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Strontium isotope stratigraphy of the Gabbs Formation (Nevada): implications for global Norian–Rhaetian correlations and faunal turnover

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The Luning and Gabbs formations in west-central Nevada, USA represent a Late Triassic shallow marine sedimentary succession with global significance (the Gabbs Formation was a candidate for the basal Jurassic GSSP). Typically, the Norian–Rhaetian stage boundary is placed at the contact between the formations, and the Rhaetian–Hettangian boundary (the Triassic–Jurassic boundary) is within the Müller Canyon Member of the Gabbs Formation. However, the use of different biostratigraphical index-species schemes in Norian–Rhaetian successions between Tethys and Panthalassa, the two largest ocean basins at the time, makes precise correlation problematic. Here, we compare $^{87}Sr/^{86}Sr$ measurements of well-preserved carbonate shell material from Nevada to the well-known and biostratigraphically constrained $^{87}Sr/^{86}Sr$ record from Tethys, where a negative excursion in $^{87}Sr/^{86}Sr$ is noted across the Norian–Rhaetian boundary. Our new $^{87}Sr/^{86}Sr$ data from the Luning and Gabbs formations reveal a comparable trend, with a sharp drop in $^{87}Sr/^{86}Sr$ within the Nun Mine Member of the Gabbs Formation, suggesting the position of the Norian–Rhaetian boundary is higher in the succession, and not between the Luning and Gabbs formations as previously defined. Relating the stage boundary using global isotopic signals is a useful tool for biostratigraphical correlation of successions between Tethys and Panthalassa, and for estimating the rate of faunal turnover at the Norian–Rhaetian stage boundary in comparison with the succeeding Late Triassic mass extinction. If correct, this biostratigraphical–chemostratigraphical correlation suggests that the current index groups for the Panthalassic stage boundary should be changed. ☐ *Biostratigraphy, conodonts, Gabbs Formation, Norian–Rhaetian boundary, Panthalassa, strontium chemostratigraphy.*

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The end-Triassic mass extinction is one of the five great biotic crises of the Phanerozoic (Sepkoski 1984; Alroy 2008; Greene *et al.* 2012), which coincides with a notable carbonate gap in most marine boundary sections around the world (Greene *et al.* 2012). The sedimentary succession in New York Canyon, Nevada, a former Triassic–Jurassic GSSP candidate (Lucas *et al.* 2007), preserves one of the clearest examples of this lithological transition, with a rapid shift from carbonate to shale across the Triassic–Jurassic (T/J) boundary (Guex *et al.* 2004; Greene *et al.* 2012). This section is also important for faunal studies insofar as it represents an example of the few Late Triassic–Early Jurassic shallow marine successions from the Panthalassa Ocean – one of the two major marine realms during the Early Mesozoic. Here, the T/J boundary is found within the fossiliferous Gabbs Formation, whose faunal composition and diversity have been intensively studied as a prelude to the succeeding carbonate crisis (Laws 1982; Taylor *et al.* 1983; Guex *et al.* 2004).

Correlation of Late Triassic Panthalassic biotas with those of the other major marine realm – the Tethys – remains problematic because different biostratigraphical schemes are used in the two ocean realms. For example, the base of the ultimate stage of the Triassic, the Rhaetian, is difficult to recognize in the Gabbs Formation of west-central Nevada and its Panthalassic equivalents, because the Tethyan index ammonoids for this boundary are not known to occur, while index conodonts are rare and appear above the boundary in the Panthalassic successions (Orchard 2010). The penultimate stage of the Late Triassic, the Norian, is much longer in duration than the Rhaetian stage (ca. 24 my; Furin *et al.* 2006) and suffers from similarly problematic biostratigraphical

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correlations between the Tethyan and Panthalassic realms; only the *Juvavites magnus* ammonite biozone is known from both regions for the entire stage. Several of the same ammonoid species occur in both oceans, but their ranges are not short enough to recognize stage boundaries – a critical component in evaluating faunal turnover events and mass extinctions.

To address the problematic correlations between regions, we constructed time series strontium isotope trends from geochemically well-preserved bivalve and brachiopod fossils in the Gabbs and Luning formations for comparison with those of brachiopods and conodonts from Tethyan successions. While strontium isotope compositions of marine carbonates have often been used as a proxy for the balance between global weathering and hydrothermal inputs (Kaufman *et al.* 1993), they are also valuable as chronostratigraphical markers (Elderfield & Gieskes 1982; Veizer *et al.* 1997). Because of the long residence time of strontium in seawater, oceanic values are homogenous on short time-scales (Korte *et al.* 2003) and excursions recorded in well-preserved carbonate minerals, often of biogenic origin, should be synchronous on million year time-scales (Veizer *et al.* 1997).

Locality and ages for the section

The Luning and Gabbs formations, located in west-central Nevada (Fig. 1), were deposited in a back-arc basin during the Late Triassic and earliest Jurassic (Taylor & Guex 2002). Part of the Luning allochthon, the formations were accreted to North America during the Late Mesozoic along with many other terranes (Oldow 1981). The Gabbs Formation is comprised of three members (Taylor *et al.* 1983), including the Nun Mine Member (ca. 90 m), the Mount Hyatt Member (ca. 30 m), and the Müller Canyon Member (ca. 15 m). In New York Canyon, the Gabbs Formation conformably overlies the Luning Formation – a shallow marine carbonate succession that lithologically resembles the Gabbs Formation (the uppermost member, however, is dolomitized). The Gabbs Formation includes medium to thick-bedded (10–70 cm) limestone and interbedded shale, with intercalated mudstones, wackestones and packstones. Faunas from the Gabbs Formation are characterized by shelly shallow marine groups – bivalves are most common, and brachiopods, ammonoids, gastropods and echinoderms are also present. The beds are not typically mottled from bioturbation, but individual burrows are common. Microfossil assemblages include ostracods, sponge spicules, micro-gastropods and rare conodonts that are usually fragmented.

