GEOLOGY | THE GEOLOGICAL SOCIETY OF AMERICA®

https://doi.org/10.1130/G52950.1

Manuscript received 19 November 2024
Revised manuscript received 9 April 2025
Manuscript accepted 20 April 2025

Published online 2 May 2025

Persistent dysoxia in very shallow seas across the late Cambrian SPICE event, Durness Group, UK

Ke Feng[1], Fred Bowyer[1,2], Andrew Curtis[1], Simon W. Poulton[2], Laetitia Pichevin[1], and Rachel Wood[1,*]
[1]School of GeoSciences, University of Edinburgh, Edinburgh EH9 3FE, UK
[2]School of Earth and Environment, University of Leeds, Leeds LS2 9JT, UK

ABSTRACT

The global late Cambrian Steptoean Positive Isotopic Carbon Excursion (SPICE; ca. 495–492 Ma) has been linked to oceanic anoxia followed by a pulse of atmospheric oxygenation that in turn may have facilitated the Ordovician Radiation. To provide new insight into the evolution of very-shallow-water redox conditions across the SPICE, we present an integrated multiproxy study of carbonate rocks from the Durness Group, Scotland, UK, combining Fe speciation, redox-sensitive trace element systematics, and I/(Ca + Mg) ratios. We interpret the Durness SPICE peak to have occurred during an early highstand interval, where shallow waters were impacted by either regional mobilization of Fe^{2+} under low-oxygen conditions or episodic upwelling of deep, ferruginous, anoxic waters that followed high-frequency cycles. Unlike other records, our data show that very low marine oxygen concentrations (dysoxia) persisted before, during, and after the SPICE, confirming that a very shallow redoxcline was maintained in this region, with no evidence for any sustained increase in oxygenation. We conclude that under the prevailing low-atmospheric-oxygen conditions of the Cambrian, dysoxia was prevalent even in very shallow waters.

INTRODUCTION

The Steptoean Positive Isotopic Carbon Excursion (SPICE) was a notable global event marked by a >10‰ positive carbon isotope ($\delta^{13}C$) excursion (CIE) during the late Cambrian (ca. 495–492 Ma; Saltzman et al., 2000; Cothren et al., 2022). The onset of the SPICE broadly coincides with a major biotic turnover of trilobites (e.g., Yang et al., 2024). The rising limb of the SPICE has been linked to a global deoxygenation event characterized by an expansion of low-oxygen oceanic conditions and increased organic carbon and pyrite burial (Saltzman et al., 2000), which occurred against a backdrop of generally low sulfate concentrations (Gill et al., 2011).

The SPICE onset is characterized by the replacement of shallow-water taxa by those adapted to cold and deep-water environments and is accompanied by oxygen isotope evidence that suggests upwelling of colder deep waters onto shallow shelves (e.g., Elrick et al., 2011). The same oxygen isotope data set also indicates a gradual increase in seawater temperature through the rising limb of the SPICE, potentially linked to decreasing thermohaline circulation and a temperature-related decrease in seawater oxygen concentrations (Elrick et al., 2011). The long-term burial of organic carbon and pyrite associated with the rising limb of the SPICE, in turn, is thought to have led to an increase in atmospheric pO_2 (Saltzman et al., 2011), so promoting an increase in phytoplankton diversity and, ultimately, potentially facilitating the Ordovician Radiation (e.g., Saltzman et al., 2011).

In Laurentian sections, the SPICE peak occurs approximately coincident with maximum regression near the Sauk II–Sauk III supersequence boundary (e.g., Saltzman et al., 2004; Cothren et al., 2022), suggesting a link to tectonic changes and thus continental weathering (Pulsipher et al., 2021), but there are different interpretations of sea-level change coincident with the SPICE (e.g., Schiffbauer et al., 2017; Yang et al., 2024). The trigger for the SPICE, however, remains elusive, given that mercury and osmium concentrations do not support enhanced volcanism or weathering controls but instead indicate weak carbon-cycle feedbacks associated with inefficient silicate weathering (Frieling et al., 2024).

The shallow-marine Durness Group, NW Scotland, UK, exposes extensive carbonates that formed on a low-angle ramp as part of the vast tropical-subtropical carbonate bank of SE Laurentia (Fig. 1). Strata of the Eilean Dubh Formation archive the SPICE and are composed exclusively of very shallow limestone lithologies with evaporite pseudomorphs, with abundant evidence of frequent exposure within a sabkha, arid tidal-flat setting (see the Supplemental Material[1]). Aeolian silts (the only source of clastics) are dispersed throughout and in a few places form thin beds capping multiple high-frequency cycles (described in Raine, 2010; Raine and Smith, 2012). There is no evidence for bioturbation and only a very limited skeletal fossil record. Glauconite and Hg enrichments have been interpreted to track low oxygen levels coincident with the SPICE, followed by a transient, local oxygenation event (Pruss et al., 2019).

Here, we combine major element concentration data with multiple paleoredox proxy data, including Fe speciation, redox-sensitive trace element (RSTE) systematics, and I/(Ca + Mg) ratios, to further constrain the dynamics of the SPICE event and its aftermath. Specifically, our multiproxy approach allows a detailed assessment of the redox evolution of a very shallow depositional setting, as documented by the Durness Group, providing new insight into global-scale variability in shallow-water redox conditions under the low-atmospheric-oxygen conditions that characterized the late Cambrian.

