

Magnetostratigraphy, biostratigraphy, and chemostratigraphy of the Pignola-Abriola section: New constraints for the Norian-Rhaetian boundary

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ABSTRACT

A detailed magnetostratigraphic investigation of the Pignola-Abriola section of Norian to Rhaetian age permits the identification of 22 magnetic polarity reversals grouped in 10 magnetozones. We correlate the magnetostratigraphy of the Pignola-Abriola section with the Newark astrochronological polarity time scale (APTS). In total, 19 correlation options were tested, and only one (option 7) yielded a statistically significant correlation that was consistent with the available information on the stratigraphic age of the Newark APTS. After some adjustments to minimize erratic variations in sediment accumulation rates, a final correlation (option 7.1) was used to generate an age model of sedimentation for the Pignola-Abriola section. The Pignola-Abriola section has been correlated with Rhaetian sections from the literature, notably the current global boundary stratotype section and point candidate for the base of the Rhaetian at Steinbergkogel, Austria, where the Norian-Rhaetian boundary is proposed to be placed at a stratigraphic level containing the first appearance datum (FAD) of conodont *Misikella posthernsteini*, traced on the Newark APTS to ca. 209–210 Ma. Issues regarding the taxonomy of *M. posthernsteini*, a species characterized by transitional forms with its ancestor *Misikella hernsteini*, lead us to propose the alternative option of placing the Norian-Rhaetian boundary at a prominent negative $\delta^{13}\text{C}_{\text{org}}$ spike observed in the Pignola-Abriola section at meter 44.5, 50 cm below the level containing the FAD of *M. posthernsteini* sensu stricto and close to the base of radio-

larian *Proparvicungula moniliformis* zone. This level has been magnetostratigraphically correlated to Newark magnetozones E20r.2r at ca. 205.7 Ma. Assuming an age of ca. 201.3 Ma for the Triassic-Jurassic boundary, the Rhaetian Stage would have a duration of ~4.4 m.y.

INTRODUCTION

Current generations of time scales for the Triassic System (e.g., Ogg, 2012) are based on magnetostratigraphic correlations between marine sections and the continental Newark astrochronological polarity time scale (APTS). For marine sections, magnetostratigraphy is tied to stage boundaries that are defined biostratigraphically (e.g., Channell et al., 2003; Muttoni et al., 2004; Gallet et al., 2007), whereas the magnetostratigraphy of the Newark APTS (Kent et al., 1995; Kent and Olsen, 1999; Olsen and Kent, 1999; Olsen et al., 2011) is constrained by terrestrial biostratigraphy such as sporomorphs, tetrapod footprints, and conchostracans (e.g., Cornet, 1977, 1993; Olsen and Sues, 1986; Fowell et al., 1994; Lucas and Huber, 1993; Kozur and Weems, 2005, 2010; Lucas et al., 2012).

The base of the Rhaetian Stage (Norian-Rhaetian boundary), pending formal designation by the International Commission on Stratigraphy, is currently proposed at a stratigraphic level of the Steinbergkogel section (Austria) containing the first appearance datum (FAD) of the conodont *Misikella posthernsteini* (Krystyn, 2010). This level was magnetostratigraphically correlated to magnetozones E16r of the Newark APTS (Hüsing et al., 2011), in substantial agreement with previous inferences based on magnetostratigraphic correlations between the Pizzo Mondello (Italy) and Silická Brezová (Slovakia) marine sections, which are Carnian–Norian in age, and the

Newark APTS (Muttoni et al., 2004; Channell et al., 2003). The base of Newark magnetozones E16r is currently dated at ca. 210.3 Ma as the result of rescaling the Newark APTS (Kent and Olsen, 1999) from the base of the Orange Mountain Basalts of the Central Atlantic magmatic province (CAMP), recently dated at ca. 201.5 Ma (Blackburn et al., 2013). This would imply a duration for the Rhaetian Stage of ~9 m.y., in broad agreement with the long-Rhaetian option of Muttoni et al. (2010; see also Muttoni et al., 2004) and in contrast to the short-Rhaetian option (~2 m.y.) of Gallet et al. (2007; see discussions in Muttoni et al., 2010; Hüsing et al., 2011). The short-Rhaetian option was recently revived by Callegaro et al. (2012), who associated negative $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{187}\text{Os}/^{188}\text{Os}$ (Cohen and Coe, 2007; Kuroda et al., 2010) excursions observed starting at the base of the Rhaetian (defined by the occurrence of *M. posthernsteini*) with the emplacement of the CAMP which was considered to have started as early as ca. 202–203 Ma on the basis of $^{40}\text{Ar}/^{39}\text{Ar}$ dates (Marzoli et al., 2011; Callegaro et al., 2012), albeit recent U-Pb dates suggest rapid emplacement around ca. 201.56 Ma, coincident with the end-Triassic extinction event (Blackburn et al., 2013).

The debate over the duration of the Rhaetian (and Norian) is not yet settled, with two options proposed in the *Geological Time Scale 2012* (Ogg, 2012): The long-Tuvalian option places the Norian-Rhaetian boundary at 205.4 Ma and the Carnian-Norian boundary at 221 Ma, whereas the long-Rhaetian option has a Norian-Rhaetian boundary at 209.5 Ma and a Carnian-Norian boundary at 228.4 Ma. These alternative options arise from different approaches to time scale construction. The long-Tuvalian option is grounded in biostratigraphic correlations of terrestrial groups (conchostracans, pollens, tetrapods) between the

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continental sequences of the Germanic Basin and the Newark Supergroup–based APTS (Lucas et al., 2012). The long-Rhaetian option is based on magnetostratigraphic correlations between marine sections bearing stage-defining fossils (conodonts, ammonoids) and the Newark APTS (Channell et al., 2003; Muttoni et al., 2004, 2010; Hüsing et al., 2011). In our opinion, the terrestrial correlation approach as the basis for the long-Tuvalian option (Lucas et al., 2012) is flawed by inherent difficulties in correlating terrestrial associations of, e.g., freshwater clam shrimps (conchostracans) to marine-based stage boundaries. The base of the Rhaetian was assigned directly in the Newark Supergroup using sporomorphs (base of the Upper Balls Bluff–Upper Passaic palynofloral zone of Cornet 1977, 1993), although the typical Rhaetian taxa of Europe and Greenland have not been found in the Newark Supergroup (Cornet, 1977). As a consequence,

the Rhaetian as originally defined in the Newark Supergroup cannot be related to the Rhaetian as proposed by Krystyn (2010) and reported in the *Geological Time Scale 2012* (Ogg, 2012).

In this paper, we contribute to the definition of the Norian-Rhaetian boundary by presenting new biostratigraphic, magnetostratigraphic, and chemostratigraphic data from the Pignola-Abriola section of Italy. This section records the FAD of *M. posthernsteini*, occurring in the lower *Proparvicingula moniliformis* radiolarian zone (Giordano et al., 2010). We date these events by means of magnetostratigraphic correlation with the Newark APTS, while addressing in detail the taxonomic complexities vexing the use of the conodont *M. posthernsteini* as proxy for the Norian-Rhaetian boundary level. We also illustrate the occurrence of a prominent negative $\delta^{13}\text{C}_{\text{org}}$ excursion at meter level 44.5, ~0.5 m below the FAD of *M. posthernsteini* (within the

base of the *P. moniliformis* zone), which serves as a useful geochemical proxy for the Norian-Rhaetian boundary level. The levels containing the negative $\delta^{13}\text{C}_{\text{org}}$ excursion and the FAD of *M. posthernsteini* are traced to Newark magnetozone E20r.2r at ca. 205.7 Ma, providing a younger age for the Norian-Rhaetian boundary relative to Hüsing et al. (2011), and very similar to the Norian-Rhaetian boundary in the long-Tuvalian option described in Ogg (2012).

