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Integrated Anisian–Ladinian boundary chronology

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Abstract

We report magnetostratigraphic and biostratigraphic data from the Seceda core and the correlative outcrop section from the Dolomites of northern Italy. The Seceda rock succession consists of Tethyan marine limestones and radiometrically dated volcaniclastic layers of the Buchenstein Beds of Middle Triassic age (~ 238–242 Ma). The Seceda outcrop section was correlated to coeval sections from the literature using magnetic polarity reversals and a selection of laterally traceable and isochronous lithostratigraphic marker beds. This allowed us to import the distribution of age-diagnostic conodonts, ammonoids, and daonellas from these sections into a Seceda reference stratigraphy for the construction of an integrated biochronology extending across a consistent portion of the Anisian–Ladinian boundary interval. Among the three options selected by the Subcommission for Triassic Stratigraphy to establish the Ladinian Global Stratigraphic Section and Point, we propose to adopt the level containing the base of the Curionii ammonoid Zone at Bagolino (Southern Alps, Italy) because this level is closely associated with a global means of correlation represented by the base of polarity submagnetozone SC2r.2r. The first occurrence of *Neogondolella praehungarica* in the Dolomites predates slightly the base of the Curionii Zone and can be used to approximate the Anisian–Ladinian boundary in the absence of ammonoids.

Keywords: Middle Triassic; Magnetostratigraphy; Lithostratigraphy; Biostratigraphy; Conodonts; Dolomites; Southern Alps

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1. Introduction

We present magnetostratigraphic data from the ~ 110-m-long Seceda core (Brack et al., 2000) comprising Tethyan limestones and radiometrically dated tuff intervals of Middle Triassic age, drilled by the Geological Survey of Bozen-Bolzano in 1998 at Mount Seceda in the northwestern Dolomites (Fig. 1). With over 90% recovery, the Seceda core offers a unique opportunity to reconstruct in stratigraphic continuity a consistent portion of the Middle Triassic pattern of magnetic polarity reversals. The conodont biostratigraphy of the laterally equivalent, superbly exposed and fossiliferous outcrop section (Brack and Rieber, 1993), located ~ 200 m to the northwest of the drill site, is also presented. Biostratigraphic data from Seceda are integrated by means of magneto- and lithostratigraphic correlations with data from additional sections from the

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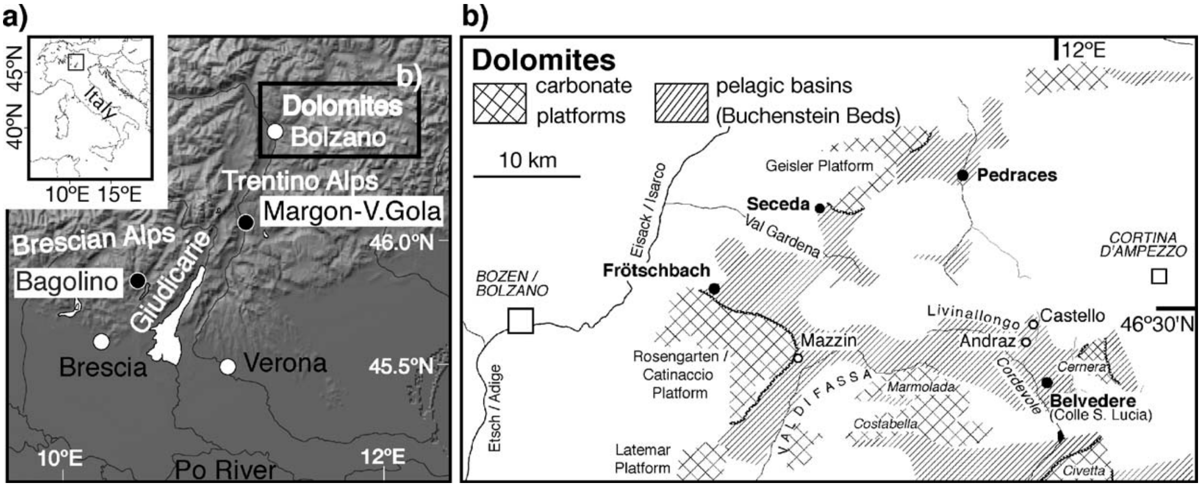


Fig. 1. (a) Global elevation model of the Alpine region with location of the stratigraphic sections discussed in the text. Seceda (this study), Frötschbach, Pedraces, Belvedere (Brack and Muttoni, 2000; this study), and Rosengarten (Maurer, 1999) are from the Dolomites; Margon-Val Gola (Gialanella et al., 2001; Brack et al., 2001) is from Trentino; Bagolino is from the Brescian Alps whereas additional sections are from the Giudicarie (Kovács et al., 1990; Brack and Rieber, 1993; Nicora and Brack, 1995; Brack and Nicora, 1998). Sections in the Dolomites are placed with respect to the distribution of Ladinian carbonate platforms and pelagic basins in panel (b). For details on the location of the Seceda core and outcrop section, see Brack et al. (2000).

Dolomites (Frötschbach, Pedraces, Belvedere, and Rosengarten), Trentino (Margon-Val Gola), Giudicarie, and Brescian Alps (e.g., Bagolino) (Fig. 1). The aim of these correlations is to contribute to the definition of the Global Stratigraphic Section and Point (GSSP) of the base of the Ladinian and completion of the Middle Triassic magnetic polarity time scale.

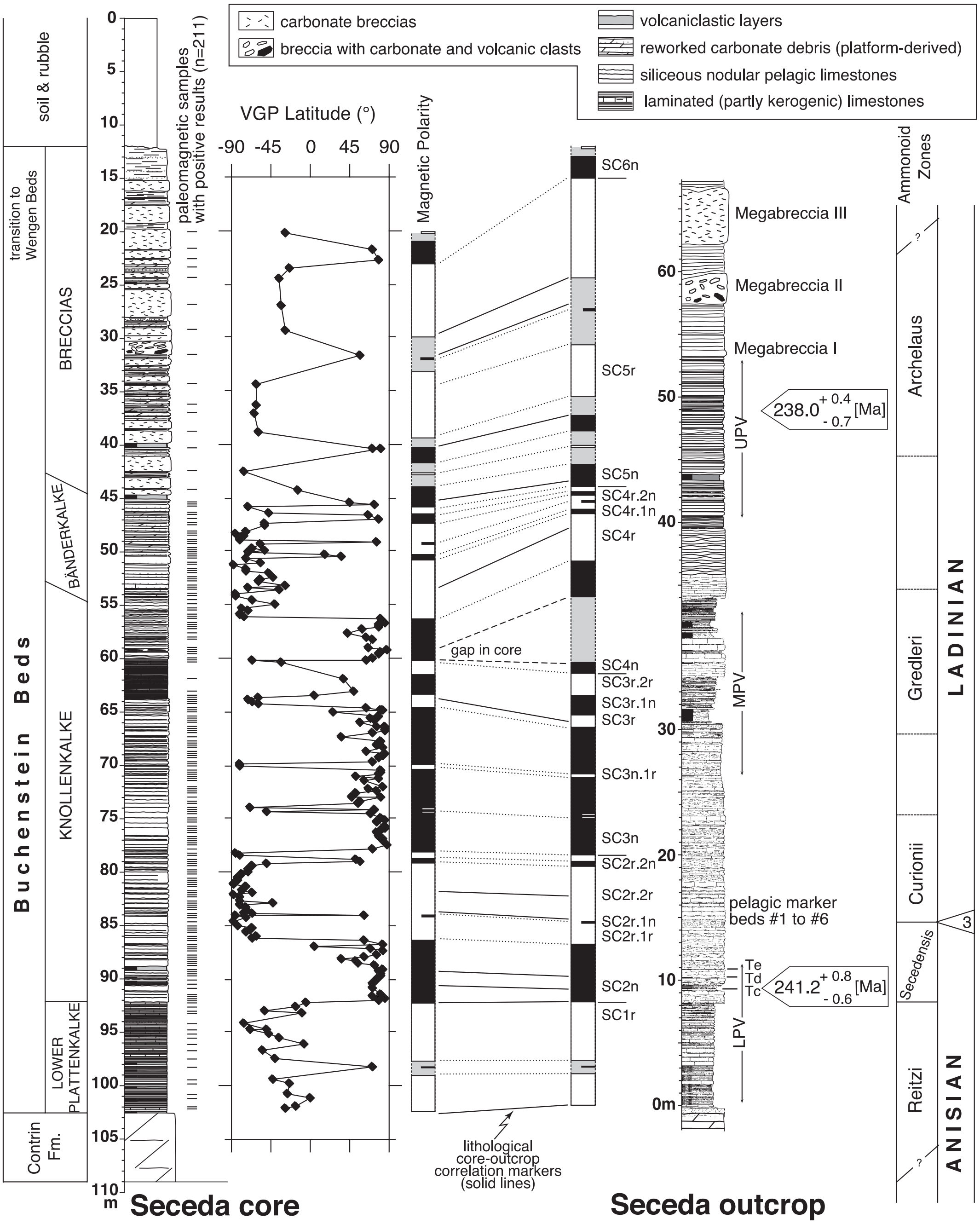
2. Lithostratigraphy

The Seceda core spans a complete succession of Buchenstein Beds limestone members and associated "Pietra Verde" volcaniclastic layers. From bottom to top, these members are as follows (Fig. 2):

(i) The "Lower Plattenkalke", consisting of less than 20 m of laminated limestones and shales rich in organic matter suggesting poorly oxygenated sea-floor conditions, deposited on top of the Upper Anisian Contrin platform or equivalent carbonates. "Lower Pietra Verde" volcaniclastic layers occur in the "Lower Plattenkalke" up to the lowermost part of the "Knollenkalke" [member (ii)] and include tuff marker-beds "Tc", "Td" and "Te" of Brack and Rieber (1993).