METHODS

Carbonate powders from micritic carbonates and grainstones were microdrilled and analyzed

Rachel Wood https://orcid.org/0000-0002-0165-5987
*Rachel.Wood@ed.ac.uk

[1]Supplemental Material. Sedimentology and stratigraphy, methods, and data tables. Please visit https://doi.org/10.1130/GEOL.S.28851395 to access the supplemental material; contact editing@geosociety.org with any questions.

CITATION: Feng, K., et al., 2025, Persistent dysoxia in very shallow seas across the late Cambrian SPICE event, Durness Group, UK: Geology, v. 53, p. 642–646, https://doi.org/10.1130/G52950.1

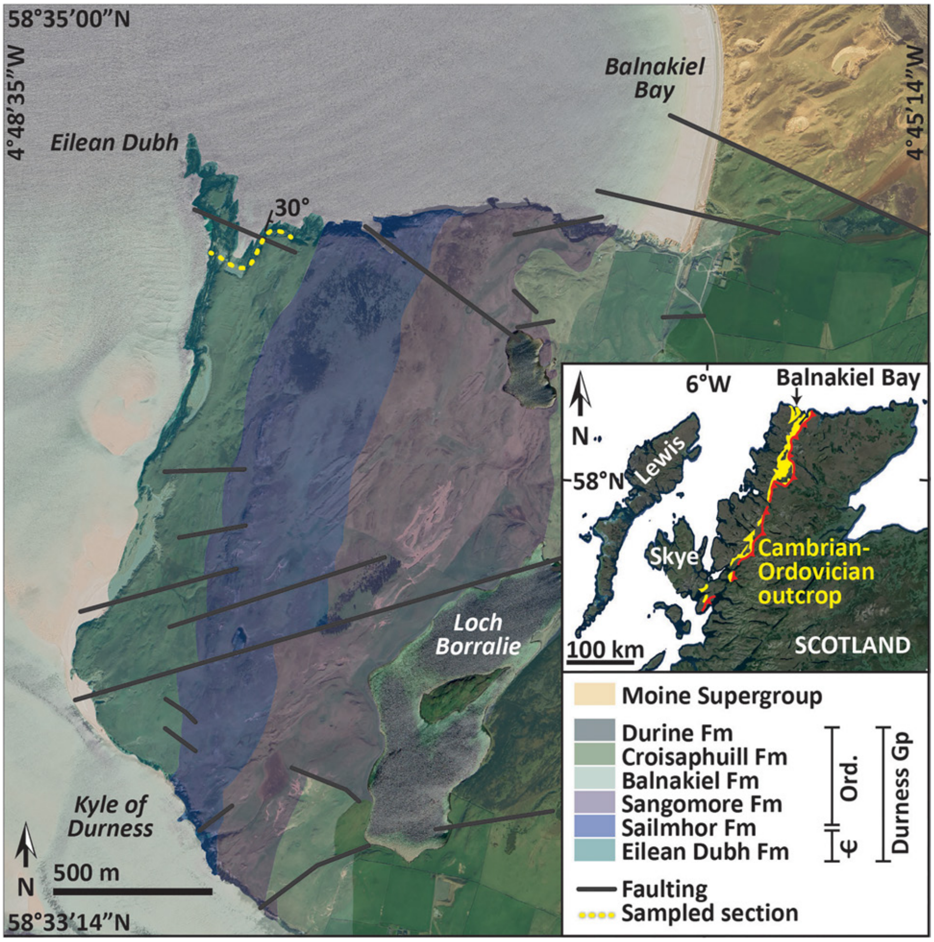

Figure 1. Geological map of Cambrian–Ordovician Durness Group, NW Scotland, UK, showing study area southwest of Balnakeil Bay, Durness (modified after Raine, 2010).

for $\delta^{13}C_{carb}$ and $\delta^{18}O_{carb}$ (carbonate) using continuous flow isotope ratio mass spectrometry at Isoanalytical Laboratories (Crew, UK). Reproducibility of standards was 0.05‰ for $\delta^{13}C$ and 0.1‰ for $\delta^{18}O$. Iron speciation analyses (Poulton and Canfield, 2005), major element concentrations using inductively coupled plasma–optical emission spectroscopy (ICP-OES), and trace element concentrations using inductively coupled plasma–mass spectrometry (ICP-MS) were all undertaken at the Cohen Laboratories, University of Leeds. Measurements of I/(Ca + Mg) ratios (Lu et al., 2018) were undertaken using ICP-OES and ICP-MS at the University of Edinburgh, using a tellurium internal standard (see the Supplemental Material for further details of methods and redox proxy systematics and Tables S1 and S2 for all data).

RESULTS AND DISCUSSION

We interpret the study interval to represent the end of the Sauk IIA to the beginning of the Sauk IIIA supersequences (Fig. 2A). Our $\delta^{13}C_{carb}$ data are consistent with previous records (Pruss et al., 2019), whereby the SPICE onset and rising limb occur within the transgression to highstand of Sauk IIB, reaching a maximum $\delta^{13}C$ value of +2.78‰ (Fig. 2B). Maximum regression across Sauk II–Sauk III is recorded near the SPICE peak (but see the Supplemental Material).

