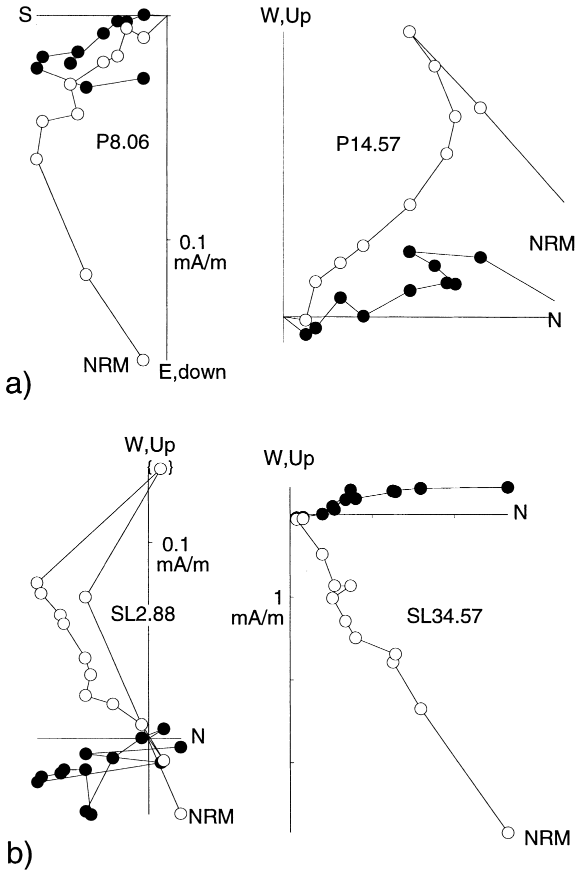


Fig. 8. Zijderveld demagnetisation diagrams of representative Buchenstein Beds limestone samples from (a) Pedraces and (b) Belvedere. Closed symbols are projections on to the horizontal plane and open symbols are projections on to the vertical plane. All diagrams are in in situ (geographic) coordinates.

characteristic component was isolated in a similar temperature range in 85% of the specimens (Fig. 8b; see also Fig. 9b).

The mean normal and reversed characteristic directions in in situ coordinates, calculated by standard Fisher (1953) statistics, become northerly and down (southerly and up) upon correction for bedding tilt at both localities (Fig. 9a, b; Table 1), however, they depart from antipodality by 16.5° and 7° at Pedraces and Belvedere, respectively. At Pedraces, the large departure from antipodality may be attributed to the presence of a large number of transitional directions over the total 35 characteristic directions isolated. At Belvedere, the

Fig. 6. Lithological column and magnetic polarity stratigraphy of the Buchenstein Beds at the portion of the Belvedere (Colle S. Lucia) section exposed above road level. Characteristic pelagic limestone beds 1–6 of the "Knollenkalke" member are reported. Black bars on the lithology column indicate the position of tuff beds. Magnetic polarity zones are shown by black (white) bars for normal (reversed) polarity; single-sample polarity zones are shown by half bars. See Fig. 4 for lithological symbols. Sample numbers are indicated to the right of the lithology column.