Fig. 2. Lithology and magnetic polarity stratigraphy of the Seceda core and correlative outcrop section. VGP latitudes are the latitudes of the characteristic component virtual geomagnetic poles. On the magnetic polarity column, black is normal polarity, white is reverse polarity, and grey represents interval with no data. Maurer and Schlager (2003) and Maurer et al. (2003) discuss in detail the lithostratigraphy and sedimentology of the Seceda core and Brack et al. (2000) its correlation to the outcrop section. For details on the distribution of macrofossils (ammonoids, daonellas) reference is made to Brack and Rieber (1993), Brack et al. (2000), Maurer and Rettori (2002), Maurer and Schlager (2003). U–Pb single zircon age data are from Mundil et al. (1996). Core depth is expressed in metres from the core top, whereas outcrop scale is in metres from the outcrop base. The metre scale of the outcrop section is that used in previous publications on the litho-biostratigraphy of the Buchenstein Beds at Seceda (e.g., Brack and Rieber, 1993, Fig. 4; Brack et al., 2000, Fig. 4). For practical reasons this metric subdivision is also adopted in this study, however, note that Brack and Rieber (1993) recognized the presence of a stratigraphic gap between metre level 33 and 34. From nearby complete exposures at Seceda, Maurer and Rettori (2002, Fig. 3) report the missing interval as consisting of up to 5 m of pelagic carbonates and volcaniclastic layers of the "Middle Pietra Verde" (MPV). This interval is introduced in the Seceda outcrop section of this study between metre level 33 and 34, and is found to largely correspond, in the Seceda core, to a stratigraphic gap located between metre level 59 and 60.

(ii) The “Knollenkalke”, consisting of 20–40 m of centimetre- to decimetre-thick nodular siliceous limestone beds deposited under well-oxygenated sea-floor conditions. Of particular interest for regional correlations are pelagic marker beds #1 to #6 in the lower “Knollenkalke” (Brack and Muttoni, 2000; Maurer and Schlager, 2003). “Middle Pietra Verde” volcaniclastic layers are located in the middle-upper portion of the “Knollenkalke” member.



(iii) The “Bänderkalke”, consisting of evenly bedded calcarenites with redeposited debris from the carbonate platform margins surrounding the Buchenstein basin (Fig. 1b). “Upper Pietra Verde” volcaniclastic layers are present in the “Bänderkalke” member at Seceda or in the uppermost “Knollenkalke” member in the Brescian Alps (e.g., Bagolino; Brack and Rieber, 1993).

(iv) Above the “Bänderkalke” follows a ~ 30 m-thick interval dominated by breccia layers with carbonate platform debris.

Two ash layers located in the “Lower Pietra Verde” and “Upper Pietra Verde” intervals at Seceda yielded U–Pb age data of 241.2 and 238.0 Ma, respectively (Fig. 2) (Mundil et al., 1996; Brack et al., 1996), indicating an average rate of sediment accumulation of ~ 10 m/m.y. Quantitative sedimentological analyses conducted on the Seceda core indicate that the non-decompacted sedimentation rate remained relatively constant in the “Knollenkalke” member and increased upsection by more than 100% in the turbidite-rich “Bänderkalke” and breccia members (Maurer et al., 2003).

3. Palaeomagnetism

Sampling for palaeomagnetism was performed on the western half of the Seceda core, which was oriented with respect to the geographic north using bedding dip (22–149°E). An average of 4 samples/m were taken in the “Knollenkalke” (Fig. 2), corresponding to a time resolution of ~ 25 k.y. About 1–2 samples/m were taken in the “Lower Plattenkalke” in limestone levels with the least visible organic content in order to limit the effects of diagenetic reduction on magnetic remanence-carrying iron oxides (Muttoni et al., 1997). A similar sampling rate was adopted in the “Bänderkalke” due to the presence of abundant non-magnetic turbiditic calcarenites. A total of 244 palaeomagnetic samples, each 11.4 cm^3 in volume, were subjected to progressive thermal demagnetization. Remanence measurements were performed on a 2G

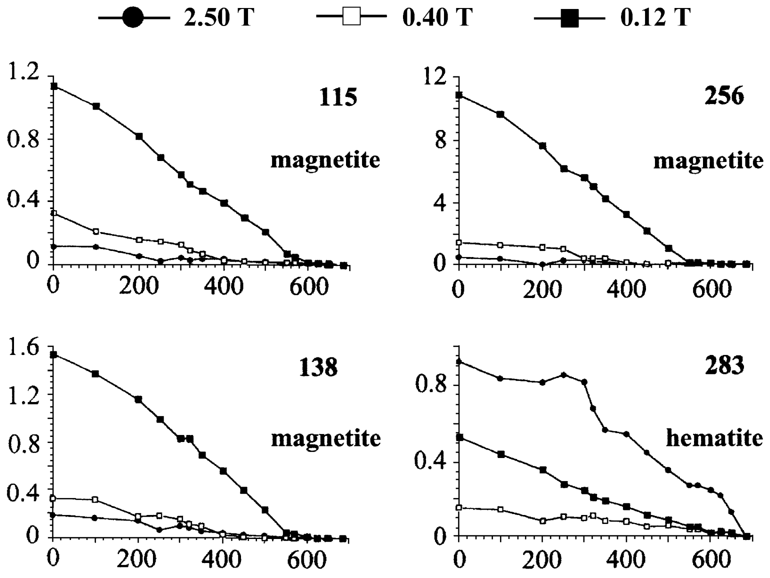


Fig. 3. Thermal unblocking characteristics of orthogonal-axes IRMs (Lowrie, 1990) of a set of representative Buchenstein Beds limestone samples from the Seceda core bearing dominant magnetite and subsidiary hematite. Temperature on the x-axis is expressed in °C; isothermal remanent magnetization (IRM) on the y-axis is expressed in 10^{-2} A/m.

3-axis cryogenic magnetometer with DC SQUID sensors located in a magnetically shielded room at the Lamont-Doherty paleomagnetics laboratory.

3.1. Palaeomagnetic properties

The mean intensity of the natural remanent magnetization (NRM) is 0.3 mA/m. The initial susceptibility, with a mean value of 3.9×10^{-5} SI, is usually stable over the laboratory heating procedure. Thermal demagnetization of three-component IRM (Lowrie, 1990) shows the occurrence of a dominant low coercivity magnetic phase with maximum unblocking temperatures of ~ 575 °C interpreted as magnetite (Fig. 3, samples 115, 138, 256). A higher coercivity and unblocking temperature phase, interpreted as hematite, was also occasionally observed (Fig. 3, sample 283).