The Luning Formation is found in the New York Canyon area, where it is heavily dolomitized. It is also found nearby in the West Union Canyon of the Berlin Ichthyosaur State Park (BISP; Fig. 1), where dolomitization is significantly less pervasive. There, the formation is comprised of the following: (1) clastic; (2) shaley limestone; (3) calcareous shale; and (4) carbonate members (Silberling 1959). The calcareous shale member contains the Carnian–Norian

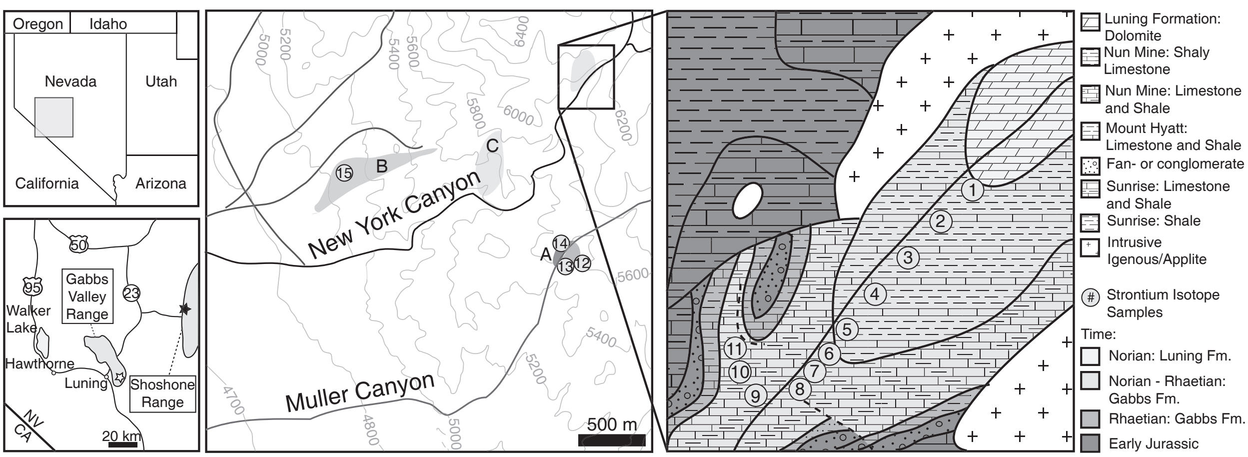

Fig. 1. Field locality maps. (Top left) Nevada, grey box shown below. (Bottom left) landmarks and the area of the Gabbs Valley Range (white star indicates the location of New York Canyon) and the Shoshone Mountains (black star indicates the location of the Berlin–Ichthyosaur State Park). (Centre) New York Canyon and Muller Canyon, with locations of samples and important sequences discussed in the text. (Right) New York Canyon Samples. Geological map modified from Hallam & Wignall (2000). Referenced sections: A – Muller Canyon. B – Reno Draw. C – Luning Draw.

boundary, as recognized by ammonoids, and the formation is unconformably overlain by Tertiary volcanics. The exact duration of time represented by the carbonate member within the Norian stage is uncertain, but its equivalent in the Shoshone Mountains is not considered to be younger than Middle Norian in age (Sandy & Stanley 1993). Typical faunas of the carbonate member include brachiopods, oysters and gastropods, with rare ammonoids and nautili.

Chronostratigraphical methods

Biostratigraphy

The relative ages of Late Triassic marine successions are typically determined using one or more biostratigraphical index groups, such as conodonts, halobiids, ammonoids, radiolarians or palynomorphs. Each group has well-known intrabasinal distributions, and they are often used to correlate sedimentary successions from different depositional environments (Carter 1994; Guex *et al.* 2004; Balini *et al.* 2010; Giordano *et al.* 2010; McRoberts 2010; Orchard 2010; Lucas *et al.* 2012). However, interbasinal correlation between the two main Triassic oceanic realms – separated by the Pangaean supercontinent until the Early Jurassic – remains problematic. The systems of each ocean are sometimes tethered by a particular clade (e.g. *J. magnus* in Lower Norian), which is assumed to appear synchronously but is difficult to confirm.

A major problem in correlating Panthalassic and Tethyan biostratigraphical zones from the Late Triassic is the presence of time-transgressive species, particularly at the Norian–Rhaetian boundary (NRB). The GSSP for this boundary has not yet been ratified, but the groups used to recognize the boundary and biozones within have been consistently used for decades. However, different index taxa are used to identify the boundary in Tethys and Panthalassa, introducing a confusing aspect to the intercontinental correlation of the stage boundary. For example, in Panthalassa, the NRB is currently recognized by the appearance of the A morphotype of *Epigondelella mosheri*. *E. mosheri* morphotype B occurs below the NRB, and *E. mosheri* morphotype C occurs above the boundary (Fig. 2; Orchard *et al.* 2007b). In Tethys, *E. mosheri* morphotype A and B also occur, but in the reverse order: *E. mosheri* morphotype A appears well before the NRB, and morphotype B appears slightly after the NRB. Similarly, in the Tethyan realm, the lowest occurrence of *Misikella posthernsteini* is widely used to recognize the NRB (Balini *et al.* 2010), and while the species also occurs

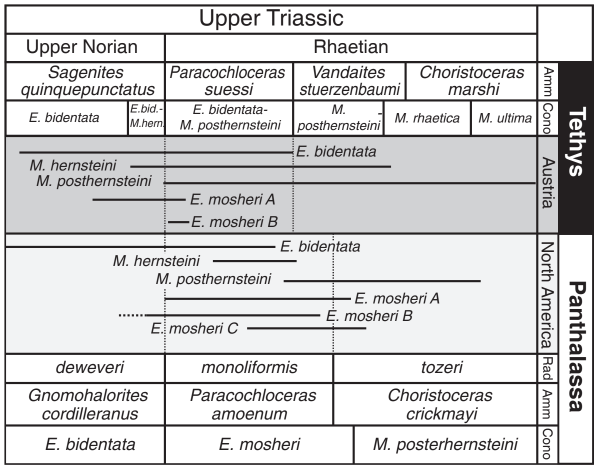

Fig. 2. Approximate ranges of biostratigraphically significant conodont species discussed in the text and correlation with other biostratigraphical zonation schemes. Modified from Orchard (2010), including all conodont ranges and biozone divisions, except North American conodont biozones, which are from Orchard *et al.* (2007a) and McRoberts *et al.* (2008). The division between *Epigondelella mosheri* and *Misikella posthernsteini* in the North American division is approximate.

in Panthalassa, it is described to have its lowest occurrence at a higher stratigraphical horizon of Rhaetian age. Similar problems exist for ammonoid biostratigraphy of the Late Triassic; the NRB is recognized by the appearance of two different ammonoids in the two oceanic realms: *Sagenites reticulatus* in Tethys and *Paracochloceras amoenum* in Panthalassa (Balini *et al.* 2010).

This dual succession of boundary-marking species and variants raises important questions regarding the temporal significance of the two different biostratigraphical schemes. While many of the same species occur in both oceans, confirming the synchroneity of their appearances in two regions separated by vast distances is difficult to test. Lacking independent means of correlation, it is difficult to determine whether an apparently time-transgressive but biostratigraphically important species like *M. posthernsteini* does post-date the NRB in Panthalassa. The implications of this include the increased uncertainty for evaluating the severity of the end-Triassic mass extinction in Panthalassa, due to the rarity of shallow marine successions and the temporal blurring of Norian–Rhaetian taxonomic ranges. Using the global chemostratigraphical signal provided by strontium isotopes, we hope to address these correlation issues.