GEOLOGICAL SETTING

The Pignola-Abriola section crops out on the western side of Mount Crocetta, along the road SP5 connecting the village of Pignola to Abriola (Potenza, southern Italy; Fig. 1, section A, coordinates: 40°33'23.50"N, 15°47'1.71"E). The road section is ~58 m thick (Fig. 2, left panel) and is complemented by an ancillary 7-m-thick

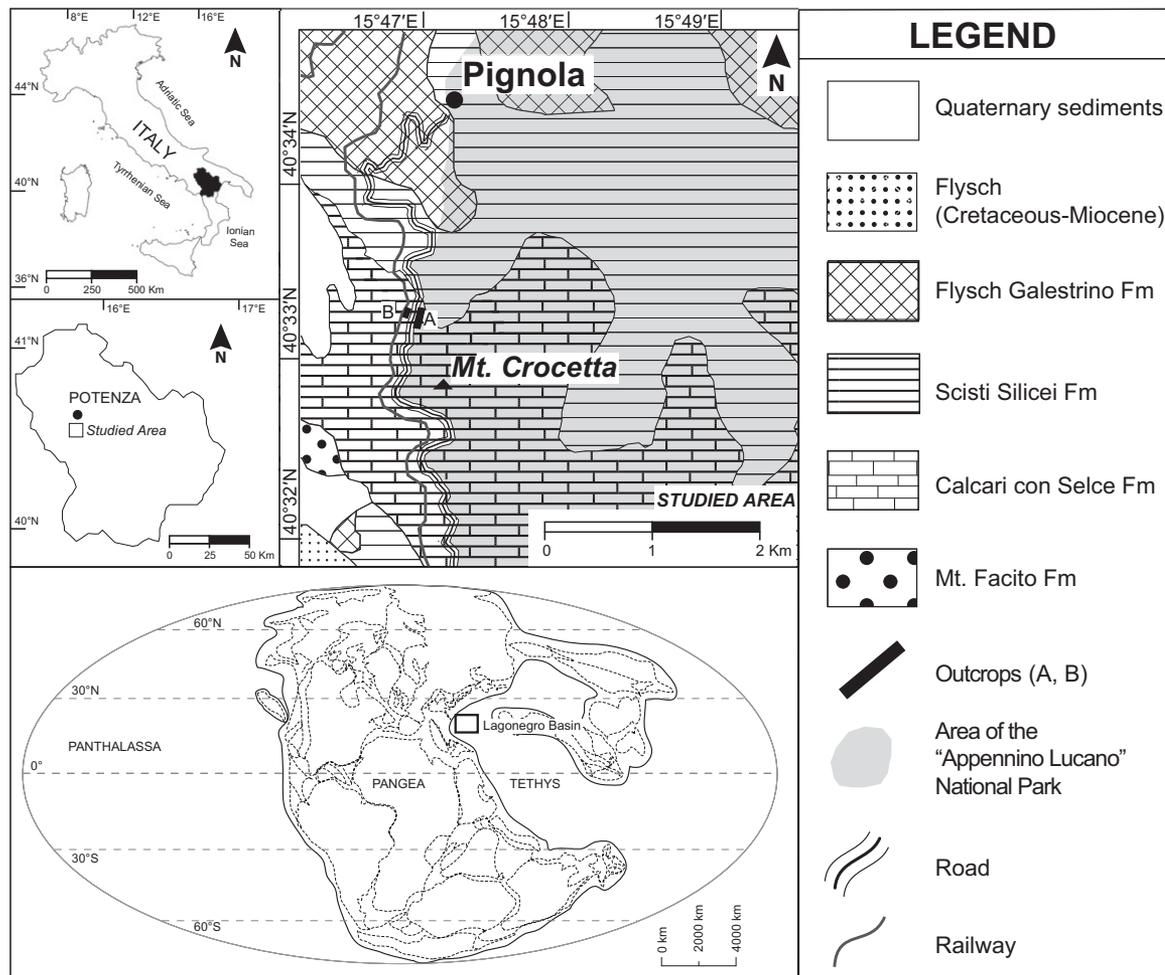


Figure 1. The Pignola-Abriola sections (A, B) are located in the southern Apennines, near Potenza (southern Italy). The main section (A) crops out on the western flank of Mount Crocetta, along the main road SP5 connecting the towns of Pignola and Abriola (40°33'23.50"N, 15°47'1.71"E), whereas the auxiliary subsection (B) crops out close to an unused railway tunnel located ~10 m below the SP5 road level (40°33'24.74"N, 15°46'59.59"E).

Magneto-biochemostratigraphy of the Pignola-Abriola section around the Norian-Rhaetian boundary

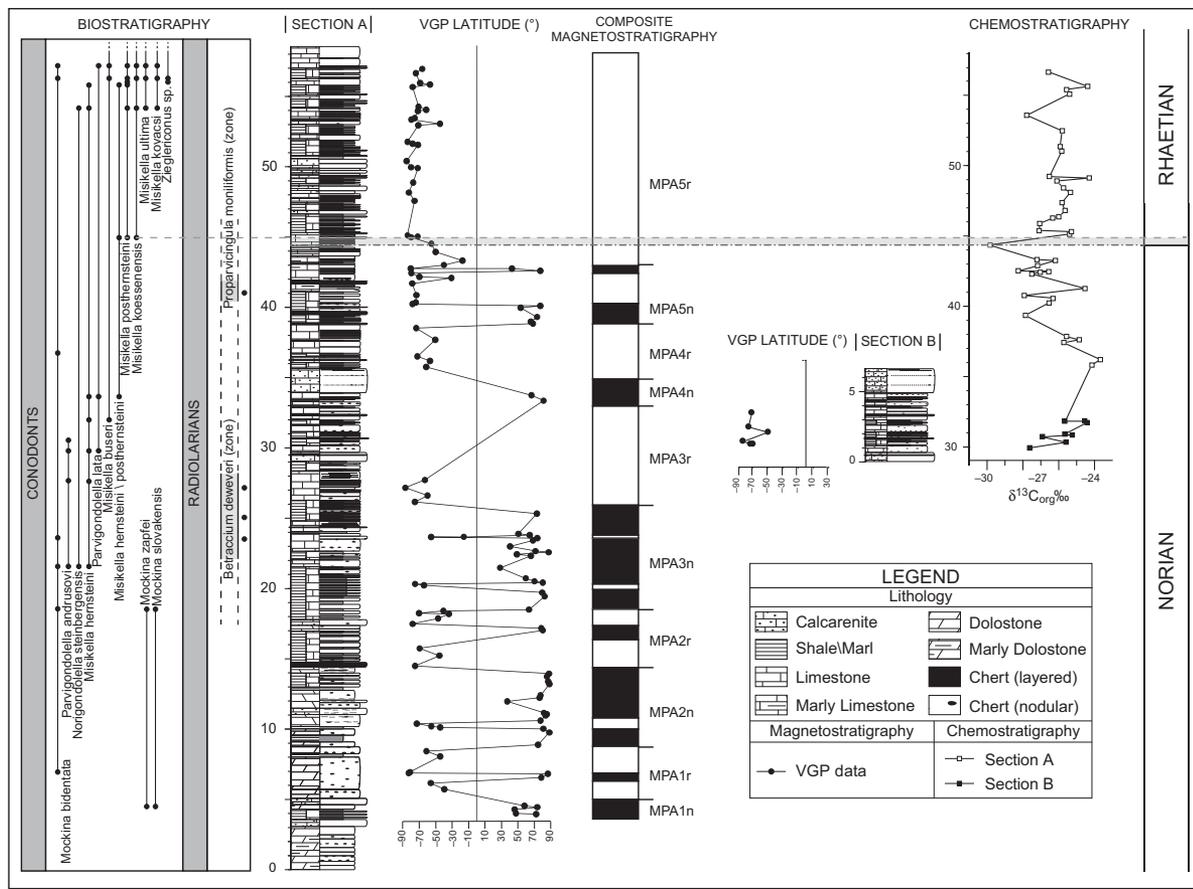


Figure 2. The Pignola-Abriola sections. From left to the right: conodont and radiolarian biostratigraphy (see Table 1 for key species), lithostratigraphy, virtual geomagnetic pole (VGP) latitudes calculated from characteristic remanent magnetization (ChRM) component directions, and derived magnetostratigraphy and chemostratigraphy ($\delta^{13}\text{C}_{\text{org}}$) of the Pignola-Abriola section. To the right is lithostratigraphy and VGP latitudes of the auxiliary subsection B. Black is normal polarity, and white is reverse polarity. The levels containing the first appearance datum (FAD) of conodont *Misikella posthernsteini sensu stricto* and the marked decrease in the $\delta^{13}\text{C}_{\text{org}}$ to $\sim\text{-30}\text{‰}$ used to define the Norian-Rhaetian boundary are highlighted by dashed horizontal lines.

subsection (Fig. 2, right panel) outcropping close to a unused railway tunnel located $\sim\text{10 m}$ below the SP5 road level (Fig. 1, section B, coordinates: $40^{\circ}33'24.74''\text{N}$, $15^{\circ}46'59.59''\text{E}$). The stratigraphic sequence is composed of the Calcareni con Selce (i.e., Cherty Limestone) Formation, which was deposited in the Lagonegro Basin, a branch of the western Tethys Ocean characterized by pelagic sedimentation since the Permian (Finetti, 1982, 2005; Catalano et al., 2001; Ciarapica and Passeri, 2002, 2005; Argnani, 2005; Rigo et al., 2012). The Calcareni con Selce Formation consists of thinly bedded cherty hemipelagic to pelagic limestones (mudstones, wackestones, and rare packstones), interbedded with shales and marls, with common radiolarians, conodonts, and sporadic bivalves. The lower part of the section is dominated by cherty limestones, often dolomitized, intercalated with very thin marls or clayey levels (Fig. 2). The upper portion is

instead dominated by an alternation of silicified limestones and black to brown or greenish, thinly laminated shales (Fig. 2), which are rich in organic matter, indicating deposition in dysoxic or anoxic conditions. Calcareniitic intercalations are also present through the section (Fig. 2). In particular, a 1.5-m-thick calcarenitic bank at $\sim\text{35 m}$ from the base of the measured section has been used as a lithostratigraphic marker to correlate the Pignola-Abriola road section (Fig. 2, left panel) to the railway tunnel subsection (Fig. 2, right panel).