Samples through the entire interval prior to the SPICE have iron concentrations <0.32 wt% (Fig. S1 in the Supplemental Material), combined with very low total organic carbon (TOC) contents (<0.03 wt%; Fig. 2C). Iron concentrations then rise to 0.42 wt% just prior to the onset of the SPICE and become highly variable, from 0.15 wt% to 1.26 wt%, following meter-scale sedimentary cycles (Fig. 2A). TOC concentrations also follow meter-scale sedimentary cycles and reach a maximum (but still <0.1 wt%) at the maximum relative water depth (the maximum flooding surface) of Sauk IIB.

Samples with iron concentrations >0.5 wt% (Clarkson et al., 2014) were analyzed for total iron/aluminum (Fe_T/Al), highly reactive/total iron (Fe_{HR}/Fe_T), and pyrite-bound iron/highly reactive iron (Fe_{py}/Fe_{HR}) ratios (Figs. 2D–2F; Table S2). Samples with Fe_T >0.5 wt% and Al >0.5 wt% have Fe_T/Al ratios ranging from 0.33 to 2.44, with seven samples yielding Fe_T/Al >0.66, indicating Fe enrichment (Fig. 2D; Clarkson et al., 2014). Samples are also characterized by Fe_{HR}/Fe_T ratios that are persistently elevated above the anoxic threshold (Fe_{HR}/Fe_T >0.38; Fig. 2E; Poulton and Canfield, 2011), with Fe_{py}/Fe_{HR} ratios that are depleted relative to the lower limit for possible euxinia (Fe_{py}/Fe_{HR} <0.60; Fig. 2F; Poulton, 2021). The common occurrence of elevated Fe_{HR}/Fe_T and Fe_T/Al ratios across the SPICE indicates at least periodic anoxic mobilization of Fe^{2+} and subsequent precipitation, while low Fe_{py}/Fe_{HR} ratios suggest limited production of sulfide, even during diagenesis.

To provide further insight into redox conditions at the site of deposition, we use a refined approach for calculating enrichment factors (termed EF*) for redox-sensitive trace metals (e.g., U, Mo, Re) in carbonate-rich lithologies (Krewer et al., 2024; Li et al., 2025; see the Supplemental Material). The resultant EF* values for U and Mo are generally low (Figs. 2G–2H; Table S2), indicating limited enrichment under anoxic water-column conditions (Tribovillard et al., 2012; Li et al., 2025). However, a cross-plot of Mo_{EF*} versus U_{EF*} (Fig. 3) reveals two pathways for the samples displaying RSTE enrichment, with the majority of elevated Mo_{EF*} values resulting from delivery to sediments via a particulate shuttle mechanism (Tribovillard et al., 2012).

We further measure I/(Ca + Mg) ratios to potentially reveal more subtle variations in oxygen availability through time (Fig. 2J; Table S2). I/(Ca + Mg) ratios are very low throughout the section (0.17–0.4 µmol/mol, mean = 0.24 µmol/mol) relative to the typical "oxic" threshold of ~2.6 µmol/mol (Glock et al., 2014; Lu et al., 2016), including prior to, during, and after the SPICE (Fig. 2J). These low values suggest limited iodide oxidation within the water column at the depth of carbonate formation (Lu et al., 2016). Calcite- and dolomite-bound iodine can be susceptible to diagenetic alteration (Hardisty et al., 2017), but the absence of any correlation between the I/(Ca + Mg) ratios and TOC, $\delta^{18}O$, and Mg/Ca (Fig. S2) argues against any significant influence from diagenetic alteration or organically bound iodine.

The iodine data suggest low but nonzero oxygen concentrations, conducive to iodate reduction (i.e., the water column was likely predominantly manganous to nitrogenous). Carbonate I/(Ca + Mg) ratios of <2.5 µmol/mol (equivalent to IO_3^- <0.25 µmol/L in seawater) indicate seawater [O_2] of <20–70 µM in modern and ancient oceans (Lu et al., 2016), suggesting that dysoxic conditions were prevalent at the site of carbonate formation throughout the Eilean Dubh Formation, consistent with the lack of large enrichments in U and Mo (Fig. 2), which would require water column anoxia. Significantly, there is no increase in I/(Ca + Mg) during or after the SPICE, but there is a broad transition from a lower interval (0–38.8 m, n = 24) where I/(Ca + Mg) values exhibit a higher mean (0.25

