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Late Permian to Late Triassic Large Igneous Provinces: Timing, Eruptive Style and Paleoenvironmental Perturbations

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The emplacement of the Siberian Traps, the Central Atlantic Magmatic Province (CAMP) and the Wrangellia have been linked to the end-Permian, the end-Triassic mass extinctions, and to the Carnian Pluvial Episode (CPE), respectively. Exploring the timing, eruptive styles, and volatile degassing of these Large Igneous Provinces (LIPs) is crucial to understand their causal link to the catastrophic environmental crises that punctuated the Triassic. In this study we review the main characteristics of these LIPs, emphasizing common features and differences, and discussing aspects that are still in debate. Estimates of CO_2 budgets and emissions from the three LIPs are based on the Nb content of little evolved basalts and highlight that early Siberian Traps and CAMP and high-Ti Wrangellia volcanics were quite CO_2-rich. On the contrary, other volcanics from the three LIPs probably emitted relatively low amounts of CO_2, which reinforces the possibility that thermogenic reactions between sills and sediments were additional fundamental suppliers of climate-modifying gases.

Keywords: triassic, siberian traps, central atlantic magmatic province (CAMP), carnian crisis, wrangellia LIP, large igneous province, mass extinction

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INTRODUCTION

The Triassic was a crucial period for shaping the modern world, in terms of the evolution of both the biosphere and the geosphere. While successful faunas and floras spread over Pangea, in the Panthalassa and Tethys oceans, the Triassic biosphere was devastated by two extreme extinctions at its dawn (ca. 252 Ma) and its end (ca. 201 Ma) and by a combined extinction and significant radiation episode at ca. 232 Ma, during the Carnian (e.g., Tanner et al., 2004; Song et al., 2013; Bernardi et al., 2018; Dal Corso et al., 2020, 2022; Wignall and Atkinson 2020). The three main biocrises coincided with the emplacement of three Large Igneous Provinces (LIPs), namely, the Siberian Traps, the Central Atlantic Magmatic Province (CAMP), and the Wrangellia (**Figure 1**). In this article, we review the main features of these LIPs, with a focus on their timing, emplacement styles, and CO_2 budgets. This is followed by an in-depth discussion of their critical roles in the Triassic environmental crises.

CONTINENTAL LARGE IGNEOUS PROVINCES: THE SIBERIAN TRAPS AND THE CAMP

High-precision geochronology proves that the main activity of the Siberian Traps and the CAMP (main pulses at 252.3–251.4 Ma and 201.6–201.0 Ma, respectively; for the Siberian Traps: Kamo