BIOSTRATIGRAPHY

The fossil content of the Pignola-Abriola section consists mainly of conodonts and pyritized radiolarians. Here, we present an updated conodont and radiolarian biostratigraphy (Fig. 2) after recent biostratigraphic data published by

Rigo et al. (2005), Bazzucchi et al. (2005), and Giordano et al. (2010).

Conodonts are well distributed along the entire section (representative specimens are listed in Table 1) and are characterized by a conodont alteration index (CAI) of 1.5 (Epstein et al., 1977; Bazzucchi et al., 2005; Rigo et al., 2005). The following main events have been recognized (Fig. 2):

- (1) the first occurrence (FO) of *Mockina bidentata* at meter 7;
- (2) the FO of *Misikella hernsteini* at meter 21.5, associated with the FO of *Parvigondolella andrusovi*;
- (3) the FO of the *Misikella hernsteini/posthernsteini* morphocline at meter 33.5;
- (4) the FO of *Misikella buseri* at meter 32;
- (5) the FAD of *Misikella posthernsteini* at meter 45 in sample PIG24, in association with *Misikella koessenensis*; and

(6) the FO of *Misikella ultima* at meter 54.

The radiolarian associations are well preserved and conform to the biozonation proposed by Carter (1993):

(1) Sample PR14 at meter 25 yielded a radiolarian assemblage referable to the *Betraccium deweveri* zone (Carter, 1993) and consisting of *Betraccium deweveri* Pessagno and Blome, *Praemesotaturnalis gracilis* Kozur and Mostler, *Tetraporobrachia* sp. aff. *T. composita* Carter, *Ayrtonius elizabethae* Sugiyama, *Citriduma* sp. A sensu Carter (1993), *Globolaxtorum* sp. cf. *G. hullae* Yeh and Cheng, *Lysemela* sp. cf. *L. olbia* Sugiyama, *Livarella valida* Yoshida and *Livarella* sp. sensu Carter (1993) (Giordano et al., 2010); a similar assemblage was found also in sample PR15 at meter 23.5, and sample PR13 at meter 27. The presence of *Globolaxtorum* sp. cf. *G. hullae* Yeh and Cheng in this assemblage is atypical, because the genus *Globolaxtorum* is usually referred only to the *Proparvicungula moniliformis* and *Globolaxtorum tozeri* zones (O'Dogherty et al., 2009).

(2) Sample PA25 at meter 41 yielded a radiolarian assemblage referable to the *Proparvicungula moniliformis* zone assemblage 1 (U.A. 2–5 in Carter, 1993) for the presence of *Fontinella primitiva* Carter, *Praemesotaturnalis* sp. cf. *P. sandspitensis* Blome, *Globolaxtorum* sp. cf. *G. hullae* Yeh and Cheng, and *Livarella densiporata* Kozur and Mostler (Bazzucchi et al., 2005; Giordano et al., 2010).

The Norian-Rhaetian boundary is conventionally placed in stratigraphic levels where the FAD of *Misikella posthernsteini* is documented (Krystyn, 2010), which is a phylogenetic descendent of *M. hernsteini* (e.g., Mostler et al., 1978; Kozur and Mock, 1991; Giordano et al., 2010). The transition from drop-shaped to heart-shaped basal cavity along with a reduction of the number of blade denticles characterize the evolution of the *M. hernsteini*/*posthernsteini* morphocline (Giordano et al., 2010). Specimens characterized by an evident furrow on the backside of the cusp and the associated inflection of the posterior margin of the basal cavity are here considered *Misikella posthernsteini* sensu stricto, as suggested by Giordano et al. (2010). At Pignola-Abriola, the presence of the *Misikella hernsteini*/*posthernsteini* morphocline, as well as the presence of the FAD of *M. posthernsteini* sensu stricto (m 45, sample PIG24) provide a reliable (and continuous) biostratigraphic signal. Furthermore, in the Pignola-Abriola section, the conodont *Misikella posthernsteini* sensu stricto appears 4 m above the base of radiolarian *Proparvicungula moniliformis* zone assemblage 1 (Fig. 2), which is commonly adopted to define the early Rhaetian (e.g., Carter, 1993; Bertinelli et al., 2005; Giordano et al., 2010).

Table 1 (on following page). Scanning electron microscope (SEM) micrographs of Upper Norian and Rhaetian radiolarians and conodonts from the Calcari con Selce Formation, Pignola-Abriola section. Radiolarians: samples PR13, PR14, and PR15 are referred to the *Betraccium deweveri* zone; sample PA25 is referred to the *Proparvicungula moniliformis* zone, assemblage 1. Scale bar = 100 μm for 1–2, 7, 9, 11–14; 112.5 μm for 3–5, 8; 150 μm for 6, 10 (after Bazzucchi et al., 2005; Giordano et al., 2010, modified). 1–2—*Betraccium deweveri* Pessagno and Blome, sample PR14. 3—*Praemesotaturnalis gracilis* (Kozur and Mostler), sample PR14. 4—*Tetraporobrachia* sp. aff. *T. composita* Carter, sample PR14. 5—*Ayrtonius elizabethae* Sugiyama, sample PR15. 6—*Citriduma* sp. A, sensu Carter (1993), sample PR13. 7—*Globolaxtorum* sp. cf. *G. hullae* (Yeh and Cheng), sample PR14. 8—*Lysemela* sp. cf. *L. olbia* Sugiyama, sample PR15. 9—*Livarella valida* Yoshida, sample PR15. 10—*Livarella* sp., sensu Carter (1993), sample PR14. 11—*Fontinella primitiva* Carter, section sample PA 25. 12—*Praemesotaturnalis* sp. cf. *P. sandspitensis* (Blome), sample PA25. 13—*Globolaxtorum hullae* (Yeh and Cheng), sample PA25. 14—*Livarella densiporata* Kozur and Mostler, sample PA25. Conodonts: Scale bar = 75 μm (after Bazzucchi et al., 2005; Giordano et al., 2010, modified): 15 (a, b, c)—*Mockina zapfei* (Kozur), sample PIG 0. 16 (a, b, c)—*Mockina slovakensis* (Kozur), sample PIG 0. 17 (a, b, c)—*Misikella hernsteini* (Mostler), sample PIG 16. 18 (a, b)—*Misikella posthernsteini* Kozur and Mock, sample PIG 24. 19 (a, b)—*Misikella kovacsii* Orchard, sample PIG 40. 20 (a, b, c)—*Misikella ultima* Kozur and Mock, sample PIG 40.

GEOCHEMISTRY

In total, 41 samples, mostly black to brown shales, from the upper portion of the Pignola-Abriola section (from meter 30 to the top of the section) were analyzed for $\delta^{13}\text{C}_{\text{org}}$ (worksheet 1 in GSA Data Repository¹). The rock samples were pulverized and acid-washed with 10% HCl in a 70 °C water bath for 3 h, and the process was repeated at least three times to thoroughly remove pyrite and carbonates. The samples were subsequently neutralized with high-purity water, dried at 30 °C overnight, and then wrapped in tin capsules and analyzed for their isotopic composition. The analyses were carried out using a GVI Isoprime continuous flow–isotope ratio mass spectrometer (CF-IRMS) at Rutgers University, adding multiple blank capsules and isotope standards for each batch of isotopic analyses (NBS 22 = –30.03‰; Coplen et al., 2006) plus a matrix matched in-house standard. Standard deviations for $\delta^{13}\text{C}_{\text{org}}$ standards during the period of analysis were better than $\sigma = 0.2\text{‰}$.

The $\delta^{13}\text{C}_{\text{org}}$ values of the Pignola-Abriola section are between –29.95‰ and –23.70‰ (Fig. 2). After a moderate increase in $\delta^{13}\text{C}_{\text{org}}$ (from –27.5‰ to –24‰ from meter 30 to 36), a large decrease to –30‰ was recorded for meter 36 to meter 44.5, immediately followed by a rapid return to higher values (–25‰, ~20 cm above). A subsequent decrease of ~2‰ is recorded at

¹GSA Data Repository item 2015069, $\delta^{13}\text{C}_{\text{org}}$ data, paleomagnetic data, Newark and Pignola-Abriola correlation statistics, and isothermal remanent magnetization statistics, is available at <http://www.geosociety.org/pubs/ft2015.htm> or by request to editing@geosociety.org.