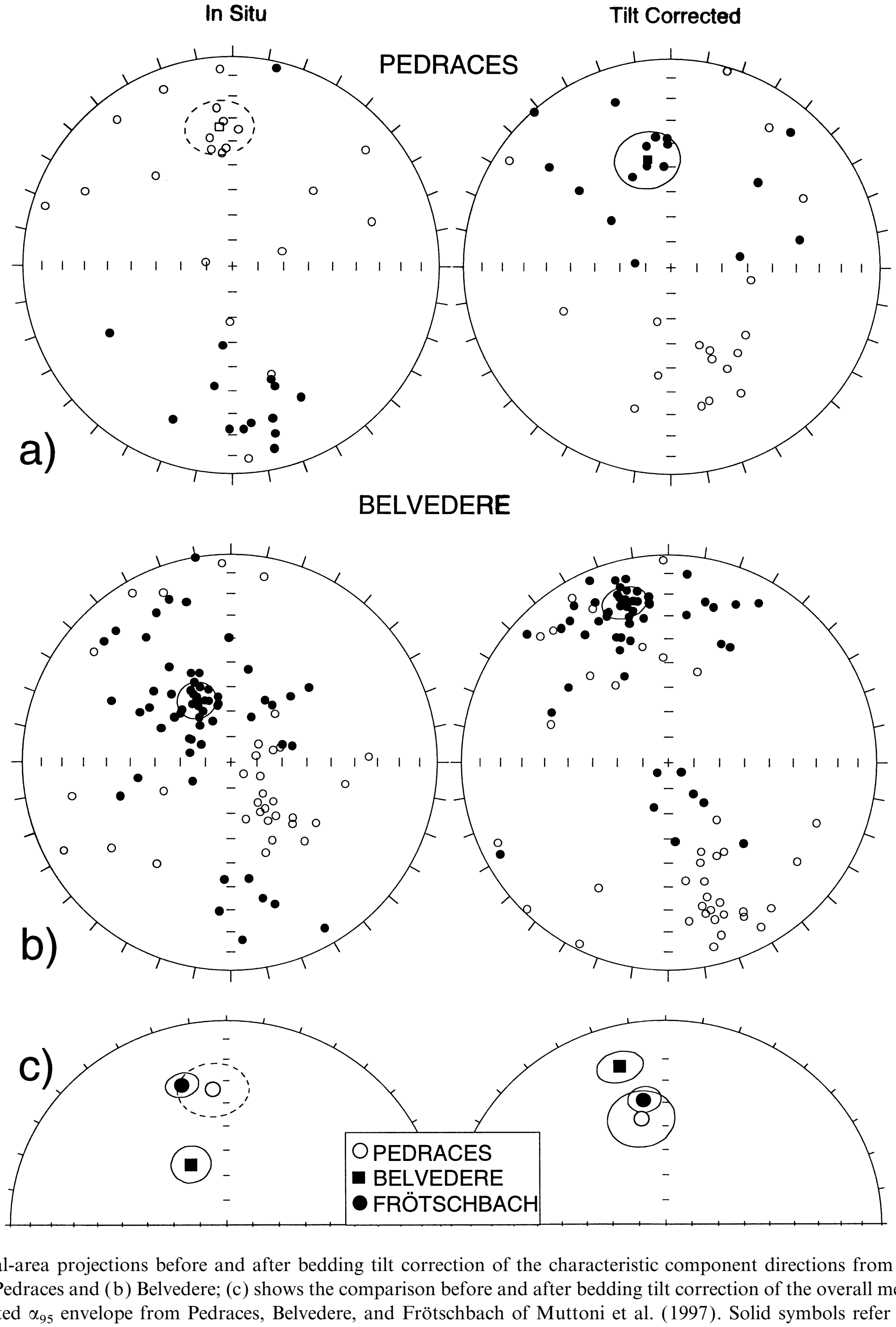


Fig. 9. Equal-area projections before and after bedding tilt correction of the characteristic component directions from Buchenstein Beds at (a) Pedraces and (b) Belvedere; (c) shows the comparison before and after bedding tilt correction of the overall mean direction and associated α_{95} envelope from Pedraces, Belvedere, and Frötschbach of Muttoni et al. (1997). Solid symbols refer to the lower hemisphere.

Table 1
Palaeomagnetic directions from Belvedere, Pedraces and Frötschbach[1]

				In Situ			Tilt Corrected				
Site	Lat/Long.	N_1/N_2	Dec. (°)	Inc. (°)	k_1	α_{95}(°)	Dec. (°)	Inc. (°)	k_2	α_{95}(°)	k_2/k_1
Belvedere	46°27′/12°03′	106/093	330.9	62.1	5	07.4	344.5	21.1	5	07.4	
Pedraces	46°31′/11°54′	041/035	354.7	−33.8	5	12.0	347.6	46.0	5	12.0	
Frötschbach[2]	46°31′/11°54′	102/092	343.3	29.3	8	05.5	350.8	38.0	8	05.7	
Overall direction			345.0	20.9	3	93.8	347.4	35.1	39	20.0	13
Palaeomagnetic pole							61.0°N/216.9°		dp/dm = 13.3°/23.1°		

