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RESEARCH ARTICLE
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Marine Strontium Isotope Evolution at the Triassic-Jurassic Transition Links Transient Changes in Continental Weathering to Volcanism of the Central Atlantic Magmatic Province

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Key Points:

- High-resolution $^{87}Sr/^{86}Sr$ data spanning 2.5 Myr across the end-Triassic extinction reveals multiphase perturbation of the marine Sr system
- Aggregation with other Sr data documents long-term and short-term changes over 8.5 Myr during the Triassic-Jurassic transition
- Modeling supports the role of Central Atlantic Magmatic Province volcanism in a stepped weathering scenario of fresh basalt and continental crust

Supporting Information:

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

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Abstract The end-Triassic extinction (ETE) is one of the most severe biotic crises in the Phanerozoic. This event was synchronous with volcanism of the Central Atlantic Magmatic Province (CAMP), the ultimate cause of the extinction and related environmental perturbations. However, the continental weathering response to CAMP-induced warming remains poorly constrained. Strontium isotope stratigraphy is a powerful correlation tool that can also provide insights into the changes in weathering regime, but the scarcity of $^{87}Sr/^{86}Sr$ data across the Triassic-Jurassic boundary (TJB) hindered the use of this method. Here we present new high-resolution $^{87}Sr/^{86}Sr$ data from bulk carbonates at Csővár, a continuous marine section that spans 2.5 Myrs across the TJB. We document a continuing decrease in $^{87}Sr/^{86}Sr$ ratio from the late Rhaetian to the ETE, terminated by a 300 kyr interval of a flat trend and followed by a transient increase in the early Hettangian that levels off. We suggest that the first in the series of perturbations is linked to the influx of non-radiogenic Sr from the weathering of freshly erupted CAMP basalts, leading to a delay in the radiogenic continental weathering response. The subsequent rise in $^{87}Sr/^{86}Sr$ after the TJB is explained by intensified continental crustal weathering from elevated CO_2 levels and reduced mantle-derived Sr flux. Using Sr flux modeling, we also find support for such multiphase, prolonged continental weathering scenarios. Aggregating the new data set with published records employing an astrochronological age model results in a highly resolved Sr isotope reference curve for an 8.5 Myr interval around the TJB.

Plain Language Summary The end-Triassic mass extinction ~201 million years ago was one of the most severe crises in the history of life, triggered by massive volcanism in areas around the present-day Central Atlantic Ocean. Although volcanism is expected to produce greenhouse warming through carbon-dioxide outgassing that leads to increased weathering in the continents, finding direct proof for such a scenario is challenging. We report new measurements of the ratios of strontium isotopes from marine limestones and reconstruct the weathering history at the Triassic-Jurassic transition. In the ocean, unradiogenic ^{86}Sr isotopes are sourced from submarine volcanism or weathering of fresh volcanic rocks from Earth's mantle, whereas radiogenic ^{87}Sr isotopes are delivered by rivers from weathering of rocks in Earth's continental crust. We find that a steady long-term decreasing trend in strontium isotope ratio was disturbed by a series of short-term changes at the end of the Triassic. Supported by modeling, we suggest that these changes reflect the eruption of basalts of the Central Atlantic Magmatic Province and the effect of volcanism in intensifying the continental weathering. Knowing more detail about one component in a cascade of environmental changes ultimately helps our understanding of a critical event in the history of the Earth and its biosphere.

1. Introduction

1.1. The End-Triassic Extinction Event and Global Change

The end-Triassic Extinction (ETE, 201.56 Ma, Blackburn et al., 2013) is one of the major mass extinction events within the Phanerozoic, characterized by an ecosystem collapse that led to major turnovers in the biological

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systems in both marine and terrestrial groups (Marshall, 2023; Sepkoski, 1996). This time interval around the Triassic-Jurassic boundary (TJB) is also characterized by severe perturbations of the ocean-atmosphere systems, such as global warming (McElwain et al., 1999), ocean acidification and decline in carbonate productivity (Greene et al., 2012), changes in sea level (Hallam & Wignall, 1999), and enhanced continental weathering (Cohen & Coe, 2007).

The ETE is also associated with disturbances in the global carbon cycle as evidenced by carbon isotope ($\delta^{13}C$) excursions (CIEs) observed in organic carbon and carbonate records (Hesselbo et al., 2002; Pálfy et al., 2001; Ward et al., 2001). Volcanism of the Central Atlantic Magmatic Province (CAMP) is increasingly accepted as the ultimate cause of the extinction and global environmental change (Pálfy & Kocsis, 2014), whereas the CAMP also initiated the breakup of the Pangea supercontinent and the opening of the Atlantic (McHone, 2000). Degassing likely triggered global warming (Capriolo et al., 2021) that promoted shallow marine anoxia (van de Schootbrugge & Wignall, 2015) and caused perturbations in the carbon cycle. Three successive negative carbon isotope excursions (NCIEs) related to the emplacement of the CAMP were identified and labeled as the "precursor" (P-NCIE), the "initial" (I-NCIE), and the "main" (M-NCIE) (Ruhl & Kürschner, 2011). The I-NCIE is associated with the main pulse of CAMP volcanism and is recognized in both marine and continental records (Deenen et al., 2010). These negative $\delta^{13}C$ anomalies are interpreted to reflect the sudden addition of isotopically light carbon to the ocean-atmosphere system, possibly as CO_2 from volcanic degassing (Hesselbo et al., 2002), thermogenic methane from contact metamorphism of organic-rich sediments (Heimdal et al., 2020), biogenic methane from dissociation of gas hydrates (Pálfy et al., 2001), or some combination of these sources (Beerling & Berner, 2002; Hesselbo et al., 2007; Schaller et al., 2011).

Elevated Hg concentrations and Hg/TOC ratios are among the best available proxies of coeval volcanism in both marine and terrestrial sedimentary successions and also helped to establish the connection between ETE and the emplacement of the CAMP (E. B. Kovács et al., 2020; Lindström et al., 2019; Percival et al., 2017; Ruhl et al., 2020; Shen, Yin, Algeo, et al., 2022; Thibodeau et al., 2016; Yager et al., 2021). Two studies have reported a major $\delta^{238}U$ negative anomaly near the TJB, indicating the global spread of marine anoxia at and after the ETE (Jost et al., 2017; Somlyay et al., 2023). Positive $\delta^{34}S_{CAS}$ anomalies are also documented around the ETE, pointing to increased oceanic anoxia and pyrite burial for these intervals (He et al., 2020; Newton et al., 2004).

Although a growing body of paleontological, sedimentological, and geochemical evidence helps characterize the ETE and its connection to the volcanism of CAMP, not all feedback mechanisms of the Earth system at this event are fully resolved yet. A key aspect in understanding the global changes associated with the extinction event is the response of the weathering regime to the CO_2 outgassing from volcanism. Enhanced continental weathering is a potential mechanism linking volcanic activity and marine environmental perturbations, whereas chemical weathering of silicate rocks contributes to climate stabilization by the drawdown of atmospheric CO_2 (Berner et al., 1983). Local weathering proxies have been widely used for the ETE, such as clay mineralogy (Shen, Yin, Zhang, et al., 2022; Zajzon et al., 2012), paleosols (van de Schootbrugge et al., 2020), and the Os isotope systems (Cohen & Coe, 2007), and suggest abrupt changes in the weathering intensity in response to the emplacement of CAMP. However, temporally highly resolved, and accurate constraints on the weathering regime are still scarce for this time interval, partly due to the dearth of continuous marine sedimentary successions across the TJB.

1.2. The Latest Triassic-Earliest Jurassic Marine $^{87}Sr/^{86}Sr$ Record

Reconstruction of the $^{87}Sr/^{86}Sr$ evolution of ancient oceans can provide insights into weathering rates, global tectonic activity, and biogeochemical cycling throughout Earth's history (Chen et al., 2022; Elderfield, 1986; McArthur, 1994; Veizer & Compston, 1974). The strontium isotope composition of seawater has changed throughout geological history due to varying inputs from its two main sources (Burke et al., 1982). Hydrothermal influx from oceanic ridges and hotspots is relatively non-radiogenic with low $^{87}Sr/^{86}Sr$ ratio (~0.703), whereas more radiogenic strontium with high $^{87}Sr/^{86}Sr$ ratio (~0.714) is derived from the weathering of old continental crust and transported by rivers and groundwater (Elderfield, 1986; Jones & Jenkyns, 2001; McArthur, 1994; Pearce et al., 2015). Consequently, the $^{87}Sr/^{86}Sr$ ratio in seawater at any given time reflects the relative balance of inputs from continental and mantle reservoirs (Chen et al., 2022). The strontium isotopic composition of the ocean is homogenous due to its long residence time (~2.5 Myr) in comparison with the three magnitudes faster mixing time of the ocean (~1,000 years) (Hodell et al., 1990), which enables the dating and global correlation of marine

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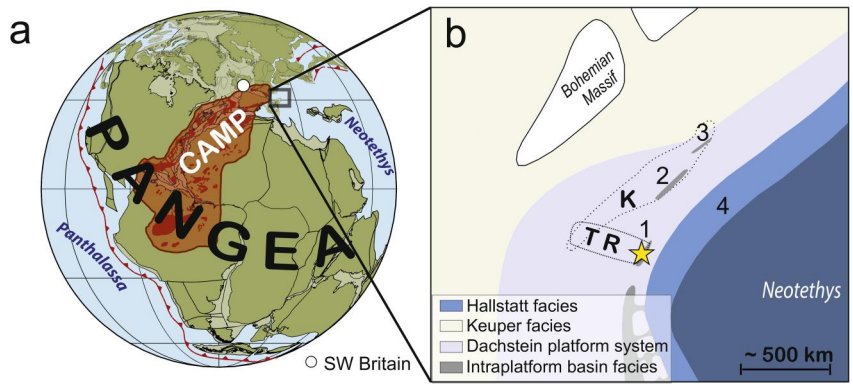

Figure 1. Late Triassic position of the Csővár section in a global (a) and regional (b) paleogeographical context. 1—Csővár Basin, 2—Eiberg Basin, 3—Zliechov Basin, 4—Zlambach section, TR—Transdanubian Range, K—Kössen-type basins. Modified after Haas and Tardy-Filácz (2004), Rizzi et al. (2020), and Pálfy and Kocsis (2014).

carbonates worldwide through the development and use of a global $^{87}Sr/^{86}Sr$ reference curve (McArthur et al., 2020, and references therein).