Chemostratigraphy

Late Triassic strontium isotope values from bioapatite of Tethyan conodonts and biocarbonate from brachiopods define a significant excursion in the Late Triassic interval. Early Norian $^{87}Sr/^{86}Sr$ values of ca. 0.7077 rise to as high as ca. 0.7082 by the Late Norian and then precipitously fall back to pre-excursion values in the Rhaetian (Korte *et al.* 2003). The return to less radiogenic values occurs between Norian–Rhaetian stage boundary conodont species, *Misikella hernsteini* and *M. posthernsteini*, and thus should represent a global chemostratigraphical marker linked to the Tethyan biostratigraphical scheme.

Reliability of the strontium record

Strontium isotope stratigraphy must be undertaken with important caveats in mind, most importantly the susceptibility of carbonates to diagenesis and metamorphism. Strontium is precipitated in the carbonate matrix of shells as a substitute for Ca with no discernible vital effects (Reinhardt *et al.* 1998), although a small (ca. 10^{-5}) positive effect has been reported for conodonts (Diener *et al.* 1996). Dolomitization and recrystallization, however, often results in flushing of strontium from carbonate minerals or addition of radiogenic strontium from the decay of ^{87}Rb in clay minerals, both of which can alter depositional isotope compositions (Atwood & Fry 1967). Samples originally composed of aragonite typically contain the highest concentrations of strontium, followed by high-magnesium calcite, then by low-Mg calcite; only minute quantities of strontium are typically preserved in dolomite (Vahrenkamp & Swart 1990). The highest quality record for this time period comes from the analysis of the low-magnesium calcite secondary layer in brachiopod shells with strontium concentrations higher than 400 ppm, and in conodonts, which typically preserve several thousand ppm of Sr in their phosphatic matrices (Korte *et al.* 2003). Regardless, an empirically derived screening system would suggest Mn/Sr values <1 coupled with $\delta^{18}O$ values greater than −10 per mil (VPDB) are more likely to preserve original $^{87}Sr/^{86}Sr$, regardless of the origin of the carbonate (e.g. Kaufman *et al.* 1993), and interaction with meteoric or metamorphic fluids most typically results in more radiogenic $^{87}Sr/^{86}Sr$ ratios (Banner & Hanson 1990). Furthermore, detailed studies reveal that non-luminescent phases as determined by cathodoluminescence more faithfully record marine $^{87}Sr/^{86}Sr$ *versus* luminescent phases (Kaufman *et al.* 1993). Thus, inversion of aragonite to calcite, a common occurrence in ancient carbonates, can indeed preserve marine $^{87}Sr/^{86}Sr$ values when water–rock interactions are low, given the abundance of strontium in the aragonite *versus* potential diagenetic fluids, even though the original shell structure is lost.

Methods

Sample collection

Gabbs Formation carbonate samples (n = 11) were collected from New York Canyon (Fig. 1) where the unit conformably overlies the Dolomite Member of the Luning Formation. Sampling in the lower Nun Mine Member commenced at the first non-dolomite limestone bed. Fossil shell samples were collected at consistent intervals (ca. 5 m; Fig. 3) to the point where the succession is terminated by an applite intrusion and a road cut. Sampling ended several metres below the intrusive rocks; specimens near the intrusion, however, showed no signs of enhanced alteration (see below). Sampling continued across the road cut up until the succession is terminated by a thrust fault; the hanging wall contained large Early Jurassic bivalves. Here, it appears that most of the Mount Hyatt Member and the entirety of the Müller Canyon Member of the Gabbs Formation are missing, while ca. 65 m of the Nun Mine Member is represented.

Four additional samples from the upper member of the Gabbs Formation and from the overlying Early Jurassic formations were included for strontium isotope analysis: one sample from uppermost Rhaetian strata in Müller Canyon (Müller Canyon Member, Gabbs Formation) and three samples from the Early Jurassic Ferguson Hill Member of the Sunrise Formation. These four additional samples were collected from other successions in the nearby area: Müller Canyon (which contains the Triassic–Jurassic boundary) and from Reno Draw (Fig. 1).

Shell material from the upper Luning Formation was sampled at consistent intervals (ca. 8 m) within the Carbonate Member (Fig. 4), which is exclusively Norian in age. A total of five samples of carbonate shell material were analysed, with the oldest sample composed of brachiopod shell material and the remaining samples composed of bivalve shell material. The brachiopod shell sampled from the Carbonate Member of the Luning Formation belongs to the *Plectoconcha* genus, and bivalves sampled from the Luning Formation and the Nun Mine Member of the Gabbs Formation include shallow infaunal bivalves such as *Tutcheria* and *Nuculana*.

Elemental and isotopic measurements

The collected samples were slabbed and polished, and shell material of bivalves and brachiopod were

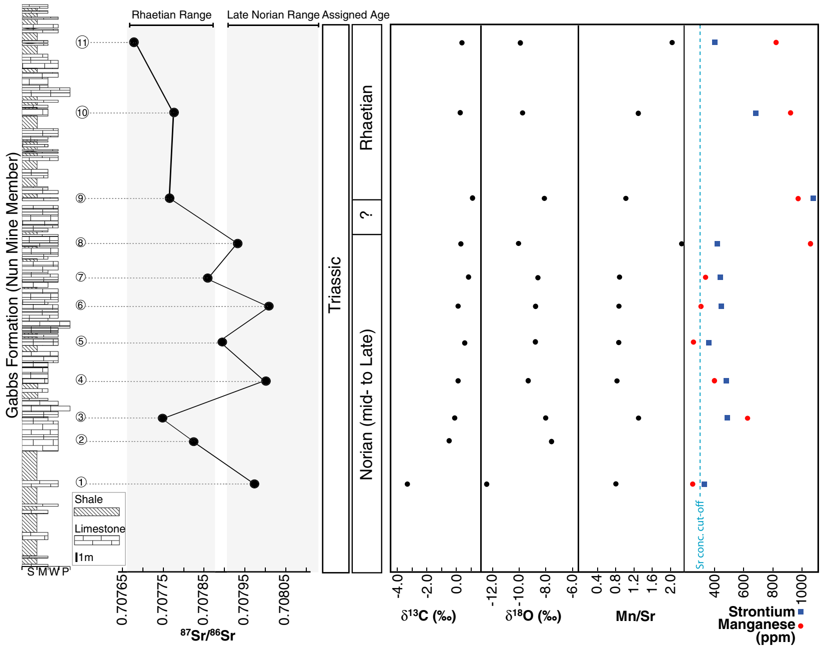

Fig. 3. Stratigraphical columns and strontium isotope values from the Nun Mine Member of the Gabbs Formation in New York Canyon, NV. Published values from Tethyan succession in Korte *et al.* (2003). All measurements are derived from bivalve shell material. (This figure is in colour in the online version)