Least-square analysis of Kirschvink (1980) was applied on vector end-point demagnetization diagrams (Zijderveld, 1967) to calculate magnetic component directions. About one-half (54%) of the samples show the presence of a steep, positively inclined magnetic component unblocked between room temperature and ~ 200 °C, which is broadly consistent with the present-day field direction (Figs. 4 and 5a). A bipolar characteristic component of magnetization oriented either northwest-and-down or southeast-and-up was successively unblocked in 86% of the samples from ~ 200 to ~ 550–575 °C, rarely up to ~ 680 °C (i.e., mostly in the magnetite temperature range; Figs. 4 and 5b). High

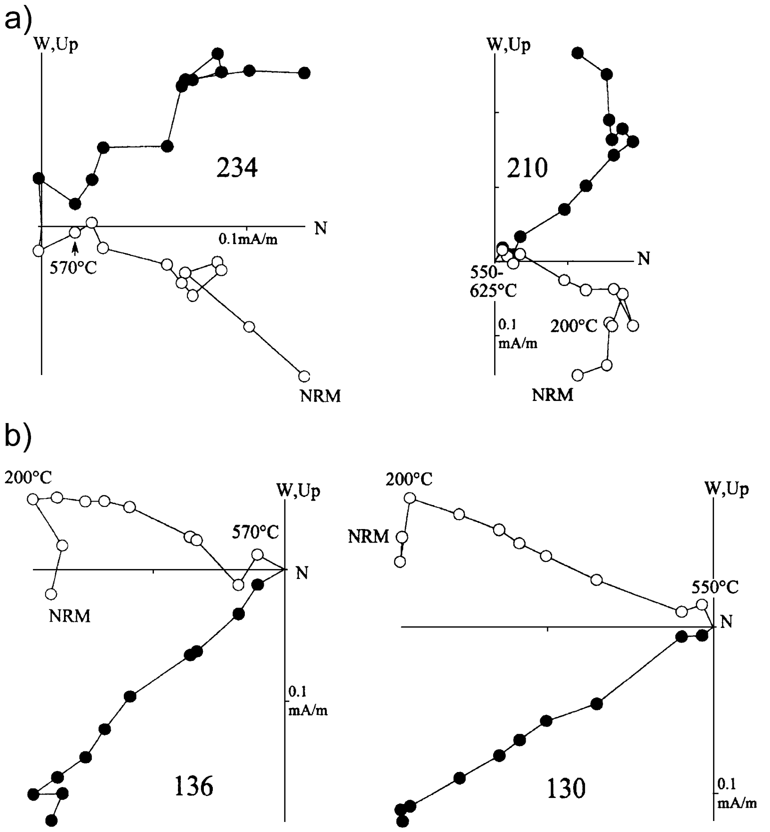


Fig. 4. Zijderveld demagnetization diagrams of representative Buchenstein Beds limestone samples from the Seceda core bearing normal (a) and reverse (b) characteristic component polarity. Closed symbols are projections onto the horizontal plane and open symbols are projections onto the vertical plane. All diagrams are in geographic coordinates. Temperature is expressed in °C.

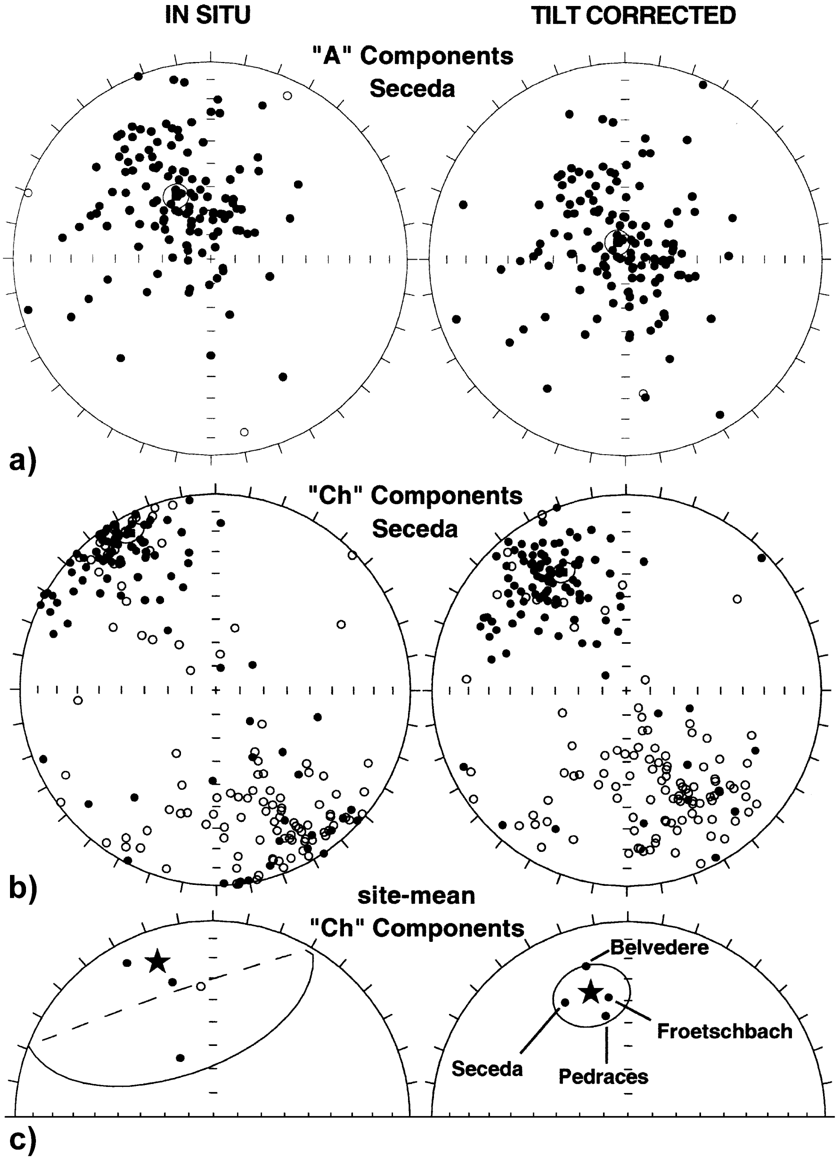


Fig. 5. Equal-area projections before and after bedding tilt correction of the Seceda core palaeomagnetic components; (a) is the initial low unblocking temperature “A” component, which is generally consistent with the present-day field direction, whereas (b) is the higher unblocking temperature characteristic “Ch” component bearing reversals. Panel (c) is a plot of the site-mean “Ch” directions from Seceda, Frötschbach, Pedraces, and Belvedere showing evident improvement in grouping upon application of bedding tilt. Solid symbols refer to the lower hemisphere. See text for discussion.

temperature magnetic components with scattered and generally positive inclinations were also observed and tentatively attributed to drilling-induced overprints.

The site-mean characteristic component direction in geographic coordinates, calculated by standard Fisher (1953) statistics, did not vary substantially in orientation upon tilting correction because of the moderate homoclinal bedding dip at Seceda (Fig. 5b). We inverted all characteristic directions to common polarity and calculated a tilt corrected average direction of Dec. = 331.9°, Inc. = 32.1° (Table 1) corresponding to a palaeomagnetic pole located at 239.7°E, 52.7°N (dm–dm = 2.8°–5.0°).

The site-mean characteristic component directions from the Seceda core, Frötschbach, Pedraces, and Belvedere (Brack and Muttoni, 2000) are highly scattered in geographic coordinates (Fig. 5c; Table 1). A ten-fold increase in the Fisher precision parameter k, significant at 95% confidence level according to the conservative criteria of McElhinny (1964), occurred at 100% untilting. The precision parameter k showed a peak at partial (85%) untilting (Dec. = 344.5°, Inc. = 32.2°, $\alpha_{95} = 10.7°$, $k_{85} = 74.5$, $k_{85}/k_0 = 18$, $N = 4$), which we attribute to imprecise bedding attitude at one site. The angular distance between the overall mean direction at 85% and 100% tilting correction is only 2.5°. Successful magneto- and lithostratigraphic correlations between distant sections as outlined below and in Brack and Muttoni (2000) suggest that the Buchenstein Beds characteristic remanence is the original Triassic magnetization acquired before Cenozoic Alpine deformation. The overall palaeomagnetic pole of the Buchenstein Beds at 100% untilting lies at 223.9°E, 59.2°N (Table 1) in agreement with coeval data from Libya (Muttoni et al., 2001). We therefore confirm the substantial coherence of palaeomagnetic data from the Dolomites (Adria) and Africa, which was observed within typical palaeomagnetic resolution of a few degrees since Permian times (Muttoni et al., 2001). Paleogeographic reconstructions using a compilation of Adria-Africa data imply that the Triassic magnetization of the Buchenstein Beds was acquired in the northern hemisphere (Muttoni et al., 1996) at a paleolatitude of about 19 ± 9°N.