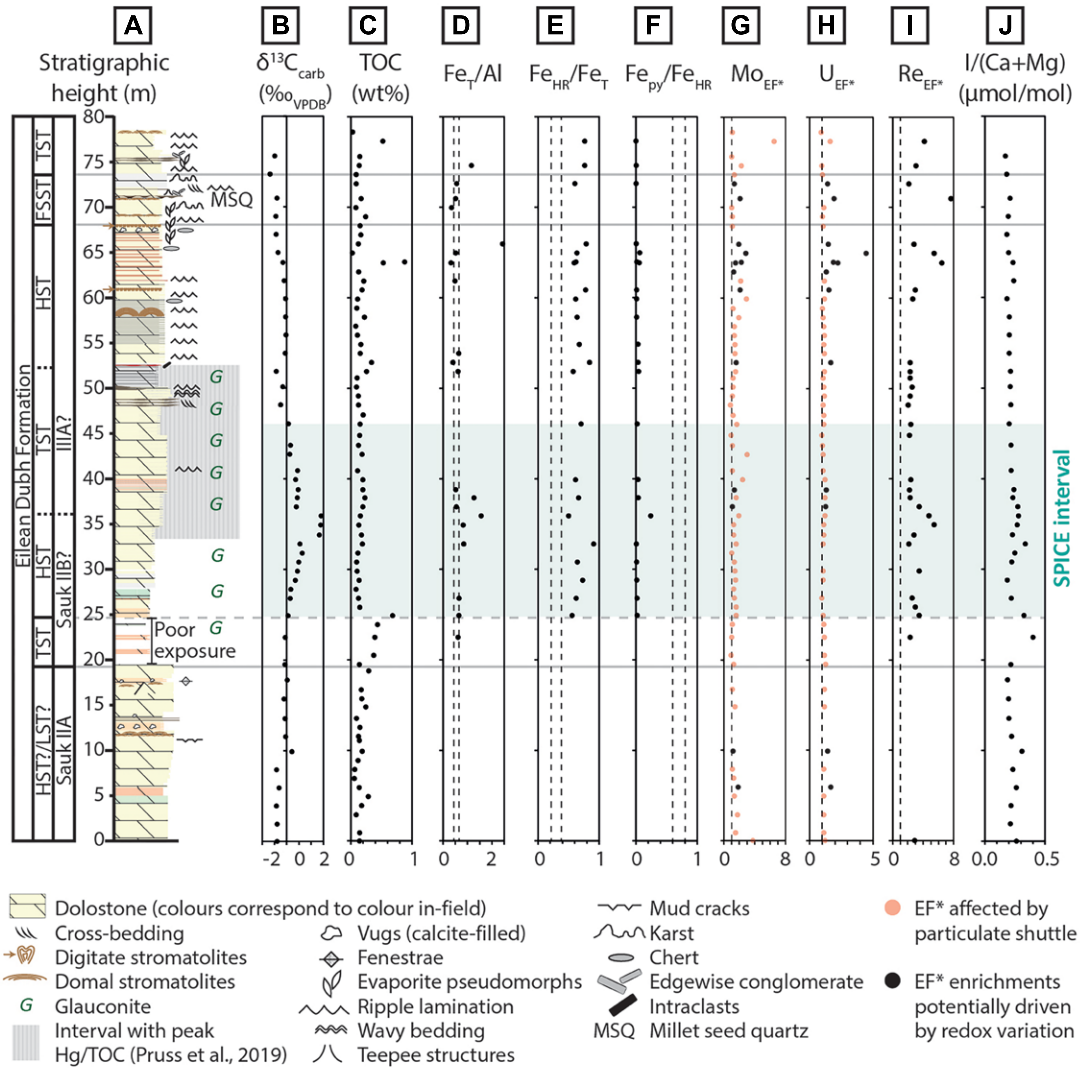

Figure 2. Redox dynamics through the late Cambrian Steptoean Positive Isotopic Carbon Excursion (SPICE) event (shaded in green), Eilean Dubh Formation. (A) Stratigraphy and correlation with Sauk supersequences (modified from Raine, 2010). Horizontal gray dashed line is maximum flooding surface. LST—lowstand systems tract; TST—transgressive systems tract; HST—highstand systems tract; FSST—falling stage systems tract. (B) C isotope ($\delta^{13}C_{carb}$) record (this study). VPDB—Vienna Peedee belemnite. (C) Total organic carbon (TOC). (D) Fe_T/Al ratios (Fe_T—total iron) for samples with >0.5 wt% Fe_T and >0.5 wt% Al. Vertical dashed lines bracket range of normal oxic values (0.44–0.66) (Clarkson et al., 2014). (E) Fe_{HR}/Fe_T ratios (Fe_{HR}—highly reactive iron), where vertical dashed lines represent empirically derived "oxic" (<0.22) and "anoxic" (>0.38) threshold ratios, separated by an equivocal zone (Poulton and Canfield, 2011). (F) Fe_{py}/Fe_{HR} ratios (Fe_{py}—pyrite-bound iron), where vertical dashed lines represent empirically derived ferruginous (<0.60) and euxinic (>0.80) thresholds, separated by an equivocal zone that may represent euxinia (Poulton, 2021). (G) Mo enrichment factors (Mo_{EF*}). (H) U enrichment factors (U_{EF*}). (I) Re enrichment factors (Re_{EF*}). (J) I/(Ca + Mg).

µmol/mol) and higher standard deviation (0.05 µmol/mol) to an upper interval (40.9–75.6 m, $n = 18$) that exhibits a slightly lower mean (0.21 µmol/mol) and lower standard deviation (0.02 = µmol/mol). Marginally elevated I/(Ca + Mg) values are largely restricted to two horizons in the lower interval, prior to the SPICE (~20–25 m during the transgressive systems tract [TST] of Sauk IIB, and a short-lived peak represented by a single sample at 32.8 m, during the highstand systems tract [HST] of Sauk IIB; Fig. 2J).

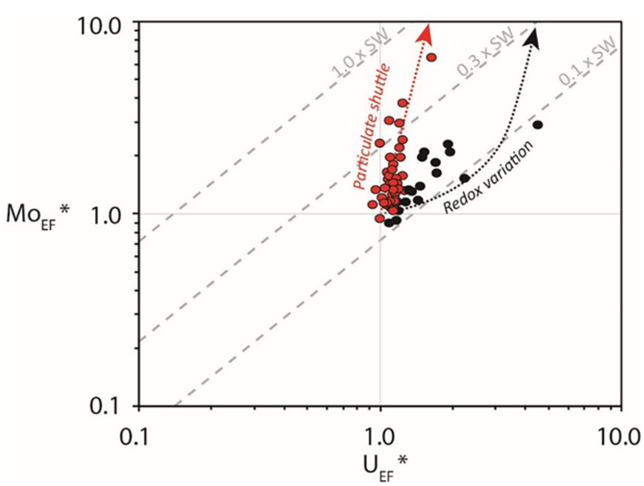

Figure 3. Cross-plot of revised Mo and U enrichment factors (EF*) for carbonate samples of Eilean Dubh Formation. SW—sea water.