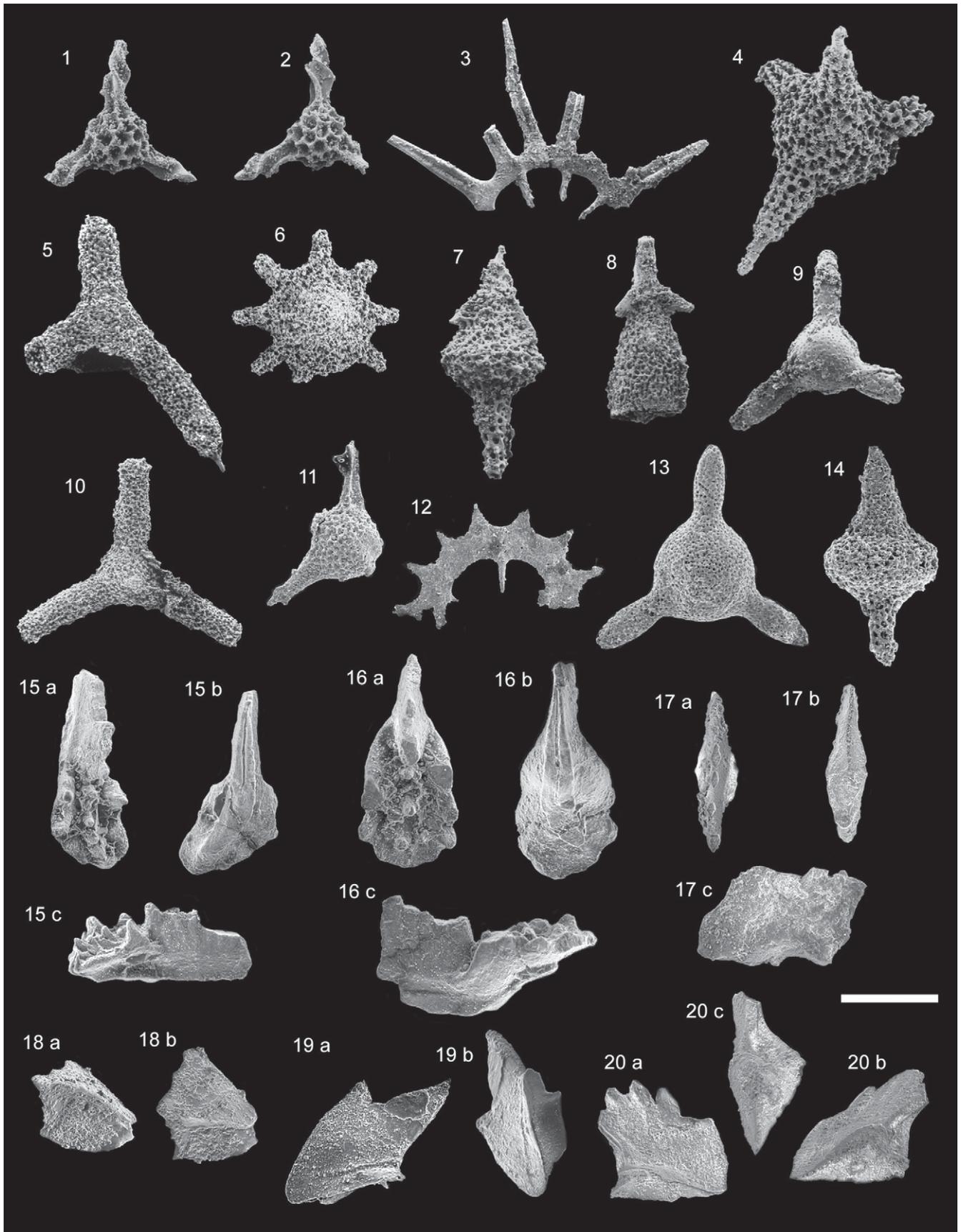
meter 53.5 (close to the level containing the FO of *Misikella ultima*; Fig. 2). Notably, the low $\delta^{13}\text{C}_{\text{org}}$ of ~–30‰ at meter 44.5 is just below the level containing the FAD of *Misikella posthernsteini* sensu stricto, and within the base of the *Proparvicungula moniliformis* zone (Fig. 2).

PALEOMAGNETISM

In total, 220 oriented core samples were collected from the Pignola-Abriola section and analyzed at the Alpine Laboratory of Paleomagnetism (Peveragno, Italy). Rock magnetic properties were studied on a representative set of samples by means of thermal decay of a three-component isothermal remanent magnetization (IRM) imparted at fields of 2.5 T, 0.4 T, and 0.12 T (Lowrie, 1990) and IRM acquisition curves.

The lower part of the section (samples P1.34, P3.10, P3.43; Fig. 3A) is characterized by a high-coercivity mineral with maximum unblocking temperatures (T_B) of 650–675 °C, attributed to hematite, coexisting with a lower-coercivity mineral with T_B of 525–575 °C, interpreted as magnetite; an inflection at ~350 °C in the 0.4 T curve observed in sample P1.34 suggests the presence of iron sulfides. Samples from the upper part of the section (GNM497 at 33 m; GNM48 at 43.5 m; GNM119 at 57 m) appear dominated by the high-coercivity hematite phase (Fig. 3A). IRM curves of these samples show no tendency to saturate even at applied fields of 2.5 T (Fig. 3B). The cumulative log-Gaussian (CLG) analysis (Kruiver et al., 2001) reveals the presence in these samples of two magnetic phases with contrasting coercivities: a high-coercivity phase with coercivity of remanence ($B_{1/2}$) = 1.6–2 T, which accounts

TABLE 1. RADIOLARIANS AND CONODONTS FROM THE PIGNOLA-ABRIOLA SECTION



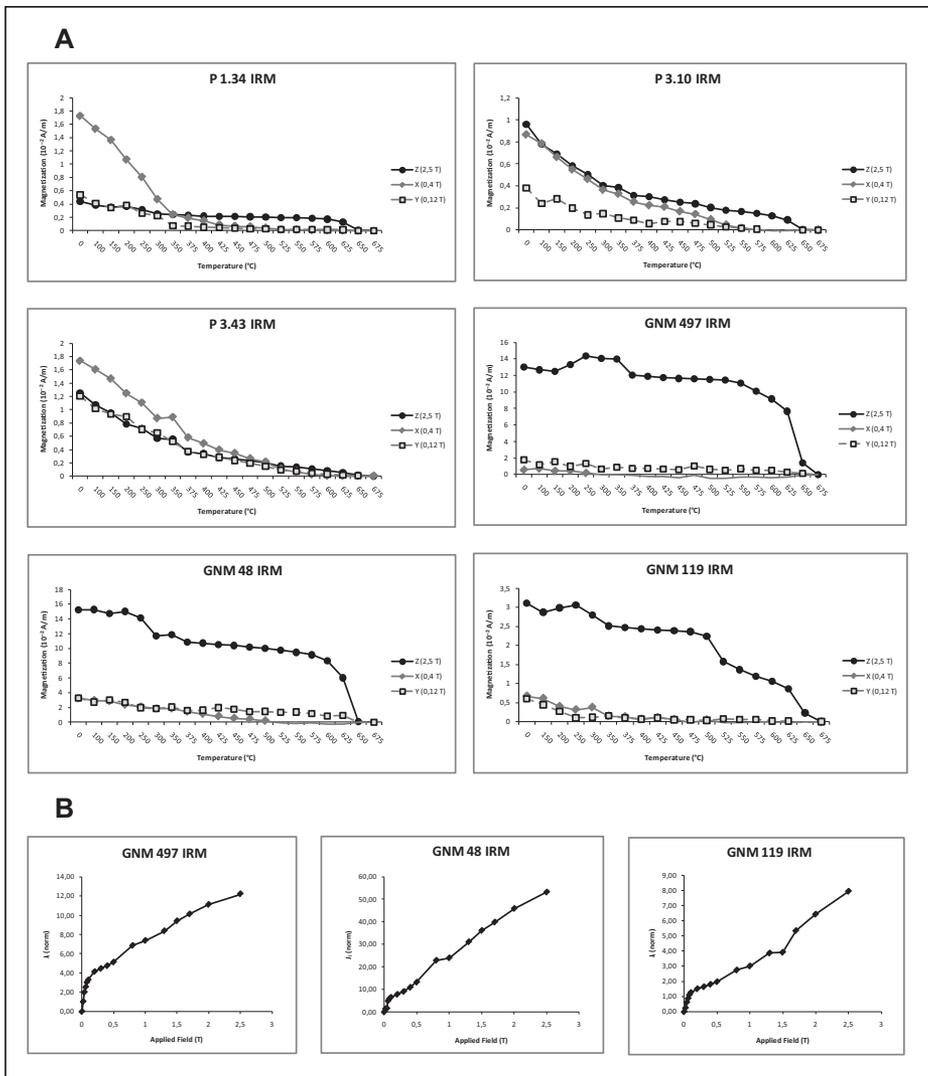


Figure 3. Thermal demagnetization of a three-component isothermal remanent magnetization (IRM) (A) and IRM acquisition curves (B) for representative samples from Pignola-Abriola showing the presence of a variable mixture of hematite and magnetite. See text for discussion.

for ~60%–85% of the IRM, and a subordinate low-coercivity phase with $B_{1/2} = 0.1$ T, which accounts for the remainder of the IRM (Fig. 1; GSA Data Repository [see footnote 1]). The presence of higher amounts of (detrital) hematite in the upper part of the section may correlate with the increase in terrigenous input (shales and marls) observed in the upper part of the section (Fig. 2).