Despite several studies investigating the long-term change of the $^{87}Sr/^{86}Sr$ ratio in Late Triassic-Early Jurassic records (Callegaro et al., 2012; Jones et al., 1994; Korte et al., 2003; Z. Kovács et al., 2020; Onoue et al., 2022; Tackett et al., 2014; Todaro et al., 2022), a reliable, continuous, and stratigraphically highly resolved and well-constrained data set is still lacking across the TJB. The scarcity of such $^{87}Sr/^{86}Sr$ data hampers our understanding of the major environmental changes during this time interval. It remains controversial whether the emplacement of CAMP led to a significant change (or to any change) in the continuous long-term decrease of the $^{87}Sr/^{86}Sr$ ratio in the Late Triassic (Callegaro et al., 2012; Cohen & Coe, 2007; Jones et al., 1994; Korte et al., 2003; Z. Kovács et al., 2020; McArthur, 2008). Some records indicate a brief reversal of this Late Triassic declining trend during the latest Rhaetian and earliest Hettangian, followed by a phase of negligible change or even a transient increase, that persisted throughout the Hettangian stage (Callegaro et al., 2012; Cohen & Coe, 2007). This pattern, however, is not reflected in the global reference curve (McArthur, 1994; McArthur et al., 2012, 2020). A LOESS statistical analysis of selected data implies a minor deceleration in the decline of marine $^{87}Sr/^{86}Sr$ ratio during the Hettangian (McArthur et al., 2020). However, there are no precise constraints for the magnitude or timing of this shift within the crucial time interval of the TJB due to the scarcity of reliable fossil skeletal materials (Korte et al., 2018; McArthur, 2008). The credibility of this interpretation also relies on the accuracy of the geological time scale, the correlation of sampling localities in Austria and the UK where $^{87}Sr/^{86}Sr$ data originated, as well as the preservation state of the samples (Hesselbo et al., 2002; Jones et al., 1994; Korte et al., 2003).

To resolve these issues, here we present the first high-resolution $^{87}Sr/^{86}Sr$ data set across the TJB interval from a continuous marine section at Csővár in Hungary. We use the generated bulk carbonate Sr isotope data to assess the complex interplay between magmatic activity, weathering, and climate during the Triassic-Jurassic (T-J) transition. Furthermore, we develop an astrochronological framework to enhance the correlation with other sections and aggregate the previously published Sr isotope data for an improved global reference curve for strontium isotope stratigraphy (SIS) across this critical interval of Earth history. We employ modeling to reveal the most likely scenario of forcing the observed evolution of the marine Sr isotope ratio and use it to reconstruct the changes in weathering regimes across the TJB.

2. Geological and Stratigraphic Setting

The Rhaetian to Hettangian Vár-hegy (Castle Hill) section near the village of Csővár in north-central Hungary, ~40 km northeast of Budapest (47°49′12.32″N 19°18′28.23″E, referred to as the Csővár section hereafter), is one of the rare continuous marine sections through the TJB globally (Pálfy & Dosztály, 2000). The outcrops of the area are situated within the fault-bounded Nézsa-Csővár block, which forms part of the Transdanubian Range Unit that, in turn, belongs to the ALCAPA Unit (or terrane) within the Alpine-Carpathian orogenic system (Haas & Tardy-Filácz, 2004). It represents the distal margin of the Dachstein Carbonate Platform along the western Neotethys shelf during the Late Triassic (Haas et al., 2010) (Figure 1). At this time, the shelf was divided

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into intra- and periplatform basins, such as the Csővár Basin, where the Csővár Formation was deposited. The formation consists of limestone deposited in slope, toe-of-slope and basinal environments (Haas et al., 1997).

The TJB at Csővár is recognized using biostratigraphy and carbon isotope chemostratigraphy. The fossil record of the Csővár section includes ammonoids, conodonts, radiolarians, foraminifera, and palynomorphs but is generally sparse. Nevertheless, a detailed biostratigraphical framework was developed that allows for constraining the TJB to a narrow stratigraphic interval (Götz et al., 2009; E. B. Kovács et al., 2020; Kozur, 1991, 1993; Pálfy & Dosztály, 2000; Pálfy et al., 2001, 2007). A distinctive negative carbon isotope anomaly associated with the ETE was recorded from the Csővár section, recognized as one of the first NCIEs reported globally for the TJB (Pálfy et al., 2001). Subsequently, new high-resolution $\delta^{13}C_{carb}$ measurements on the Csővár section yielded a similar pattern (E. B. Kovács et al., 2020; Pálfy et al., 2007). The largest negative peak with an approximately −6‰ shift, observed between 17 and 18.4 m, is identified as the globally recognized I-NCIE. The P-NCIE and the extensive M-NCIE are not unambiguously evident in the Csővár record. In addition, a major mercury anomaly was detected, coincident with the I-NCIE, inferred to represent the onset of the extrusive phase of CAMP volcanism (E. B. Kovács et al., 2020). A negative shift in $\delta^{238}U$ between 17.6 and 21.6 m is aligned with the I-NCIE and Hg anomalies, suggesting that globally significant seafloor anoxia also developed at the end of the Triassic and continued into the earliest Jurassic (Somlyay et al., 2023).

The cyclostratigraphical analysis of elemental and stable isotope geochemical data from the Csővár section revealed periodicities comparable to the orbital cycles of the ∼405 kyr long- and ∼124 kyr short eccentricities, the ∼34 kyr obliquity, and the ∼17–21 kyr precession (Vallner et al., 2023). Thus, an astrochronological age model was developed for the approximately 52 m thick measured section, suggesting that it was deposited in 2.9–3 Myr, with an average sedimentation rate of 1.73–1.79 cm/kyr. Combining the cyclostratigraphy with previously published bio- and chemostratigraphical data allows the placement of the TJB at 21.8–22.2 m (i.e., Beds 58–59) (Vallner et al., 2023).

3. Materials and Methods

3.1. Sampling and Preparation of Bulk Carbonate

Fine-grained, micritic limestone bulk rock samples were collected from the Csővár section and used for geochemical analyses. In total, 70 samples were chosen for $^{87}Sr/^{86}Sr$ isotope measurements and elemental characterization. The sampled levels are identical to, but represent a selected subset of, those previously used to generate a high-resolution $\delta^{13}C_{carb}$ curve (E. B. Kovács et al., 2020) and carry out a cyclostratigraphical analysis (Vallner et al., 2023). The sample spacing is intentionally uneven, 20 cm around the ETE and TJB but less dense below and above. Any veins, stylolites, faults, and slumps were avoided during the sampling of the outcrop. Thin sections were prepared, and samples were selected for micro-drilling at Yale University after diagenetic screening based on petrographic observations, carefully targeting the fine micrite fraction while avoiding any visible minor veins, surface weathering, dolomite or coarse-grained calciturbidite. Selected samples were micro-drilled with a tungsten-carbide bit to obtain powder for leaching.

3.2. Leaching of Samples

Strontium concentration in carbonate samples is generally low, making them sensitive to contamination from other phases during dissolution. This is particularly a concern for detrital silicate minerals, as they can introduce significant amounts of strontium into the sample skewing the analytical results. Therefore, the samples were subjected to multi-step leaching procedures at the Yale Metal Geochemistry Center, Yale University, USA.

A pre-leach was applied, where samples were treated with 1 N ammonium acetate for a period of 30 min to remove loosely bound Rb and Sr cations. Samples were then centrifuged, with the supernatant being discarded and the solid powder being washed with ultrapure water (MQ2). This step was used to remove any sorption exchangeable ions from the samples. After the pre-leach, to target the calcite phase, while avoiding any dissolution of detrital phases, the samples were digested in dilute 0.02 N HCl for 4 hr then centrifuged and the supernatant collected. This was repeated for 2 hr and then for 10 min of digestion.

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3.3. Major and Minor Element Analysis

The ratios of elements such as Li, Mg, Sr, Al, Mn, and Fe relative to Ca were determined using a Thermo Scientific Element XR Inductively Coupled Plasma Mass Spectrometer (ICP-MS) at the Yale Metal Geochemistry Center. The analysis was performed on a portion of the sample solutions that were first diluted with 5% HNO_3 and spiked with 1 ppb of indium. Based on the measured Sr concentrations in the solutions, a specific amount of the aliquot was pipetted to achieve a target Sr concentration of 300 ppb.

3.4. Strontium Isotope Analysis

Column chromatography for the measurement of $^{87}Sr/^{86}Sr$ ratios was done in a Class 1,000 cleanroom at the Isotope Climatology and Environmental Research Center at the Institute for Nuclear Research (ATOMKI) in Debrecen, Hungary. The samples were treated twice with 67% HNO_3 and dried, then dissolved in 4 × 1 ml 8 M HNO_3. For the column chemistry, crown-ether based Sr-Spec Resin (100–150 μm particle size) from Triskem International, France was used. Following the column chemistry, samples were treated with 2 × 1 ml 67% HNO_3, dried, and lastly each sample was dissolved in 1 ml 3% HNO_3 for strontium isotope analysis. Strontium isotope ratios ($^{87}Sr/^{86}Sr$) were measured on a Thermo Scientific NEPTUNE Plus multi-collector ICP-MS (MC-ICP-MS) equipped with an Aridus-3 (CETAC) desolvation system. Measured isotopic ratios for $^{87}Sr/^{86}Sr$ are corrected for instrumental mass discrimination using $^{88}Sr/^{86}Sr = 8.375209$ as well as by applying an interference correction for $^{87}Rb^+$ and $^{86}Kr^+$ with $^{85}Rb^+$ and $^{83}Kr^+$, respectively. The measured ratios were calibrated against the standard NBS987 (NIST® SRM® 987) to the reported value of 0.710248 (McArthur et al., 2020). The uncertainties of the samples range between 0.000015 (0.0021%) and 0.000033 (0.0045%), with an average of 0.000017 (0.0025%) (±1σ). Nine standard NIST® SRM® 987 solutions that underwent column chemistry in the same manner as the limestone samples were analyzed and yielded a mean $^{87}Sr/^{86}Sr$ value of 0.710246 ± 0.000005 (±1σ), in good agreement with previous studies (McArthur et al., 2020, and references therein). Based on the results, the reproducibility was 0.000020 (±1σ), 28 ppm. Duplicate carbonate samples that went through the same leach process were within 0.005‰.

3.5. Stable Isotope Analysis

Thirty-one selected samples were run for carbon and oxygen isotopes at the Yale Analytical and Stable Isotope Center, using a KIEL IV Carbonate Device connected to a Thermo MAT 253 Isotope Ratio Mass Spectrometer. Carbon and oxygen isotopes aided in identifying the carbon isotope excursions associated with the TJB.

4. Results

4.1. Major and Minor Elements

A total of 70 samples were measured for major and minor elemental compositions. To accurately determine the most reliable $^{87}Sr/^{86}Sr$ ratios of pristine calcite, we used geochemical indicators, such as the Mn/Sr, Mn/Ca, Mg/Ca, Sr/Ca, and Rb/Sr ratios, to assess the detrital contribution and diagenetic alteration of carbonates. For the Mn/Sr ratio, the samples show an average of 0.17003, a minimum of 0.01287 and a maximum of 3.41425 (ppm/ppm). The Mn/Ca ratio has an average of 0.23928, with a minimum of 0.05 and a maximum of 1.4 (mmol/mol). The Mg/Ca ratio has an average of 0.00602, with a minimum of 0.00238 and a maximum of 0.01147 (ppm/ppm). The Sr/Ca ratio yields an average of 2.12101, with a minimum of 0.24 and a maximum of 3.54 (mmol/mol). The detrital Rb/Sr ratio has an average of 0.00025, with a minimum of 0 and a maximum of 0.00296 (ppm/ppm).

