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Towards accurate numerical calibration of the Late Triassic: High-precision U-Pb geochronology constraints on the duration of the Rhaetian

Jörn-Frederik Wotzlaw^{1*}, Jean Guex², Annachiara Bartolini³, Yves Gallet⁴, Leopold Krystyn⁵, Christopher A. McRoberts⁶, David Taylor⁷, Blair Schoene⁸, and Urs Schaltegger¹

¹Section of Earth and Environmental Sciences, University of Geneva, 1201 Geneva, Switzerland

²Institute of Earth Sciences, University of Lausanne, 1015 Lausanne, Switzerland

³Muséum National d'Histoire Naturelle, 75005 Paris, France

⁴Equipe de Paléomagnétisme, Institut de Physique du Globe de Paris, 75238 Paris, France

⁵Institute of Paleontology, University of Vienna, 1090 Vienna, Austria

⁶Geology Department, State University of New York Cortland, Cortland, New York 13045, USA

⁷Department of Geological Sciences, University of Oregon, Eugene, Oregon 97403, USA

⁸Department of Geosciences, Princeton University, Princeton, New Jersey 08544, USA

ABSTRACT

Numerical calibration of the Late Triassic stages is arguably the most controversial issue in Mesozoic stratigraphy, despite its importance for assessing mechanisms of environmental perturbations and associated biologic consequences preceding the end-Triassic mass extinction. Here we report new chemical abrasion–isotope dilution–thermal ionization mass spectrometry zircon U-Pb dates for volcanic ash beds within the Aramachay Formation of the Pucara Group in northern Peru that place precise constraints on the age of the Norian–Rhaetian boundary (NRB) and the duration of the Rhaetian. The sampled ash bed–bearing interval is located just above the last occurrence of the bivalve *Monotis subcircularis*, placing this stratigraphic sequence in the uppermost Norian, perhaps ranging into the earliest Rhaetian. Zircon U-Pb dates of ash beds constrain the deposition age of this interval to be between 205.70 ± 0.15 Ma and 205.30 ± 0.14 Ma, providing precise constraints on the age of the NRB. Combined with previously published zircon U-Pb dates for ash beds bracketing the Triassic–Jurassic boundary, we estimate a duration of 4.14 ± 0.39 m.y. for the Rhaetian. This ends a prolonged controversy about the duration of this stage and has fundamental implications for the rates of paleoenvironmental deterioration that culminated in the end-Triassic mass extinction.

INTRODUCTION

The uppermost Triassic stage, the Rhaetian, is framed by two biotic and environmental crises. At its top, the end-Triassic crisis is marked by one of the most severe mass extinctions of the Phanerozoic, followed by a recovery phase associated with important perturbations in the carbon cycle and strong climatic changes during the earliest Jurassic (e.g., Olsen et al., 2002; Guex et al., 2004; McElwain et al., 2009; Ruhl and Kürschner, 2011). This crisis was likely driven by several pulses in volcanic activity during the emplacement of the Central Atlantic Magmatic Province (CAMP; Marzoli et al., 2004; Schoene et al., 2010; Blackburn et al., 2013). At its base (Norian–Rhaetian boundary, NRB), the Norian crisis is much less pronounced than the end-Triassic extinction, but it nevertheless affected a large proportion of ammonoids and saw the near total disappearance of the bivalve *Monotis*, which was dominant in the late Norian seas almost globally (e.g., McRoberts et al., 2008). Low-paleolatitude conodont faunas of the Tethys Ocean show a dramatic turnover from robust *Epigondolella*-dominated to fragile and tiny *Misikella* associations at the NRB (Krystyn and Kürschner, 2005; Krystyn, 2008). The abiotic causes of the NRB crisis are not well known, but the very end of the Norian

is characterized by a worldwide regression, which induced important changes in marine lithofacies between the Norian and Rhaetian Stages (Golebiowski, 1990).