3.2. Magnetostratigraphy

A virtual geomagnetic pole (VGP) was calculated for each characteristic component direction in tilt corrected coordinates. Assuming that the Dolomites were located in the northern hemisphere and 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). Each magnetozone is prefixed by the acronym for the source of the magnetostratigraphy (i.e., "SC" for Seceda core). The latitude of the specimens VGPs defines a sequence of ~24 magnetozones from SC1r to SC6n in which submagnetozones can be embedded (e.g., SC2r.2n, SC3n.1r, etc.; Fig. 2). A single sample-based submagnetozone of stratigraphic relevance, termed SC2r.1n, is comprised within magnetozone SC2r. Towards the core top, as well as at its very bottom, the coarser sampling rate adopted resulted

Table 1
Paleomagnetic directions from the Buchenstein Beds of the Dolomites

Locality	n_1/n_2	In Situ				Tilt Corrected				
		k	α_{95}	Dec.	Inc.	k	α_{95}	Dec.	Inc.	Reference
1 Seceda	244/211	6	4.4	331.5	10.1	6	4.4	331.9	32.1	this study
2 Belvedere	106/093	5	7.4	330.9	62.1	5	7.4	344.5	21.1	Brack and Muttoni (2000)
3 Pedraces	041/035	5	12.0	354.7	−33.8	5	12.0	347.6	46.0	Brack and Muttoni (2000)
4 Frötschbach	102/092	8	5.5	343.3	29.3	8	5.5	350.8	38.0	Muttoni et al. (1997)
overall direction	$N=4$	4	52.1	340.8	17.7	42	14.3	343.4	34.5	
overall paleopole	$N=4$					dp/dm 9.4/16.4	Long. 223.9	Lat. 59.2		

n_1 is the total number of paleomagnetic samples, n_2 is the number of samples used in statistical analysis; k and α_{95} are Fisher precision parameter and 95% confidence interval around the mean direction, respectively; Dec. and Inc. are the Declination and Inclination of the site-mean characteristic component directions before (In Situ) and after (Tilt Corrected) correction for bedding tilt; dp/dm are the confidence ovals around the overall mean paleomagnetic pole; Long. and Lat. are the Longitude and Latitude of the overall mean paleomagnetic pole, calculated at a nominal point located at 46.2°N, 11°E (central Dolomites).

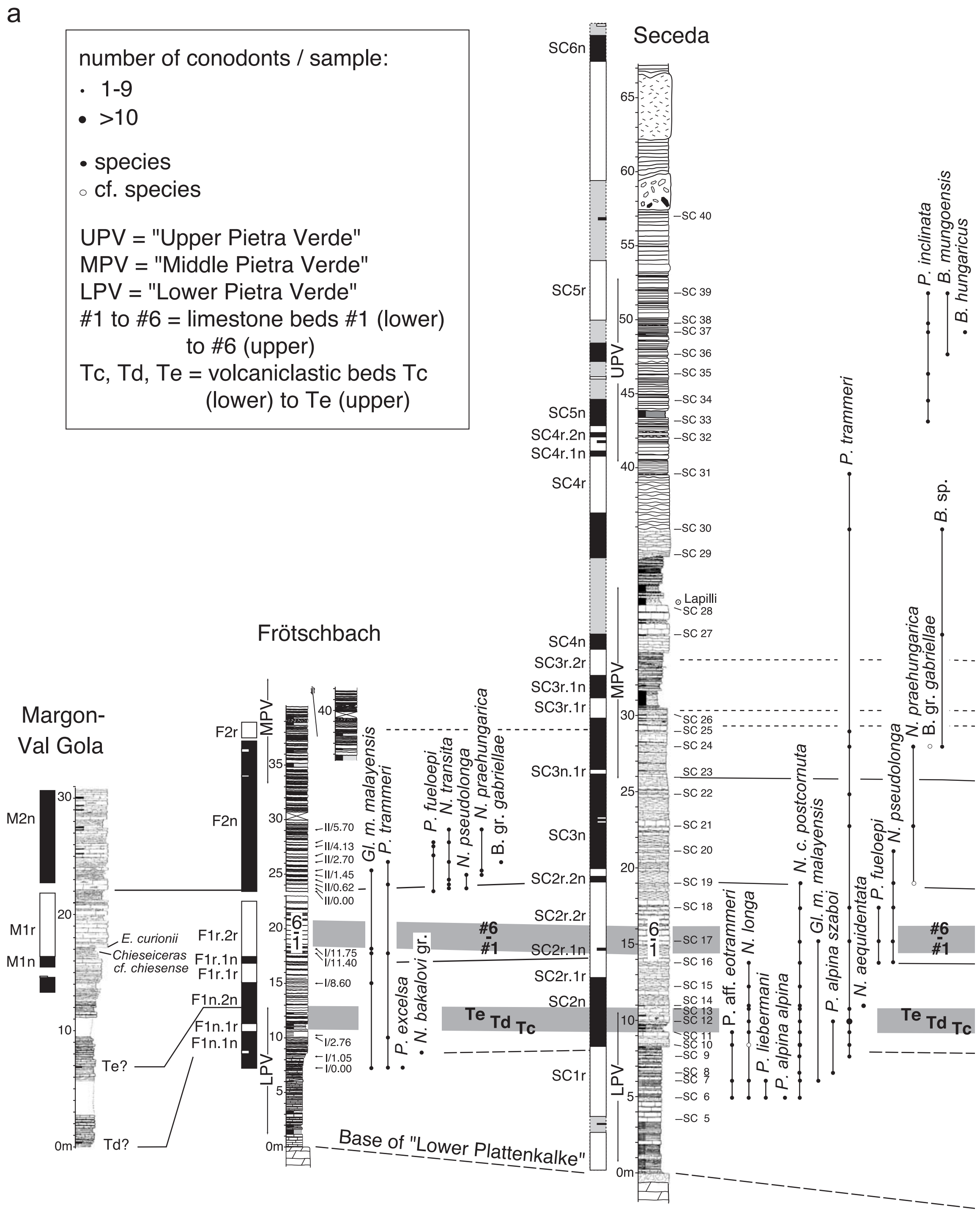


Fig. 6. Magnetostratigraphic and lithostratigraphic correlations of conodont-bearing sections from the Dolomites and Trentino discussed in the text.

in a poorer definition of the magnetozone sequence (Fig. 2).

4. Correlation of Buchenstein Beds sections

4.1. Magnetostratigraphic correlations

Magnetostratigraphic and lithostratigraphic data from Seceda are in good agreement with coeval data from Frötschbach, Pedraces, and Belvedere from the Dolomites (Brack and Muttoni, 2000), as well as Margon-Val Gola from Trentino (Gialanella et al., 2001; Brack et al., 2001) (Fig. 6). The sequence of polarity reversals SC2n-SC3n at Seceda corresponds as a whole to F1n-F2n at Frötschbach, P1n-P3n at Pedraces, SL1r-SL2n at Belvedere, and M1n-M2n at Margon-Val Gola, and is roughly comprised between the "Plattenkalke"–"Knollenkalke" boundary and the "Middle Pietra Verde" interval. Submagnetozone F1n.1r, located at Frötschbach across tuff marker bed "Tc", was not identified at Seceda because this stratigraphic interval was not accessible for sampling. The single sample-based submagnetozone SC2r.1n corresponds to submagnetozone F1r.1n at Frötschbach, P2n at Pedraces, and M1n at Margon-Val Gola

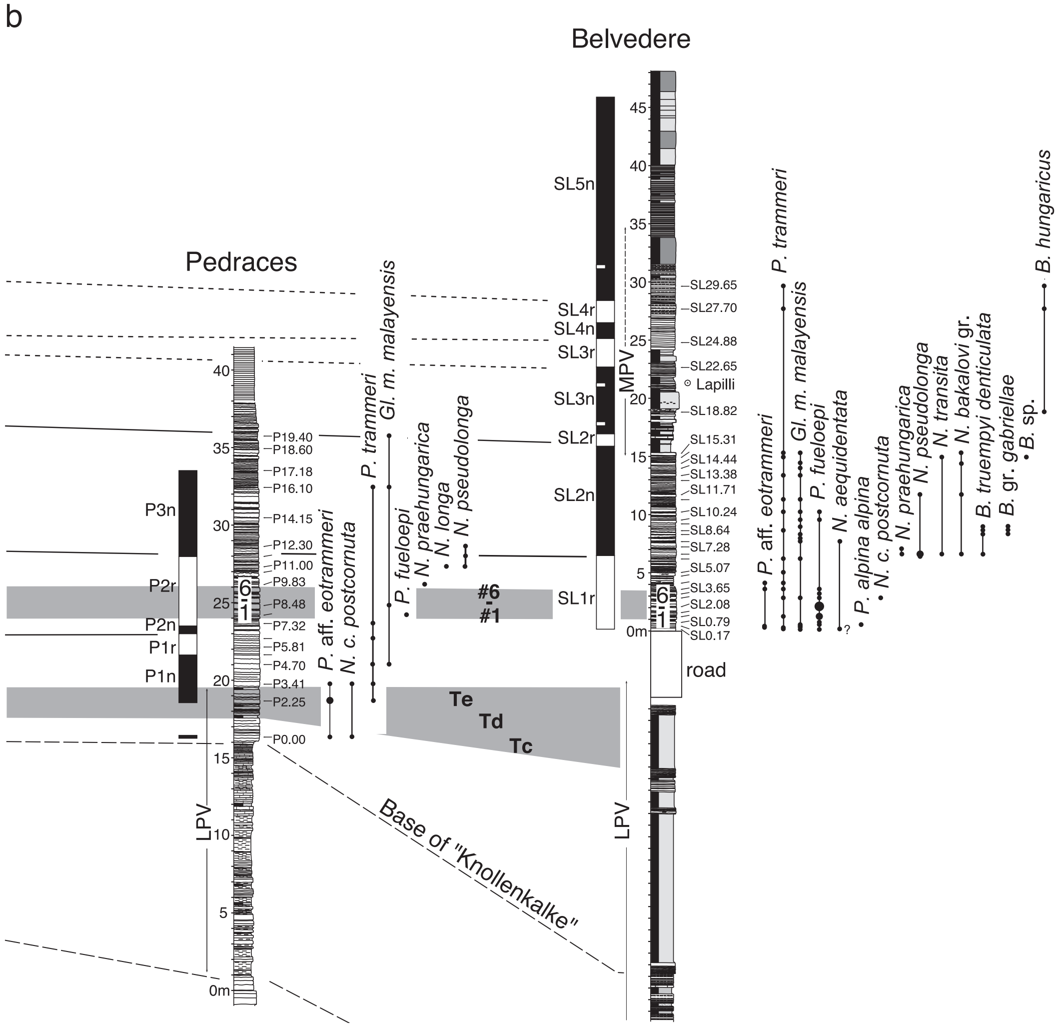


Fig. 6 (*continued*).