4.2. Stable Isotopes

The newly obtained carbon isotope ($\delta^{13}C_{carb}$) values range from −3.6‰ to +3.32‰, with an average of −0.91‰ (Figure 2). Oxygen isotope ($\delta^{18}O$) data vary from −5.43‰ to −0.62‰, with an average of −2.23‰. The carbon isotope record is used to identify the major anomalies that are used for global correlation, primarily the I-NCIE. The carbon isotope trend of the new data is in good agreement with the results of previous stable isotope studies of the Csővár section (E. B. Kovács et al., 2020; Pálfy et al., 2001, 2007). From the base of the section, the first 10 m yield values around an average of 1.6‰. At 11 m there is an abrupt negative shift reaching −0.15‰, the peak is followed by a 6 m gap in analyses, the trend then returns to more positive values. At 18 m, the most negative value of −3.51‰ is reached, followed by another negative peak of −3.17‰ at 21.65 m. After these major anomalies,

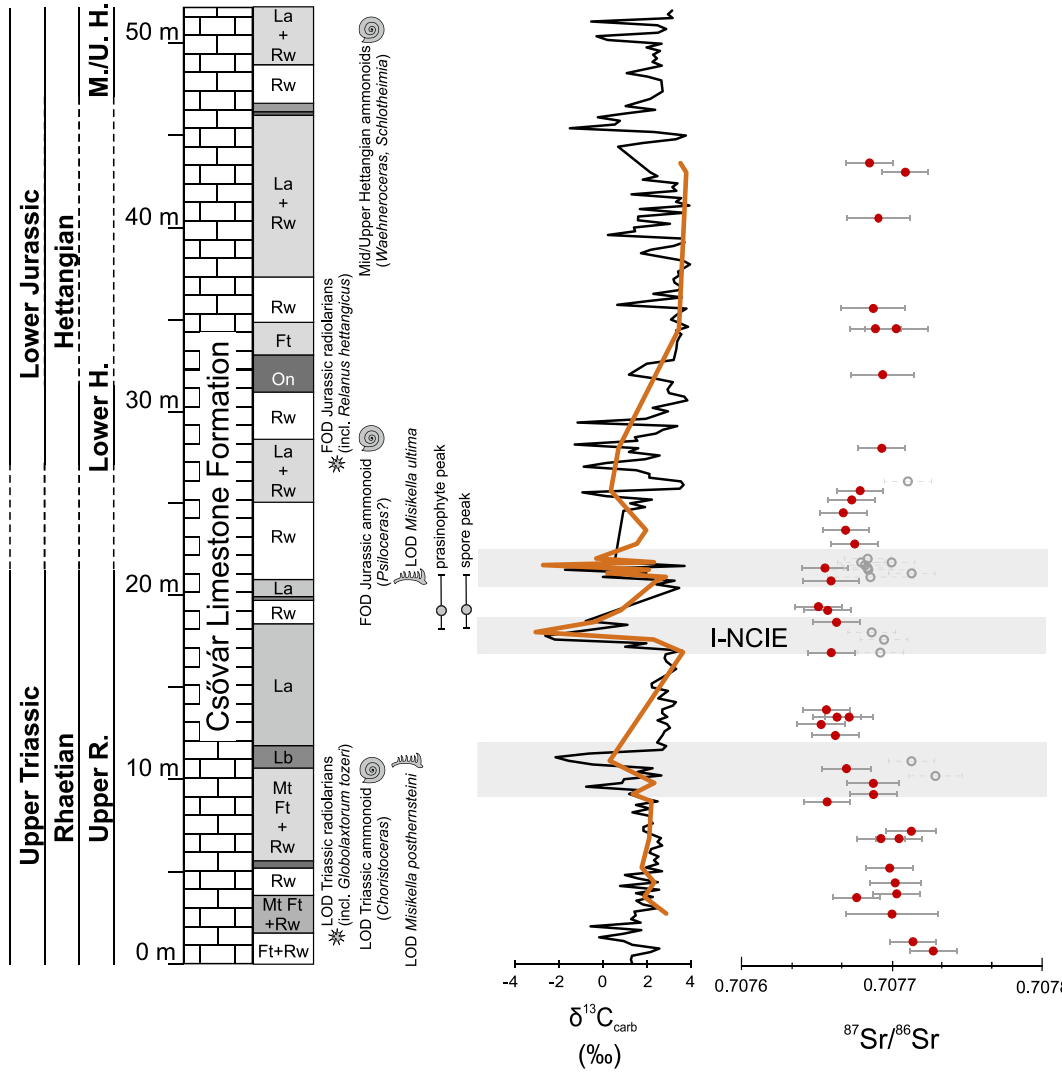

Figure 2. Strontium and carbon isotope data from the Csővár section and their litho-, bio-, and chronostratigraphic contexts. Carbon isotope curve from E. B. Kovács et al. (2020) (black line) and new data (orange line). Strontium isotope values marked by filled red circles and error bars are deemed reliable, and those with open gray circles display a positive offset (see text for discussion). Gray shaded horizontal bars denote the most prominent negative carbon isotope excursions that also correspond to levels with anomalously positive Sr ratios. Lithologic and microfacies log from Haas and Tardy-Filácz (2004) and E. B. Kovács et al. (2020). Rw: radiolarian wackestone, La: calcisiltite-calcilutite laminate, Ft: fine-grained turbidite, Mt: medium-grained turbidite, Lb: lithoclastic-bioclastic grainstone/packstone, On: oncoid, grapestone/packstone/wackestone. Biostratigraphy from Pálfy and Dosztály (2000), Pálfy et al. (2001), Götz et al. (2009), and E. B. Kovács et al. (2020).

there is a gradual return to more positive values interrupted by a longer and more subtle negative shift reaching −0.1‰ at 25.7 m. The oxygen isotope values show a similar trend, with an average of −1.4‰ for the first 10 m. A peak of −3.25‰ at 18 m and the most negative value of −3.59‰ at 21.65 m. After the peak, the remainder of the section has an average value of −2.34‰.

4.3. Strontium Isotopes

The here generated $^{87}Sr/^{86}Sr$ ratios range from 0.70763 to 0.70895, with an average of 0.70772 (Figure 2), in broad agreement with previous Late Triassic-Early Jurassic SIS studies (Korte et al., 2003; Z. Kovács et al., 2020; Onoue et al., 2022). The general trend of the profile from the base of the section is a continuous decrease in $^{87}Sr/^{86}Sr$ from 0.70773 to 0.70765 at 13 m, followed by a segment of no distinctive change up to 21.5 m, after which there is an increase in the $^{87}Sr/^{86}Sr$ to 0.70771 at 26.2 m and the values remain around 0.70769 up to the end

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of the section (Figure 2). These long-term subtle trends are interrupted by short-term positive $^{87}Sr/^{86}Sr$ anomalies. Three major positive anomalies are distinguished: the first one between 8.8 and 12.4 m, reaching its peak at 10.2 m, 0.70773, and the second one is between 16.9 and 18.55 m, reaching 0.70769. The third one is between 21 and 22 m, reaching 0.70771 at 21.2 m. A fourth minor, but distinguishable positive peak with small amplitude is observed at 26.2 m, reaching 0.70771.

5. Discussion

5.1. Assessment of Possible Diagenetic Overprint

To faithfully reconstruct the $^{87}Sr/^{86}Sr$ ratio of ancient seawater, the analyzed material must be well-preserved. Although the results from bulk carbonates that are prone to subtle post-depositional alteration may be considered less reliable, they, nevertheless, can fall within the range of $^{87}Sr/^{86}Sr$ ratios measured in skeletal material of marine fossils. Geochemical screening and appropriate Sr extraction techniques increase the likelihood of obtaining marine signatures. Furthermore, in stratigraphic sequences where well-preserved fossils are scarce or non-existent, such as in the Precambrian or during mass extinction events such as the end-Permian or the ETE, the use of bulk carbonate rock remains the only practical method of continuous sampling for seawater $^{87}Sr/^{86}Sr$ studies (Chen et al., 2022; Halverson et al., 2007; Z. Kovács et al., 2020; Onoue et al., 2022; Saltzman & Sedlacek, 2013). The dissolution of bulk carbonate may lead to contamination of strontium from detrital aluminosilicate and diagenetic secondary phases, potentially resulting in inaccurate results; therefore, proper diagenetic screening is needed (McArthur et al., 2020). Here, we evaluated the diagenetic alteration of every sample, and used only the results of the least altered ones in the reconstruction of $^{87}Sr/^{86}Sr$ trends.

The recent revision of the Precambrian seawater $^{87}Sr/^{86}Sr$ curve, including new guidelines on different dissolution and diagenetic screening methods used in Sr isotopic work, provides the basis of our screening protocol for the bulk carbonate samples from the Csővár section (Chen et al., 2022). We used geochemical element ratios and cross-plot diagrams for assessing possible diagenetic processes that influenced the geochemical signal of the sedimentary sequence (Figures S1 and S2 in Supporting Information S1). Geochemical screening was carried out using four elemental ratios, Mn/Sr, Mg/Ca, Sr/Ca, and Rb/Sr, combined with stable isotope data ($\delta^{13}C$, $\delta^{18}O$) and the assessment of $^{87}Sr/^{86}Sr$ ratios. The Mn/Sr and Sr/Ca ratios are useful geochemical proxies to evaluate the preservation state of the samples, as both enrichment of Mn and depletion of Sr in a sample may indicate post-depositional alteration of the primary carbonate. Using the Mg/Ca ratio together with Mn/Sr and Sr/Ca ratios can help to identify the modification of the primary carbonate during dolomitization. The Rb/Sr ratio is commonly used to evaluate the influence of terrigenous input on limestone samples. Possible clastic contamination of samples was assessed based on the trace elemental compositions, and the affected samples were excluded. In general, diagenesis may lead to a decrease in Sr concentration in the samples and alteration results in more radiogenic and higher $^{87}Sr/^{86}Sr$ ratios (Veizer & Compston, 1974). Therefore, significantly elevated $^{87}Sr/^{86}Sr$ ratios were considered altered. Specifically, we applied the following criteria to evaluate if the samples are well-preserved and represent the primary Sr signal:

$Mn/Sr < 0.1$ (Chen et al., 2022; D. Li et al., 2011; Zhou et al., 2020)
$Mg/Ca < 0.05$ (Chen et al., 2022; D. Li et al., 2011)
$Sr/Ca > 1$
$Rb/Sr < 0.04$ (Onoue et al., 2018, 2022)

Additional sample screening was done using cross-plots (see Figure S1 in Supporting Information S1). Samples that did not meet the criteria were excluded from further analysis and interpretation. Overall, out of the 70 samples measured for Sr isotope stratigraphy (Figure S3 in Supporting Information S1), results of 52 samples were used in the interpretation (Figure 2).

5.2. The $\delta^{13}C_{carb}$ Record

The trend of the here reported $\delta^{13}C_{carb}$ data from the new suite of samples for Sr analysis agrees well with the values reported in previous studies of the Csővár section, in particular the more recent, higher resolution $\delta^{13}C_{carb}$ data (E. B. Kovács et al., 2020) (Figure 2). The $\delta^{13}C_{carb}$ curve displays major negative isotope anomalies that can be used for global chemostratigraphic correlations.