Intervals of elevated Re_{EF*} (max = 7.57), in the general absence of co-enrichments in U (Fig. 2I), support the dysoxic bottom-water conditions indicated by the low but nonzero iodine data (Li et al., 2025). However, some samples higher in the section (~62–66 m) record appreciable U_{EF*} values (Fig. 2H), likely corresponding to the short-lived development of anoxic conditions at the sediment-water interface, which is consistent with elevated TOC (Fig. 2C) and muted I/(Ca + Mg) ratios (Fig. 2J).

The strong evidence for dysoxic conditions throughout most of the section, along with evidence for the operation of a particulate shuttle that sequestered Mo in the sediment (Fig. 3), suggests that the observed enrichments in Fe_{HR}/Fe_T reflect water-column mobilization of Fe^{2+} under regional anoxic conditions rather than an elevated source from intense continental weathering (see Wei et al., 2021). This is supported by the occurrence of elevated Fe_T/Al ratios in parts of the section (Fig. 2), given that both Fe_T and Al are generally con-

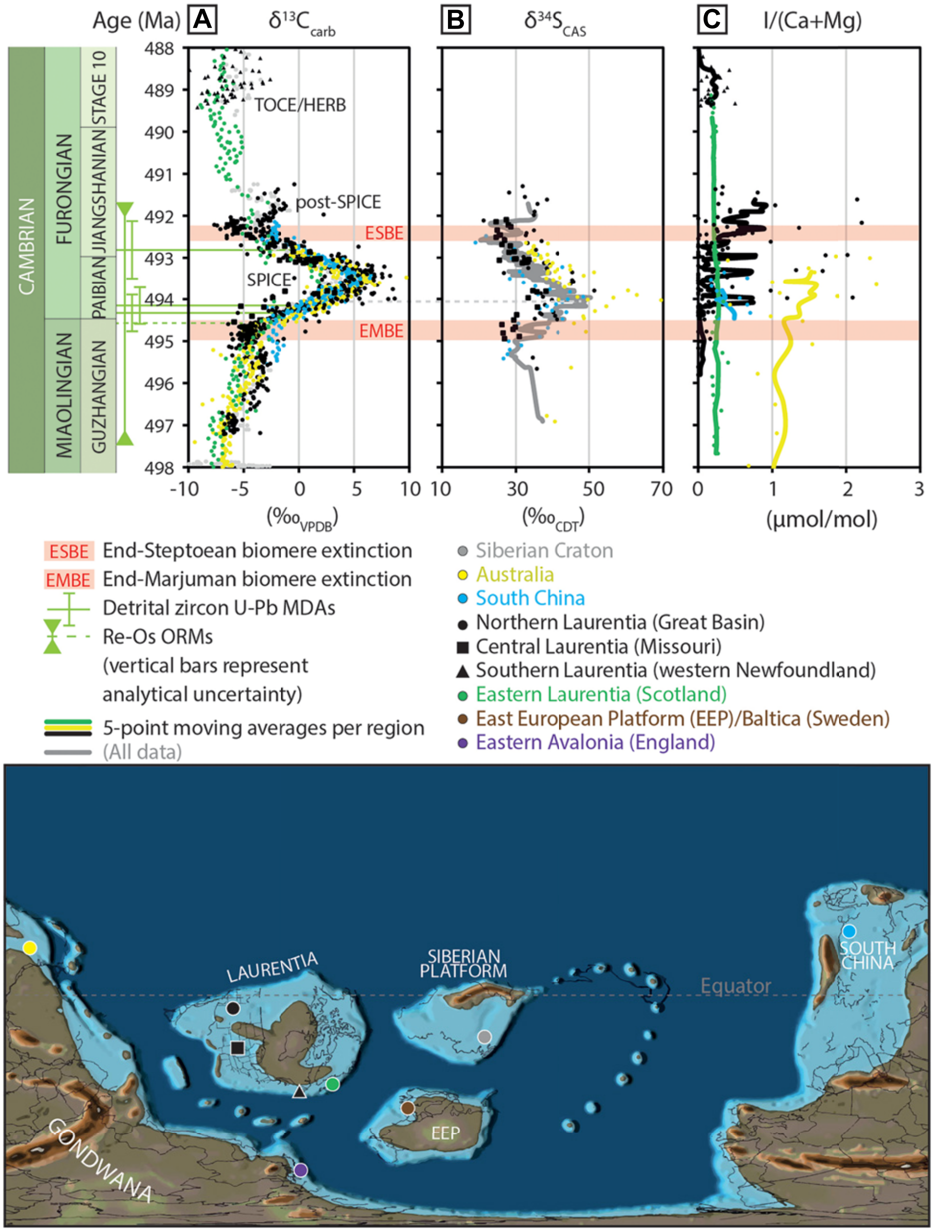

Figure 4. Global and regional geochemical expression of Steptoean Positive Isotopic Carbon Excursion (SPICE) event within a common age model and late Cambrian paleogeography for $\delta^{13}C_{carb}$ (A), $\delta^{34}S_{CAS}$ (carbonate associated silicate) (B), and I/(Ca + Mg) (C) (Gill et al., 2011; He et al., 2024; Pruss et al., 2019; Zhang et al., 2024). Biomere extinctions from Zhang et al. (2024); detrital zircon U-Pb data from Cothren et al. (2022); Re-Os age from Rooney et al. (2022); paleomap output from Scotese (2021). VPDB—Vienna Peedee belemnite; V-CDT—Vienna Canyon Diablo Troilite; MDAs—maximum depositional ages; ORMs—organic-rich mudrocks; HERB—*Hellnmaria*–Red Tops Boundary; TOCE—top of Cambrian Excursion.

sidered immobile during chemical weathering (Canfield, 1997), and instead, elevated Fe_T/Al ratios reflect water-column drawdown of mobilized Fe^{2+} (Raiswell et al., 2018). Thus, taken together, our combined multiproxy paleoredox data indicate dominantly dysoxic conditions at the site of deposition, with persistent enrichments in Fe_{HR} being due to oxidation of Fe^{2+} sourced from either regional sediment-to-water mobilization under anoxic conditions or upwelling of ferruginous deeper waters.

COMPARISON WITH COEVAL RECORDS ACROSS THE SPICE

In the Durness Group, we interpret the onset of the SPICE rising limb to correspond with a TST and the peak of the SPICE with the HST, which is consistent with the overall pattern of sea-level change recorded in sections in the United States (Saltzman et al., 2004). This stacking pattern is shared by most sections that record the SPICE and is also noted for many other positive CIEs, including during the Ediacaran Shuram and the lower Cambrian (Bowyer et al., 2024).