(Brack et al., 2001). Correlative magnetozone boundaries SC2r-SC3n, F1r.2r-F2n, P2r-P3n, and SL1r-SL2n occur within laterally recognizable limestone beds with similar lithological characteristics. The high sampling resolution adopted at Seceda allowed us to define at the top of SC2r an additional submagnetozone termed SC2r.2n. Upsection, we tentatively correlate SC3r.1r to F2r and SL3r, and SC3r.1n to SL4n. Finally, the interval SC3r.2r-SC4n at Seceda may correlate to the volcaniclastic-rich, expanded interval SL4r-SL5n at Belvedere. The Seceda magnetic polarity sequence expands Buchenstein Beds magnetostratigraphy of Brack and Muttoni (2000) into the Anisian (with magnetozone SC1r) and into the Upper Ladinian (with magnetozones SC4r-SC6n).

4.2. Lithostratigraphic correlations

A selection of easily recognizable lithostratigraphic marker beds were proven laterally traceable with respect to magnetostratigraphic correlations at Buchenstein Beds sections in the Dolomites (Seceda, Frötschbach, Pedraces, and Belvedere; Brack and Muttoni, 2000; this study), and were, at least in part, also recognized elsewhere in the Dolomites (Rosengarten; Maurer, 1999), as well as at Buchenstein Beds sections located outside the Dolomites in Trentino (Margon-Val; Gola; Gialanella et al., 2001; Brack et al., 2001), Giudicarie, and Brescian Alps (e.g., Bagolino) (Brack and Rieber, 1993). These isochronous marker beds are:

(i) Tuff levels “Tc”, “Td” and “Te” within the “Lower Pietra Verde” interval.
(ii) The general distribution of “Lower-“, “Middle-“ and “Upper Pietra Verde” intervals.
(iii) Pelagic limestone beds #1 to #6 in the “Knollenkalke” member.

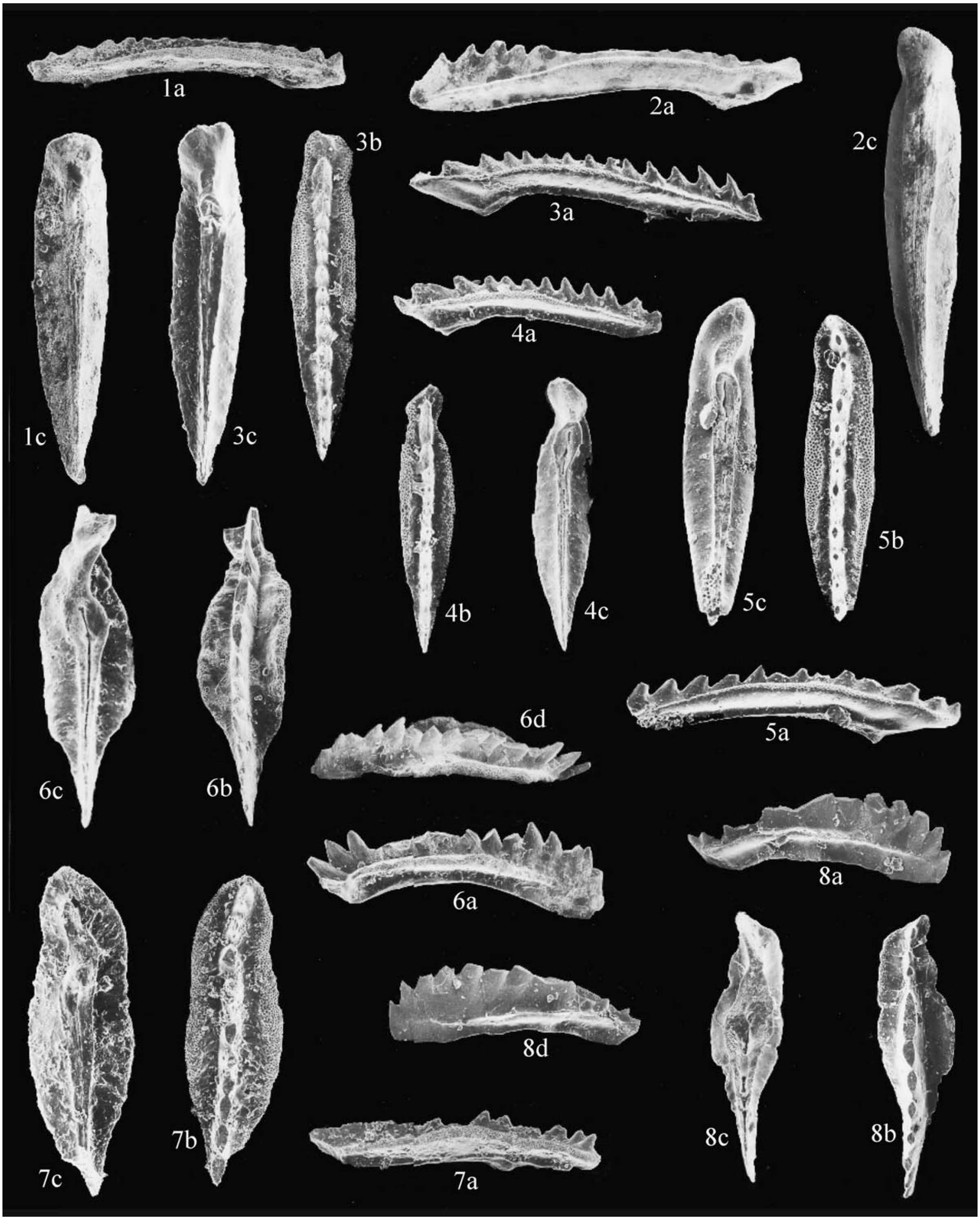
These lithostratigraphic marker beds, in conjunction with magnetic polarity reversal boundaries, constitute a powerful tool to correlate Buchenstein Beds sections across the Southern Alps.

5. Integrated Anisian–Ladinian boundary biochronology

Triassic stage boundaries are historically based on ammonoid biostratigraphy. In its absence, conodont biostratigraphy is also widely used. Age-diagnostic ammonoids are present in the Buchenstein Beds (Brack and Rieber, 1993), whereas conodonts have been thus far discontinuously recorded (Nicora and Brack, 1995; Muttoni et al., 1997; Brack and Nicora, 1998). Conodonts from Seceda, Pedraces, and Belvedere are from this study, whereas those from Frötschbach are updated from Muttoni et al. (1997). Conodonts were obtained essentially from the upper part of the “Lower Plattenkalke” member upwards (Fig. 6, Plates I–III); Table 2) at an average sampling rate of ∼ 1 sample/m corresponding to a time resolution of ∼ 100 k.y. Each sample weighted 3–5 kg on average and yielded well preserved specimens with alteration index (CAI) = 1–2.