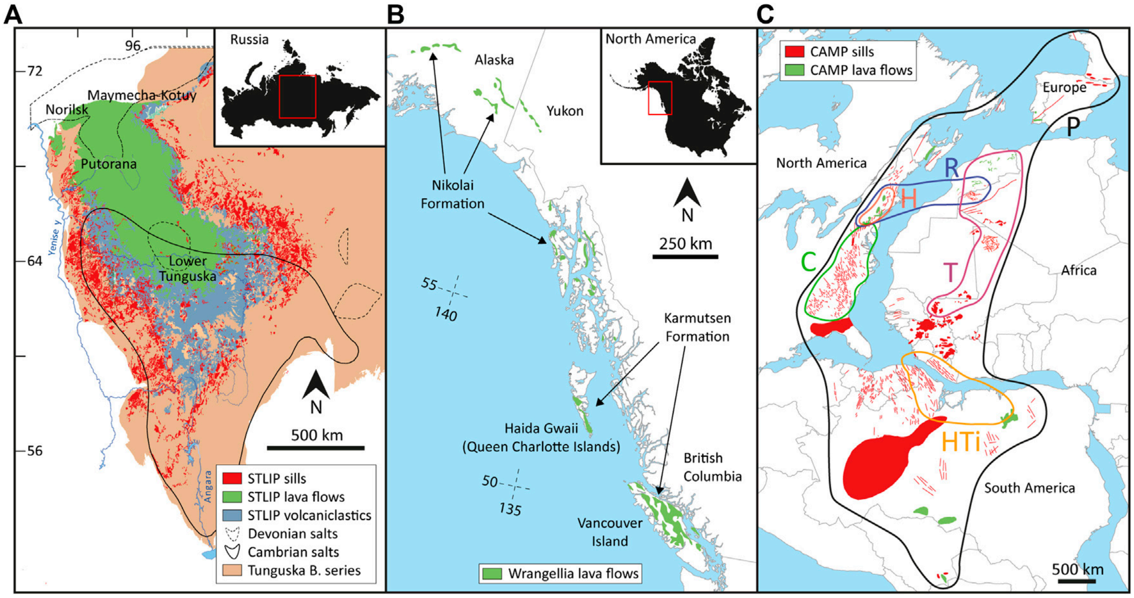

FIGURE 1 | Simplified sketches of **(A)** the Siberian Traps (modified after Svensen et al., 2018) **(B)** the Wrangellia (modified after Lassiter et al., 1995), and **(C)** the CAMP (modified after Capriolo et al., 2020). **(C)** Coloured lines represent the geographic distribution of the six geochemical groups of the CAMP magmas identified by Marzoli et al. (2018): P=Prevalent, HTi=high-Ti, T=Tiourjdal, R=Recurrent, C=Carolina, H=Holyoke.

et al., 2003; Burgess and Bowring, 2015; Burgess et al., 2017; Augland et al., 2019; for the CAMP: Blackburn et al., 2013; Davies et al., 2017, 2021; Marzoli et al., 2019) spanned the end-Permian and end-Triassic extinction intervals, respectively (251.94–251.88 Ma and 201.51–201.36 Ma; Schoene et al., 2010; Burgess et al., 2014; Wotzlaw et al., 2014). The pulsed nature of these LIPs was inferred from magnetostratigraphy and biostratigraphy (e.g., Knight et al., 2004; Panfili et al., 2019; Latyshev et al., 2020), yielding eruption rates possibly two orders of magnitude greater than the most voluminous present-day eruptions, such as those at Hawai'i (e.g., Patrick et al., 2020). The Siberian Traps and the CAMP are among the most voluminous known LIPs (both ca. 3 ± 1 million km^3; Saunders and Reichow, 2009; Marzoli et al., 2018), although a precise estimate of the original and preserved magma volume remains challenging. Large parts of the Siberian Traps are intrusive, subaerial, and huge volumes of volcanics were likely removed by erosion. The best-studied part of the province is on the Siberian Craton, at a paleolatitude of ca. 50–60°N, over an area of ca. 2.5 million km^2 (**Figure 1A**). The CAMP was emplaced over 10 million km^2 straddling the equator, and has been similarly partly eroded away, as demonstrated by the sparsely preserved lava piles (**Figure 1C**).

The first emplacement stage of the Siberian Traps started shortly before 252.24 ± 0.12 Ma with initial pyroclastic eruptions followed by effusive activity emplaced in ca 0.30 Ma. From 251.91 ± 0.07 Ma, the extrusive activity waned and shifted to dominantly intrusive for ca. 0.40 Ma, building the vast network of sills in the Tunguska Basin. These tholeiitic magmas were produced by shallower and extensive melting of a mixed peridotitic-pyroxenitic mantle (Sobolev et al., 2011; Callegaro et al., 2021). Renewed extrusive activity is recognized from 251.48 ± 0.09 Ma, marking the beginning of the third phase of the Siberian Traps. During this phase, tholeiitic extrusive and intrusive activities were accompanied by mafic to felsic alkaline intrusions in Maymecha-Kotuy and Taimyr areas (Elkins-Tanton et al., 2007; Sobolev et al., 2009; Augland et al., 2019). Alkaline melts were produced from a deep (5.5 GPa) and volatile-rich (carbonated) mantle source (Elkins-Tanton et al., 2007). The youngest sill dated in Tunguska (251.35 ± 0.09 Ma; Burgess and Bowring, 2015), and the Guli carbonatitic complex in the Maymecha-Kotuy region (250.20 ± 0.30 Ma; Kamo et al., 2003) represent the youngest known Siberian Traps products.