micro-drilled to extract powder for elemental and isotopic analysis. Sampled shell material was derived from shells found in fresh breaks in the carbonate material (thereby not subjected to surface weathering), and the material was drilled from the outer shell body. Concentrations of Sr and Mn in the drilled samples were measured at USC using an Ultima-C ICP-AES. Calibration curves for Sr and Mn were based on serial dilution of a solution standard (Inorganic Ventures' ICP-MS Complete Standard), and uncertainties of sample measurements are estimated at 5% for Sr and 10% for Mn (Table S1).

Micro-drilled powders of shell material (ca. 5 mg) were sequentially leached (3×) with 0.2 M ammonium acetate (pH ca. 8.2) and rinsed after each leach with Milli-Q® ultrapure water. Leached samples were then acidified with distilled 0.5 M acetic acid and allowed to react for 12 h. The supernatant was separated from insoluble residues by centrifugation and then decanted, dried and dissolved with 200 μl of 3 M HNO_3. Strontium was separated by cation exchange using polyethylene columns with ca. 1 cm of Eichrom® Sr-specific resin above a filter composed of quartz wool. The samples were leached with sequential treatments of 3 M and 7 M HNO_3 to remove Rb, Ca and REEs, and the Sr subsequently eluted with 0.05 M HNO_3 and collected into a V-shaped polyethylene beaker. Dried Sr was transferred onto degassed (ca. 4.2 A) high-purity Re filaments with 0.7 μl of Ta_2O_5 activator. Strontium samples were ionized under high vacuum at temperatures between 1350 and 1550 °C using a VG Sector 54 thermal ionization mass spectrometer in the University of Maryland Geology Department. Analysis of the NBS 987 strontium standard (n = 11) during the analytical sessions when samples were measured yielded a value of 0.710247 ± 0.000014.

At the University of Maryland Paleoclimate CoLaboratory, a refined method for the analysis and correction of carbon (δ^{13}C) and oxygen (δ^{18}O) isotopic composition of 10–100 μg carbonate samples by continuous flow mass spectrometry has been recently developed (Spötl 2011). Up to 180 samples loaded into 3.7-ml Labco Exetainer vials and sealed with Labco septa are flushed with 99.999% helium and manually acidified at 60 °C. The carbon dioxide analyte gas is isolated via gas chromatography, and water is removed using a Nafion trap prior to admission into an Elementar Isoprime stable isotope mass spectrometer fitted with a continuous flow interface. Data are corrected via automated Matlab scripting on the VPDB–LSVEC scale (Coplen *et al.* 2006) using periodic in-run measurement of international reference carbonate materials and/or in-house standard carbonates, from which empirical corrections for signal amplitude, sequential drift and one- or two-point mean corrections are applied. Precision for both isotopes is routinely better than 0.1‰. Including acidification, flush fill, reaction and

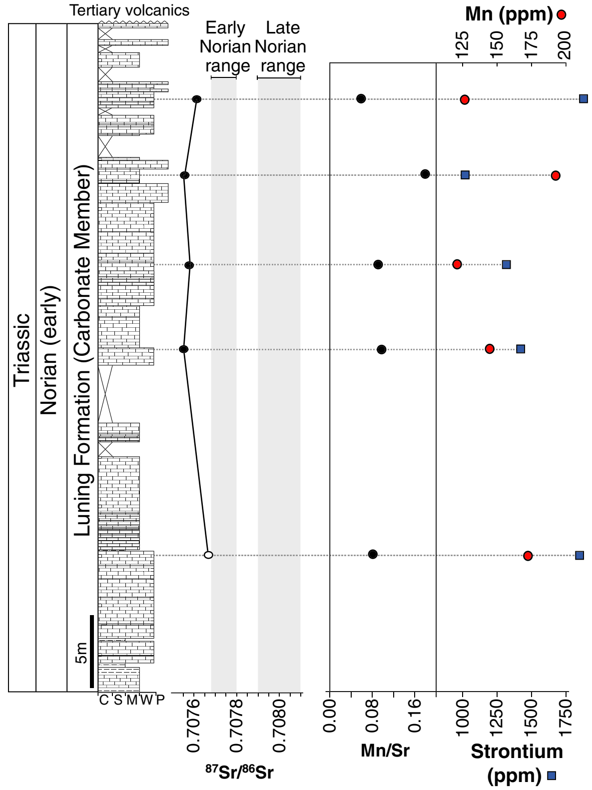

Fig. 4. Stratigraphy, sampling horizons, $^{87}Sr/^{86}Sr$ and strontium/manganese concentrations from the carbonate member of the Luning Formation in the Shoshone Mountains at Berlin–Ichthyosaur State Park. Strontium values indicated by an open circle come from brachiopod shell material, black circles represent bivalve shell material. Published ranges of $^{87}Sr/^{86}Sr$ from Korte *et al.* (2003). C = covered; S = shale; M = mudstone; W = wackestone; P = packstone. (This figure is in colour in the online version)

analysis, true throughput exclusive of correcting standards is 2–3 samples/h, or up to 144 samples over a 40 h analytical session.

Results

Petrography and cathodoluminescence

Thin sections were prepared and evaluated from shell-bearing samples, examined by cathodoluminescence and micro-drilled for isotopic analysis (Fig. 5). The carbonate samples are identified as either mudstones or wackestones, containing up to 20% of shelly material, including bivalves, brachiopods and echinoderms, in a micrite matrix. Of the thin sections examined, none of the bivalve or brachiopod shells were brightly luminescent, while the carbonate matrix was occasionally moderately luminescent (Fig. 5). The stratigraphically lowest sample from NYC (NYC 1) contained bivalve shell material with dull luminescence, notable only because it was the only sample in which the shell material was more luminescent than the micrite matrix.

Elemental abundances

Elemental analyses of samples from this study (Table 1, Figs 3, 4) show that the Luning Formation is enriched in Sr (up to 2000 ppm) and depleted in Mn (<200 ppm) relative to both the Gabbs and Sunrise formations. The Gabbs samples contain approximately equal amounts of Sr (ranging between 361 and 1069 ppm) and Mn (284–1049 ppm) similar to the ranges seen in the Sunrise Formation samples. Given the generally high Sr contents of all of these samples, the Mn/Sr is uniformly low in all three units, but especially so in the Luning Formation.