Similar ancestor–descendant faunal associations of paragondolellids and neogondolellids characterize conodont biostratigraphy at Seceda, Frötschbach, Pedraces, and Belvedere, providing confidence about the occurrence, at a gross scale, of a laterally reproducible vertical sequence of bio-events. However, close inspection of Fig. 6 reveals that the vertical distributions of correlative conodont species, when tested in detail against our dense network of magneto- and lithostratigraphic correlations, can be offset on the order of metres from section to section despite the adoption of similar average sampling rates at comparable rates of sediment accumulation (e.g., the first occurrences of *Neogondolella pseudolonga*, *Paragondolella fueloepi*, *Budurovignathus* gr. *gabriellae,* and *B. hungaricus*; Fig. 6). We infer that conodont events were discontinuously recorded in the Buchenstein Beds of

Plate I. a,c. *Neogondolella pseudolonga* Kovács, Kozur and Mietto, sample SL11.71, X70. 2a,c. *Neogondolella pseudolonga* Kovács, Kozur and Mietto, transitional to *N. bakalovi* Budurov and Stefanov, sample SL11.71, X70. 3a–c. *Neogondolella bakalovi* Budurov and Stefanov, sample SL14.44, X90. 4a–c. *Neogondolella bakalovi* Budurov and Stefanov, juvenile specimen, sample SL15.31, X90. 5a–c. *Neogondolella bakalovi* Budurov and Stefanov, sample SL15.31, X90. 6a–d. *Budurovignathus hungaricus* (Kozur and Vegh), sample SL27.70, X90. 7a–c. *Budurovignathus truempyi denticulata* Hirsch, sample SL8.31, X90. 8a–d. *Budurovignathus hungaricus* (Kozur and Vegh), transitional to *B. mungoensis* (Diebel), sample SC37, X90. a,d = lateral view; b = upper view; c = lower view.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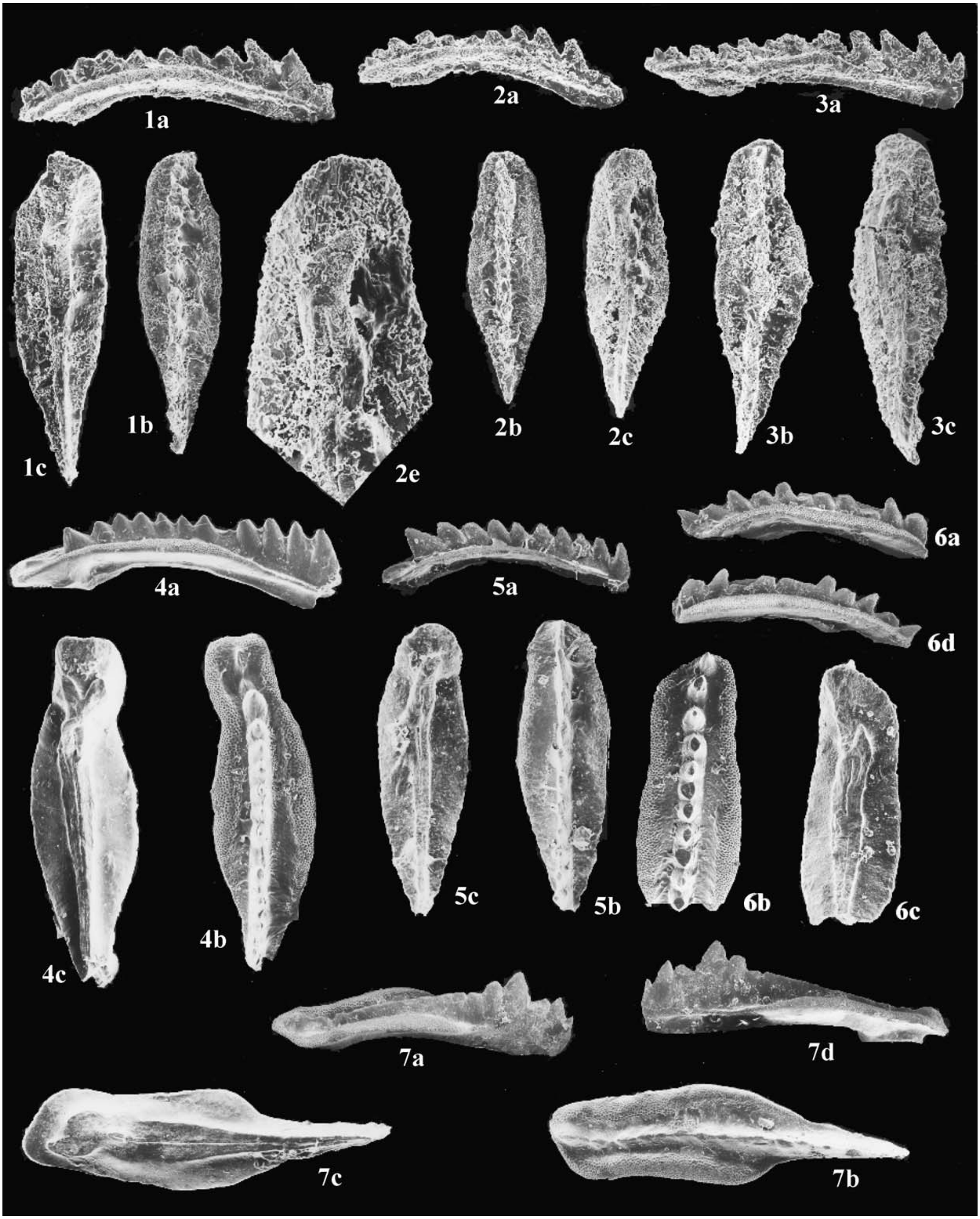
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the Dolomites probably because of a combination of different factors such as preservation, insufficient sampling resolution, ecological variations, etc.

To augment the definition of conodont biostratigraphy across the Anisian–Ladinian boundary, we integrated data from Seceda, Frötschbach, Pedraces, and Belvedere (Fig. 6) with data from Rosengarten in the Dolomites (Maurer, 1999), as well as from sections in the Brescian Alps (e.g., Bagolino) and Giudicarie (Kovács et al., 1990; Nicora and Brack, 1995; Brack and Nicora, 1998). Biostratigraphic data from the Dolomites were projected into the Seceda outcrop reference stratigraphy, whereas those from the Brescian Alps and Giudicarie into the Bagolino reference stratigraphy, by means of magneto- and lithostratigraphic correlations as described above (Fig. 7). Where magnetostratigraphy was not available (Rosengarten), or magnetization was proven of secondary origin (Bagolino; Muttoni and Kent, 1994), the use of isochronous lithostratigraphic marker beds was adopted for correlation.

The following events characterize our integrated Anisian–Ladinian boundary biochronology (Fig. 7):

(i) The upper Trinodosus to lower Reitzi ammonoid zones (~ 242 Ma and older) are characterized by an association of neogondolellids (*Neoogondolella constricta cornuta, N. constricta balkanica*, *N. longa, N. constricta postcornuta, N. transita*) and paragondolellids (*Paragondoolella liebermani, P. excelsa, P.* aff. *eotrammeri, P. alpina* gr.).

(ii) In the middle Reitzi to Secedensis ammonoid Zones (~ 242–240.7 Ma), seven new taxa first occur, among others, *P. fueloepi*, *P. trammeri* and *N. bakalovi* gr., which are closely associated with the base of the Secedensis Zone, located at the first appearance of the ammonoid genus *Ticinites* (Brack et al., 2003) at metre level 8.1 in the reference Seceda outcrop section, ~ 1.5 m below volcaniclastic level “Tc” dated at 241.2 (+0.8/−0.6) Ma (Mundil et al., 1996). Some of these lowest conodont occurrences may be associated with the facies transition “Lower Plattenkalke”-“Knollenkalke”. The upper Reitzi interval records also a daonellas association with *Daonella serpianensis, D. cerneraensis, D. angulata, D. elongata* and *D. caudata*.

(iii) The interval comprised between the Secedensis Zone and the middle–upper part of the overlying Curionii Zone (~ 241–240 Ma) is characterized by the highest specific variability of paragondolellids and neogondolellids, with most of the taxa previously described occurring simultaneously. In particular, *N. aequidentata* is almost entirely restricted to the uppermost Secedensis Zone, whereas the first occurrence of *N. praehungarica* seems to slightly predate the base of the Curionii Zone. *Daonella* cf. *golana* occurs within the Secedensis Zone.

(iv) In the upper Curionii Zone and the basal portion of the (poorly defined) Gredleri Zone (~ 240–239 Ma), an abrupt decrease in specific variability occurs, characterized by the substitution of the relatively abundant paragondolellids and neogondolellids association of interval (iii) with an association dominated by fewer species of the genera *Budurovignathus* (*Budurovignathus* gr. *gabriellae, B. truempyi denticulata, B.* sp., *B. hungaricus*).