The beginning of the second (intrusive) phase is considered as the deadly subinterval of the Siberian Traps (Burgess et al., 2017), since it coincides with the beginning of the extinction horizon at Meishan (251.94 ± 0.04 Ma; Burgess et al., 2014), Dongpan and Penglaitan (251.94 ± 0.03 Ma and 251.98 ± 0.03 Ma; Baresel et al., 2017), China. Even if these tholeiitic magmas were probably volatile poor (Sibik et al., 2015), the interaction between the sills and the sedimentary host-rocks (i.e., evaporites, carbonates, marlstones, and coal) likely produced large amounts of thermogenic carbon, sulfur and halocarbon species (Svensen et al., 2018; Callegaro et al., 2021; Sibik et al., 2021).

The end of the Triassic witnessed the emplacement of the CAMP mainly between 201.64 ± 0.03 Ma and 201.36 ± 0.02 Ma (Blackburn et al., 2013; Davies et al., 2017, 2021; Marzoli et al., 2019), coincident with the main end-Triassic extinction interval (201.51 ± 0.15 to 201.36 ± 0.15 Ma; Schoene et al., 2010; Wotzlaw et al., 2014). Basaltic magmas erupted as short-lived pulses (Knight et al., 2004; Marzoli et al., 2019) during this magmatic phase have been shown to be rich in CO_2 and SO_2 (Callegaro et al., 2014a; Capriolo et al., 2020) and possibly triggered the dramatic increase in CO_2, the rise of temperature and the climatic perturbations heralding the end of the Triassic (Landwehrs et al., 2020; Lindström et al., 2021; Capriolo et al., 2022). Later erupted magmas, for example, in North America and Africa (Holyoke and Recurrent groups; Blackburn et al., 2013; Marzoli et al., 2018, 2019) appear to be less voluminous and possibly had limited environmental effects.

Similar to the Siberian Traps, CAMP magmas are mainly preserved as large sills intruding Paleozoic terrestrial sediments in South America and North-western Africa, and Triassic terrestrial sediments in North America and Europe (Marzoli et al., 2018 and references therein). The CAMP basalts mobilized large amounts of organic carbon and possibly halogens from evaporitic deposits (Heimdal et al., 2018, 2019; Capriolo et al., 2021). Available geochronological data indicate that some CAMP intrusions are older than the preserved (and dated) erupted basalts (Davies et al., 2017). However, the intrusion of sills in Amazonia and north-western Africa seems to be relatively prolonged from ca. 201.53 ± 0.07 Ma to ca. 201.35 ± 0.03 Ma (Davies et al., 2017, 2021), i.e., spanning the entire end-Triassic extinction interval (Schoene et al., 2010). However, it is still unclear whether CAMP intrusions occurred in pulses, thus emitting thermogenic volatiles at high rates, and playing a catastrophic role in the end-Triassic crisis.

Unlike the Siberian Traps, CAMP magmas are relatively uniform in composition, mainly being tholeiitic basalts. Whether such relatively high degree mantle melts originated from the deep or shallow mantle is still disputed (e.g., Ruiz-Martinez et al., 2012; Tegner et al., 2019; Boscaini et al., 2022). CAMP basalts lack geochemical signatures of a mantle plume originating from the deep mantle but show a subduction signature, which is best interpreted as reflecting the presence of recycled subducted continental rocks (sediments, mainly; Callegaro et al., 2013; Merle et al., 2014; Shellnutt et al., 2018; Marzoli et al., 2019). The absence of alkaline mafic rocks or carbonatites in the CAMP calls against a significant contribution from particularly CO_2-rich metasomatized mantle portions. In contrast to the Siberian Traps, evidence for explosive volcanic activity is rare for the CAMP, whose lavas are mostly compound pahoehoe flows (e.g., El Hacimi et al., 2011) and therefore occurred as fissure eruptions like the historical Laki eruption in Iceland.