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The carbon isotope trend of this study distinctly exhibits the I-NCIE, starting at 17.8 m, aligned closely with the pattern observed previously (E. B. Kovács et al., 2020). This concurrence underscores the reliability and consistency of the identified excursion and makes ground for its global correlation.

On the other hand, correlation of an earlier anomaly at ∼11 m previously tentatively suggested as the P-NCIE (E. B. Kovács et al., 2020), is revised here on the basis of cyclostratigraphy (Vallner et al., 2023). The time elapsed between this earlier anomaly and the onset of I-NCIE is 413 kyr, which, compared to other sections and the duration of CAMP activity, is too long (Davies et al., 2017; Vallner et al., 2023) for an unambiguous correlation with the P-NCIE.

5.3. Characteristics of the High-Resolution $^{87}Sr/^{86}Sr$ Curve

The $^{87}Sr/^{86}Sr$ profile of the Csővár section exhibit only gradual changes (Figure 2), which is typical of sedimentary sequences without stratigraphic gaps (Jones et al., 1994). The Sr isotope data, generated here for 2.5 Myr within the T-J transition (Vallner et al., 2023), records subtle shifts in the $^{87}Sr/^{86}Sr$ ratio that likely reflect the long-term global trend in the Sr isotope ratio. On the other hand, sudden changes, commonly less than 1 Myr in duration, may represent local changes in weathering or alteration of the original $^{87}Sr/^{86}Sr$ compositions (Richter & Turekian, 1993).

The $^{87}Sr/^{86}Sr$ record of the Csővár section displays three distinct short positive anomalies that coincide with NCIEs (Figure 2). The rate of change in these intervals is too high to reflect solely global changes in the ocean system. Considering that the diagenesis screening did not indicate alteration of these samples, this signal is inferred to reflect changes in the local weathering regime.

In a comparable record, an abrupt shift to radiogenic $^{87}Sr/^{86}Sr$ values was reported from the Fatra Formation in the Kardolína section (Onoue et al., 2022), which was located on the ramp of the southern margin of the Bohemian Massif in the NW Tethys region (Figure 1). The Fatra Formation was deposited in a semi-restricted, shallow marine pull-apart basin, the Zliechov Basin that was a part of the Austroalpine-West Carpathian shelf (Michalík et al., 2007). The rapid shift in the $^{87}Sr/^{86}Sr$ ratio in the Kardolína section between the P-NCIE and I-NCIE is interpreted as a local or regional response to an increase in continental weathering driven by large-scale input of CO_2 from CAMP activity, rather than global changes in seawater Sr isotope ratios (Onoue et al., 2022).

The amplitude of the positive $^{87}Sr/^{86}Sr$ shift in the Kardolína section is more than five times greater than that of the Csővár section, which can be accounted for by the differences in depositional settings at the two sites. The Rhaetian Fatra Formation was deposited on the southern edge of the Bohemian Massif and reflects the increased weathering of the hinterland dominated by Variscan granitoids. The Csővár basin, on the other hand, was an intraplatform basin close to the distal margin of the Dachstein platform and farther from continental influence, which may explain why the short-term positive $^{87}Sr/^{86}Sr$ shifts are more subdued. The coincidence of these short-term shifts in the Sr isotope signal with N-CIEs suggests that CAMP-induced transient pulses of local weathering intensity are correlated with carbon cycle perturbations. However, to understand the long-term global changes occurring during the ETE interval and the T-J transition as a response to CAMP activity, elevated atmospheric CO_2 levels, and variations in continental weathering, only the screened $^{87}Sr/^{86}Sr$ values (excluding the positive anomalies) from the Csővár section are used (Figure 2).

The base of the Csővár section yields values starting from ∼0.70773, which is in accordance with the extension of the persistent unradiogenic trend from the Late Norian (Z. Kovács et al., 2020; McArthur et al., 2020). For the decreasing $^{87}Sr/^{86}Sr$ trend in the Early Rhaetian, three possible explanations were proposed (Z. Kovács et al., 2020; Onoue et al., 2022): (a) the dissolution of carbonates predating the Norian, which are characterized by low $^{87}Sr/^{86}Sr$ ratios, (b) partial dissolution of widespread Late Triassic marine and continental evaporites with low $^{87}Sr/^{86}Sr$ ratios, or (c) the development of continental rift basins during the incipient breakup of Pangea, which could have led to the influx of isotopically light Sr from the mantle, resulting in lower Sr isotope ratios. The decreasing trend to ∼0.70765 continues up to 13 m, followed by a leveling at values between ∼0.70765–0.70766 up to ∼21 m. This flat interval with no trend is characterized by the most unradiogenic values in the section and is attributed to a large mantle-derived Sr flux to the oceans related to the early phase of CAMP activity (Heimdal et al., 2020). The flat segment transitions into an increasing trend between ∼21 and ∼26 m toward a more radiogenic value of ∼0.70769, which remains relatively constant for the remainder of the section. The start of the increasing trend in the $^{87}Sr/^{86}Sr$ ratios postdates the I-NCIE and could be caused by the continental weathering

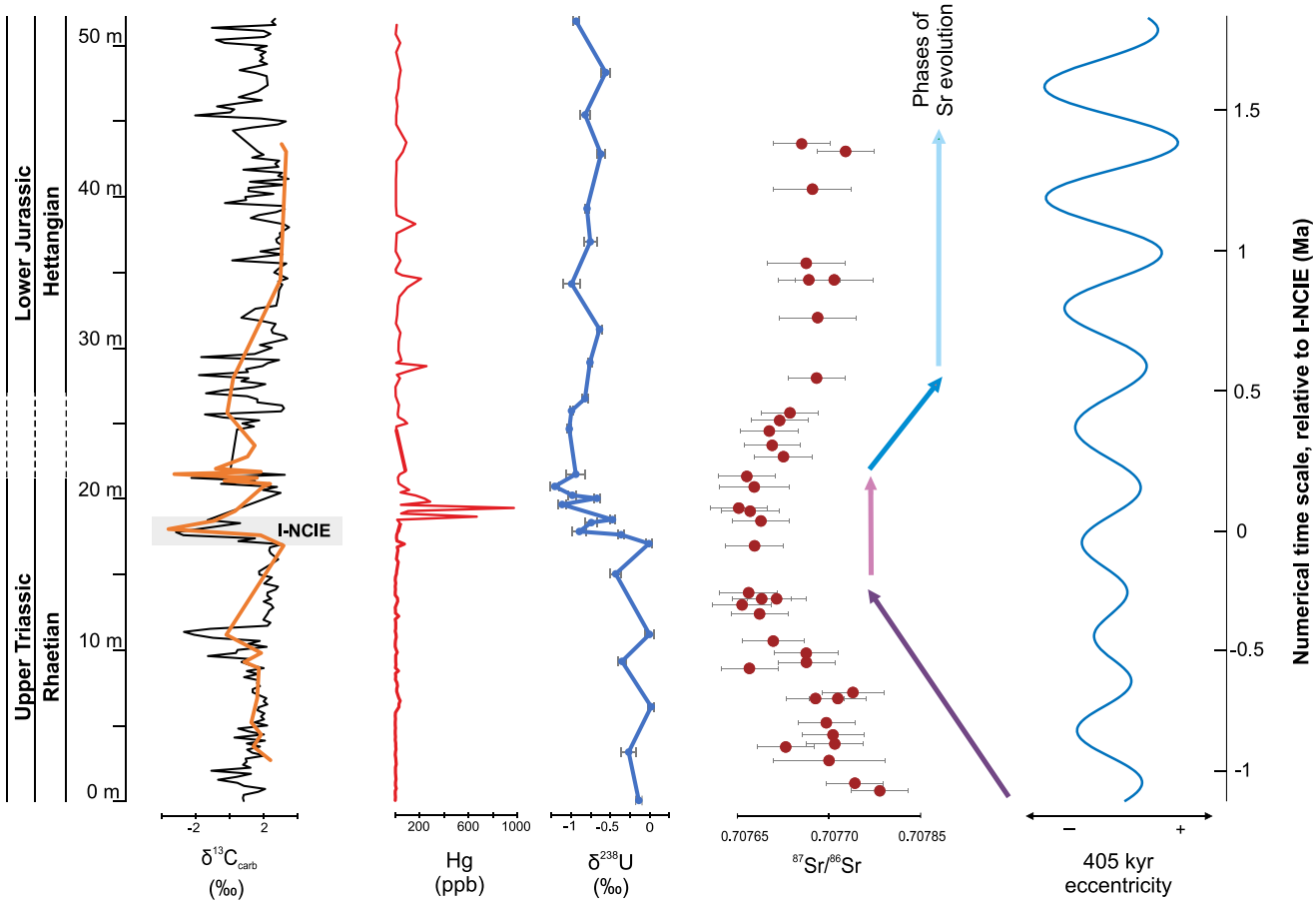

Figure 3. Multiproxy geochemical records of the Csővár section. $\delta^{13}C$ from E. B. Kovács et al. (2020) in black and this study in orange. Hg concentrations from E. B. Kovács et al. (2020), $\delta^{238}U$ from Somlyay et al. (2023), $^{87}Sr/^{86}Sr$ this study. Filtered long eccentricity cycles and numerical time scales from Vallner et al. (2023).

increase in response to elevated atmospheric CO_2 levels triggered by the emplacement of CAMP. The complex, multiphase evolution of the Sr isotope curve in the Csővár section reveals multiple shifts in the balance of unradiogenic and radiogenic Sr fluxes. Correlation with the onset of CAMP volcanism and the I-NCIE allows to infer changes in continental weathering intensity together with changes in exposed areas of fresh basalts.

5.4. Integrating the $^{87}Sr/^{86}Sr$ Record With Other Geochemical Proxies

The newly obtained data are consistent with previous geochemical studies conducted in the Csővár section and expand our knowledge about the events and feedback mechanisms during the ETE. Major mercury anomalies coincident with the I-NCIE, with Hg concentration peaks at 18.8 m (668 ppb) and 19.4 m (972 ppb), were interpreted to reflect the onset of the extrusive phase of CAMP volcanism (E. B. Kovács et al., 2020) (Figure 3). Additional but less pronounced Hg peaks were also observed in the Hettangian part of the Csővár section, which are likely associated with later pulses of CAMP activity. Notably, however, no Hg enrichment was observed before the I-NCIE. Similarly, the $\delta^{238}U$ values display a relatively high average of −0.22‰, with no major shift before the I-NCIE (Somlyay et al., 2023) (Figure 3). A substantial drop in $\delta^{238}U$ to −0.93‰ at 17.6 m indicates a major and abrupt increase in the global extent of bottom-water anoxia. The onset of this negative shift in the uranium isotope ratios corresponds with the I-NCIE at 17.8 m and indicates a link between the carbon cycle perturbation and marine anoxia with the CAMP volcanism as their possible common cause (Somlyay et al., 2023). The protracted excursion of uranium isotopes suggests that there were sustained oxygen-depleted conditions globally even after the TJB. Coincidently, the more radiogenic $^{87}Sr/^{86}Sr$ trend after the event is congruent with this observation, as it is likely the result of enhanced weathering intensity, which eventually led to elevated nutrient delivery and higher primary productivity in coastal areas (Jost et al., 2017; Meyer & Kump, 2008; Shen, Yin, Zhang, et al., 2022). Additionally, the influx of less dense freshwater may have facilitated the development of

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water column stratification that, together with the elevated seawater temperatures, could cause a decline in oxygen solubility and inefficient ventilation, ultimately leading to the formation and persistence of anoxic bottom conditions (Jost et al., 2017; Somlyay et al., 2023).