The natural remanent magnetization (NRM) of samples, measured on a 2G Enterprises DC-SQUID cryogenic magnetometer, is on average 0.08 mA/m. All samples were thermally demagnetized in steps of 50 °C or 25 °C up to a maximum of 675 °C, and the component structure of the NRM was plotted on vector end-point demagnetization diagrams (Fig. 4;

Zijderveld, 1967). After removal of spurious magnetizations between room temperature and ~100–300 °C, a characteristic remanent magnetization (ChRM) was isolated up to 450–550 °C (maximum of 625 °C) in ~55% of the samples ($N = 121$; worksheet 3, GSA Data Repository [see footnote 1]) and found to be broadly oriented either N and down or S and up in tilt-corrected coordinates (Fig. 5). These ChRM component directions are distributed in tilt-corrected coordinates around an overall mean of Dec = 15.9°E, Inc = 32.5° ($k = 8.4$, $\alpha_{95} = 4.7^\circ$, $N = 121$; Table 2). No fold test could be performed because of the homoclinal bedding tilt of the section, whereas the reversal test (McFadden and McElhinny, 1990) was positive (for detailed statistics, see worksheet 3, GSA

Data Repository [see footnote 1]). Based on these results and the consistent magnetostratigraphic correlations with sections from the literature, as discussed later herein, we regard the ChRM component as primary in origin. We checked the ChRM component directions for sedimentary inclination shallowing due to sedimentary and/or compaction processes. The elongation/inclination (E/I) statistical method of Tauxe and Kent (2004) was applied to the ChRM directions, obtaining a flattening factor of $f = 0.6$ and a corrected mean inclination of 47.7° (min = 39.0°, max = 53.7°), corresponding to a paleolatitude for Pignola-Abriola of ~28.8°N (Table 2). A paleomagnetic pole was calculated for Pignola-Abriola using the tilt-corrected mean ChRM direction corrected for inclination shallowing (lat. = 72.5°N, long. = 143.0°E; Table 2) and compared to the 201 Ma Adria-Africa paleopole of Muttoni et al. (2013) located at lat. = 69.3°N, long. = 243.8°E. The Pignola-Abriola paleopole is displaced by ~32.8° clockwise relative to the reference Adria-Africa paleopole, probably as a result of vertical-axis tectonic rotation of the sampling area during Apennine tectonics.

A virtual geomagnetic pole (VGP) was calculated for each ChRM component direction in tilt-corrected coordinates. The latitude of the sample VGP relative to the north pole of the paleomagnetic axis was used for interpreting the magnetic polarity stratigraphy, where VGP latitudes approaching +90° or -90° are attributed to normal or reverse polarity, respectively. An overall sequence of five polarity magnetozones, labeled from magnetozones MPA1 to MPA5, was established starting at the base of the section (Fig. 2). Each magnetozones was subdivided into a lower, predominantly normal and an upper, predominantly reverse portion, in which submagnetozones can be embedded. No obvious relation was observed between magnetic polarity stratigraphy and the magnetic mineralogy of the samples. The FAD of *Misikella posthernsteini* sensu stricto falls within magnetozones MPA5r at ~45 m, while the new proposed Norian-Rhaetian boundary coincident with the $\delta^{13}\text{C}_{\text{org}}$ negative spike occurs inside the same magnetozones at ~44.5 m (Fig. 2).

DISCUSSION

Correlations with Tethyan Sections from the Literature

The magnetostratigraphy of the Pignola-Abriola section is comparable with that of the Steinbergkogel section (Hüsing et al., 2011), which at present is the only global boundary stratotype section and point (GSSP) candidate

Magneto-biochemostratigraphy of the Pignola-Abriola section around the Norian-Rhaetian boundary

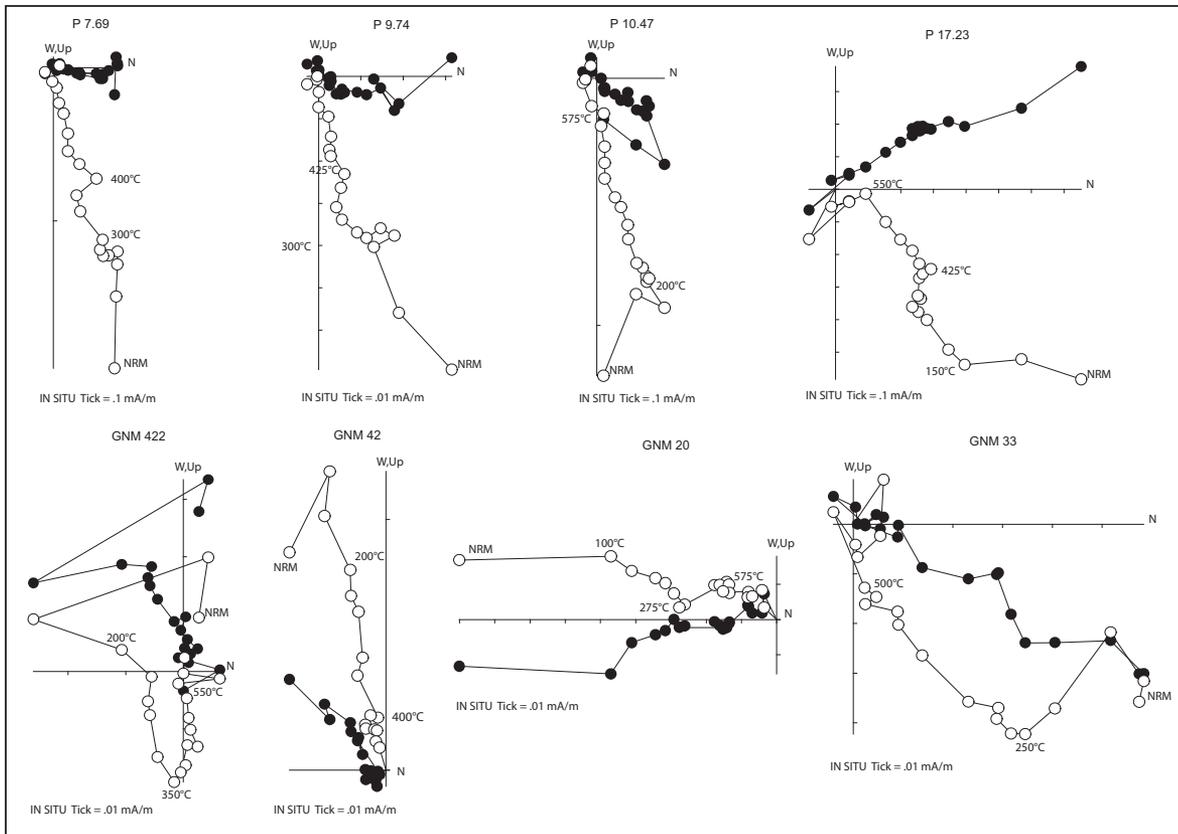


Figure 4. Vector end-point demagnetization diagrams for representative samples from Pignola-Abriola. Closed circles are projections onto the horizontal plane, and open circles are projections onto the vertical plane for in situ (geographic) coordinates. Temperatures are expressed in °C. NRM—natural remanent magnetization.