[1] Lat./Long., latitude/longitude of the sampling site; N_1, number of standard 11.4 cm^3 specimens cut from core samples; N_2, number of palaeomagnetic directions used to calculate the mean. Dec./Inc., declination/inclination; k_1, precision parameter in in situ coordinates; k_2 precision parameter in tilt-corrected coordinates; α_{95}, radius of cone of 95% confidence about the mean direction; k_2/k_1, precision parameter ratio. Average bedding latitudes are as follows: Belvedere, 357°E/43° (i.e. strata dipping to the NNW by 43°); Pedraces, 205°E/91°; Frötschbach, 110°E/26° up to the top of the magnetic polarity zone F1r.2r, between 178°E/8° and 152°E/7.5° at the base of the magnetic polarity zone F2n, and 118°E/9.5° up to the top of the section. The palaeomagnetic pole is calculated from the overall mean direction at 100% unfolding and is referred to a nominal site located at 46.5°N, 11.8°E (Dolomites).
[2] From Muttoni et al. (1997).

93 characteristic bipolar and transitional directions pass the reversal test, classified as "C" according to McFadden and McElhinny (1990) criteria.

The mean characteristic component directions from Pedraces, Belvedere and Frötschbach pass the fold at 95% level of confidence according to the conservative criteria of McElhinny (1964) ($k_2/k_1 = 13$; $F(4.4)_{0.05} = 6.39$; Table 1). There is a peak value of the Fisher precision parameter k at 80% unfolding. Successful magneto-lithostratigraphic correlations between distant sections as outlined below suggest, however, that the Buchenstein Beds characteristic component is the original Triassic magnetisation. The increase of k at partial unfolding may therefore be related to incorrect tilting correction at one of the sections.

4.2. Magnetostratigraphy

A virtual geomagnetic pole (VGP) was calculated for each of the characteristic component directions in tilt-corrected coordinates at Pedraces (Fig. 5) and Belvedere (Fig. 6). Assuming that the Dolomites were north of the equator during the Middle Triassic (Muttoni et al., 1996b) 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 palaeomagnetic axis was used for interpreting the polarity stratigraphy (Lowrie and Alvarez, 1977; Kent et al., 1995). 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. For identification of polarity magnetozones (defined by at least two adjacent samples), we adopt the nomenclature of Kent et al. (1995). Each magnetozone is prefixed by the acronym for the source of the magnetostratigraphy [i.e. "P" for Pedraces, "SL" for Belvedere (Colle S. Lucia)]. The latitude of the VGPs defines at Pedraces a sequence of reversals from magnetozone P1n to P3n (Fig. 5), and at Belvedere from magnetozone SL1r to SL5n (Fig. 6).

5. Magnetostratigraphic control and lithostratigraphy

Magnetostratigraphic and lithostratigraphic data at Frötschbach, Pedraces and Belvedere show excellent agreement (Figs. 4 and 10). The sequence of polarity reversals from submagnetozone F1n.2n to F1r.2r at Frötschbach corresponds to submagnetozones P1n to P2r at Pedraces, and are comprised between tuff bed "Tc" and limestone beds 1–6. In particular, submagnetozone boundary F1n.2n/F1r.1r and P1n/P1r occur within a correlative interval of nodular limestones beds, whereas submagnetozones F1r.1n and P2n are comprised of two correlative decimetre-thick limestone beds at both sections. Submagnetozone boundary F1r.2r/F2n at Frötschbach corresponds to boundaries P2r/P3n and SL1r/SL2n at Pedraces and Belvedere, respectively. At Frötschbach, this magnetozone boundary is constrained to an interval between 1.7 and 2.5 m above pelagic marker bed 6, whereas at Pedraces the same reversal lies between 1.8 and 2.25 m above marker bed 6. In the somewhat generally thicker succession at Belvedere, the same reversal boundary is located between 2.9 and 3.25 m above pelagic marker bed 6.

The magnetostratigraphic correlations here proposed suggest that the following laterally continuous lithological markers are isochronous, from bottom to top (Figs. 4 and 10): the "Lower Plattenkalke"/"Knollenkalke" boundary, tuff beds "Tc", "Td", "Te" and limestone beds 1–6. The isochroneity of the sharp lithological break between the "Lower Plattenkalke" and the "Knollenkalke" is further supported by the occurrence of *Daonella* of the *elongata*-group in a narrow interval just below the top of the "Lower Plattenkalke" at Seceda, Frötschbach and Pedraces in the northwestern Dolomites. The precise correlation of magnetozones and of individual tuff beds in the "Middle Pietra Verde" interval between Frötschbach and Belvedere is as yet uncertain.