Oceanic Large Igneous Province: The Wrangellia

The Wrangellia LIP presently crops out along the north-western margin of North America (**Figure 1B**). It represents one of the best-preserved accreted oceanic plateaus on Earth, which contrast starkly with continental LIPs in terms of mantle processes, emplacement style and, possibly, environmental implications (Kerr, 2005).

The origin of the Wrangellia tholeiitic basalts has been attributed to deep mantle processes (i.e., mantle plume; Richards et al., 1991; Lassiter et al., 1995; Greene et al., 2009a; Greene et al., 2009b; Shellnutt et al., 2021). The early emplaced low-Ti basalts (0.4–1.2 TiO_2 wt%) were probably sourced from partial melting of a rising mantle plume and show a significant contribution from the subduction-modified lithospheric mantle (Greene et al., 2009a; Greene et al., 2009b). Conversely, the later high-Ti basalts (1.4–2.4 TiO_2 wt%) were sourced chiefly from the mantle plume (Greene et al., 2009a; Greene et al., 2009b).

As an oceanic plateau, the magmatic products of the Wrangellia are considerably different from those of continental LIPs like the Siberian Traps and the CAMP and include tholeiitic submarine and subaerial flows. Few sills beneath and interbedded with the lavas are also present. A total volume of at least 1 million km^3 was estimated for the entire LIP (Greene et al., 2010). Pillow lavas at the base of the volcanic succession are ubiquitous over the entire province. However, they form thinner sequences (~500 vs. ~2,500 m) and are highly vesicular in Alaska and Yukon compared to south-western Canada (Vancouver Island), suggesting a southward deepening of the emplacement depth (Greene et al., 2010). This is consistent with subaerial pahoehoe lavas being relatively more abundant in Alaska and Yukon, where they pile up to 3,500 m (Greene et al., 2010).

The age of the Wrangellia is poorly constrained. A maximum time span of ca. 2 Ma has been inferred from magnetostratigraphic studies (Greene et al., 2010 and references therein). Valuable constraints are offered by biostratigraphy. *Daonella*-bearing shales unconformably underlie the lowest basalts of the volcanic sequence. *Daonella* would indicate a maximum Ladinian age (Smith and MacKevet, 1970; Brack et al., 2005), but *Daonella* is also known from younger Triassic strata (e.g., Fürsich and Wendt, 1977). The termination of Wrangellia volcanism was marked by the establishment of stable carbonate production on top of volcanic successions and was geographically diachronous. On Vancouver Island, the uppermost basalts of the Karmutsen Formation are interbedded with sediments bearing ammonoids and bivalve *Halobia* of the Tuvalian 1 *dilleri* Zone (Upper Carnian; Carlisle and Susuki, 1974). On Haida Gwaii (Queen Charlotte Islands), the volcanic sequence is overlain by the carbonate-dominated Kunga Group that yields conodonts and ammonoids of the Tuvalian 2-3 *welleri* Zone (Desrochers and Orchard, 1991). In south-western Yukon, the volcanism continued to at least the early Norian, evidenced by conodonts recovered from interbedded limestones in the Nikolai Formation (Israel et al., 2006). Ar/Ar and U-Pb ages for the Wrangellia magmatic rocks span between 232 and 226 Ma (Greene et al., 2010 and references therein). However, samples selected for Ar/Ar dating showed widespread alteration leading to large age uncertainties (up to 11 Ma), disturbed spectra, and excess argon. Zircons and baddeleyite selected for U-Pb dating were not chemically abraded, likely yielding ages younger than the actual crystallization ages.