In contrast, the changes in the $^{87}Sr/^{86}Sr$ ratio in the section appear to commence before the I-NCIE. The leveling off in the $^{87}Sr/^{86}Sr$ ratio begins at ~13 m, predating the onset of the eruptive activity of CAMP as recorded by the Hg spike. Intrusion of dike and sill systems could have resulted in the release of massive amounts of isotopically light carbon as thermogenic methane from subsurface organic-rich strata (Heimdal et al., 2020; Ruhl & Kürschner, 2011). The resultant increase in atmospheric greenhouse gas concentration is expected to drive intensified weathering. However, the $^{87}Sr/^{86}Sr$ record from Csővár does not show any shift to radiogenic values before the TJB, only a leveling off of the $^{87}Sr/^{86}Sr$ curve. Possibly, any increase in continentally derived radiogenic Sr was compensated by the unradiogenic Sr input from weathering of newly erupted CAMP basalts, resulting in a relatively stable, dynamically balanced seawater $^{87}Sr/^{86}Sr$ ratio. Following the I-NCIE and TJB, there is a delayed turn toward radiogenic trend in the $^{87}Sr/^{86}Sr$ ratio, which then levels off again and persists up to the end of the section, that is, middle/late Hettangian. The rise in radiogenic Sr was delayed due to direct unradiogenic influx and weathering of CAMP, which initially counterbalanced the influx of continental crustal Sr. Ultimately, prolonged weathering of continental crust outpaced the unradiogenic Sr input from the rapid weathering of CAMP-derived basalts (Cohen & Coe, 2007), which led to a delayed but pronounced rise in radiogenic Sr in the system. This suggests that prolonged weathering played a crucial role in regulating the geochemical response of the Earth system to CAMP activity.

5.5. Astrochronological Framework and Correlation of Sections Sourcing Sr Data

Major challenges in reconstructing the changes in marine $^{87}Sr/^{86}Sr$ ratios through the T-J transition stem from correlation ambiguities and lack of precise age control in sections that yielded the isotope data. To resolve these issues, here we attempt to incorporate the new Csővár record into a global data set of $^{87}Sr/^{86}Sr$ ratios reported in earlier publications. To develop a highly resolved reference curve for the T-J transition, we use a robust astrochronological framework of overlapping sections correlated by selected chemo- and biostratigraphic tie points.

The recently developed cyclostratigraphy for the Csővár section (Vallner et al., 2023) is useful for correlation with other TJB sections. Cyclostratigraphy of several representative sections in the Northern Calcareous was used to constrain the Late Triassic numeric time scale (Galbrun et al., 2020), while strontium isotope analyses were carried out in the same set of sections (Z. Kovács et al., 2020). Combining data from these two studies, we attempt to provide numerical age constraints for the samples analyzed for $^{87}Sr/^{86}Sr$ by Z. Kovács et al. (2020) to allow their direct comparison with the new data from the Csővár section.

We argue that the approach of a cyclostratigraphic analysis of a Rhaetian composite record assembled from four overlapping Austrian reference sections (Steinbergkogel, Zlambach, Eiberg, and Kuhjoch) (Galbrun et al., 2020) is fraught with problems caused by different lithologies. Instead, we re-analyzed the individual sections for cyclostratigraphy separately, based on the magnetic susceptibility variations reported by Galbrun et al. (2020). We also re-assessed the correlation of sections that was originally established on their bio- and lithostratigraphy (Galbrun et al., 2020). We focus on those sections that have a well-established and biostratigraphically constrained carbon isotope record, such as the Eiberg and Zlambach sections (see Supporting Information). Although the cyclostratigraphic analysis of the Kuhjoch section, that serves as the Hettangian GSSP (Hillebrandt et al., 2013), was also attempted, it proved unsuitable to assign astrochronological ages to the samples with Sr data (Z. Kovács et al., 2020) for poor preservation of cyclicity. The Eiberg and Zlambach sections were correlated based on biostratigraphy (Galbrun et al., 2020), as the boundary of the Rhaetian *Vandaites stuerzenbaumi* and *Choristoceras marshi* zones is well-defined in both sections. The correlation between the Eiberg and Kuhjoch sections is based on the presence of a dark, organic-rich regional marker bed marking the top of the Kössen Formation, referred to as the "T-bed," located at the top of the Eiberg section and near the base of the Kuhjoch section. In these two sections, the T-bed is characterized by a rapid increase in magnetic susceptibility intensity and a marked negative carbon isotope shift, identified as the I-NCIE. Thus, the Alpine sections can be correlated with the Csővár section via the I-NCIE. The numerical age of the I-NCIE is set to 201.56 (Blackburn et al., 2013; Davies et al., 2017), providing an anchor for the floating astrochronologies. The age of the TJB, based on the first occurrence of the ammonoid *Psiloceras spelae tirolicum* (Hillebrandt et al., 2013) is 201.36 ± 0.17 Ma (Wotzlaw

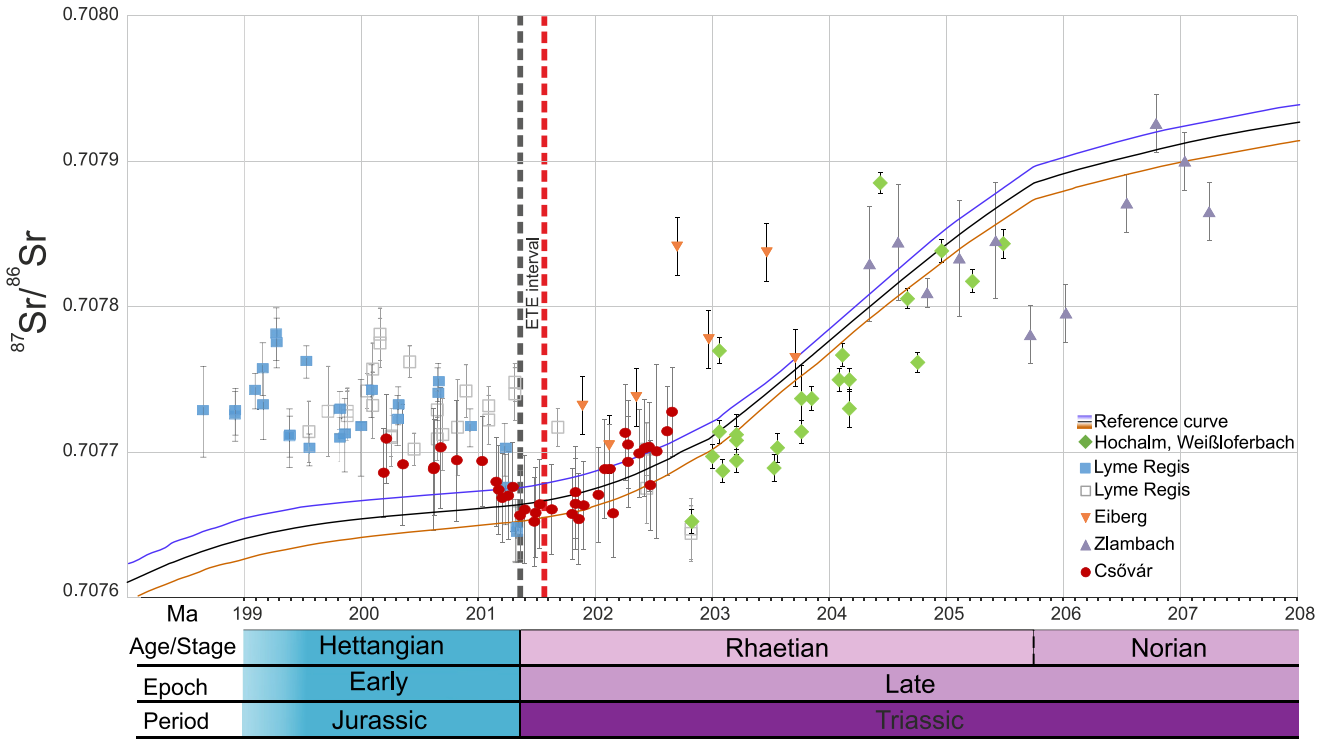

Figure 4. Compilation of selected $^{87}Sr/^{86}Sr$ data from the Triassic-Jurassic boundary (TJB) interval and their comparison with the reference curve in GTS 2020 (McArthur et al., 2020). Error bars are 2sd. Diamonds: Hochalm, Weißloferbach brachiopods (Korte et al., 2003), squares: Lyme Regis oysters (Jones et al., 1994), orange triangles: bulk carbonate from Eiberg, purple triangles: bulk carbonate from Zlambach (the Northern Calcareous Alps) (Z. Kovács et al., 2020), circles: bulk carbonate from Csővár (this study). The red dashed line represents the I-NCIE at 201.56 Ma (Davies et al., 2017), and the black dashed line represents the TJB at 201.36 Ma. Ages are plotted using correlated floating astrochronological age models (see Text and Supporting Information S1) or recalculated to the GTS 2020 (Gradstein et al., 2020). From Lyme Regis, the age of open squares is based on recalculation, and that of solid squares are astrochonologically calibrated after Weedon et al. (2018).

et al., 2014). The $^{87}Sr/^{86}Sr$ ratios determined from the Alpine sections are characterized by considerable scatter, but overall, their trend aligns well with the long-term Late Triassic decline (Z. Kovács et al., 2020) (Figure 4).

Although the Kuhjoch section could not be confidently astronomically calibrated, its Sr data warrant discussion nonetheless. Samples in close proximity to the T-bed (within 30 cm) have high values (~0.7078) (Z. Kovács et al., 2020). At similar stratigraphic positions around the I-NCIE in the Csővár section, samples yield lower values at ~0.70765. Because secondary alteration commonly leads to an increase in Sr isotope ratios, the lower values from Csővár are considered more reliable, also suggested by their better alignment with the global $^{87}Sr/^{86}Sr$ trend. As for the lowermost Hettangian, two samples from Kuhjoch show high values of 0.70784 and 0.70780, which are higher than any other Hettangian data (Jones et al., 1994; Z. Kovács et al., 2020) (Figure S4 in Supporting Information S1). This questions the reliability of the samples from Kuhjoch and stresses the importance of new data from the Hettangian.