This prelude to the end-Triassic crisis was marked by several extinction episodes and/or by a stepwise reduction in biodiversity. To better understand this complex biodiversity pattern and its relationship with abiotic mechanisms, temporal constraints are of critical importance. Despite this importance, the duration of the Rhaetian stage is strongly debated, leading to the concept of a short (~4 m.y.) versus long Rhaetian (up to ~10 m.y.; for a synthesis, see Ogg, 2012). These different estimates are primarily based on magnetostratigraphic correlations of biostratigraphically constrained marine sections and the continental Newark Basin sequence (eastern North America). In this study, we present new high-precision zircon U-Pb dates obtained from volcanic ash beds intercalated with uppermost Norian to Rhaetian marine sediments in northern Peru. To our knowledge, this is the only locality worldwide where biostratigraphically defined upper Norian–Rhaetian strata are associated with zircon-bearing volcanic ash beds. These data allow us to independently constrain the duration of the Rhaetian Stage, which has important implications for the construction of a reliable Late Triassic geological time scale.

BIOSTRATIGRAPHIC DEFINITION OF THE NORIAN–RHAETIAN BOUNDARY AND THE SIGNIFICANCE OF BIVALVE BIOCHRONOLOGY IN THE PUCARA BASIN

The biostratigraphic definition of the NRB has been the subject of a long debate. After a thorough discussion through the Subcommittee on Triassic Stratigraphy (Krystyn, 2010), the base of the Rhaetian is taken as the first occurrence (FO) of the conodont *Misikella posthernsteini*. This option appears as the most satisfactory because the NRB is then located just above the great Norian crisis marked by the disappearance of almost all monothid bivalves and a significant turnover in ammonoid and conodont faunas (e.g., McRoberts et al., 2008; Krystyn and Kürschner, 2005).

We recently carried out detailed stratigraphic research in the Utcubamba Valley, northern Peru, where the Aramachay Formation (Pucara Group) contains a complete upper Norian to lower Sinemurian marine sedimentary sequence (Fig. 1; Schaltegger et al., 2008). The thickest sequence is located near Levanto (Fig. 1B) and consists of soft brown siltstones alternating with slightly more calcareous beds. The Rhaetian of that sequence is poor in ammonoids; the few collected specimens allow, however, a reliable correlation with the standard ammonoid zonations used in the upper Rhaetian and lower Jurassic. The base of the Jurassic (Triassic–Jurassic boundary, TJB) is marked by the FO of ammonite *Psiloceras spelae* (Fig. 2). The highest Rhaetian ammonoid-bearing beds con-

*E-mail: joern.wotzlaw@unige.ch.

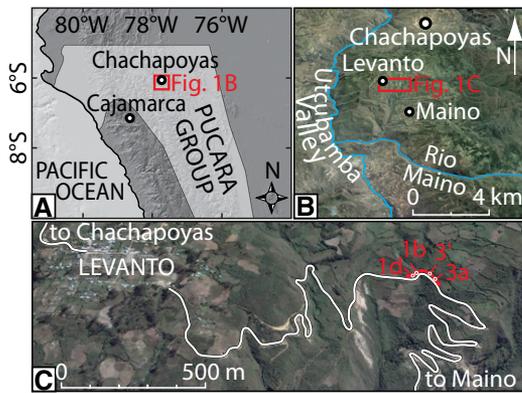


Figure 1. Geographical framework and geological setting of study area. A: Digital elevation model of northern and central Peru showing location of study area and extent of Pucara Group. **B:** Google Earth™ image with details of study area. **C:** Google Earth™ image of study area with location of the studied sequence with sampled fossiliferous horizons and volcanic ash beds indicated by red labels (see the Data Repository [see footnote 1]).

tain *Choristoceras crickmayi* and *C. marshi*, and the lowest contain a rich middle Rhaetian fauna with *Vandaites saximontanus*.