The lack of high precision radioisotopic ages for the Wrangellia precludes the possibility to constrain the onset of magmatism, and to distinguish different pulses in the volcanic activity, in turn hindering reconstruction of rates of volcanic or thermogenic gas discharges. This is crucial as the Wrangellia has been tentatively linked to a period of significant climate changes and biological turnover during the Late Triassic, known as CPE

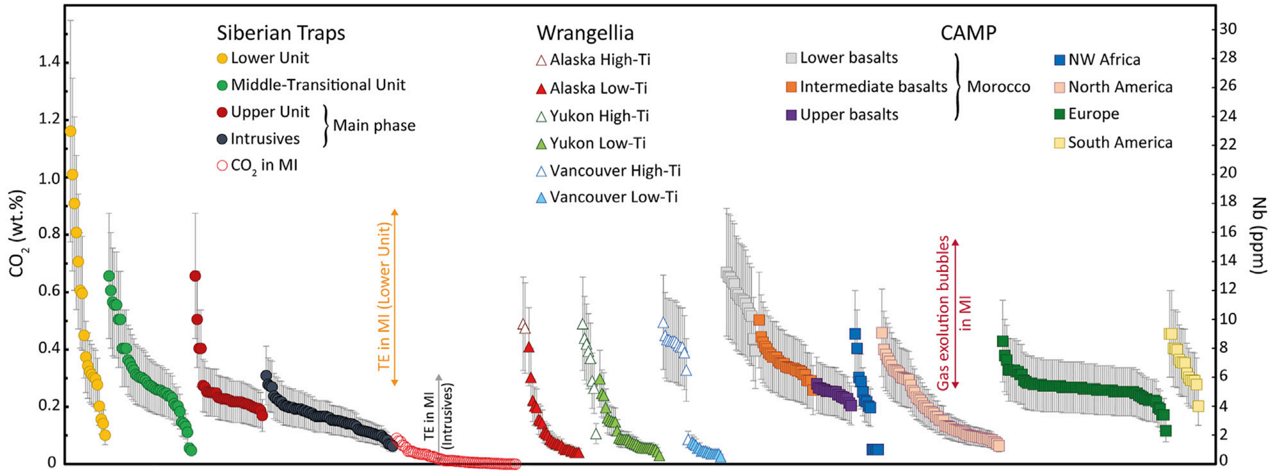

FIGURE 2 | Initial maximum CO_2 budgets obtained from Nb whole-rock concentrations of magmas for the Siberian Traps (circles), the Wrangellia (triangles) and the CAMP (squares). Following Rosenthal et al. (2015), we assumed CO_2/Nb = 505 ± 168, which corresponds to mantle source CO_2 of 75 ± 25 ppm. Data are filtered for MgO > 7wt%. Maximum and minimum MgO contents are 22.9–7.1 wt% (average 10.2 wt%) for the Siberian Traps, 17.5–7.1 wt% (average 9.8 wt%) for the Wrangellia, and 16.6–7.0 wt% (average 8.7 wt%) for the CAMP. Data are plotted in ranked order. Siberian Traps: data from GEOROC Database (http://georoc.mpch-mainz.gwdg.de/); Hawkesworth et al. (1995); Sobolev et al. (2009, 2011); Sibik et al. (2015); Callegaro et al. (2021). Wrangellia: data from Greene et al. (2009a), Greene et al. (2009b), Greene et al. (2010). CAMP: data from De Min et al. (2003); Jourdan et al. (2003); Deckart et al. (2005); Verati et al. (2005); Merle et al. (2011, 2014); Callegaro et al. (2013, 2014b); Bertrand et al. (2014); Marzoli et al. (2019). All data are reported in the **Supplementary Appendix Table**. CO_2 concentrations measured from melt inclusions (MI) for the Siberian Traps (Black et al., 2014; Sibik et al., 2015) are reported for comparison (open circles). Yellow and grey arrows represent CO_2 estimates obtained from trace element (TE) concentrations in melt inclusions following the same approach as whole-rock data. CO_2 concentrations obtained from MI of the Gudchikhinsky Formation (yellow colour; Lower Unit) and of intrusives of the main phase of the Siberian Traps (grey colour; Sibik et al., 2015) are ca. 0.3–0.9 wt% and ca. 0–0.3 wt%, respectively, consistent with the results obtained from whole-rock data. Red arrow represents CO_2 concentrations estimated from gas exsolution bubbles preserved in melt inclusion of CAMP magmas (Capriolo et al., 2020).