An extensive Early Jurassic $^{87}Sr/^{86}Sr$ data set for the Hettangian was generated using mainly oyster shells from Lyme Regis, Dorset (UK) (Jones et al., 1994). The original ages assigned by Jones et al. (1994) were distributed among numerical tie-points using the assumption of equal durations for ammonite subzones, but this method must be approached with caution (McArthur, 2008; Pálfy & Dosztály, 2000). Moreover, three samples formerly regarded as Rhaetian (H7, H12, H22) originate from strata in the lower Blue Lias, which is now considered Hettangian (Weedon et al., 2018). Because of uncertainties regarding the numerical ages of Jones et al. (1994), we not only recalculated their ages according to the Geologic Time Scale 2020 (GTS 2020) (Gradstein et al., 2020) but also employed an alternative approach, using the cyclostratigraphic and biostratigraphic age model of Weedon et al. (2019) to establish numerical ages for the $^{87}Sr/^{86}Sr$ ratios of Lyme Regis. The I-NCIE has not been identified at Lyme Regis (Korte et al., 2009); therefore, the age of the first known bed from the Tilmanni Zone (H6) is set to 201.36 Ma, that is, approximated using the age of the TJB (Hillebrandt et al., 2013; Wotzlaw

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et al., 2014). However, a controversy surrounds the duration of ~4.1 Myr for the Hettangian proposed from a combined analysis of four sections in SW England, including Lyme Regis (Weedon et al., 2019). Nevertheless, such long stage duration is at odds with several other studies (Hüsing et al., 2014; Ruhl et al., 2010; Storm et al., 2020), including that from the Csővár section (Vallner et al., 2023). Based on astrochronologically derived ages exclusively from the Lyme Regis section, the Hettangian is still suggested to span ~3 Myr, a duration that remains longer than suggested by others (Weedon et al., 2019).

5.6. Integration of the $^{87}Sr/^{86}Sr$ Record With Global Data for an Improved Reference Curve

To maximize the usefulness of the new results reported here, the Csővár record is aggregated with and compared to published $^{87}Sr/^{86}Sr$ data from England (Jones et al., 1994) and the Northern Calcareous Alps in Austria (Korte et al., 2003; Z. Kovács et al., 2020) both for an improved reference curve and for insights into the drivers of the observed changes. In addition, we also present a comparison with the latest reference curve in the GTS 2020 (McArthur et al., 2020) (Figure 4). Following the opinion of McArthur et al. (2020), no conodont data is used in this compilation due to their sensitivity to alteration after burial, commonly resulting in significant offset of their $^{87}Sr/^{86}Sr$ values. The Rhaetian brachiopod data of Korte et al. (2003) are included with numerical ages recalculated using the GTS 2020. The Hettangian data from oyster samples (Jones et al., 1994) were excluded from GTS 2020, due to their assumed secondary alteration (McArthur, 2008) mainly on two grounds: (a) the relatively high $^{87}Sr/^{86}Sr$ values which could be attributed to alteration, and (b) the steepness of the early Hettangian slope of the resultant reference curve that was deemed excessive and caused by these high values and/or their erroneously identified ages (McArthur, 2008). McArthur (2008) examined the oysters from Lyme Regis by visual inspection alone; and judged them to be thin-shelled and poorly preserved. However, no additional geochemical screening was performed on these oysters, and the original assessment using Mn and Fe concentrations convincingly excluded any significant alteration effect (Jones et al., 1994). We note that this suite of data was still used in the GTS 2004 (McArthur & Howarth, 2004), attesting to the conflicting views of these samples. In conclusion, we suggest that they record primary seawater signatures, based on a close fit with the data from Csővár, in addition to the geochemical indicators of well-preserved skeletal calcite (Jones et al., 1994). We recalculated their age to the GTS 2020 (from Jones et al., 1994), but note that the lowest datapoints from the Blue Lias oysters are now regarded as Hettangian in age (for more details, see Supporting Information). We also present this $^{87}Sr/^{86}Sr$ data set (Jones et al., 1994) along the numerical age model from cyclostratigraphy of the Dorset coast section (Weedon et al., 2018). The $^{87}Sr/^{86}Sr$ values from the Northern Calcareous Alps (Z. Kovács et al., 2020) and the Csővár section are also astronomically calibrated and correlated using the I-NCIE, numerically calibrated at 201.564 Ma (Blackburn et al., 2013; Davies et al., 2017). To focus on the long-term global changes, the values corresponding to the short-term and presumably local positive $^{87}Sr/^{86}Sr$ anomalies (see Section 5.3.) are omitted from the Csővár data set. Thus, the Sr isotope data from Csővár spanning ~2.5 Myr, is substantially expanded by the compiled data set, covering ~8.5 Myr across the T-J transition (Figure 4).

The compiled data set displays a continuous decrease from the Late Triassic until the ETE interval. This trend starts in the Norian, as revealed by the brachiopod samples of Korte et al. (2003). Bulk carbonate data provide a wider context but show some scatter, especially from the Eiberg section, nevertheless also support the overall decrease in the Late Triassic (Z. Kovács et al., 2020). The Eiberg section consists of mixed siliciclastics and carbonates deposited in an intraplatform basin. There is less scatter in the data from the Zlambach section that exposes a sequence deposited on a toe-of-slope to an open marine basinal environment between the Dachstein platform and the Hallstatt basin.

The long-term decreasing trend continues with the Csővár record that fits well with the data from the Northern Calcareous Alps (Korte et al., 2003; Z. Kovács et al., 2020). The decline of the $^{87}Sr/^{86}Sr$ ratio terminates at the ETE and gives way to a short flat segment with no significant change for ~300 kyr. This trough at the ETE interval is followed by an increasing trend in the earliest Hettangian. The Csővár data thus connect the decreasing Rhaetian values from the Alps to the increasing Hettangian trend observed in England. Notably, in both the Csővár and the Dorset records, the rising limb gives way to another protracted nearly flat segment up to the Middle-Late Hettangian, supporting the case that the samples of Jones et al. (1994) indeed reflect the original seawater Sr signal.

The pattern of the Csővár $^{87}Sr/^{86}Sr$ ratios suggests the injection of significant amounts of unradiogenic Sr into seawater due to the emplacement of CAMP and weathering of basalt during the ETE interval. However, such a

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Table 1
Parametrization of the Sr Box Model

Symbol	Description	Modern value	Model value	Source
F_{riv}^{Sr}	Continental weathering flux	66.1×10^9 mol yr^{-1}	66.1×10^9 mol yr^{-1}	Peucker-Ehrenbrink and Fiske (2019)
R_{riv}^{Sr}	Continental weathering isotopic composition	0.7104	0.7101	Allègre et al. (2010)
F_{HT}^{Sr}	Hydrothermal flux	8.4×10^9 mol yr^{-1}	14.1×10^9 mol yr^{-1}	Peucker-Ehrenbrink and Fiske (2019)
R_{HT}^{Sr}	Hydrothermal isotopic composition	0.7035	0.7035	Peucker-Ehrenbrink and Fiske (2019)
F_{dia}^{Sr}	Diagenetic flux	5.5×10^9 mol yr^{-1}	5.5×10^9 mol yr^{-1}	Peucker-Ehrenbrink and Fiske (2019)
R_{dia}^{Sr}	Diagenetic isotopic composition	0.70849	0.70733	G. Li and Elderfield (2013)
N^{Sr}	Amount of Sr in seawater	1.25×10^{17} mol	1.25×10^{17} mol	Palmer and Edmond (1989)

Note. Strontium fluxes and isotopic estimates adapted from Yobo et al. (2021) and references therein.

direct impact of CAMP on marine $^{87}Sr/^{86}Sr$ appears counterbalanced by other related changes in the Earth surface system. Ultimately, enhanced hydrological cycling and increased continental weathering of more radiogenic continental rocks due to elevated CO_2 could have contributed to the delivery of relatively radiogenic Sr to the global ocean with higher $^{87}Sr/^{86}Sr$ ratios, first canceling out the decrease and then resulting in a Hettangian rise in seawater $^{87}Sr/^{86}Sr$ (Cohen & Coe, 2007).

In a global context, the average values of the Csővár data yield relatively low $^{87}Sr/^{86}Sr$ values of only limited scatter that aligns well with the general trend of previously published data, indicating that well-preserved bulk carbonate samples yield reliable results. The characteristic pattern serves as a basis for interpretation and validation of modeling results. Previously, the scarcity of reliable data from the TJB interval severely limited the applicability of SIS. The inclusion of results from the Csővár section significantly extends and enhances the robustness of the global $^{87}Sr/^{86}Sr$ data set by filling a gap in the T-J transition interval and revealing a rise in the marine $^{87}Sr/^{86}Sr$ ratio after the TJB, following the Late Triassic long-term decrease and a temporary flattening of the curve. Although the oyster data of Lyme Regis (Jones et al., 1994) are in good agreement with the Sr isotope ratios presented here, more data is needed to confirm the $^{87}Sr/^{86}Sr$ trend of the Hettangian. An unresolved issue is to constrain the start of the return of the long-term declining trend in the Sinemurian (Jones & Jenkyns, 2001), which may be connected with the opening of the Central Atlantic ocean basin (Marzoli et al., 2018). The decreasing trend is terminated by a rebound to more radiogenic values only near the Pliensbachian-Toarcian boundary, with a low $^{87}Sr/^{86}Sr$ ratio close to 0.7070 at the next inflection point of the curve (McArthur et al., 2000), which is likely related to the emplacement of the Karoo-Ferrar large igneous province (LIP), marking another event of global significance.

5.7. Modeling Sr Flux Perturbations Around the TJB

We use strontium isotope mass balance box modeling to explore the cycling of strontium among the Earth's oceanic, crustal, and mantle reservoirs and can thus provide additional insights into the observational record. By incorporating knowledge of strontium isotope ratios, fluxes, and reservoirs, models can reproduce changes in seawater composition and therefore help in identifying the underlying mechanisms that influenced the strontium cycle during the TJB interval. Here, we use a simple forward box model to estimate the impact of perturbations on the ocean Sr cycle that could explain the changes in seawater $^{87}Sr/^{86}Sr$ ratio observed during the TJB interval. Thereby, we examine how continental weathering and hydrothermal inputs of Sr may have responded to extensive LIP volcanism. Here, the hydrothermal input is understood as the sum of all mantle-derived Sr inputs and is not restricted to Sr input from MORB-related hydrothermal sources. We employ a model developed by Yobo et al. (2021), where a coupled Sr mass and Sr-isotope mass balance approach was used. The model parameters are derived from modern values but are adapted to the end-Triassic (Table 1). The following Equation 1 was employed to compute changes in the oceanic Sr inventory over time:

$$\frac{dN^{Sr}}{dt} = F_{riv} + F_H + F_{dia} - F_{ppt} \quad (1)$$

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where N^{Sr} represents the number of moles of strontium present in the oceans, and the variables correspond to the fluxes of strontium, which include riverine sources (continental weathering, F_{riv}), hydrothermal sources (F_H), diagenetic sources (F_{dia}), and carbonate precipitation flux (F_{ppt}), respectively. Changes in ocean $^{87}Sr/^{86}Sr$ over time were calculated using Equation 2:

$$\frac{dR^{Sr}_{SW}}{dt} = \frac{F^{Sr}_{riv}\left(R^{Sr}_{riv} - R^{Sr}_{SW}\right) + F^{Sr}_{H}\left(R^{Sr}_{H} - R^{Sr}_{SW}\right) + F^{Sr}_{dia}\left(R^{Sr}_{dia} - R^{Sr}_{SW}\right)}{N_{Sr}} \quad (2)$$

where R^{Sr}_{SW} represents the $^{87}Sr/^{86}Sr$ ratio of the oceanic Sr reservoir, influenced by the $^{87}Sr/^{86}Sr$ ratios of Sr inputs from riverine (R^{Sr}_{riv}), hydrothermal (R^{Sr}_{H}), and diagenetic (R^{Sr}_{dia}) sources, respectively.