Carbon and oxygen isotopes

Results of carbon and oxygen isotope measurements of micro-drilled shells from the Gabbs, Sunrise and Luning formations are reported in Table 1, and for the Gabbs samples illustrated in Figure 3. With the exception of the lowest sample from a predominantly shaley interval, most of the Gabbs samples lie near 0‰ for C and −9‰ for O. The three Sunrise Formation samples range from −5.3 to 0.6‰ for C and −9.2 to −7.9‰ for O, while the single analysed Luning sample has $\delta^{13}C = 2.1‰$ and $\delta^{18}O = -12.4‰$.

Strontium isotopes

The range of Sr isotope compositions of micro-drilled samples from this study is relatively small, although those from the Gabbs Formation are more radiogenic (ranging from 0.70768 to 0.70801) than those from either the Luning (0.70753 to 0.70764) or Sunrise (0.70764 to 0.70781) formations. Most notably, there is an apparent up-section decline in the $^{87}Sr/^{86}Sr$ of Gabbs Formation samples from within the Nun Mine Member.

Discussion

Sample quality and preservation

The shelly material sampled from fine-grained carbonate mudstone and wackestone samples collected for this study was well preserved and found to be largely non-luminescent relative to surrounding micrite. Bivalve shells were largely neomorphosed from aragonite to calcite during burial, but most of these

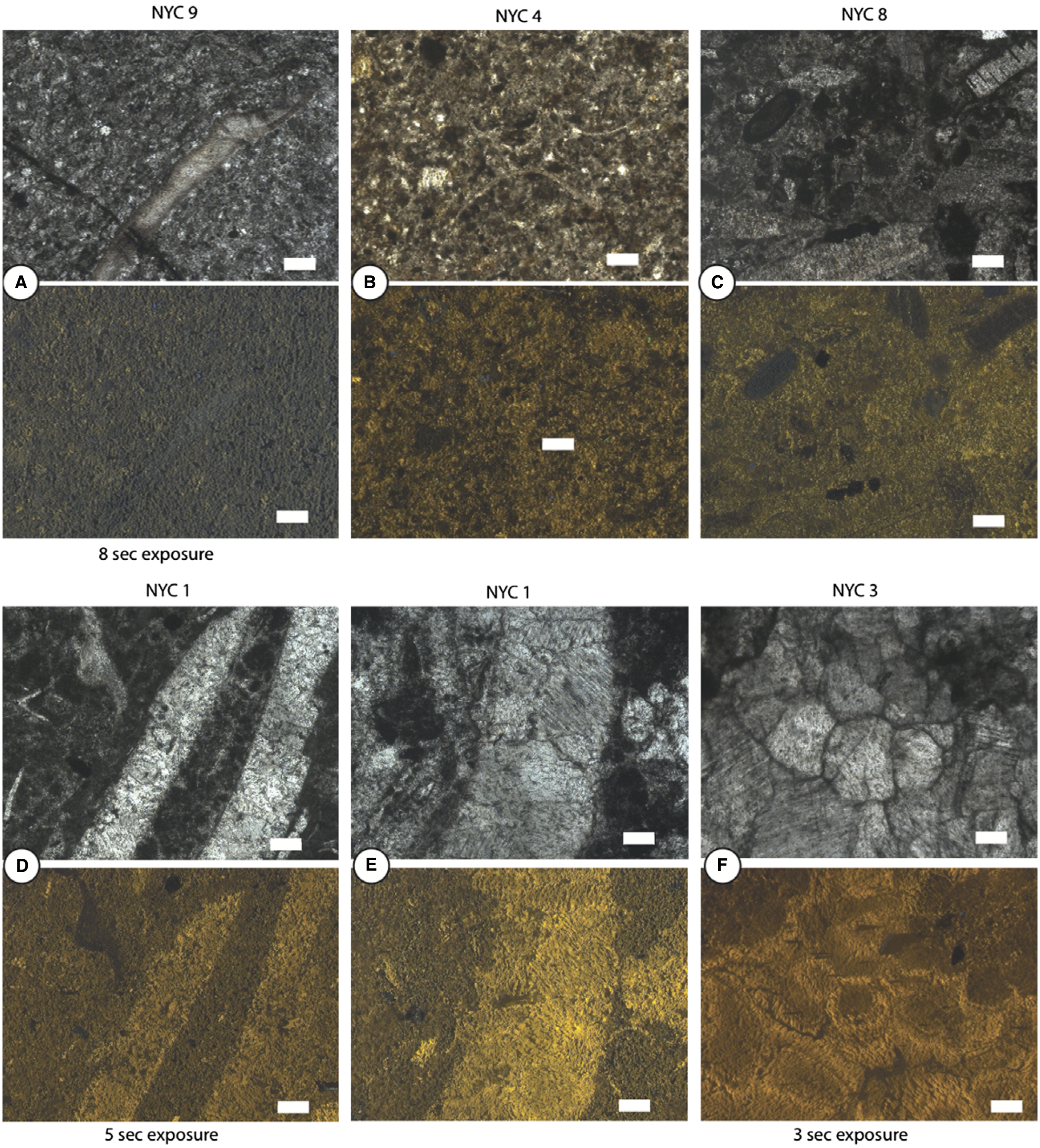

Fig. 5. Different luminescence (Lm) in carbonates from the Nun Mine Member. Top image is in natural light and the bottom image is the same region in cathodoluminescence. A, lowest observed Lm in sample 6, with non-lum matrix and shells. B, C, slightly luminescent matrix with non-luminescent shells. D, dull luminescence in matrix and slightly more in bivalve shell. E, moderately luminescent calcite vein. F, brightly luminescent void-fill. Exposure time is 4 s unless otherwise indicated. Scale bar = 0.2 mm. (This figure is in colour in the online version)

samples (as well as those of brachiopods) retained high and consistent concentrations of strontium as well as low Mn/Sr, suggesting insignificant interaction with meteoric fluids (Banner 1995). Furthermore, the Sr isotope range of samples from this study was narrow, although two closely spaced samples from the lower Gabbs Formation (Fig. 3) have $^{87}Sr/^{86}Sr$ compositions slightly lower than the average of other Norian samples from the same succession. Furthermore, a comparison of bivalve and brachiopod data from the Luning Formation (Fig. 4) reveals little difference in $^{87}Sr/^{86}Sr$ compositions, supporting the view that vital effects were also negligible.