(Dal Corso et al., 2020). The finding of four negative carbon isotope excursions (NCIEs) correlated with Hg spikes in sedimentary strata across the CPE suggest a volcanic origin for this event (Dal Corso et al., 2018, 2020; Lu et al., 2021; Mazaheri-Johari et al., 2021). The duration of the CPE was inferred to be of ca. 1.2 to 1.7 Ma based on magnetostratigraphic, biostratigraphic and cyclostratigraphic studies (Zhang et al., 2015; Miller et al., 2017; Bernardi et al., 2018; Dal Corso et al., 2020). Accordingly, two tuffaceous claystones intercalated with CPE-related rocks of the Jiyuan Basin (China) were dated at 233.10 ± 1.30 and 232.90 ± 2.10 Ma (LA-ICP-MS U-Pb zircon ages; Lu et al., 2021). However, although the ages of the Wrangellia and the CPE partially overlap, their relative timing remains highly debated.

DISCUSSION AND CONCLUDING REMARKS

Eruptions of the Siberian Traps, the CAMP, and the Wrangellia LIPs deeply reshaped the Triassic world. In particular, the Siberian Traps and the CAMP emplaced in continental settings as pulsed magmatic events, and both bear strong evidence of interaction between magmas and sedimentary country rocks. A clear difference between these LIPs is shown by the widespread explosive volcanism and abundant alkaline magmatism marking the early and final phases of the Siberian Traps, but unknown for the CAMP. On the other hand, the Wrangellia presents substantial differences as it was emplaced in an oceanic setting, and partially consists of subaqueous lava flows. Due to the lack of high-precision geochronology it is also impossible to clarify whether its magmatic activity was pulsed or continuous.

A recurrent aspect of the Triassic period is that multiple NCIEs were reported worldwide for the end-Permian (e.g., Wu et al., 2021) and end-Triassic mass extinction intervals (Ruhl et al., 2020), as well as for the CPE (Sun et al., 2019; Dal Corso et al., 2018, 2020). NCIEs would testify for the injection of large quantities of isotopically depleted CO_2 into the atmosphere and oceans. Likely, CO_2 (and other greenhouse and poisonous gases) would have been released either from the erupted magmas (Capriolo et al., 2020) or from devolatilization of the intruded host-rocks (Svensen et al., 2009; Capriolo et al., 2021), implying that LIPs-related magmatism was the main driver for catastrophic environmental changes of the Triassic. Since the magnitude of these global crises is also related to the rates at which volatiles were generated, quantifying the process of magma degassing is crucial. Direct estimates of released CO_2 were obtained from fresh, non-recrystallized melt inclusions (e.g., Sobolev et al., 2009; Black et al., 2014; Sibik et al., 2015; Capriolo et al., 2020). However, these are few (and potentially not entirely representative) for the Siberian Traps and the CAMP, and completely lacking for the Wrangellia. We therefore adopted here the approach of Rosenthal et al. (2015) to estimate the initial CO_2 contents of basaltic magmas from their incompatible trace element compositions. In fact, Nb and CO_2 behave similarly during partial mantle melting, both strongly partitioning into the melt phase. However, at shallow depth in the crust, CO_2 is degassed as magma ascends towards the surface (Capriolo et al., 2020), while Nb remains in the melt. We applied this proxy to whole-rock compositions of the three Triassic LIPs (**Figure 2**) filtered for basalts with MgO >7 wt% to consider only those magmas closer to the composition of mantle-derived primitive melts, as suggested by Hernandez Nava et al. (2021).