The documented isochroneity and lateral continuity of lithological marker beds allow precise correlations. The "Lower Plattenkalke" and the basal portion of the "Knollenkalke" are characterised by strong lateral variation of "Lower Pietra Verde" thickness between the northwestern Dolomites and the Livinallongo/Upper Cordevole Valley in the central Dolomites. Tuff beds "Tc" and "Td" increase in thickness by more than 100% (Fig. 4). The centimetre-thick volcaniclastic levels present below tuff bed "Tc" at around the "Plattenkalke"/"Knollenkalke" boundary at Seceda, Frötschbach and Pedraces correlate to an interval of more than 10 m of "Pietra Verde" at Castello and Belvedere (Fig. 11). In the overlying "Knollenkalke" up to the "Middle Pietra Verde", sedimentation is more homogeneous. Magnetostratigraphic and lithostratigraphic correlations document here the persistence and lateral reproducibility over tens of kilometres of bedding patterns. This indicates that the studied sections belonged to a coherent basinal area where the average sedimentation rate of pelagic carbonates, of the order of 10 m/Ma, was not subject to substantial variations. Only a very modest increase in thickness of correlative "Knollenkalke" pelagic intervals (e.g., limestone beds 1–6, Figs. 4 and 10) is observed between the northwestern Dolomites (Seceda and Frötschbach) and the Livinallongo/Upper Cordevole Valley (Belvedere and Andraz/Castello). At Pedraces in the northwestern Dolomites, bedding thickness is slightly reduced possibly because of tectonic compaction (owing to alpine deformation, bedding planes are vertical at this locality).

6. Implications for platform evolution and basin topography

By combining the stratigraphic information from the Buchenstein basin with those from the surrounding carbonate platforms, we propose a refined reconstruction of the geological and stratigraphical evolution of the northwestern and central Dolomites in the late Anisian to early Ladinian. The comparison of the Buchenstein lithostratigraphy and ammonoid biostratigraphy (Brack and Rieber, 1993) with data from the Latemar platform (Brack and Rieber, 1993; De Zanche et al., 1995; Brack et al., 1996, and unpublished new ammonoid data), as well as from the slope-basin interfingering at Rosengarten (Maurer, 1999) allow the timing of platform evolution to be summarised as follows. Platforms on top of the upper Anisian Contrin and equivalent formations started to grow during the (?lower)/middle Reitzi Zone just before or at