Most significant for the definition of the NRB in the Levanto section is the last occurrence of large monotid bivalves, identified as *Monotis subcircularis* (Fig. 2; Fig. DR2 in the GSA Data Repository¹), which occur in hard gray and massive silty limestones at the base of the section. *M. subcircularis* and other large monotid bivalves underwent nearly complete extinction at the top of the Norian. Only two dwarf species occur in the lowest Rhaetian of the western Tethys, one crossing the NRB and the other first appearing in the basal Rhaetian (McRoberts, 2010). The extinction of large *Monotis* at the top of the Norian is correlative with the top of the *Sagenites quinquepunctatus* ammonoid zone in the Tethys and the top of the *Gnomohalorites cordilleranus* ammonoid zone in the Americas. At the proposed global boundary stratotype section and point (GSSP) at Steinbergkogel (Austria), *Monotis* beds are rare and disappear ~14 m below the NRB (Krystyn, 2008). This succession is entirely consistent with that from the Hernstein locality (eastern Austria). The Hernstein succession contains many more *Monotis* beds, with the last occurring ~1.7 m below the FO of *M. posthernsteini* and ~4 m below the FO of *Paracochloceras*, thus being closely associated with the NRB (McRoberts et al., 2008). There is some provinciality exhibited in *Monotis* distribution at the species level, with only few species occurring in both Tethys and Panthalassa, compromising intercontinental correlations. However, our key species for the correlation of the NRB, *M. subcircularis*, is perhaps the most studied *Monotis* species anywhere in the world; it is among the largest and most widely distributed throughout eastern and western Panthalassa. Significant occurrences are known from North and South America, northern Russia, Japan, Timor, and New Zealand (see Tozer, 1980, for a review) that are all demonstrably late Norian. In North America, it is commonly associated with ammonoids and conodonts and usually does not survive to the very top of the *G. cordilleranus* zone (e.g., Grant-Mackie and Silberling, 1990; Silberling et al., 1997; McRoberts, 2010, 2011). We thus argue that the extinctions of large monotid bivalves and of most ammonoids are synchronous at sub-zone resolution. When assuming that this extinction is synchronous globally, our bivalve biochronology allows a reliable correla-