Existing records show that widespread anoxia, or a shallow redoxcline, was pervasive across the continental shelves of western Laurentia during the pre- and early-SPICE interval (He et al., 2024). However, the low values of I/(Ca + Mg) recorded here, which remain within a narrow range during the whole interval studied, indicate relatively invariable low-oxygen conditions and notably a shallow marine redoxcline throughout the entire pre- to post-SPICE interval. By contrast, far higher mean I/(Ca + Mg) values have been recorded from other regions, including sections of Australia and the Great Basin of Laurentia (Fig. 4). These sites also record increasing I/(Ca + Mg) values either coincident with or after the SPICE, interpreted to reflect increasing local marine (and possibly atmospheric) oxygen concentrations driven by progressive organic carbon and pyrite burial (Fig. 4) (He et al., 2024). Such an increase in atmospheric oxygen concentrations would be expected to impact the shallow-marine redox state directly, and so it is noteworthy that the very shallow setting represented by the Eilean Dubh Formation does not record clear evidence for this increase.

Shelf and slope oceanic waters around the Iapetan and Laurentian continental margins during the latest Cambrian to Early Ordovician were generally poorly oxygenated, with shallow redoxclines or expanded oxygen minimum zones (OMZs) (e.g., Kozik et al., 2023). The ambient greenhouse climate would have favored the expansion of OMZs (e.g., Elrick et al., 2011), and ocean circulation may also have created heterogenous distribution of nutrients and redox conditions (e.g., LeRoy et al., 2021).

Our data confirm that, unlike all other shallow marine records of SPICE events observed in other margins of Laurentia (UK, USA), South China, and Australia, the shallow waters of SE Laurentia did not experience any significant post-SPICE rise in oxygen (Fig. 4). It is possible that this could be due to seawater cooling, stimulating global ocean circulation (Zhang et al., 2024), accentuating continental margin upwelling (Stouffer et al., 2006), augmenting local productivity, and thereby expanding OMZs (Zhang et al., 2024). Such cooling is consistent with upwelling at the onset of the rising limb of the SPICE during the TST.

CONCLUSIONS

The Durness Group preserves a very-shallow-marine carbonate record from SE Laurentia across the late Cambrian SPICE and highlights the significant regional expression of this event, closely coupled to global sea-level change. Multiproxy paleoredox data show that the Durness SPICE interval was characterized by the introduction of ferruginous, anoxic waters into dysoxic shallow waters. Significantly, we show that very-low-marine-oxygen conditions persisted before, during, and after the SPICE, even in shallow waters, confirming that this region, unlike all others around Gondwana, retained a shallow redoxcline and experienced no increase in oxygenation post-SPICE. We conclude that under the generally low-atmospheric-oxygen state of the Cambrian, dysoxia was prevalent in some regions even in very shallow waters, with the apparent global variability in shallow-water redox conditions likely reflecting local productivity controls and/or upwelling dynamics.

ACKNOWLEDGEMENTS

This work was supported by UK Research and Innovation (UKRI) projects NE/T008458/1, NE/Z000122, and EP/Y008790/1. We thank M. Yilales Agelvis, S. Reid, Y. Xiong, and A. Hobson for technical support, and NatureScot for permission to sample the Eilean Dubh Formation at Durness. We thank the anonymous reviewers of this work.

REFERENCES CITED

Bowyer, F.T., Wood, R.A., and Yilales, M., 2024, Sea level controls on Ediacaran-Cambrian animal radiations: Science Advances, v. 10, https://doi.org/10.1126/sciadv.ado6462.