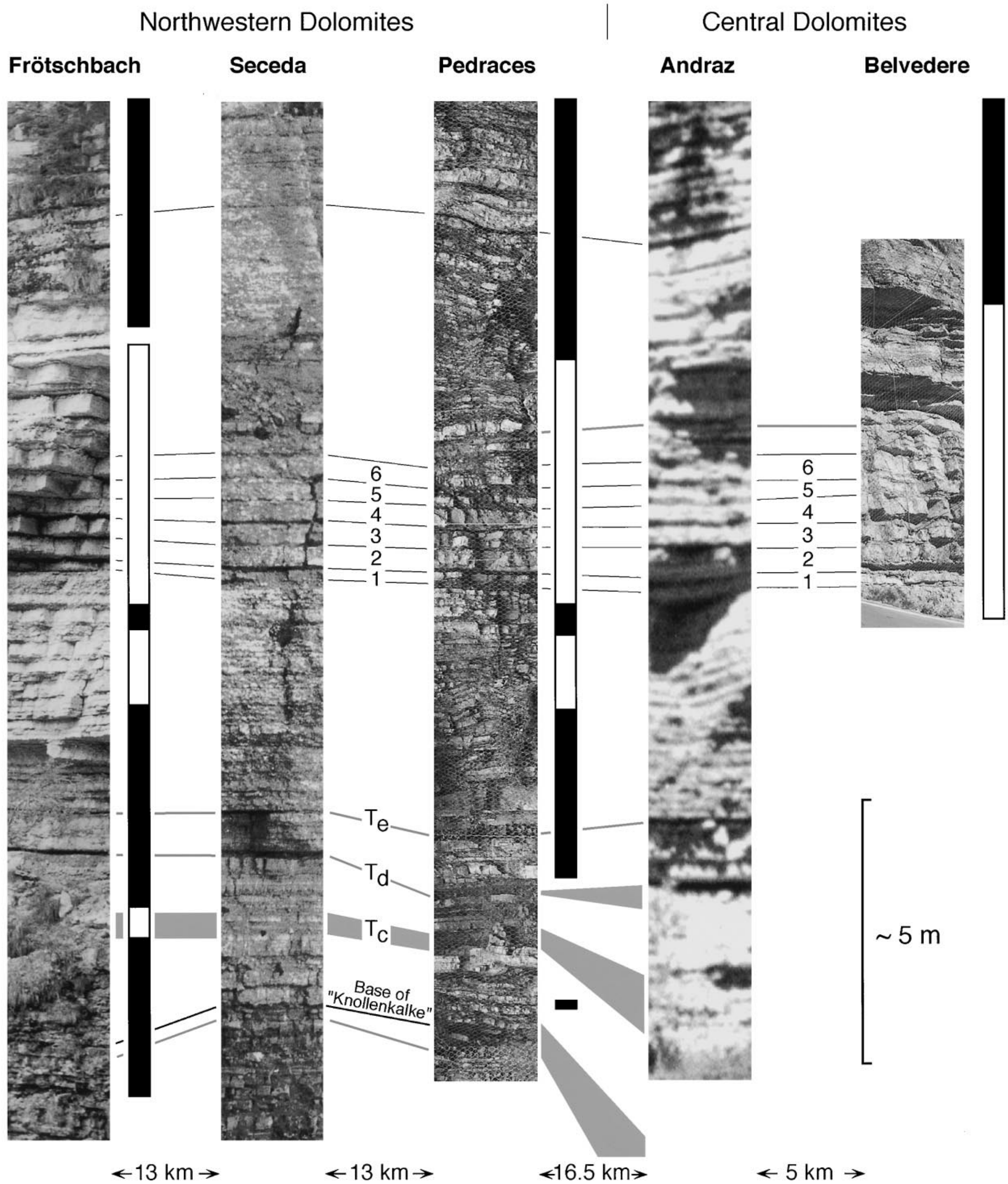
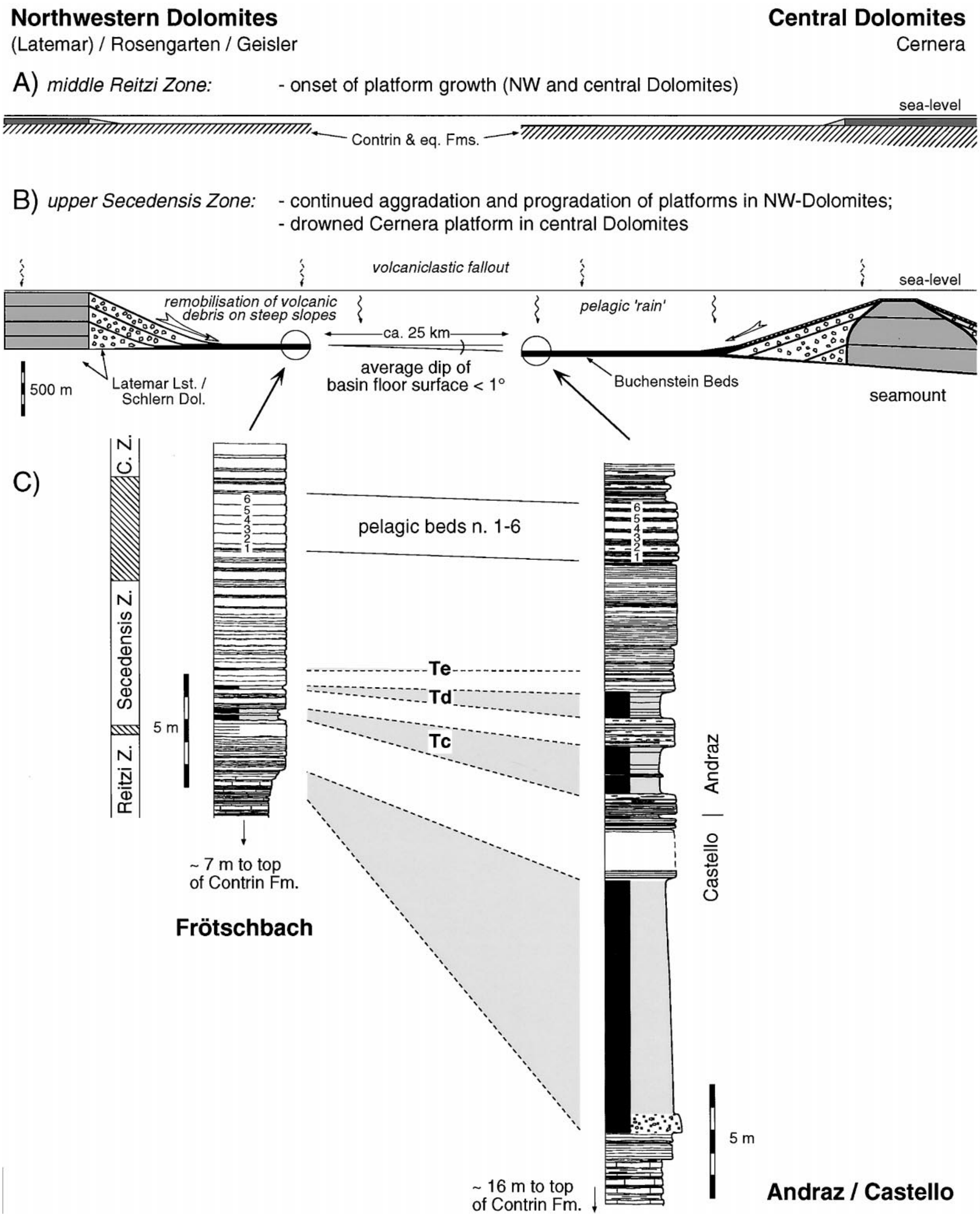