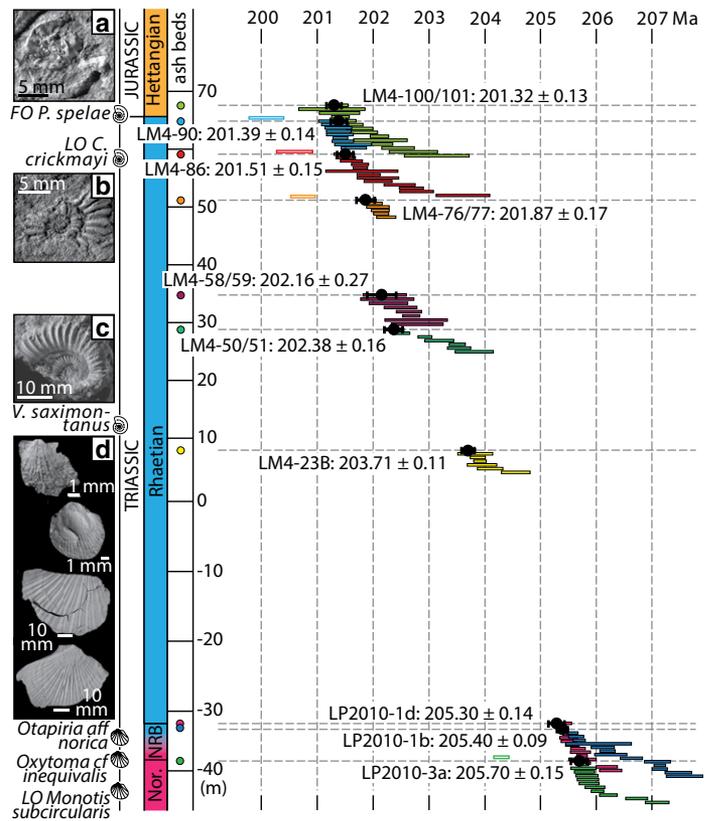


Figure 2. Summary of biostratigraphy and U-Pb geochronology for Late Triassic of the Pucara Group, northern Peru. Stratigraphic column shows occurrences (FO—first occurrence; LO—last occurrence) of characteristic ammonites and bivalves and locations of ash beds (colored dots). Photographs to the left of stratigraphic column show representative specimen of collected fossils: (a) *Psiloceras spelaie*; (b) *Choristoceras crickmayi*; (c) *Vandaites saximontanus*; (d) from top to bottom, *Oxytoma* cf. *O. inaequalvis*, *Otapiria* aff. *O. norica*, and two specimens of *Monotis subcircularis*. Recalculated previously published (Schoene et al., 2010; Guex et al., 2012; see text) and new U-Pb isotope dilution–thermal ionization mass spectrometry (ID-TIMS) dates from single zircons are color-coded to the corresponding ash bed. Ash bed deposition ages were computed employing a Bayesian Monte Carlo–based approach that enforces stratigraphic continuity (Guex et al., 2012). Computed deposition ages are shown as black dots and are given next to the sample names in Ma. All uncertainties are 2σ . Nor.—Norian; NRB—Norian-Rhaetian boundary.

tion of the Levanto section with Tethyan sequences and places the studied stratigraphic interval in the uppermost Norian, perhaps ranging into the lowermost Rhaetian.

The sampled interval also contains horizons with different bivalves that provide additional support for a latest Norian or perhaps earliest Rhaetian age (see the Data Repository). One horizon located ~5 m above the last *Monotis* bed contains *Oxytoma* that are similar to *Oxytoma* cf. *O. inaequalvis* from upper Norian strata in coastal Chile (Cecioni and Westermann, 1968). Some 5 m farther upsection, another horizon contains an abundant fauna of *Otapiria*, which are closely related to *Otapiria norica* known from the late Norian *G. cordilleranus* ammonoid zone of northeastern British Columbia (McRoberts, 2011). In general, *Otapiria*, although known from as old as Carnian strata, is more common from Rhaetian to Hettangian strata.

These biochronologic constraints, particularly the last occurrence of *M. subcircularis*, place the ash bed–bearing stratigraphic interval in the uppermost Norian close to the NRB, possibly ranging into the lowermost Rhaetian. Zircon U-Pb dates of intercalated ash beds thus provide precise

¹GSA Data Repository item 2014201, analytical methods, supplementary details of bivalve biochronology, U-Pb data table, and supplementary figures, is available online at www.geosociety.org/pubs/ft2014.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

estimates for the age of the NRB, and in combination with the previously reported age of the TJB (Schoene et al., 2010), constrain the duration of the Rhaetian.

CA-ID-TIMS ZIRCON U-PB GEOCHRONOLOGY

New constraints on the numerical age of the NRB are derived from high-precision zircon U-Pb dates, obtained from volcanic ash beds sampled from the ~10-m-thick stratigraphic interval above the highest *Monotis* beds (Fig. 2). All U-Pb dates were obtained from single zircons employing chemical abrasion–isotope dilution–thermal ionization mass spectrometry (CA-ID-TIMS) techniques at the University of Geneva, Switzerland (Schoene et al., 2010; see the Data Repository for details). All U-Pb dates were calculated relative to the most recent calibration of the EARTHTIME ^{202}Pb – ^{205}Pb – ^{233}U – ^{235}U tracer solution (version 3.0; www.earth-time.org). Uncertainties are reported at the 95% confidence level.

Zircon U-Pb data for sampled ash beds reveal complex zircon populations with the spread in single crystal $^{206}\text{Pb}/^{238}\text{U}$ dates exceeding analytical scatter (Table DR1 in the Data Repository; Fig. DR1). Similar complexities were observed by Schoene et al. (2010) and Guex et al. (2012), and we here follow their approach to estimate the time of ash bed deposition from the youngest $^{206}\text{Pb}/^{238}\text{U}$ dates of the main zircon populations (Fig. 2). We further take advantage of the stratigraphic continuity to compute ash bed deposition ages employing a Bayesian Monte Carlo-based approach introduced by Guex et al. (2012). This approach takes the youngest $^{206}\text{Pb}/^{238}\text{U}$ dates of stratigraphically consecutive ash beds and their uncertainties as the input parameters and computes a total of 10^6 random age models. Age models that violate stratigraphic superposition are discarded before computing a new ash bed deposition age while constructing a stratigraphically consistent age model (Fig. 2).