for the base of the Rhaetian Stage (Krystyn et al., 2007a, 2007b), assuming that the occurrence of conodont *Misikella posthernsteini* at Steinbergkogel (plate 1 in Krystyn et al., 2007a) is equivalent to the FO of *Misikella hernsteini/posthernsteini* transitional forms at Pignola-Abriola (sensu Giordano et al., 2010). Hence, the main reversal portion of the Steinbergkogel magnetostratigraphy from magnetozone ST1/B– to magnetozone ST1/H– at Steinbergkogel STKA section (equivalent to ST2/B– to ST2/H– at Steinbergkogel STKB+C section), has been correlated to magnetozones MPA3r to MPA5r of the Pignola-Abriola section (Fig. 6). Also, part of the magnetostratigraphy of the Oyuklu section (Gallet et al., 2007), from magnetozone OyB– to OyD–, is comparable with MPA4r to MPA5r of the Pignola-Abriola section, and with ST/D– to ST/H– of the Steinbergkogel section (Fig. 6). Furthermore, the lower portion of the Pignola-Abriola section is magnetostratigraphically correlated with the upper part of the Pizzo Mondello section (Muttoni et al., 2004). Using the updated biostratigraphic calibration of the Pizzo Mondello magnetostratigraphy (Mazza et al., 2012),

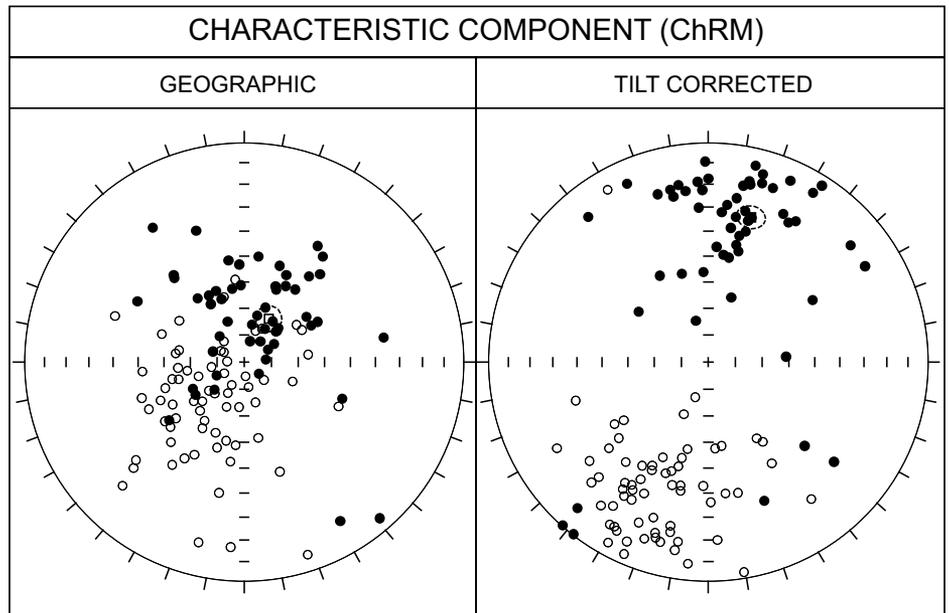


Figure 5. Equal-area projections for characteristic remanent magnetization (ChRM) component directions isolated at Pignola-Abriola for in situ (geographic) and tilt-corrected coordinates (see Table 2 for Fisher statistics parameters). For the ChRM component directions, see also worksheet 3, GSA Data Repository (see text footnote 1).

TABLE 2. PALEOMAGNETIC DIRECTIONS AND POLE FROM THE PIGNOLA-ABRIOLA SECTION

Mean directions from the Pignola-Abriola section													
In situ						Tilt-corrected							
Comp.	N	k	α_{95}	Dec.	Inc.	k	α_{95}	Dec.	Inc.	Inc. corr.	Inc. corr.		f
											Max.	Min.	
ChRM	121	8.2	4.8°	30°E	71.5°	8.4	4.7°	15.9°E	32.5°	47.7°	53.7°	39.0°	0.6
Paleomagnetic pole, paleolatitude, and rotation from tilt-corrected filtered 'Ch' directions, corrected for inclination flattening:													
Lat. (°N)		Long. (°E)		A_{95}	Paleolatitude (°N)		Paleolatitude (°N)		Rotation				
							Max.	Min.					
72.5		143.0		4.0°	28.8		34.2	22.0	32.8°CW				

Note: Comp.—paleomagnetic component; N—number of samples; k, α_{95} —standard Fisher precision parameters; Dec.—mean declination; Inc.—mean inclination; Inc. corr.—mean inclination corrected for inclination flattening; f—flattening factor; Lat.—Latitude; Long.—Longitude; A_{95} —95% circular confidence about the pole; Rotation—tectonic rotation of the site (relative to the 201 Ma Adria-Africa reference paleopole of Muttoni et al., 2013), where CW—clockwise.

magnetozones MPA1n to MPA3n at Pignola-Abriola have been correlated to magnetozones PM-8n to PM-12n at Pizzo Mondello (Fig. 6). Moreover, data from Pignola-Abriola have been compared with the magnetobiostratigraphy of the Brumano and Italcementi Quarry sections (Lombardian Basin, southern Alps, Italy), which encompasses a portion of the Rhaetian (with specimens attributed to *Misikella*) up to the Triassic-Jurassic boundary as defined by pollens (Muttoni et al., 2010, 2014). Awaiting for a formal redefinition of the *Misikella* specimens in the Brumano section following the new definition of *Misikella posthernsteini* sensu stricto adopted in this study (after Giordano et al., 2010), we stress that all *Misikella* specimens at Brumano occur below the recovered magnetostratigraphy (Muttoni et al., 2010, 2014), and thus the sequence of Brumano-Italcementi Quarry magnetozones from BIT1n to BIT5n is regarded as largely younger than the Pignola-Abriola magnetostratigraphy (Fig. 6).

Correlation with the Newark APTS

The correlation between the Pignola-Abriola section and the Newark APTS was performed using the statistical approach proposed in Muttoni et al. (2004). Assuming that thickness is a linear proxy of time, the duration of Newark magnetozones was compared with the thickness of Pignola-Abriola magnetozones (Fig. 7). The Pignola-Abriola polarity reversal sequence in linear depth coordinates was placed alongside the top of the Newark APTS (at magnetozones E23r) in linear age coordinates. A linear correlation coefficient (R) relating the thickness of each of the $N = 22$ complete Pignola-Abriola magnetozones to the duration of the relative Newark magnetozones was calculated, from which a t value was derived, where $t = R \cdot \sqrt{[N - 2] / [1 - R^2]}$, R is the linear correlation coefficient, and N is the number of matching magnetozones in the moving window, i.e., 22. The Pignola-Abriola sequence was then slid

by two polarity zones along the Newark APTS (in order to maintain internal polarity consistency in correlation), R and t were recalculated, and the exercise was repeated until all 19 possibilities were explored (Fig. 7; statistical procedure with correlation options and analysis of t -values is reported in worksheet 2 of GSA Data Repository [see footnote 1]).