The Sr input fluxes and their $^{87}Sr/^{86}Sr$ ratios were obtained from present-day estimates and adjusted to end-Triassic values whenever possible and justified (Table 1). The model was run for 3 million years, which is in broad agreement with the time of deposition for the studied section at Csővár (Vallner et al., 2023).

The initial Sr isotope mass balance is normalized to the end-Triassic contemporaneous seawater isotope value (~0.70773) (Figure 5). Therefore, the initial $^{87}Sr/^{86}Sr$ ratio of all continental weathering sources of Sr (F_{riv}) is adjusted from 0.71040 (present-day ratio) to 0.7086 to achieve a steady state $^{87}Sr/^{86}Sr$ ratio of ~0.70773 for end-Triassic seawater based on values obtained from the base of the Csővár section. This adjustment may not reflect the true value of the continental weathering regime; it only serves as an initial value that makes comparison possible with the assumed steady state baseline conditions. The primary input fluxes of Sr to the oceans, F_{riv} and F_H, drive changes in the oceanic Sr cycle (Allègre et al., 2010; Elderfield, 1986; G. Li & Elderfield, 2013; Peucker-Ehrenbrink & Fiske, 2019). Modifying either one or both fluxes induce changes in the $^{87}Sr/^{86}Sr$ ratio of seawater, which would then gradually approach a new steady state $^{87}Sr/^{86}Sr$ ratio and slow down exponentially with time. In order to accurately simulate past changes, incorporating geological constraints is essential for implementing the box model and achieving the most realistic scenario. In this way, previous studies, models, and proxy data were considered when modeling the changes in Sr fluxes to the ocean (Z. Kovács et al., 2020; Yobo et al., 2021). These model scenarios reflect the change in Sr flux with respect to the presumed initial state and attempt to reproduce the stepwise nature of change and the protracted rise in the $^{87}Sr/^{86}Sr$ ratio.

From multiple model-runs with different setups, two of the resulting scenarios best replicated our observational data (Figure 5): (a) the mantle-derived flux set to 1.5× (Scenario A) or (b) the mantle-derived flux set to 2× (Scenario B) compared to the assumed initial steady state and in response to CAMP volcanism. The perturbation of 1.5–2.0× starts with the onset of the early CAMP activity and lasts until the end of the main phase of CAMP activity (Heimdal et al., 2020). We note that the entire chronological range of CAMP activity is longer than that of the peak intensity of the volcanic eruptions. The most pronounced hydrothermal perturbation was set to align with the early and main phases of CAMP activity, which are considered the most intense (Marzoli et al., 2018). This time interval corresponds to the flat segment in the Csővár Sr record. The decreasing trend in the $^{87}Sr/^{86}Sr$ ratio is reproduced by reducing the weathering rates compared to the initial steady state. The box model illustrates the relative shifts between the two primary Sr fluxes only, demonstrating that the decreasing trend occurred due to the increased dominance of the hydrothermal flux over the riverine flux. This simple box model cannot take into account any possible Late Triassic dissolution of carbonates and evaporites. Nevertheless, these processes may have plausibly exerted an additional influence on the fluxes utilized in the model (Z. Kovács et al., 2020; Onoue et al., 2022). The assumption of the early opening of rift basins is supported by multiple pieces of evidence for the early onset of hydrothermal activity in the Late Triassic (Callegaro et al., 2012; Z. Kovács et al., 2020). The $^{87}Sr/^{86}Sr$ ratio remains around its nadir in response to the onset of the extrusive phase of the CAMP volcanism for ~300 kyr, then increases toward more radiogenic values. This rise in $^{87}Sr/^{86}Sr$ ratios observed during the TJB interval may have been caused by either (a) the intensification in continental crustal weathering (Cohen & Coe, 2007; Shen, Yin, Zhang, et al., 2022) in response to the elevated atmospheric CO_2 concentrations (Schaller et al., 2011) or (b) a rapid decrease in mantle-derived Sr flux. However, the eruptions of large volumes of equatorial CAMP basalts ($^{87}Sr/^{86}Sr$ ~ 0.7035–0.7050 (Heimdal et al., 2019; Merle et al., 2011)) would have intensified volcanic weathering as well, forcing the oceanic $^{87}Sr/^{86}Sr$ ratio toward unradiogenic values. Furthermore, the erosion and intense weathering of the CAMP basalts started immediately after their emplacement (Cohen & Coe, 2002, 2007), which aligns with the fluctuations in atmospheric CO_2 levels responding to the episodic volcanic and/or thermogenic CO_2 release (Schaller et al., 2011). We suggest the ~300 kyr stable low

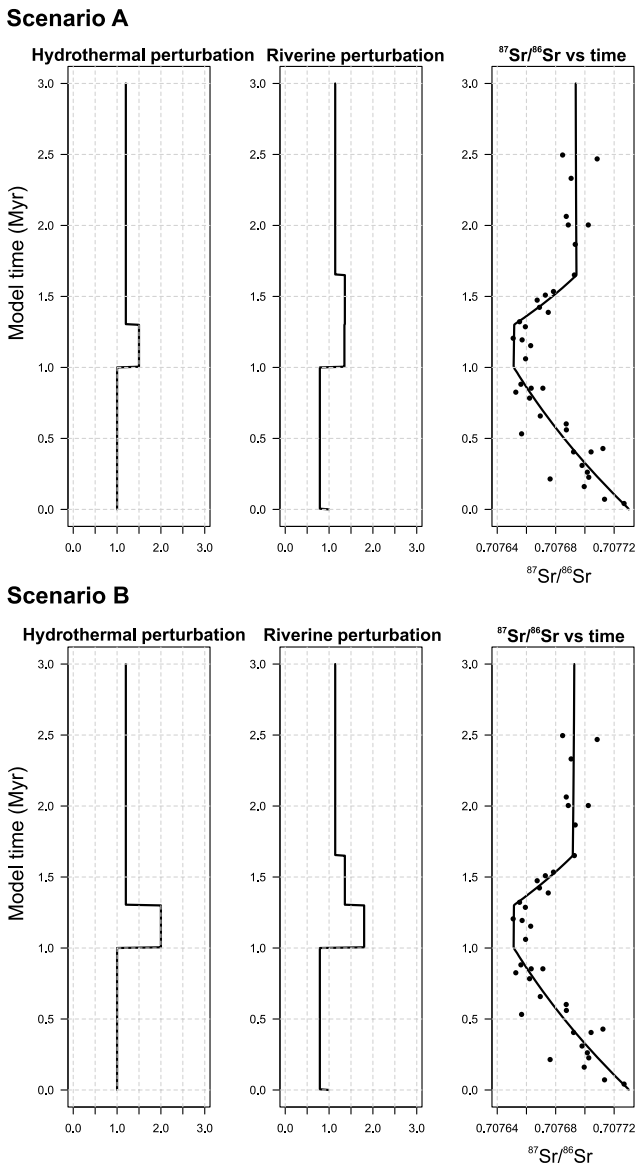

Figure 5. Box model simulations of perturbations in both the hydrothermal and riverine Sr fluxes required to reproduce the change in seawater $^{87}Sr/^{86}Sr$ ratios during the T-J transition observed in the Csővár section. The emplacement of Central Atlantic Magmatic Province (CAMP) and the contemporaneous carbon isotope excursion (I-NCIE) begin at 1 Myr model time, with perturbations normalized to the assumed steady state at model time 0 Myr. Scenario A: Hydrothermal flux increased by 1.5× at the onset of large igneous province (LIP) eruptions. The hydrothermal flux falls back to 1.2× from 1.3 Myr model time but remains elevated throughout. To achieve a decreasing trend till 1 Myr, the riverine flux is reduced to 0.79×. The riverine flux in response to the onset of CAMP increases to 1.35× and remains elevated till 1.65 Myr, resulting in a radiogenic trend that is then reduced to 1.14× and remains elevated until the end of the model. Scenario B: Hydrothermal flux increased by 2× at the onset of LIP eruptions, then fell back to 1.2× from 1.3 Myr. To balance the high hydrothermal flux, the riverine perturbation increases to 1.8× in response to CAMP and recovers stepwise to 1.36× at 1.3 Myr and 1.14× at 1.65 Myr. In both scenarios, the hydrothermal and weathering fluxes remain elevated, reflecting the ongoing volcanism of CAMP and the incipient opening of the Atlantic in the earliest Jurassic.

$^{87}Sr/^{86}Sr$ ratios were caused by the excess unradiogenic Sr from weathered fresh basalts at the start of the extrusive phase of CAMP volcanism counteracting the increasing contribution from enhanced continental crustal weathering. The duration of this interval is probably tied to CAMP emplacement but likely also reflects the weathering history of the basalt. Although CAMP volcanism resulted in the subaerial emplacement of massive amounts of basalt (Marzoli et al., 2018), thick soil cover would have developed in regions of lower elevation, decreasing the weathering rates. Our multiphase prolonged weathering scenario is supported by the measured $^{87}Sr/^{86}Sr$ ratios from Csővár and the Sr flux modeling across the TJB interval. Scenario B (with a twofold increase in the mantle-derived Sr and the intensified continental weathering) provides the best model-data fit. Schaller et al. (2011) argued for a doubling of atmospheric pCO_2 in response to the first CAMP pulse, followed by a decrease to pre-eruption concentrations over ~300 kyr. After the first peak of pCO_2, there was a decline to below background levels, which can be attributed to the prompt consumption of CO_2 resulting from an overall increase in continental weathering (Schaller et al., 2012). The proposed scenario (Scenario B, Figure 5) for the Sr isotopic signal is also consistent with $^{187}Os/^{188}Os$ changes across the TJB (Figure 6), related to the release of significant amounts of unradiogenic Os into the global ocean from the weathering of young mantle-derived basalts (Cohen & Coe, 2002, 2007; Kuroda et al., 2010). This pattern agrees well with the occurrence of the minimum and inflections in the marine $^{87}Sr/^{86}Sr$ record, as both can be linked to the emplacement and immediate weathering of the flood basalt province.

We find that the $^{87}Sr/^{86}Sr$ ratio remained consistently low immediately following the initial CAMP eruptions for ~300 kyr, suggesting an unradiogenic ^{86}Sr dominated weathering flux in the global oceanic Sr budget. As the highly weatherable CAMP basalts were largely consumed or developed a thick soil cover (Cohen & Coe, 2002, 2007; Marzoli et al., 2018), the proportion of unradiogenic components progressively decreased, explaining the delayed onset and protracted increase in $^{87}Sr/^{86}Sr$ ratio.

5.8. Comparison With the Sr Isotope Record of Other LIP-Driven Global Events

Similar to the ETE associated with the CAMP volcanism, other LIPs have also been identified as possible drivers of environmental, climatic, and biotic changes throughout Earth history (Bond & Grasby, 2017; Wignall, 2005). As the control of various LIP emplacements on the marine $^{87}Sr/^{86}Sr$ ratios is still debated (Ingram & DePaolo, 2022), a brief comparison of our end-Triassic case study and other analogous events is warranted.