Canfield, D.E., 1997, The geochemistry of river particulates from the continental USA: Major elements: Geochimica et Cosmochimica Acta, v. 61, p. 3349–3365, https://doi.org/10.1016/S0016-7037(97)00172-5.

Clarkson, M.O., Poulton, S.W., Guilbaud, R., and Wood, R.A., 2014, Assessing the utility of Fe/Al and Fe-speciation to record water column redox conditions in carbonate-rich sediments: Chemical Geology, v. 382, p. 111–122, https://doi.org/10.1016/j.chemgeo.2014.05.031.

Cothren, H.R., Farrel, R.P., Sundberg, F.A., Dehler, C.M., and Schmitz, M.D., 2022, Novel age constraints for the onset of the Steptoean Positive Isotopic Carbon Excursion (SPICE) and the late Cambrian time scale using high-precision U-Pb detrital zircon ages: Geology, v. 50, p. 1415–1420, https://doi.org/10.1130/G50434.1.

Elrick, M., Rieboldt, S., Saltzman, M., and McKay, R.M., 2011, Oxygen-isotope trends and seawater temperature changes across the Late Cambrian Steptoean positive carbon-isotope excursion (SPICE event): Geology, v. 39, p. 987–990, https://doi.org/10.1130/G32109.1.

Frieling, J., Mather, T.A., Fendley, I.M., Jenkyns, H.C., Zhao, Z., Dahl, T.W., Bergquist, B.A., Cheng, K., Nielsen, A.T., and Dickson, A.J., 2024, No evidence for a volcanic trigger for late Cambrian carbon-cycle perturbations: Geology, v. 52, p. 12–16, https://doi.org/10.1130/G51570.1.

Gill, B.C., Lyons, T.W., Young, S.A., Kump, L.R., Knoll, A.H., and Saltzman, M.R., 2011, Geochemical evidence for widespread euxinia in the later Cambrian ocean: Nature, v. 469, p. 80–83, https://doi.org/10.1038/nature09700.

Glock, N., Liebetrau, V., and Eisenhauer, A., 2014, I/Ca ratios in benthic foraminifera from the Peruvian oxygen minimum zone: Analytical methodology and evaluation as a proxy for redox conditions: Biogeosciences, v. 11, p. 7077–7095, https://doi.org/10.5194/bg-11-7077-2014.

Hardisty, D.S., et al., 2017, Perspectives on Proterozoic surface ocean redox from iodine contents in ancient and recent carbonate: Earth and Planetary Science Letters, v. 463, p. 159–170, https://doi.org/10.1016/j.epsl.2017.01.032.

He, R., Pohl, A., Prow, A., Jiang, G., Huan, C.C., Saltzman, M.R., and Lu, Z., 2024, The dynamic ocean redox evolution during the late Cambrian SPICE: Evidence from the I/Ca proxy: Global and Planetary Change, v. 233, https://doi.org/10.1016/j.gloplacha.2024.104354.

Kozik, N.P., Young, S.A., Lindskog, A., Ahlberg, P., and Owens, J.D., 2023, Protracted oxygenation across the Cambrian–Ordovician transition: A key initiator of the Great Ordovician Biodiversification Event?: Geobiology, v. 21, p. 323–340, https://doi.org/10.1111/gbi.12545.

Krewer, C., Poulton, S.W., Newton, R.J., März, C., Mills, B.J.W., and Wagner, T., 2024, Controls on the termination of Cretaceous Oceanic Anoxic Event 2 in the Tarfaya Basin, Morocco: American Journal of Science, v. 324, 11, https://doi.org/10.2475/001c.118797.

LeRoy, M.A., Gill, B.C., Sperling, E.A., McKenzie, N.R., and Park, T.-Y.S., 2021, Variable redox conditions as an evolutionary driver? A multi-basin comparison of redox in the middle and later Cambrian oceans (Drumian-Paibian): Palaeogeography, Palaeoclimatology, Palaeoecology, v. 566, https://doi.org/10.1016/j.palaeo.2020.110209.

Li, S., Wignall, P.B., and Poulton, S.W., 2025, Co-application of rhenium, vanadium, uranium and molybdenum as paleo-redox proxies: Insight from modern and ancient environments: Chemical Geology, v. 674, https://doi.org/10.1016/j.chemgeo.2024.122565.

Lu, W., et al., 2018, Late inception of a resiliently oxygenated upper ocean: Science, v. 361, p. 174–177, https://doi.org/10.1126/science.aar5372.

Lu, Z., Hoogakker, B.A.A., Hillenbrand, C.-D., Zhou, X., Thomas, E., Gutchess, K.M., Lu, W., Jones, L., and Rickaby, R.E.M., 2016, Oxygen depletion recorded in upper waters of the glacial Southern Ocean: Nature Communications, v. 7, https://doi.org/10.1038/ncomms11146.

Poulton, S.W., 2021, The Iron Speciation Paleoredox Proxy: Cambridge, UK, Cambridge University Press, https://doi.org/10.1017/9781108847148.

Poulton, S.W., and Canfield, D.E., 2005, Development of a sequential extraction procedure for iron: Implications for iron partitioning in continentally derived particulates: Chemical Geology, v. 214, p. 209–221, https://doi.org/10.1016/j.chemgeo.2004.09.003.