Fig. 10. Sequence of magnetic reversals with tight lithostratigraphic control in the lower part of the Buchenstein Beds from the northwestern and central Dolomites. Correlative volcaniclastic "Pietra Verde" intervals are indicated by shaded areas. Andraz is out of focus because the picture was taken from a large distance. Due to distortion introduced by perspective, metre scale is only approximate (for exact scale refer to Fig. 4).



Northwestern Dolomites
(Latemar) / Rosengarten / Geisler
Central Dolomites
Cernera
A) middle Reitzi Zone:
- onset of platform growth (NW and central Dolomites)
sea-level
Contrin & eq. Fms.
B) upper Secedensis Zone:
- continued aggradation and progradation of platforms in NW-Dolomites;
- drowned Cernera platform in central Dolomites
volcaniclastic fallout
sea-level
remobilisation of volcanic debris on steep slopes
pelagic 'rain'
ca. 25 km
average dip of basin floor surface < 1°
500 m
Latemar Lst. / Schlern Dol.
Buchenstein Beds
seamount
C)
C. Z.
Secedensis Z.
Reitzi Z.
5 m
pelagic beds n. 1-6
6
5
4
3
2
1
Te
Td
Tc
~ 7 m to top of Contrin Fm.
Frötschbach
Andraz
Castello
5 m
~ 16 m to top of Contrin Fm.
Andraz / Castello

the onset of "Lower Plattenkalke" sedimentation (Fig. 11a). In the northwestern Dolomites, platforms continued to aggrade in the Secedensis and Curionii Zones during the deposition of the "Knollenkalke" member (Fig. 11b). Before the end of the Curionii Zone, these platforms reached a thickness of more than 700 m and their mode of growth switched to progradation. Therefore, more than 700 m of platform interior beds in the northwestern Dolomites correlate, in the basin, to less than 35 m of pelagic limestones of the "Lower Plattenkalke" and "Knollenkalke" members. In the central Dolomites, the Cernera platform showed higher rates of aggradation during "Lower Plattenkalke" sedimentation (middle/upper Reitzi Zone) compared with platforms in the northwestern Dolomites, and eventually drowned during the onset of "Knollenkalke" deposition in the latest Reitzi Zone. The sharp and isochronous transition between the laminated, organic matter-rich "Lower Plattenkalke", and the bioturbated nodular "Knollenkalke" (Fig. 12) closely correlates with the drowning of the Cernera platform, which might have caused a major change in water circulation and oxygen content within the Buchenstein basin. At this stage, as indicated by the thickness of platform sediments, the water depth in the Buchenstein basin was around 300 m in the western Dolomites and more than 500 m in the Central Dolomites.