CO_2 concentrations estimated for magmas of the Siberian Traps are significantly variable within the three magmatic phases previously described (**Figure 2**). High-Ti lava flows of the Lower Unit and the low-Ti magmas of the Middle-Transitional Unit yielded the highest calculated CO_2 contents (ca. 0.1–1.2 and 0.05–0.7 wt%, respectively; **Figure 2**). In contrast, lavas of the Upper Unit and correlated intrusions, which characterize the second and more voluminous Siberian main phase, yielded lower CO_2 contents (ca. 0.1–0.3 wt%; **Figure 2**). Within CAMP, the earliest erupted basalts from north-western Africa are relatively enriched in CO_2 (0.4–0.7 wt%), while the slightly later and ubiquitous low-Ti magmas of the Prevalent group (Callegaro et al., 2013; Merle et al., 2014; Marzoli et al., 2018, 2019) yielded slightly lower CO_2 concentrations (ca. 0.1 to 0.5 wt%; **Figure 2**). These results would imply that, for both the Siberian Traps and the CAMP, the highest concentrations of mantle-derived CO_2 were produced from magmas of the initial phases. Interestingly, the end-Permian extinction coincides with the initial emplacement of the volatile-poor sills of the Siberian Traps, while the end-Triassic extinction coincides with the effusive activity of the CAMP, whose lavas are relatively CO_2-rich (Capriolo et al., 2020). The fact that variable amounts of mantle-derived CO_2 from the magmas produced similar environmental consequences suggests that additional isotopically depleted CO_2 was likely released during the intrusive Siberian Traps activity. In this case, a significant part of the emitted CO_2 (and possibly other gases, e.g., CH_4, SO_2 and halocarbons) may have been produced thermogenically from the intruded host rocks (e.g., Svensen et al., 2009, 2018; Capriolo et al., 2021) highlighting the crucial role of sedimentary basins as additional suppliers of climate-modifying gases. Noteworthy, the early terrestrial onset of the end-Permian extinction seems to suggest that mantle-derived halogens were key environmental impactors during the first phase of the Siberian Traps (Sobolev et al., 2011; Dal Corso et al., 2022).

Geochemical data for the Wrangellia are relatively scarce. However, the high-Ti basalts have the highest Nb and thus possibly the highest CO_2 contents (ca. 0.3–0.5 wt%), while the low-Ti basalts were relatively Nb and thus CO_2-depleted (≤0.3 wt %). This difference may imply that the overall production of CO_2 increased when magmas were predominantly sourced from the mantle plume source, i.e., with minor or no contribution from the lithospheric mantle.

To summarize, in this study, we reviewed the main features of the Siberian Traps, the Wrangellia and the CAMP LIPs, which impacted the Triassic world. High-precision geochronology strongly links the Siberian Traps and the CAMP to the end-Permian and the end-Triassic mass extinctions, respectively. A similar cause-and-effect scenario between the Wrangellia and the CPE seems plausible based on paleontological, biostratigraphic and geochemical studies. However, further high-precision dating on both lava flows and intrusions is necessary to constrain the onset, evolution, and cessation of this LIP, as well as its emplacement mechanisms.

Using previously published data, we estimated maximum CO_2 contents for magmas of the three Triassic LIPs. Even if these estimates are based on proxy data, our results highlight that the mantle-related CO_2 budgets of the more primitive basalts seem to vary during the overall life cycle of each LIP, suggesting that different mantle sources or melting regimes came into play to produce these exceptionally voluminous volcanic events. These observations stress the fact that each LIP is a unique case-study and building paradigms that apply to all LIPs when discussing their relationship to concurrent Earth crises is not straightforward.

AUTHOR CONTRIBUTIONS

AB wrote the review on Wrangellia, compiled data from the literature and produced the figures. SC wrote the review on the Siberian Traps. AM designed the project and wrote the review on the CAMP. YS contributed to the review on Wrangellia.

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SUPPLEMENTARY MATERIAL

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