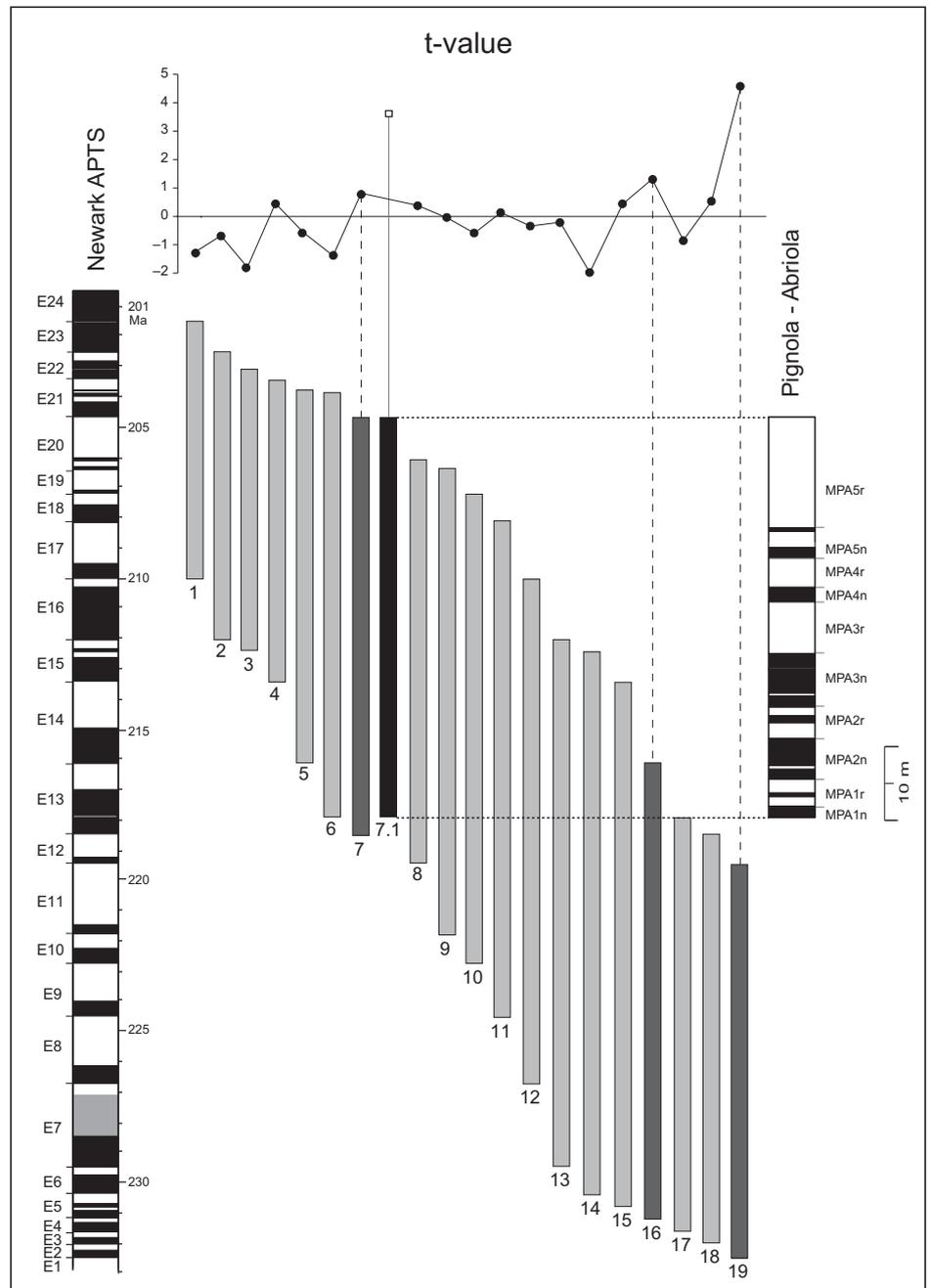
For $N = 22$ (the number of matching reversals in moving window), each correlation has 20 degrees of freedom. A Student t -test shows that only correlation coefficients with a t value larger than 1.725 are significant at the 95% level. According to the Student t -test, only correlation option 19 is reliable at more than 95% confidence level (Fig. 7), though it can be excluded on stratigraphic grounds. Precisely, option 19 places the Norian-Rhaetian boundary of the Pignola-Abriola section in the Carnian-Norian portion of the Newark sequence, as deduced from correlations of the Pizzo Mondello and Silická Brezová sections to the Newark APTS (Muttoni et al., 2004; Channell et al., 2003). For this reason, we decided to contemplate correla-

tion options characterized by lower values of t (around 1). As a consequence, options 16 and 7 were considered as acceptable (Fig. 7). Option 16 is affected by the same problem as option 19 insofar as it places the Norian-Rhaetian boundary within the Norian Stage as implied by the Pizzo Mondello and Silická Brezová to Newark correlations discussed earlier. In addition, option 16 also implies sudden (and unexplained) variations in sediment accumulation rates of the Pignola-Abriola section.

Correlation option 7 results are more coherent with the available magneto-biostratigraphic correlations of Tethyan sections to the Newark APTS and will be investigated in detail. Option 7 links Pignola-Abriola magnetozones MPA1n with Newark E13n.1n at the base, and magnetozones MPA11r with E20r at the top (Fig. 7). However, this correlation implies sudden variations in sediment accumulation rates in the middle of the Pignola-Abriola section. Moreover, the lower part of Pignola-Abriola is considered Sevatian (late Norian) in age, but according to correlation 7, it should correspond to Newark

Figure 6 (on following page). The Norian-Rhaetian magnetostratigraphy, biostratigraphy, and chemostratigraphy of the Pignola-Abriola section correlated to data from marine sections from the literature, such as Steinbergkogel (Hüsing et al., 2011), which is the current global stratotype section and point (GSSP) candidate for the Rhaetian Stage (Krystyn et al., 2007a, 2007b), Oyuklu (Gallet et al., 2007), Brumano-Italcementi Quarry (Muttoni et al., 2010, 2014), and Pizzo Mondello (Muttoni et al., 2004). In this work, specimens originally attributed to *Misikella posthernsteini* at Steinbergkogel (Krystyn et al., 2007a, 2007b) are here considered *M. posthernsteini* sensu lato (s.l.) and attributed to the *M. hernsteini/posthernsteini* “transitional forms” (sensu Giordano et al., 2010). Key biostratigraphic events at Pizzo Mondello are after Mazza et al. (2012). The Pignola-Abriola section is correlated to the Newark astrochronological polarity time scale (APTS; left column) using preferred correlation option 7.1. The lower-right panel shows the derived age model of sedimentation for Pignola-Abriola with an increase in sedimentation rate in the upper part of the section where the terrigenous input is higher. The Norian-Rhaetian boundary, placed at a level coincident with a rapid decrease in $\delta^{13}C_{org}$ to $\sim 30\%$, which virtually coincides with the level containing the first appearance datum (FAD) of conodont *Misikella posthernsteini* sensu stricto within the *Proparvicungula moniliformis* radiolarian zone, is traced within Newark magnetozones E20r at 205.7 Ma.

Figure 7. Pignola-Abriola geomagnetic reversal sequence in linear depth coordinates was slid aside the Newark astrochronological polarity time scale (APTS) in linear age coordinates maintaining the internal polarity coherency, and a t value was calculated for each of the 19 possible correlation options. Positive (negative) t -values refer to positive (negative) slopes of the linear function relating Pignola-Abriola magnetozone thickness to Newark magnetozone duration. Statistically significant options 16 and 19 were rejected for incoherence with the available stratigraphic data, whereas a modified version of correlation option 7, termed option 7.1, is considered the best solution that is in agreement with (or does not violate) the available stratigraphic data. See text for discussion.



magnetozones considered close to the Carnian-Norian boundary (Fig. 7; see also Muttoni et al., 2004).

In conclusion, no statistical correlation matches perfectly, and some “adjustments” are necessary. An alternative version of statistical correlation option 7, termed option 7.1 (black bar in Fig. 7), solves the problems outlined for option 7, increases statistical significance, and is coherent with the Pizzo Mondello and Pignola-Abriola magneto-biostratigraphies and correlations to the Newark APTS. Preferred option 7.1 is similar to statistical option 7 in range (MPA1n corresponding to E13n.1n, and MPA11r corresponding to E20r.2r) but differs from statistical option 7 in linking MPA1n with E13n.2n, MPA1r (0.1r, 0.1n, 0.2r) with E13r, MPA2n (0.1n, 0.1r, 0.2n) with E14n, and MPA11r with E20r, whereas magnetozones from MPA2r to MPA11n have been correlated with Newark magnetozones from E14r to E20n. Preferred correlation option 7.1 implies a correlation of the Steinbergkogel section to the Newark APTS from magnetozone E17n to E21n (Fig. 6) that is substantially equivalent to the correlation originally proposed by Hüsing et al. (2011). The correlation of the largely younger Brumano-Italcementi Quarry sections to the Newark APTS is the same of Muttoni et al. (2010, 2014), pending a formal redefinition of the *Misikella* specimens at Brumano (see also earlier discussion).

Using preferred correlation option 7.1, an age model for the Pignola-Abriola section can be derived. The age model shows a change in sedimentation rate from the lower to the upper part of the section (Fig. 6). From the base to

meter 24.5, the mean sedimentation rate is of ~ 2.6 m/m.y., while from meter 24.5 to 40, the mean sedimentation rate increases to ~ 5.6 m/m.y. From meter 40 to the section top, the sedimentation rate increases further to ~ 9.8 m/m.y. This is coherent with the lithostratigraphy of the section, suggesting a general increase of terrigenous input in the upper part of the section. According to the proposed age model, the Norian-Rhaetian boundary defined by the level containing the FAD of *M. posthernsteini* sensu stricto at meter 45 should correspond to an estimated age of ca. 205.7 Ma

(Fig. 6), which is substantially equivalent to the age of the prominent negative $\delta^{13}\text{C}_{\text{org}}$ excursion to $\sim 30\text{‰}$ observed at meter 44.5 (Fig. 6).