Table 1. Stratigraphical information and strontium, carbon and oxygen isotopic values for shell samples from the Luning, Gabbs and Sunrise formations.

Sample name	Form.	Member	$^{87}Sr/^{86}Sr$	Prev. age	New age	$^{87}Sr/^{86}Sr$ ratio	Sr (ppt)	Mn (ppt)	Mn/Sr ratio	$\delta^{13}C$	$\delta^{18}0$
BISP 1	Luning	Carbonate	0.7076461	E. Norian	E. Norian	100	1.975	0.174	0.088	2.14	−12.41
BISP 2	Luning	Carbonate	0.7075309	E. Norian	E. Norian	87	1.436	0.141	0.098		
BISP 3	Luning	Carbonate	0.7075599	E. Norian	E. Norian	47	1.357	0.122	0.090		
BISP 4	Luning	Carbonate	0.7075390	E. Norian	E. Norian	57	1.110	0.194	0.174		
BISP 5	Luning	Carbonate	0.7075757	E. Norian	E. Norian	92	2.053	0.131	0.064		
NYC 1	Gabbs	Nun Mine	0.7079695	Rhaetian	Late Norian	103	0.319	0.254	0.796	−3.48	−12.29
NYC 2	Gabbs	Nun Mine	0.7078258	Rhaetian	Late Norian	96				−0.60	−7.52
NYC 3	Gabbs	Nun Mine	0.7077460	Rhaetian	Late Norian	111	0.488	0.630	1.292	−0.20	−8.00
NYC 4	Gabbs	Nun Mine	0.7080025	Rhaetian	Late Norian	96	0.481	0.403	0.839	0.04	−9.29
NYC 5	Gabbs	Nun Mine	0.7078868	Rhaetian	Late Norian	104	0.361	0.258	0.715	0.50	−8.78
NYC 6	Gabbs	Nun Mine	0.7080138	Rhaetian	Late Norian	96	0.449	0.312	0.695	0.02	−8.78
NYC 7	Gabbs	Nun Mine	0.7078550	Rhaetian	Late Norian	112	0.444	0.342	0.770	0.74	−8.59
NYC 8	Gabbs	Nun Mine	0.7079305	Rhaetian	Late Norian	84	0.422	1.050	2.488	0.20	−10.00
NYC 9	Gabbs	Nun Mine	0.7077691	Rhaetian	Rhaetian	102	1.069	0.968	0.905	1.03	−8.13
NYC 10	Gabbs	Nun Mine	0.7077787	Rhaetian	Rhaetian	96	0.679	0.918	1.352	0.17	−9.71
NYC 11	Gabbs	Nun Mine	0.7076792	Rhaetian	Rhaetian	95	0.405	0.822	2.032	0.27	−9.87
NYC 12	Gabbs	Muller Cyn.	0.7077150	Rhaetian	Rhaetian	107	0.596	0.522	0.876	1.18	−9.06
NYC 13	Sunrise	Ferg. Hill	0.7077246	E. Jurassic	E. Jurassic	106	0.322	0.208	0.645	−0.88	−7.93
NYC 14	Sunrise	Ferg. Hill	0.7078143	E. Jurassic	E. Jurassic	103	0.529	0.406	0.768	−5.26	−9.18
NYC 15	Sunrise	Ferg. Hill	0.7076357	E. Jurassic	E. Jurassic	104	0.512	0.352	0.687	0.61	−7.92

NYC, New York Canyon; BISP, Berlin–Ichthyosaur State Park; MC, Müller Canyon; RD, Reno Draw.

Carbon and oxygen isotope results from samples of the Gabbs Formation are similarly constant with the exception of the sample (NYC 1) from a shaley interval near the base of the unit, which is depleted in both ^{13}C and ^{18}O (and has the lowest Sr abundance) relative to all other samples from the unit. It is likely that this sample has been diagenetically altered and is not considered further here.

Chemostratigraphical correlations

Chemostratigraphical correlation of widely separated Triassic successions is possible if samples are well preserved and established isotope trends reveal significant secular variations that are global in scope. The oxygen isotope system in carbonates is prone to meteoric and metamorphic alteration due to the solubility of these minerals and the preponderance of oxygen in solutions (Banner & Hanson 1990; Kaufman *et al.* 1993). On the other hand, the carbon isotope system is more resistant to alteration due to the lack of carbon in diagenetic fluids (Banner & Hanson 1990). Nonetheless, it may be difficult to constrain whether carbon isotope variations between successions are temporal, facies dependent or related to environmental gradients along ocean margins (Swart 2008). We compared Late Norian to earliest Rhaetian carbon and oxygen isotopic compositions of shell-derived carbonate material from the Gabbs Formation with equivalents in Panthalassa (British Columbia, Canada; Ward *et al.* 2004) and Tethys (Korte *et al.* 2005). This analysis revealed strong contrasts in $\delta^{18}O$ values between sections, but $\delta^{13}C$ values were near zero or moderately positive in all samples (Fig. 3). Small variations in carbon isotope composition between sections in the Tethyan and Panthalassic realms likely reflect depositional differences between the different water masses rather than diagenetic grades, especially considering the consistency of strontium isotope compositions.

Due to the isotopic homogeneity and long residence time (ca. 1–2 Ma) of strontium in the world oceans, $^{87}Sr/^{86}Sr$ of well-preserved biogenic carbonates have been used in concert with biostratigraphy to tell relative Phanerozoic time (e.g. Depaolo & Ingram 1985). Our petrographic, elemental, isotopic and stratigraphical tests suggest that our samples are well preserved and hence useful for Sr isotope correlations. Notably, samples of brachiopods and bivalves from the Luning Formation at the Berlin–Ichthyosaur State Park yielded values that were less radiogenic than values reported from Early and Late Norian conodonts in Tethys (Fig. 4; Korte *et al.* 2003). This may be interpreted as a difference between the small vital effect of strontium incorporation into conodonts that is not observed in brachiopods (Diener *et al.* 1996). The conodont values from Tethys may be ca. 10^{-5} more radiogenic than the brachiopod and bivalve shell samples from Panthalassa. The $^{87}Sr/^{86}Sr$ of most of the *lower* Nun Mine Member (Lower Gabbs Formation) samples are within the published range of Late Norian samples (ca. 0.7079–0.7081) from the Tethyan realm (Korte *et al.* 2003), while two others near the base of the interval fell in the lower range of published Rhaetian values, which are based on brachiopods and conodonts (Table 1 and Fig. 3). NYC samples 2 and 3 are indistinct both petrographically and geochemically from samples above and below. Insofar as alteration of strontium isotopes typically results in more radiogenic compositions (Banner 1995), it seems possible that these abnormally low values record a short-term oceanic signal that has not been recorded elsewhere. By comparison, strontium isotopic values of all samples from the *upper* Nun Mine Member had consistently lower values (ranging from 0.7077 to 0.7078) – all within the Rhaetian range reported from the Tethys equivalent. Finally, all samples from above the New York Canyon sequence (samples 12–15) had $^{87}Sr/^{86}Sr$ values consistent with their reported ages from the Rhaetian or Early Jurassic intervals (Korte *et al.* 2003).