The emplacement of the Siberian Traps is considered to be the ultimate driver of the end-Permian extinction, the most severe mass extinction in the Phanerozoic (Benton & Twitchett, 2003; Dal Corso et al., 2022). The global oceanic Sr isotopic signal increased continuously from the Paleozoic minimum value in the Middle Permian (Capitanian) to the Early Triassic (Korte & Ullmann, 2018; McArthur et al., 2020). Contradictorily, both a short-term acceleration (Song et al., 2015) and deceleration (Korte & Ullmann, 2018) in the rate of $^{87}Sr/^{86}Sr$ ratio increase have been previously proposed to reflect the Siberian Traps LIP emplacement and the associated changes in weathering rates. However, the roles of riverine Sr flux (more radiogenic values) and fresh basalt weathering (more unradiogenic isotopic composition) received different emphases (Korte & Ullmann, 2018; Song et al., 2015). As

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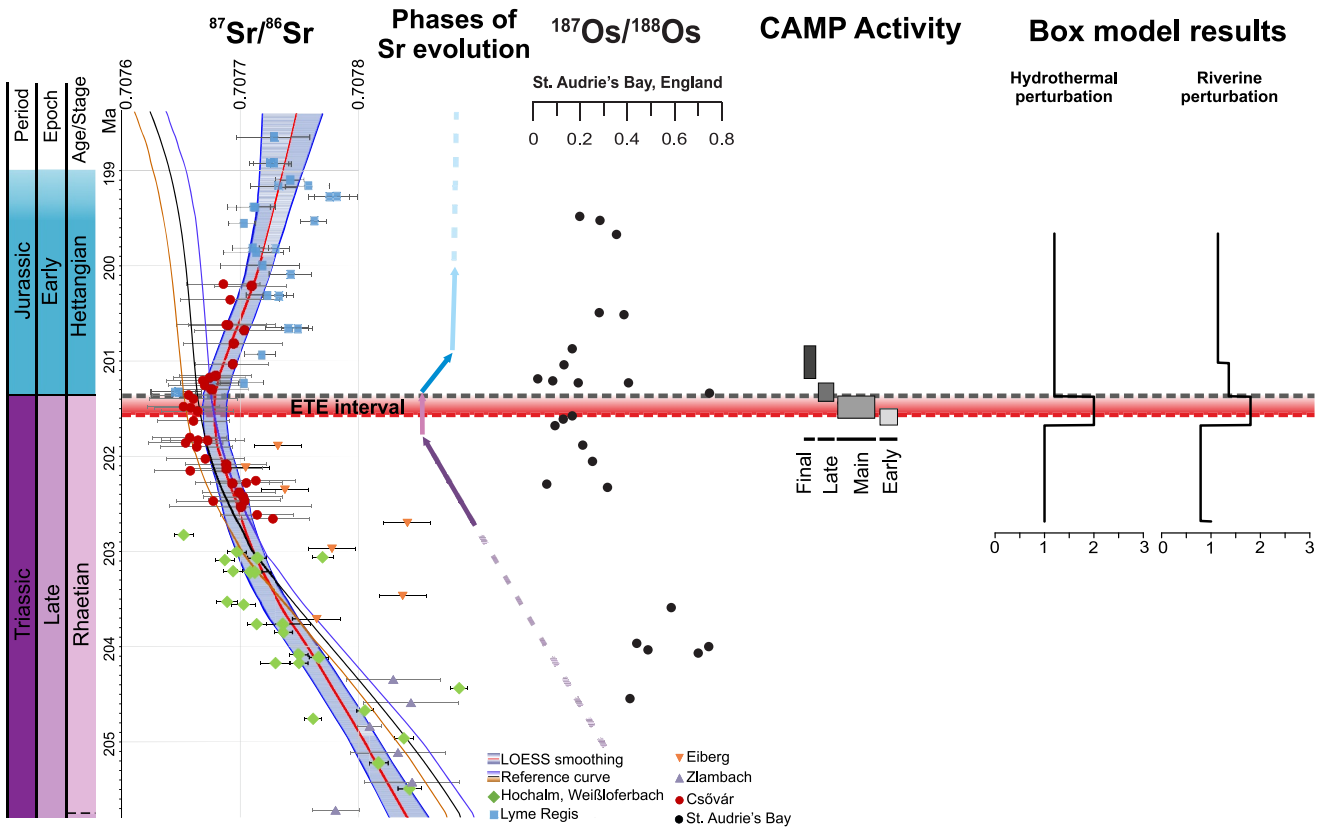

Figure 6. Comparison of a new LOESS smoothed curve ($f = 0.5$) of the compiled $^{87}Sr/^{86}Sr$ data set and the reference curve of McArthur et al. (2020) for the Triassic-Jurassic boundary interval. Data sources are the same as in Figure 4. The osmium isotope data are from Cohen and Coe (2002). The age distribution of Central Atlantic Magmatic Province basalts (extrusive phases) is from Heimdal et al. (2020). Box model output (twofold hydrothermal perturbation) is from this study (Scenario B).

our study questions the validity of conodont Sr isotope data, we regard the brachiopod-based data and proposed acceleration (Korte & Ullmann, 2018) to be more likely than the conodont-based measurements and suggested deceleration (Song et al., 2015). Although the long-term trends in the Late Permian and Late Triassic are opposite, a stepwise short-term response in the Sr system to the emplacement and weathering of continental flood basalts and climatically enhanced weathering of the continental crust occurs at both the EPE and ETE.

Following the CAMP, the Karoo-Ferrar LIP was emplaced in the Early Jurassic, coinciding with a second-order extinction event and perturbations in the marine biogeochemical cycles (Jenkyns, 2010; Pálfy & Smith, 2000). A Sr isotope profile is established at very high resolution and integrated with ammonite biostratigraphy in Yorkshire, England (McArthur et al., 2000). The long-term decline in $^{87}Sr/^{86}Sr$ is terminated at a clear inflection point near the Pliensbachian-Toarcian boundary and followed by a steep rise in the Early Toarcian (Jones et al., 1994), coincident with the Jenkyns Event (or Toarcian Oceanic Anoxic Event, T-OAE). Thus, this hyperthermal event, triggered by the Karoo-Ferrar LIP volcanism, is expressed in a climate-driven increase in radiogenic continental weathering flux.

The Cretaceous is punctuated by several Oceanic Anoxic Events (OAEs) that are also associated with LIP volcanism and show distinctive $^{87}Sr/^{86}Sr$ signatures (Ingram & DePaolo, 2022; Jenkyns, 2010). The characteristic response at major Cretaceous OAEs is observed as pronounced negative $^{87}Sr/^{86}Sr$ excursions. The declines in the $^{87}Sr/^{86}Sr$ during both the Early Aptian OAE 1a (or Selli Event) (Bodin et al., 2015; Jones & Jenkyns, 2001) and the Cenomanian-Turonian OAE 2 (or Bonarelli Event) (Frijia & Parente, 2008; Yobo et al., 2021), were likely driven by the sudden increase in mantle-sourced submarine volcanism, as both events are synchronous with the genesis of oceanic plateau basalts.

As demonstrated above, the geochemical response to LIP-associated global events is not uniform. The changes in the global $^{87}Sr/^{86}Sr$ ratio associated with LIP-driven events are the result of complex processes, with each case

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exhibiting unique characteristics. First-order differences exist between continental and submarine LIP emplacements on the $^{87}Sr/^{86}Sr$ ratio. The balance is also affected by ongoing system-wide changes in the background, such as long-term climate change and orogenic activity, which can influence the weathering rates, erosion patterns, and sediment transport, affecting the marine Sr isotopic composition. Therefore, a case-by-case approach is needed for understanding the specific factors at play in each LIP event and their relative influence on the global oceanic $^{87}Sr/^{86}Sr$ ratio. In the T-J transition, the CAMP-induced changes revealed in this study provide an example of continental flood basalts emplaced at low latitudes. In this case, at hundred-thousands-year scale first the transient effect of weathering of freshly erupted lava is predominant, before the protracted, climatically driven increase in continental crustal weathering becomes more significant in influencing the global $^{87}Sr/^{86}Sr$ ratio.

6. Conclusions

Here, we present the first high-resolution $^{87}Sr/^{86}Sr$ data set across the TJB interval from the biostratigraphically and chemostratigraphically well-constrained continuous marine TJB section at Csővár, to resolve uncertainties about the timing and magnitude of change in the mantle-derived and continental weathering fluxes of Sr to the global ocean. Based on the 52 well-preserved samples that represent a 2.5 Myr depositional history, anchored to carbon isotope stratigraphy and cyclostratigraphy, the $^{87}Sr/^{86}Sr$ ratio displays modest but distinctive variations: (a) the steady but gentle latest Triassic decline is terminated by (b) a near stagnant, low isotopic ratio near the system boundary (near the initial NCIE), followed by (c) an increase in the $^{87}Sr/^{86}Sr$ ratio in the earliest Jurassic, then a (d) leveling off in the values.

The Sr data from Csővár is aggregated with published data from the Northern Calcareous Alps and SW England that are also astrochronologically dated and correlated using integrated carbon isotope stratigraphy and biostratigraphy. The composite data set spans 8.5 Myr across the T-J transition. From the late Norian, it displays a long-term decrease that is followed by a complex, multiphase perturbation starting near the ETE, a 300 kyr interval of stagnant, low isotopic ratio and a subsequent rise in the marine $^{87}Sr/^{86}Sr$ ratio before achieving a new steady-state in the Hettangian. This suggests that the influx of unradiogenic Sr into coeval seawater from the weathering of fresh CAMP basalt delayed the prolonged continental crustal weathering response, caused by elevated atmospheric CO_2 levels, supplying radiogenic Sr to the global ocean and increasing the $^{87}Sr/^{86}Sr$ ratios.

We can reproduce the $^{87}Sr/^{86}Sr$ results using a forward mass balance model output with forcing from early hydrothermal activity in the latest Triassic, followed by emplacement and weathering of freshly erupted basalts that transiently withheld the development of a radiogenic trend. A radiogenic Sr pulse only commenced after the peak eruptive phase of CAMP and after large volumes of CAMP had been rapidly eroded.

The new $^{87}Sr/^{86}Sr$ data from Csővár incorporated into a larger data set as well as forward box model simulations of the Sr flux, point toward a complex, multiphase scenario of enhanced continental weathering during the TJB interval. Our results increase the resolution and the correlation power of Sr isotope stratigraphy across the T-J transition. However, further Sr isotope studies are needed from other marine successions in this interval, with a similar level of detail to validate the proposed mechanisms for the changes in the global Sr isotopic signal. The comparison of our results with other global events of LIP-related environmental and biotic perturbations highlights that, although enhanced weathering is a common element of the cascade of environmental effects, each event may be unique and different in their detailed history as recorded in the Sr isotope evolution.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

All geochemical, elemental composition and isotope data together with box-model R code are presented as Supporting Information S1. The supplementary materials are archived at Zenodo (Heszler, 2024) under https://doi.org/10.5281/zenodo.10522076.

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