(v) The Gredleri-Archelaus interval (~ 239–237.5 Ma) is particularly poor in conodonts, with *Paragondolella inclinata* and *Budurovignathus mungoensis* first occurring in the Gredleri-Archelaus transition zone, just below the first occurrence of *Daonella pichleri*. *B. hungaricus,*

Plate II. 1a–c. *Budurovignathus* gr. *gabriellae*, sample SL 8.31, X90. 2a–e. *Budurovignathus* gr. *gabriellae*, sample SL 8.31, X90 (2a–d), X120 (2e). 3a–c. *Budurovignathus* gr. *gabriellae*, sample SL 8.31, X90. 4ac. *Neogondolella praehungarica* (Kovács), sample SC 21, X90. 5a–c. *Neogondolella praehungarica* (Kovács), sample SC 24, X90. 6a–d. *Budurovignathus* gr. *gabriellae*, sample SL 8.64, X90. 7a–d. *Budurovignathus* sp., sample SC 24, X70. a,d = lateral view; b = upper view; c = lower view; e = enlargement. Paleontological remarks on *Budurovignathus* gr. *gabriellae*. *Budurovignathus gabriellae* Kozur et al. (1994) is a smooth *Budurovignathus* with sigmoidally bent broad platform, broadly rounded platform end, 7 to 8 widely separated long denticles uniformly posteriorly inclined, no distinct cusp, and a basal cavity located at the beginning of the posterior third of the unit. According to the authors, *B. gabriellae* is the oldest known species of *Budurovignathus* (upper Fassanian), with morphological characteristics transitional to *Neogondolella*. With respect to *B. gabriellae*, our specimens of *B.* gr. *gabriellae* have more denticles (12–13), which are posteriorly inclined, separated apically, but more fused than in *B. gabriellae*. Some *B.* gr. *gabriellae* specimens have a pointed posterior end (Plate II, 6a–d), and may represent a form transitional to *B. truempyi denticulata* (Hirsch, 1971).

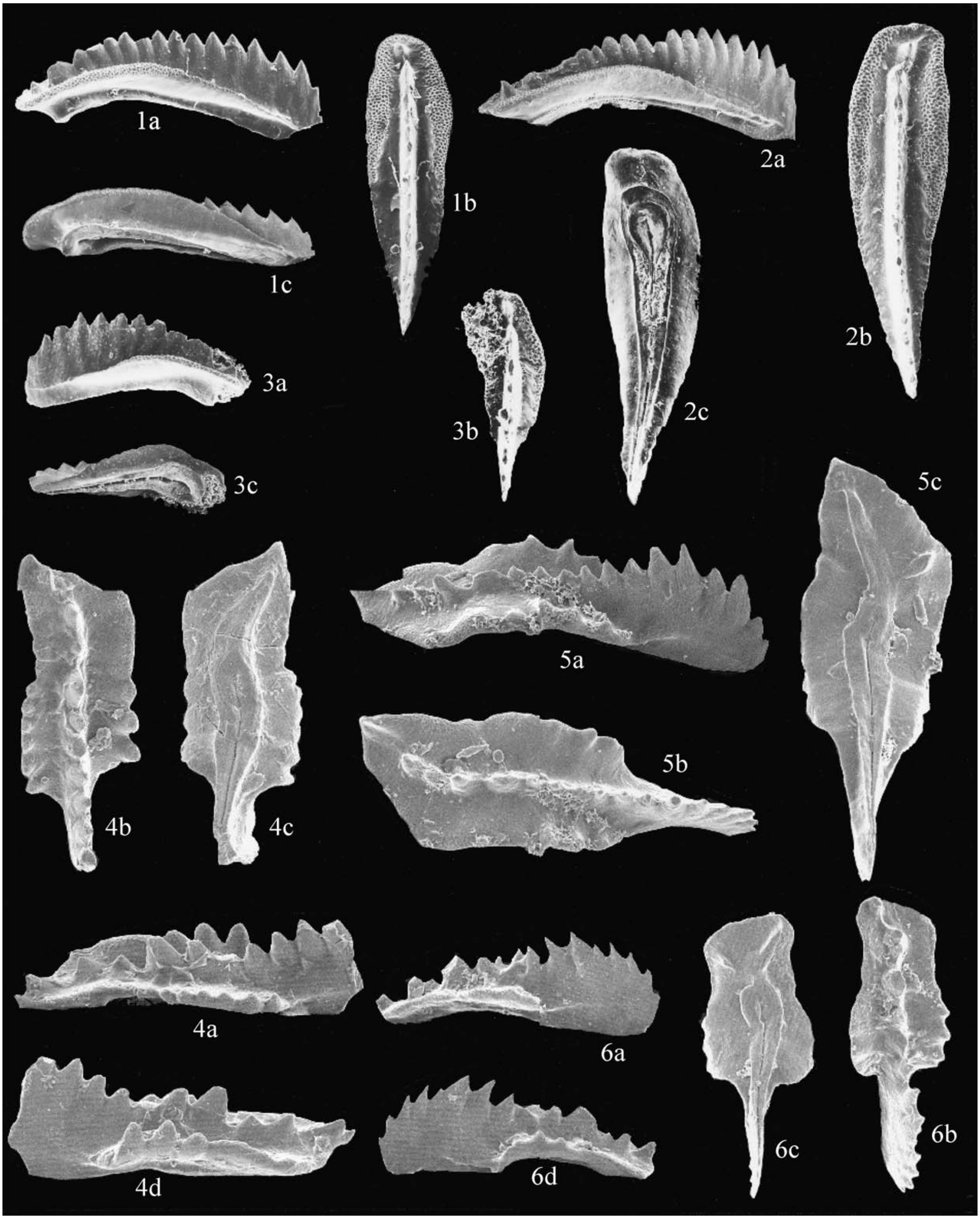
1a
1b
2a
1c
2b
3a
3b
2c
3c
5c
4b
4c
5a
5b
4a
6a
4d
6d
6c
6b

Table 2
The vertical distribution of conodont samples with respect to the ammonoid zonation at Frötschbach, Seceda, Belvedere and Pedraces as reported in Fig. 6

FROETSCHBACH		SECEDA	
FBII 5.70	Curionii or Gredleri Zone	SC 41	Archelaus or Regoledanus Zone
FBI 11.75–FBII 4.54	Curionii Zone	SC 36–40	Archelaus Zone
FBI 2.76–8.60	Secedensis Zone	SC 30–35	Gredleri or Archelaus Zone
FBI 0.00	Reitzi Zone	SC 26–29	Gredleri Zone
		SC 22–25	Curionii or Gredleri Zone
		SC 17–21	Curionii Zone
		SC 10–16	Secedensis Zone
		SC 5–9	(upper) Reitzi Zone

BELVEDERE		PEDRACES	
SL 22.65–29.65	Gredleri Zone	P 17.18–22.54	Curionii or Gredleri Zone
SL 12.97–18.82	Curionii or Gredleri Zone	P 7.32–16.10	Curionii Zone
SL 0.79–11.71	Curionii Zone	P 2.25–6.35	Secedensis Zone
SL 0.17–0.57	Secedensis Zone	P 0.00	(top) Reitzi Zone

P. inclinata, and *B. mungoensis* characterize the Archelaus Zone in association with *Daonella tyrolensis* and *D.* gr. *lommeli*.

6. Identification of potential Ladinian GSSPs

The three candidates for the position of the base of the Ladinian Stage selected by the Subcommission for Triassic Stratigraphy are, from older to younger: (#1) the level containing the base of the Reitzi Zone s.s. in the Felsöörs section, Balaton Highlands, Hungary (Vörös et al., 2003);(#2) the level containing the base of the Avisianum Subzone in the Bagolino section, Southern Alps, Italy (Mietto et al., 2003); and (#3) the level containing the base of the Curionii Zone in the Bagolino section, Southern Alps, Italy (Brack et al., 2003). The composite magneto- and biostratigraphic record discussed above fully covers Option #3. Options #1 and #2 lie below the lowermost palaeomagnetic reversal at Seceda and are therefore not discussed in this paper.

6.1. Option #3—base of the Curionii Zone

The base of the Curionii Zone, located at the first occurrence of *Eoprotrachyceras curionii,* is accurately established at sections in the Brescian Alps (Bagolino), Giudicarie, as well as in Trentino (Margon-Val Gola) (Brack and Rieber, 1993, 1986). The magnetostratigraphic correlation as outlined above (Fig. 6) and in Brack et al. (2001) predicts the level corresponding to the base of the Curionii Zone to be located at metre level 14.5 in the reference Seceda outcrop section (= metre level 83.7 in the Seceda core), immediately below limestone marker bed #1. The base of the Curionii Zone is shortly preceded by the occurrence of marker taxa *Chieseiceras chiesense* at Seceda, Bagolino, and related sections in the Brescian Prealps, and *Chieseiceras* cf. *chiesense* at Margon-Val Gola. The base of reversal SC2r.2r closely approximates the base of the Curionii Zone at Seceda and has an interpolated age of ~ 240.7 Ma. At Bagolino, the first occurrence of conodont *N. praehungarica* predates the base of the Curionii Zone.