THE NUMERICAL AGE OF THE NORIAN-RHAETIAN BOUNDARY AND THE DURATION OF THE RHAETIAN

Our correlation of the NRB based on bivalve biochronology and the new high-precision U-Pb dates constrain the numerical age of the NRB to be between 205.70 ± 0.15 Ma and 205.30 ± 0.14 Ma (Fig. 2). Assuming that the NRB is located somewhere within the ash bed–bearing stratigraphic interval above the last *Monotis* beds, our best estimate for the age of this stage boundary is the mean age of 205.50 ± 0.35 Ma. This new age estimate can be combined with previously published U-Pb dates for the middle Rhaetian to Early Jurassic (Schoene et al., 2010; Guex et al., 2012) in order to estimate the duration of the Rhaetian. All three U-Pb data sets were produced in the same laboratory using the same tracer solution. However, the previous data sets (Schoene et al., 2010; Guex et al., 2012) were calculated relative to a previous working calibration of the EARTHTIME tracer. We recalculated the older data using the new tracer calibration (ver. 3.0; www.earth-time.org), allowing comparison of all data sets while ignoring systematic uncertainties (Fig. 2). Most importantly for the discussion on the duration of the Rhaetian, the age of the TJB reported by Schoene et al. (2010; 201.31 ± 0.18 Ma), becomes older by ~0.025%, that is, 201.36 ± 0.17 Ma. Furthermore, the onset of the marine carbon isotope excursion, considered to reflect the onset of the end-Triassic extinction (ETE), occurs just before 201.51 ± 0.15 Ma. This latter date is still equivalent to the recalculated date for the North Mountain Basalt (NMB) of 201.481 ± 0.021 Ma. The recently reported date of 201.566 ± 0.031 Ma for the same sample of NMB (Blackburn et al., 2013) does not overlap with our recalculated NMB date at the 95% confidence interval, despite being relative to the same calibration of the EARTHTIME tracer and despite using the same physical constants. This ~0.03% bias between the mean values of the two data sets does not affect the conclusions of either study, but remains a target for high-precision U-Pb intercalibration in future work. Using our new estimate for the age of the NRB and the re-calibrated age for the TJB, we estimate the duration of the Rhaetian to be 4.14 ± 0.39 m.y.

IMPLICATIONS FOR THE CORRELATION OF MARINE TETHYAN SECTIONS AND THE CONTINENTAL NEWARK BASIN

Our estimate for the duration of the Rhaetian helps to partly resolve previous debates about the duration of Late Triassic stages. Several attempts were made to correlate different magnetostratigraphic data sets obtained from biostratigraphically constrained marine Tethyan sections with the floating astrochronology of the continental Newark Basin sequence. However, published magnetic polarity data sets from Tethyan sections are difficult to correlate to each other, and a unique correlation with the Newark sequence is currently not possible. Various correlation schemes broadly can be grouped in two options for the duration of the Rhaetian. Figure 3 compares these different options with our U-Pb geochronologic constraints from the Pucara Basin. Our new independent data support previous claims suggesting a short duration of the Rhaetian (e.g., Gallet et al., 2003, 2007; Kozur and Weems, 2005; option 1 of Ogg, 2012). Regarding the long Rhaetian options (Muttoni et al., 2010; Olsen et al., 2010; Hüsing et al., 2011; option 2 of Ogg, 2012), it is worth stressing that the correlations were performed assuming that the entire Rhaetian was recorded in the Newark Basin. This assumption was, however, questioned by several authors on the basis of biostratigraphic arguments (e.g., van Veen, 1995;