For correlation of the Norian–Rhaetian boundary, we are particularly focused on the noted drop in $^{87}Sr/^{86}Sr$ compositions of samples within the Nun Mine Member, which appears between NYC sample 8 and 9 (Fig. 3). However, NYC sample 8 contains significantly higher concentrations of Mn, suggesting that its Sr isotope composition may have been altered to higher values (although luminescent properties and carbon and oxygen isotope compositions of this sample are consistent with others from the Nun Mine Member). In this case, the Norian–Rhaetian isotope excursion might occur slightly lower in the Gabbs Formation.

Age of the Gabbs Formation

The contrast in $^{87}Sr/^{86}Sr$ within the Nun Mine Member suggests a Late Norian age for the lower part of the succession and a Rhaetian age for the upper part, as well as the overlying Mount Hyatt Member. This chemostratigraphical age assignment is in contrast to previous determinations based on the occurrence of earliest Rhaetian biostratigraphical index fossils, such as *E. mosheri* morphotype A (Orchard *et al.* 2007a; Fig. 6), which place the entirety of the Gabbs Formation in the Rhaetian stage.

Assuming that all samples are well preserved, the pattern of $^{87}Sr/^{86}Sr$ variations in Berlin–Ichthyosaur State Park and New York Canyon indicates that the

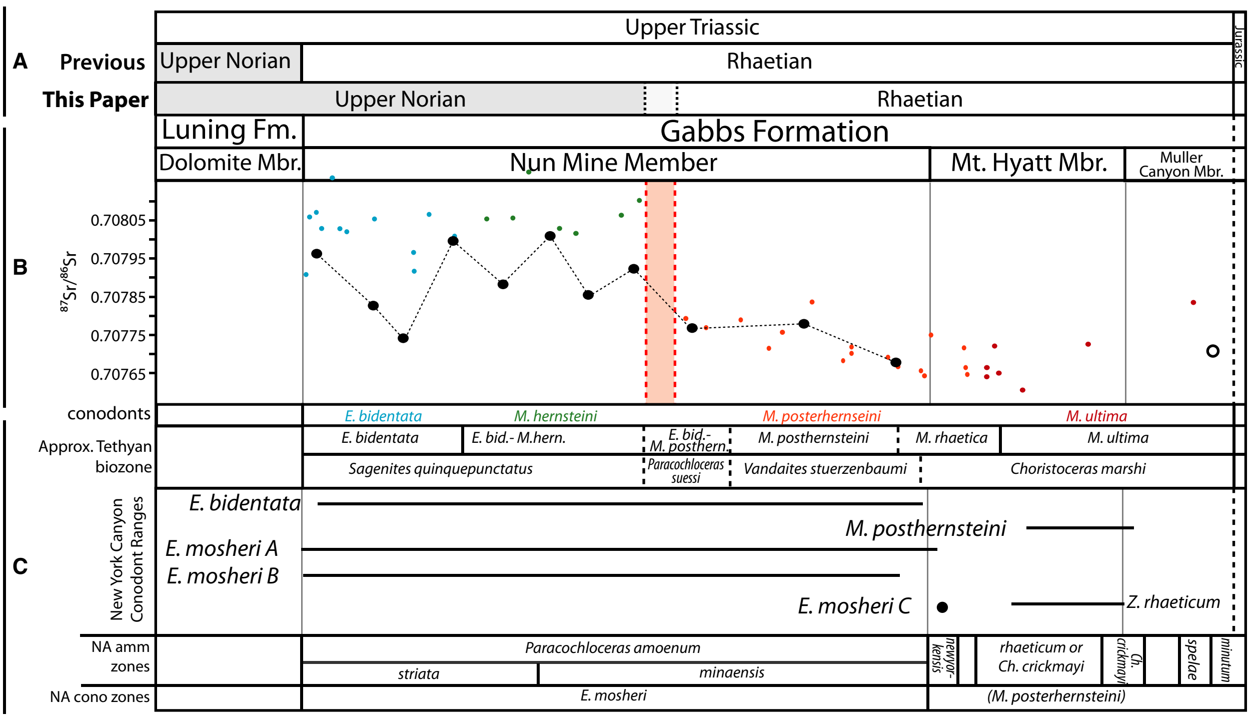

Fig. 6. Stratigraphical correlation and age determinations of the Gabbs Formation. A, previous ages attributed to the upper Luning Formation and Gabbs Formation, and updated ages based on chemostratigraphy in (B). B, $^{87}Sr/^{86}Sr$ from Tethyan conodonts (coloured circles with corresponding conodont taxa, except for several data from the Rhaetian biozones which include brachiopod measurements correlated to that particular conodont biozone) from Korte *et al.* (2003), and $^{87}Sr/^{86}Sr$ from the Nun Mine Member (NMM) of the Gabbs Formation (black closed circles), correlated to the conodont ranges in (C), and an upper Muller Canyon Member sample (open black circle). Tethyan measurements correlated to New York Canyon values based on range similarity. Distributions of conodont-strontium data points from Tethys are based on stratigraphical superposition (see Korte *et al.* 2003); those from this study are shown in Figures 3 and 4. C, approximate conodont ranges from the Gabbs Formation of New York Canyon and North American biozones from Orchard *et al.* (2007a,b). Luning Formation ranges were not reported. (This figure is in colour in the online version)

strontium isotope composition of seawater throughout the exceptionally long Norian stage may be more complicated than previously estimated (Korte *et al.* 2003). A broader range of $^{87}Sr/^{86}Sr$ values during the Norian is not unexpected. Despite representing only two conodont biozones, this stage is estimated to have lasted for ca. 24 million years (Furin *et al.* 2006). Specifically, the non-radiogenic values from carbonate shells in the Luning Formation have not been previously recorded in Norian-aged successions elsewhere (although they are consistent with those from the Carnian and very similar to Early Norian values). Furthermore, our results suggest that there may be a significant excursion to less radiogenic values in the Late Norian lower Nun Mine Member of the Gabbs Formation. It is possible that short-term climatic, tectonic or even extraterrestrial events could have impacted the strontium isotope composition of seawater during this interval. On the other hand, the upper part of the Nun Mine Member and lower Mount Hyatt Member exhibit values entirely consistent with Rhaetian compilations (Fig. 3). In Korte *et al.* (2003), no Rhaetian fossils produced $^{87}Sr/^{86}Sr$ values in the Late Norian range.