7. Geochronological implications for the duration of the Ladinian

Our composite sequence of ~ 24 biostratigraphically calibrated magnetic polarity reversals covers a

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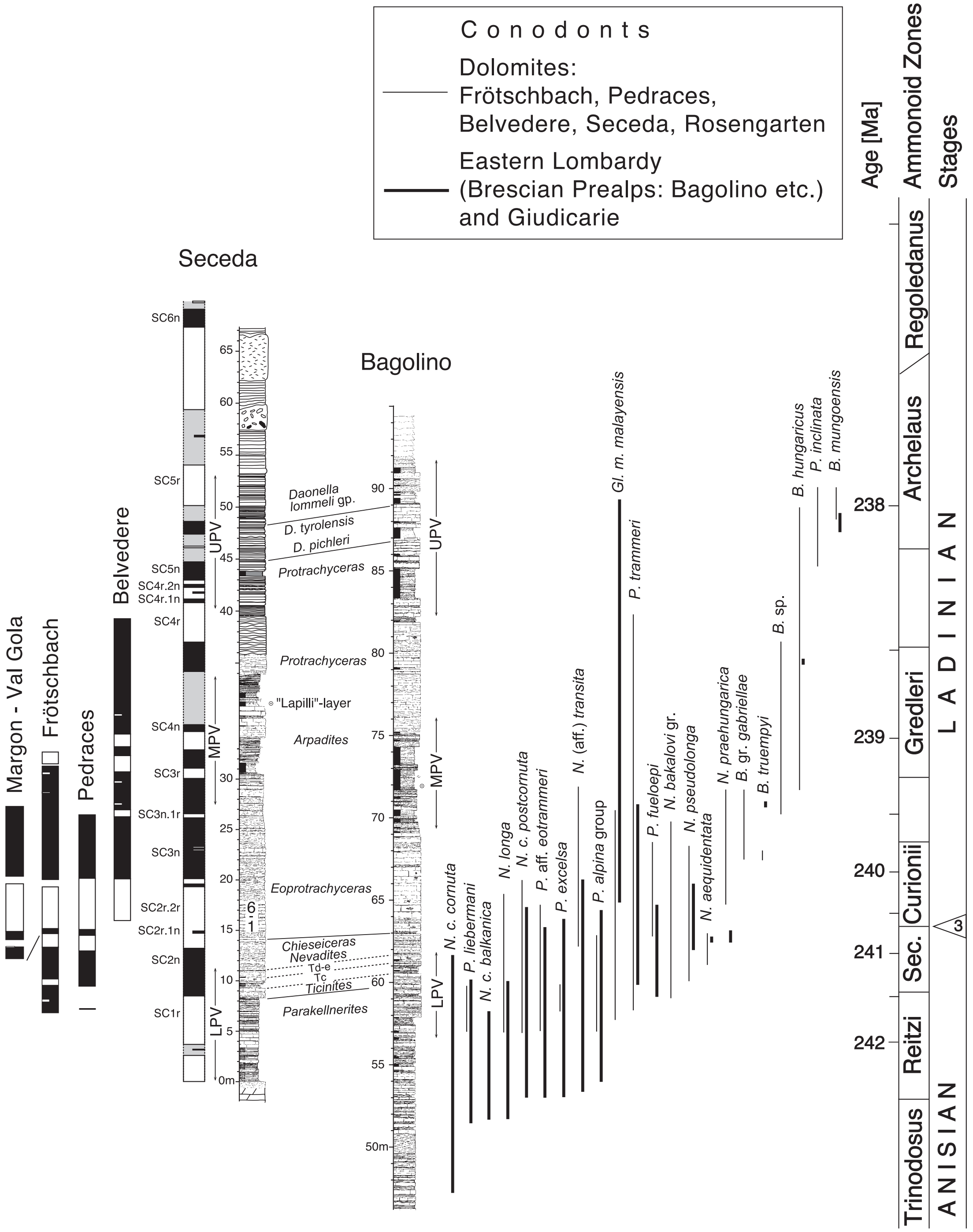
Plate III. 1a–c. *Paragondolella inclinata* (Kovács), sample SC 35, X90. 2a–c. *Paragondolella inclinata* (Kovács), sample SC 39, X90. 3a–c. *Paragondolella inclinata* (Kovács), sample SC 34, X90. 4a–d. *Budurovignathus mungoensis* (Diebel), sample SC39, X90. 5a–c. *Budurovignathus mungoensis* (Diebel), sample SC36, X90. 6a–d. *Budurovignathus mungoensis* (Diebel), sample SC36, X90. a,d = lateral view; b = upper view; c = lower–lower–oblique view.


Conodonts
Dolomites: Frötschbach, Pedraces, Belvedere, Seceda, Rosengarten
Eastern Lombardy (Brescian Prealps: Bagolino etc.) and Giudicarie
Margon - Val Gola
Frötschbach
Pedraces
Belvedere
Seceda
Bagolino
SC6n
SC5r
SC5n
SC4r.2n
SC4r.1n
SC4r
SC4n
SC3r
SC3n.1r
SC3n
SC2r.2r
SC2r.1n
SC2n
SC1r
LPV
MPV
UPV
Daonella lommeli gp.
D. tyrolensis
D. pichleri
Protrachyceras
Protrachyceras
"Lapilli"-layer
Arpadites
Eoprotrachyceras
Chieseiceras
Nevadites
Td-e
Tc
Ticinites
Parakellnerites
61
0m
50m
N. c. cornuta
P. liebermani
N. c. balkanica
N. longa
N. c. postcornuta
P. aff. eotrammeri
P. excelsa
N. (aff.) transita
P. alpina group
Gl. m. malayensis
P. trammeri
P. fueloepi
N. bakalovi gr.
N. pseudolonga
N. aequidentata
N. praehungarica
B. gr. gabriellae
B. truempyi
B. sp.
B. hungaricus
P. inclinata
B. mungoensis
Age [Ma]
238
239
240
241
242
Ammonoid Zones
Regoledanus
Archelaus
Gredleri
Curionii
Sec.
Reitzi
Trinodosus
Stages
LADINIAN
ANISIAN
3

Ladinian time span of ~ 4 m.y. from ~ 242 Ma to slightly less than 238 Ma. The stratigraphic interval where geochronological and magnetostratigraphic control is best, i.e., excluding the core top and its very bottom, is characterized by a reversal frequency of ~ 4 rev/m.y. We estimate the duration of the Ladinian by assuming a Ladinian–Carnian boundary at ~ 235 Ma (Fig. 7) in agreement with numeric age data and field observations on Upper Ladinian rocks in the Dolomites. The Upper Ladinian granites at Predazzo, with a U–Pb zircon age of 237.3 (+0.4/−1.0) Ma (Brack et al., 1997), postdate the Buchenstein Beds and intrude clastic rocks of the overlying and rapidly deposited and heterogeneous volcano-sedimentary Wengen Group. Upwards this unit grades into the clastic San Cassiano Formation, which in its lower portion contains the Ladinian–Carnian boundary (Broglio Loriga et al., 1999). The duration of the Ladinian Stage (i.e., from the base of the Curionii Zone to the top of the Regoledanus Zone) may therefore range between 6 and 7 m.y.

8. Conclusions

(i) For the construction of a biostratigraphically calibrated Anisian–Ladinian boundary chronology, preference was given to high-resolution magnetostratigraphic and lithostratigraphic correlations proven to be isochronous within the Buchenstein Beds of the Southern Alps.

(ii) The integration of data from several individual sections using magneto- and lithostratigraphic correlations allowed us to construct a composite conodont distribution chart across a relevant portion of the Anisian–Ladinian boundary interval.

(iii) Among the three candidate biostratigraphic events to locate the Ladinian GSSP, we propose to adopt the level containing the base of the Curionii ammonoid Zone in the Bagolino section, closely corresponding to the base of polarity reversal SC2r.2r. The first occurrence of conodont *Neogondolella praehungarica* at Bagolino predates slightly the base of the Curionii Zone and therefore represents a useful stratigraphic tool at sections lacking ammonoid biostratigraphy.

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Fig. 7. Integrated Anisian–Ladinian boundary stratigraphy and biochronology. Biostratigraphic data from the Dolomites are from this study (Fig. 6) and Rosengarten (Maurer, 1999), and are projected onto Seceda outcrop reference stratigraphy. Biostratigraphic data from the Brescian Alps and Giudicarie (Kovács et al., 1990; Nicora and Brack, 1995; Brack and Nicora, 1998) are projected onto Bagolino reference stratigraphy. Numeric age values are derived from interpolation of Mundil et al. (1996) dates taking into account a significant increase in sedimentation rate above the “Knollenkalke”-“Bänderkalke” transition at Seceda (Maurer et al., 2003). The proposed candidate for the Ladinian GSSP is the level containing the base of the Curionii ammonoid Zone in the Bagolino section, corresponding to polarity reversal SC2r.1n-SC2r.2r.

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