The differential subsidence between the northwestern and central Dolomites is manifested in the basin by the lateral variation of "Lower Pietra Verde" thickness. The general scarcity of slumping features in the "Lower Plattenkalke" and in the lower part of the "Knollenkalke" indicates that the average inclination of the basin floor was small, probably less than 1°, dipping towards the central Dolomites. Therefore, in the slightly more subsiding and unstable central Dolomites, thicker volcaniclastic beds sometimes comprised of multiple stacks of (?turbiditic) volcaniclastic layers, probably resulted from the instantaneous redeposition of volcanic debris reworked from adjacent, steep carbonate platform slopes. Only traces of volcaniclastic material are known from carbonate platform slopes in the western Dolomites, where clinoform stratifications are as steep as 20–35° (Kenter, 1990; Maurer, 1999). Alternatively, the central Dolomites with thick "Pietra Verde" could

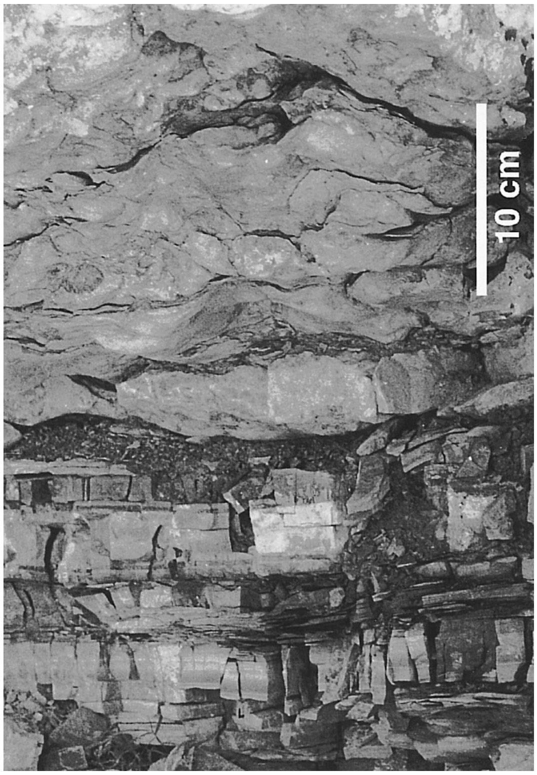


Fig. 12. View of the sharp boundary between the laminated organic matter-rich "Lower Plattenkalke" (lower part) and the bioturbated nodular "Knollenkalke" (upper part) as exposed at Seceda, indicating an abrupt switch of water circulation.

Fig. 11. Schematic representation of the temporal and spatial evolution of a platform–basin transect between the northwestern and central Dolomites at the time corresponding to (A) the middle Reitzi ammonoid zone, (B) the upper Secedensis Zone, and (C) comparison of two selected stratigraphic intervals of Buchenstein Beds comprised of the uppermost Reitzi to lowermost Curionii Zones (for the complete sequence of ammonoid zones in this interval, see Fig. 4). Note the high variability in thickness of "Lower Pietra Verde" intervals (black bars, shaded intervals) compared to the lateral uniformity of the intervening and overlying pelagic limestones. See text for discussion.

also have been located closer to active volcanic centres. A clear spatial trend of volcanic particles grain size, however, has not yet been observed.

The deposition of the pelagic limestones of the "Knollenkalke" was dominated by the uniform sedimentation of small volumes of platform-derived carbonate mud transported in suspension throughout the basin, and by the post mortem fallout of pelagic organisms (e.g., remains of ammonoids, thin-shelled pelecypods, radiolarians; pelagic "rain" in Fig. 11b), in a tectonically quiet environment characterised by almost uniform subsidence. In the northwestern Dolomites, pelagic strata with laterally homogeneous characteristics such as marker beds 1–6 can usually be identified even in the close vicinity of the toe-of-slope of active carbonate platforms (e.g. Rosengarten, Geisler-Seceda). This indicates that, in spite of the pronounced topographic relief of the rapidly aggrading and prograding platforms, the transition between the toe-of-slope and basin plain was confined to a narrow belt, less than 1.5 km wide. In contrast to the punctuated rapid deposition of large volumes of volcaniclastic fallout materials, the average flux of pelagic carbonate and siliceous particles was more gradual and much lower. In platform slope settings, the fine-grained pelagic carbonate material may have contributed to the rapid cementation of the predominantly coarse detritus of reef- and upper foreslope-derived boundstones. Although bioclastic turbiditic grainstones are found in the lowermost slope portions (e.g. Harris, 1994), only few turbiditic beds have as yet been recognised in the "Knollenkalke" member of the pelagic Buchenstein Beds.