Poulton, S.W., and Canfield, D.E., 2011, Ferruginous conditions: A dominant feature of the ocean through Earth's history: Elements, v. 7, p. 107–112, https://doi.org/10.2113/gselements.7.2.107.

Pruss, S.B., Jones, D.S., Fike, D.A., Tosca, N.J., and Wignall, P.B., 2019, Marine anoxia and sedimentary mercury enrichments during the Late Cambrian SPICE event in northern Scotland: Geology, v. 47, p. 475–478, https://doi.org/10.1130/G45871.1.

Pulsipher, M.A., Schiffbauer, J.D., Jeffrey, M.J., Huntley, J.W., Fike, D.A., and Shelton, K.L., 2021, A meta-analysis of the Steptoean Positive Carbon Isotope Excursion: The SPICEraq database: Earth-Science Reviews, v. 212, https://doi.org/10.1016/j.earscirev.2020.103442.

Raine, R.J., 2010, The Durness Group of NW Scotland: A stratigraphical and sedimentological study of a Cambro-Ordovician passive margin succession [Ph.D. thesis]: Birmingham, UK, University of Birmingham, 240 p.

Raine, R.J., and Smith, M.P., 2012, Sequence stratigraphy of the Scottish Laurentian margin and recognition of the Sauk megasequence, *in* Derby, J.R., et al., eds., The Great American Carbonate Bank: The Geology and Economic Resources of the Cambrian–Ordovician Sauk Megasequence of Laurentia: American Association of Petroleum Geologists Memoir 98, p. 575–596, https://doi.org/10.1306/13331508M983507.

Raiswell, R., Hardisty, D.S., Lyons, T.W., Canfield, D.E., Owens, J.D., Planavsky, N.J., Poulton, S.W., and Reinhard, C.T., 2018, The iron paleoredox proxies: A guide to the pitfalls, problems and proper practice: American Journal of Science, v. 318, p. 491–526, https://doi.org/10.2475/05.2018.03.

Rooney, A.D., Millikin, A.E., and Ahlberg, P., 2022, Re-Os geochronology for the Cambrian SPICE event: Insights into euxinia and enhanced continental weathering from radiogenic isotopes: Geology, v. 50, p. 716–720, https://doi.org/10.1130/G49833.1.

Saltzman, M.R., Ripperdan, R.L., Brasier, M.D., Lohmann, K.C., Robison, R.A., Chang, W., Peng, S., Ergaliev, E.K., and Runnegar, B., 2000, A global carbon isotope excursion (SPICE) during the Late Cambrian: Relation to trilobite extinctions, organic-matter burial and sea level: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 162, p. 211–223, https://doi.org/10.1016/S0031-0182(00)00128-0.

Saltzman, M.R., Cowan, C.A., Runkel, A.C., Runnegar, B., Stewart, M.C., and Palmer, A.R., 2004, The Late Cambrian SPICE ($\delta^{13}C$) event and the Sauk II-Sauk III regression: New evidence from Laurentian basins in Utah, Iowa, and Newfoundland: Journal of Sedimentary Research, v. 74, p. 366–377, https://doi.org/10.1306/120203740366.

Saltzman, M.R., Young, S.A., Kump, L.R., Gill, B.C., Lyons, T.W., and Runnegar, B., 2011, Pulse of atmospheric oxygen during the late Cambrian: Proceedings of the National Academy of Sciences of the United States of America, v. 108, p. 3876–3881, https://doi.org/10.1073/pnas.1011836108.

Schiffbauer, J.D., Huntley, J.W., Fike, D.A., Jeffrey, M.J., Gregg, J.M., and Shelton, K.L., 2017, Decoupling biogeochemical records, extinction, and environmental change during the Cambrian SPICE event: Science Advances, v. 3, https://doi.org/10.1126/sciadv.1602158.

Scotese, C.R., 2021, An atlas of Phanerozoic paleogeographic maps: The seas come in and the seas go out: Annual Review of Earth and Planetary Sciences, v. 49, p. 679–728, https://doi.org/10.1146/annurev-earth-081320-064052.

Stouffer, R.J., et al., 2006, Investigating the causes of the response of the thermohaline circulation to past and future climate changes: Journal of Climate, v. 19, p. 1365–1387, https://doi.org/10.1175/JCLI3689.1.

Tribovillard, N., Algeo, T.J., Baudin, F., and Riboulleau, A., 2012, Analysis of marine environmental conditions based on molybdenum–uranium covariation—Applications to Mesozoic paleoceanography: Chemical Geology, v. 324–325, p. 46–58, https://doi.org/10.1016/j.chemgeo.2011.09.009.

Wei, G.-Y., et al., 2021, A chemical weathering control on the delivery of particulate iron to the continental shelf: Geochimica et Cosmochimica Acta, v. 308, p. 204–216, https://doi.org/10.1016/j.gca.2021.05.058.

Yang, A., et al., 2024, Shallow ocean deoxygenation drove trilobite turnover during the late Cambrian SPICE event: Geology, v. 52, p. 661–666, https://doi.org/10.1130/G52200.1.

Zhang, L., Algeo, T.J., Zhao, L., Dahl, T.W., Chen, Z.-Q., Zhang, Z., Poulton, S.W., Hughes, N.C., Gou, X., and Li, C., 2024, Environmental and trilobite diversity changes during the middle-late Cambrian SPICE event: Geological Society of America Bulletin, v. 136, p. 810–828, https://doi.org/10.1130/B36421.1.

Printed in the USA