Discrepancies with other studies

Orchard *et al.* (2007a) documented a succession of conodonts from the Nun Mine Member where it conformably overlies the Luning Formation at the Luning Draw locality (Taylor *et al.* 1983), only 1 km from the section described here. Identical lithologies and lower formational contacts with the Luning Formation allow for a reasonable comparison between the two successions. In Panthalassa, the Norian–Rhaetian boundary succession is biostratigraphically characterized by the uppermost Norian conodont *bidentata* biozone and the stage boundary recognized by the first occurrence of *E. mosheri* morphotype A. In New York Canyon, Orchard *et al.* (2007a) reported *E. mosheri* morphotypes A and B, and Late Norian–Rhaetian conodont *Epigondolella bidentata* in the Nun Mine Member of the Gabbs Formation (Fig. 6), supporting a Rhaetian age for the Gabbs Formation. *Epigondelella mosheri* morphotype C, which appears in the Early Rhaetian, does not appear until the Mount Hyatt Member. These authors also reported *Parvigondolella* spp. A and B in the lower 15 m of the Nun Mine Member – also known from Late Norian formations in British Columbia (Orchard *et al.* 2007b).

Here, we report strontium isotope values from the lower Gabbs Formation consistent with those reported from Late Norian conodonts *Epigondolella* (=*Mockina*) *bidentata* and *M. hernsteini* in Tethys, overlain by values consistent with the earliest Rhaetian conodont *M. posthernsteini* (Fig. 3). This result conflicts with an entirely Rhaetian age of the Nun Mine Member of the Gabbs Formation and suggests a Late Norian age for the lower portion of the unit.

The temporal discrepancy may be attributed to two potential sources of error. First, the strontium isotope composition of the Tethys ocean might be distinct from the contemporaneous Panthalassa ocean mass. While possible, this is an unlikely scenario given that Sr isotopic ratios are considered well mixed in marine systems and the long residence time of this element in seawater. The factors that control the strontium isotope composition of non-restricted oceans are likely to be non-regional in scope and produce differential values only in the immediate area of weathering material (Reinhardt *et al.* 1998) or in extremely restricted depositional environments. The homogeneity of the strontium isotope record in our sections from Nevada is supported by the consistently similar Rhaetian values in the upper Nun Mine Member and in higher samples of Early Jurassic age. Second, the conodonts *E. mosheri* morphotypes A and B have a longer Panthalassic range than previously thought, with an earlier FAD. Therefore, it is possible that both *E. mosheri* morphotypes A and B occur below the Norian–Rhaetian boundary in this region, just as morphotype A does in the Tethyan region. This hypothesis may be tested by measuring the strontium isotopes of these species in other sedimentary successions of the same presumed age.

The most parsimonious explanation is a Late Norian age for the lower half of the Nun Mine Member of the Gabbs Formation, which requires a shift in age determinations for several Panthalassic biostratigraphical groups. The biostratigraphical support for this includes the presence of *Parvigondolella* spp. B in the Nun Mine Member and other Norian successions (Orchard *et al.* 2007a) and the Late Norian occurrence of *E. mosheri* morphotype A in Tethys (Orchard 2010). If confirmed, this modification of the Panthalassic biostratigraphical scheme is important for Norian and Rhaetian faunal studies throughout eastern Panthalassa and biostratigraphical successions of ammonoids, halobiids and radiolarians across the Norian–Rhaetian boundary.

Interpretation of strontium isotope values

While a comprehensive interpretation for the causes of the strontium isotope excursions is outside the scope of this paper, we note that the earliest Rhaetian negative excursion occurs several million years before the Triassic–Jurassic mass-extinction boundary. This event is closely correlated to the main eruptive phase of the Central Atlantic Magmatic Province (CAMP). The basalt flows of this large igneous province cover an enormous range of terrestrial deposits, and it follows that an oceanic spreading phase may have initiated earlier (Callegaro *et al.* 2012), which would have left little sedimentary trace in the marine record. The negative strontium isotope excursion is interrupted by a small positive jump and plateau in the Hettangian stage (Callegaro *et al.* 2012) as it is most likely related to continental rifting and weathering. The negative excursion then continues into the Early Jurassic and is most likely related to the continuing weathering of terrestrial CAMP basalt deposits. As non-radiogenic strontium may be sourced from basalt or hydrothermal vent fluids, oceanic crust rifting prior to continental rifting would provide a parsimonious explanation for the timing, magnitude and direction of this excursion.

Conclusions

Previous biostratigraphical research has produced several highly resolved index fossil successions for Late Triassic faunas in both Tethyan and Panthalassic sedimentary sequences, but correlating the faunal successions has proven difficult. Strontium isotope chemostratigraphy is a useful tool for testing the synchroneity of biozones during isotopic excursions. In this study, strontium isotope analyses of bivalve and brachiopod shells suggest two key revisions to Panthalassic biostratigraphy: (1) the Gabbs Formation is not entirely Rhaetian in age, with the lower half of the Nun Mine Member related to Late Norian events; and (2) the Norian–Rhaetian boundary is not defined by the first occurrence of *E. mosheri* morphotype A in Panthalassa; it likely precedes the Norian–Rhaetian boundary, as the morphotype does in Tethys. More research is needed to determine appropriate boundary-delineating species based on these revised temporal schemes. This revision should be reflected in future biostratigraphically dated sedimentary successions from Panthalassic terranes.

Furthermore, our strontium isotope results of Norian bivalve and brachiopod carbonates in Panthalassa reveal significant differences with those defined by conodont analyses from Tethyan sections used in time-series compilations. In particular, Luning Formation $^{87}Sr/^{86}Sr$ values are less radiogenic than previously reported Early Norian values, and the lowest Nun Mine Member appears to preserve a previously undocumented strontium isotope negative excursion of unknown origin.

The strontium isotope excursion at the Norian–Rhaetian boundary is a useful global correlation tool for concurrent biostratigraphical schemes. Further work on Middle Norian marine sections is needed to characterize the excursion documented by Korte *et al.* (2003) between the Early and Late Norian. Additionally, age corrections should be made for faunal collections from this important fossiliferous Panthalassic locality to clarify the temporal ranges of the macrofossils that occur within these formations.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Table S1. Isotopic and concentration measurements for carbonate samples from the formations described in the text.