7. Possible implications for the time significance of pelagic bedding patterns and for the Latemar controversy

Assuming pelagic carbonate accumulation rates between 7.5 and 23 m/Ma (mean of around 10 m/Ma; see Section 2.3.), the duration of the deposition of individual "Knollenkalke" layers such as limestone beds 1–6, characterised by a total thickness of 2–2.5 m, is of the order of 14–56 ka, with average values between 30 and 45 ka. In the Milankovitch band of astronomical forcing, these estimates largely overlap with the obliquity frequency range estimated for the Triassic (Berger et al., 1992). A precessional ($\sim$20 ka) control was proposed for the 598 platform interior cycles at Latemar in the northwestern Dolomites, implying a minimum duration for this interval of 12 Ma (e.g. Goldhammer et al., 1990, 1993; Hinnov and Goldhammer, 1991). Ammonoids from Latemar including a new fauna collected from the topmost cycles at Latemar (Curionii Zone or slightly older; T. Bechstädt, R. Zühlke, H. Rieber, pers. commun.) suggest that the correlative basinal interval in the Buchenstein Beds is less than 25 m thick, i.e. more restricted than the maximum interval of around 35 m previously estimated by Brack et al. (1996) on the basis of fossils from a stratigraphically younger position in the uppermost part of the Latemar slope (Fauna L3 in Brack et al., 1996). At Frötschbach, this Latemar-correlative interval is comprised between metre level 5 and 30 (Fig. 4), whereas at Seceda between metre level 6 and 26 (Brack and Rieber, 1993, fig. 7). By accepting a total duration of the Latemar cycles of 12 Ma or more, the net accumulation rate in the coeval Buchenstein basin would be as low as 2 m/Ma or less, in contradiction with our estimates based on isotopic age data. The resolution of the Latemar controversy requires further investigation through a detailed cyclostratigraphic analysis of the basinal stratal patterns which is presently in progress.

8. Conclusions

We have obtained a dual-polarity characteristic component of magnetisation carried by magnetite at two sections from the Dolomites, namely Pedraces and Belvedere. Palaeomagnetic results from Pedraces and Belvedere correlate and expand upwards the Frötschbach dated magnetostratigraphy of Muttoni et al., 1996a, 1997 and references therein (Fig. 4). Correlations with other Tethyan magnetostratigraphic sections from the literature (Gallet et al., 1998) are discussed in Muttoni et al. (in press). The composite sequence of 13 magnetozones recognised so far in the Buchenstein Beds represent an isotopically-constrained time span of the order of 2–4 Ma, implying a reversal frequency of 2–6 rev/Ma, somewhat higher than the average geomagnetic reversal frequency of 2 rev/Ma for the Late Triassic Newark sequence (Kent et al., 1995). This composite magnetostratigraphy is biostratigraphically constrained at the base within the upper Reitzi ammonoid Zone, whereas the uppermost reversals at Belvedere presumably pertain to the Gredleri or Archelaus Zones but as yet lack accurate biostratigraphic control.

Magnetostratigraphic data from the study sections show good agreement. The average rates of pelagic sediment accumulation based on isotopic age data of the order of 10 m/Ma, coupled with the sampling resolution here adopted, imply an uncertainty in magnetozone boundary correlations of less than 100 ka. The comparison of magnetostratigraphic and lithostratigraphic data from Pedraces, Belvedere and Frötschbach shows that selected, laterally traceable lithostratigraphic marker beds are isochronous. This allows extension of lithostratigraphic correlations with a precision superior to that of any known biostratigraphic scale of corresponding age to other sections from a palaeogeographically coherent basinal area of around 500 km^2. The eastward increase in thickness of volcaniclastic layers is in agreement with an eastward increase in subsidence as indicated by the evolution of correlative platform carbonate intervals.

Finally, the net accumulation rates for pelagic carbonates resulting from isotopic age data from the Buchenstein Beds imply a duration of individual "Knollenkalke" layers in the obliquity frequency range of the Milankovitch band. This conclusion and its implications for the interpretation of the time significance of the Latemar platform cycles need further corroboration through a detailed cyclostratigraphic analysis.

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