GSSP Proposal for the Base of the Rhaetian Stage

Based on our magneto-bio-chemostratigraphic study of the Pignola-Abriola section, coupled with the recognition of the taxonomic complexities concerning conodont *Misikella posthernsteini*, the current candidate species for

the definition of the base of the Rhaetian Stage, we suggest an alternative option for the definition of the Norian-Rhaetian boundary. We favor placing the boundary at the prominent negative $\delta^{13}\text{C}_{\text{org}}$ spike observed in the Pignola-Abriola section at meter 44.5 (immediately below the level containing the FAD of *M. posthernsteini* sensu stricto and within the base of the radiolarian *Proparvicungula moniliformis* zone). A similar $\delta^{13}\text{C}_{\text{org}}$ perturbation around the Norian-Rhaetian boundary was documented in Canada by Ward et al. (2001, 2004) and Whiteside and Ward (2011), coinciding with the disappearance of large *Monotis* (Ward et al., 2004), a typical proxy for the Norian-Rhaetian boundary (McRoberts et al., 2008). The stratigraphic level in the Pignola-Abriola section containing the \sim 30‰ spike has been magnetostratigraphically correlated to Newark magnetozones E20r.2r at ca. 205.7 Ma. This age was obtained from the Newark astrochronology, calibrated with the new numerical age of 201.5 Ma from the base of the Orange Mountain Basalts in the Newark Supergroup (Blackburn et al., 2013). Assuming an age of ca. 201.3 Ma for the Triassic-Jurassic boundary (Guex et al., 2012), which is broadly consistent with previous estimates (Schoene et al., 2010), and a proposed age of ca. 205.7 Ma for the Norian-Rhaetian boundary, the Rhaetian Stage would have a duration of \sim 4.4 m.y. (Fig. 6). Using a Carnian-Norian boundary at ca. 227 Ma (Muttoni et al., 2004), the Norian would be the longest stage of the Phanerozoic with a duration of \sim 21.3 m.y. (but see Lucas et al., 2012). Using an approximated Ladinian-Carnian age of 238 Ma, derived from an uppermost Ladinian radiometric age of 237.77 ± 0.14 Ma (Mietto et al., 2012), the Carnian would have lasted almost 10 m.y. According to these figures, the Late Triassic may have lasted \sim 36 m.y.

Comparison with Previous Time Scales

We compared our solution with alternative proposals from the literature. Krystyn et al. (2002) used Carnian-Norian data from several Tethyan sections (Kavaalani, Kavur Tepe, Pizzo Mondello lower part, Bolücektasi Tepe, and Scheiblkogel; see references in Krystyn et al., 2002) to construct a Tethyan composite magneto-biostratigraphic sequence that was correlated to Newark magnetozones E3–E22 and used it to infer a duration of the Rhaetian of only \sim 2 m.y. Later, Gallet et al. (2007) correlated data from Oyuklu, Pizzo Mondello (upper part), and the Tethyan composite sequence of Gallet et al. (2003) to the Newark APTS, suggesting that part of the Rhaetian is missing in the Newark sequence, and supporting the \sim 2 m.y. duration of the Rhaetian as proposed by Krystyn

et al. (2002). Muttoni et al. (2010) illustrated that middle Norian (Alaunian) magnetozones in the composite magneto-biostratigraphic sequence of Krystyn et al. (2002) may encompass Newark magnetozones \sim E13–E15 rather than \sim E13–E17, so that the overlying Sevatian magnetozones may correlate to Newark levels at and immediately above E15 rather than at and above E17 as proposed by Krystyn et al. (2002), thus supporting the existence of a longer ($>$ 2 m.y.) Rhaetian.

Coming to more recent times, the long-Tuvalian option of the *Geological Time Scale 2012* (Ogg, 2012), which is essentially based on data from Lucas et al. (2012), is characterized by a Carnian-Norian boundary placed at 221 Ma, a Norian-Rhaetian boundary at 205.4 Ma, and a large hiatus in the Newark Supergroup based on inferences from conchostracan biostratigraphy (Lucas et al., 2012, and references therein). According to this option, the preserved portion of the Rhaetian in the Newark Supergroup should have a duration of only \sim 0.2 m.y. (Lucas et al., 2012). A duration of \sim 8 m.y. for the Rhaetian, as proposed using marine-Newark magnetostratigraphic correlations by several authors (Channell et al., 2003; Muttoni et al., 2004, 2010; Hüsing et al., 2011), was rejected by Lucas et al. (2012) based on the inference that inserting 7.8 m.y. of missing Rhaetian in the claimed Rhaetian gap of the Newark Supergroup (7.8 m.y. = 8 m.y. of total duration of Rhaetian – 0.2 m.y. of preserved Rhaetian in the Newark) would produce an age for the base of the Newark Supergroup of 240.5 Ma; as Lucas et al. (2012) considered the base of the Newark Supergroup to coincide with the base of the Carnian (based on continental [palynomorphs, conchostracans, tetrapods] biostratigraphy), an age of 240.5 Ma is regarded as inappropriate because it would place the base of the Newark Supergroup close to the age of the Anisian-Ladinian boundary (Mundil et al., 2010). Therefore, a duration of \sim 8 m.y. for the Rhaetian is considered unacceptable according to Lucas et al. (2012), who instead adopted a duration of \sim 4 m.y. from Ogg (2004). Under the assumption of a 4 m.y. duration for the Rhaetian and only 0.2 m.y. of Rhaetian time preserved in the Newark Supergroup, Lucas et al. (2012) (and Ogg [2012] in his long-Tuvalian option) estimated an age of 221.5 Ma for the Carnian-Norian boundary, based on continental biostratigraphy, by counting \sim 405 k.y. McLaughlin cycles of Newark astrochronology.

In our opinion, the Rhaetian gap of Lucas et al. (2012) at the basis of the long-Tuvalian option (Ogg, 2012) is flawed by lack of convincing correlations between terrestrial groups and marine-based stage boundaries. For example, conchostracans from the Weser Formation of

the Germanic Basin are assigned an early Tuvalian age (late Carnian) because the Weser Formation is considered correlative with the Dolomie de Beaumont of France, which contains marine bivalves considered to be of such age (Lucas et al., 2012). As a further example, the conchostracan fauna from the Coburg Sandstein of the Germanic Basin is considered late Carnian, seemingly because it lies immediately below the beginning of a sporomorph association considered to be late Tuvalian. In general, we find difficult to decipher in Lucas et al. (2012) where and in which stratigraphic context a given continental association was found in direct association with stage-defining marine fossils.

The long-Rhaetian option of the *Geological Time Scale 2012* (Ogg, 2012) is essentially based on magnetostratigraphic correlations between marine sections bearing stage-defining fossils and the Newark APTS assumed to be continuous in the Rhaetian (Channell et al., 2003; Muttoni et al., 2004, 2010; Hüsing et al., 2011), and it shows a Carnian-Norian boundary at ca. 228.4 Ma and a Norian-Rhaetian boundary at ca. 209.5 Ma. Our new time scale for the Late Triassic could be considered an “update” of the long-Rhaetian option of (Ogg, 2012), with a Norian-Rhaetian boundary at 205.7 Ma based on data from this study and a Carnian-Norian boundary at ca. 227 Ma based on correlation of the Pizzo Mondello section with the Newark APTS (both numerical estimates obtained by rescaling the Newark APTS using an age of ca. 201.5 Ma for the base of the Orange Mountain Basalts in the Newark Supergroup; Blackburn et al., 2013). Moreover, our age of 205.7 Ma for the Norian-Rhaetian boundary is coherent with recent U/Pb ages of Wotzlav et al. (2014) that constrain the Rhaetian base between 205.70 ± 0.15 Ma and 205.3 ± 0.14 Ma.

CONCLUSIONS

Paleomagnetic data obtained from the Pignola-Abriola section provided a sequence of 22 polarity reversals grouped in 10 magnetozones. The correlation between the Pignola-Abriola section and additional Norian and Rhaetian Tethyan marine sections from the literature (Steinbergkogel, Oyuklu, Brumano, Italcementi Quarry, and Pizzo Mondello) reveals significant internal consistency.

To provide numerical age constraints on the Pignola-Abriola section, we applied a statistical correlation to the Newark APTS, which is assumed to be continuous in its younger part (contra Lucas et al., 2012). Three out of a total of 19 explored correlation options produced statistically reliable results, and after a thorough analysis, one option (7.1) is considered as the

most reliable. According to this option, the Pignola-Abriola section correlates to Newark magnetozones E13n to E20r. We place the Norian-Rhaetian boundary at Pignola-Abriola at a level coincident with a rapid decrease in $\delta^{13}\text{C}_{\text{org}}$ to $\sim\text{--}30\%$, which virtually coincides with the level containing the FAD of conodont *Misikella posthernsteini* sensu stricto within the *Proparvicungula moniliformis* radiolarian zone. This level is traced within Newark magnetozones E20r at 205.7 Ma.

Assuming an age of ca. 201.3 Ma for the Triassic-Jurassic boundary (Schoene et al., 2010; Guex et al., 2012), our study shows that the Rhaetian is $\sim\text{--}4.4$ m.y. long. Assuming a Carnian-Norian boundary age of ca. 227 Ma (Muttoni et al., 2004, 2014, and references therein), our study shows that the Norian is $\sim\text{--}21.3$ m.y. long.

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