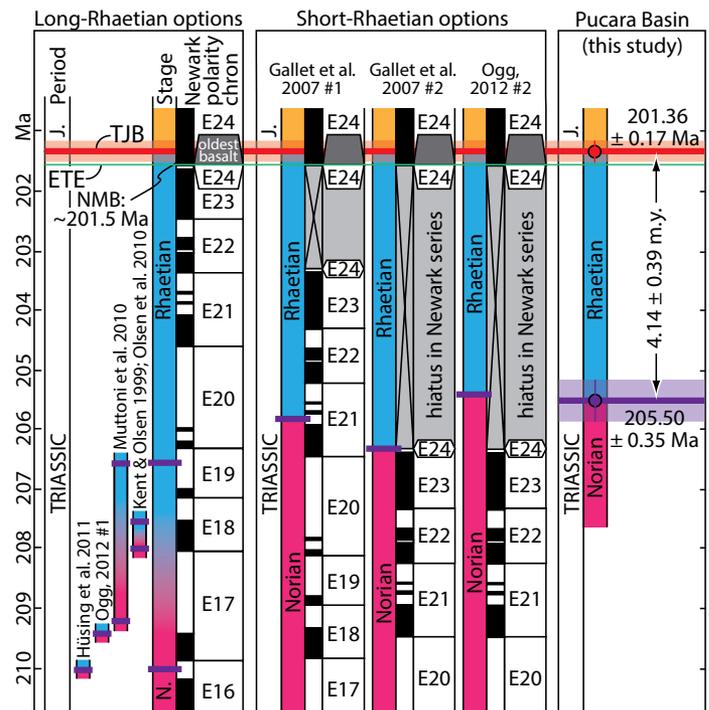


Figure 3. Comparison of various estimates for the numerical age of the Norian-Rhaetian boundary (NRB) and duration of the Rhaetian. Shown are suggested correlations of Late Triassic sequences with the astronomically tuned magnetic polarity time scale of Newark Basin, and their resulting age of the NRB (indicated by purple bars) and duration of the Rhaetian (grouped in “long-Rhaetian” and “short-Rhaetian” options) in comparison to our radioisotopic constraints. All long-Rhaetian options were scaled using the astrochronology of the Newark Basin sequence relative to the zircon U-Pb date of North Mountain Basalt (NMB; Blackburn et al., 2013; this study) that overlaps with the age of the Triassic-Jurassic boundary (TJB) in Pucara Basin. Gallet et al. (2007) roughly estimated the duration of the Rhaetian for their option 1 to be ~4.5 m.y. Ogg (2012) scaled his short-Rhaetian option using the floating Newark astrochronology relative to an estimated Carnian-Norian boundary. Same approach was used here to scale option 2 of Gallet et al. (2007). Note that all previously proposed short options require a hiatus in Newark Basin. ETE—end-Triassic extinction of Blackburn et al. (2013); J.—Jurassic; N.—Norian.

Kozur and Weems, 2005; Kürschner et al., 2007; Ogg, 2012). In contrast, Ogg (2012) concluded that a short duration of the Rhaetian would imply an almost total lack of the Rhaetian in the Newark Basin sequence (Fig. 3). A total lack of the Rhaetian, however, appears unlikely given that the same sequence of latest Rhaetian events is recorded in several Late Triassic rift basins (e.g., Deenen et al., 2010; Olsen et al., 2010; Blackburn et al., 2013). If indeed no hiatus was existing in this sequence, our independent estimate of the duration of the Rhaetian would place the NRB within magnetic polarity interval E20r of the Newark Basin sequence (Fig. 3). This result suggests that the Late Triassic time scale requires a significant revision and that magnetostratigraphic correlations between marine Tethyan sections and the continental Newark Basin need to be re-evaluated.

SUMMARY AND CONCLUSIONS

We use bivalve biochronology and high-precision zircon U-Pb geochronology to place precise constraints on the age of the NRB. Bivalve biochronology places the studied sedimentary sequence into the uppermost Norian to lowermost Rhaetian. Zircon U-Pb dates of bracketing ash beds, thus, constrain the age of the NRB, and, in combination with previously reported dates from the TJB, we estimate the duration of the Rhaetian to be 4.14 ± 0.39 m.y. These are the first zircon U-Pb dates from biochronologically constrained upper Norian to lower Rhaetian strata anywhere in the world. They support previous claims suggesting a short duration for the Rhaetian and provide independent constraints on the rates and durations of processes preceding the end-Triassic mass extinction.

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