The Lomagundi-Jatuli Event and Earth's oxygenation

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Article

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Abstract

The Palaeoproterozoic Lomagundi-Jatuli Event (LJE) is the largest positive carbonate C-isotope ($\delta^{13}\text{C}_{\text{carb}}$) excursion in Earth history. Conventional thinking is that it represents a perturbation of the global C cycle between c. 2.3–2.1 Ga linked directly to the postulated Great Oxidation Event. Here we show that the LJE worldwide is, in fact, entirely facies (i.e. palaeoenvironment) dependent. During the LJE, the C-isotope composition of open and deeper marine settings remained undisturbed, with a mean $\delta^{13}\text{C}_{\text{carb}}$ value of 1.5‰, whereas nearshore marine and coastal-evaporitic settings have means of 6.2‰ and 8.1‰, respectively. This finding refutes conventional thinking and obliges complete re-evaluation of concepts using the LJE as a means of assessing oxygenation of the atmosphere.

Introduction

The Lomagundi-Jatuli Event (LJE) is identified by remarkably high carbonate carbon isotope ($\delta^{13}\text{C}_{\text{carb}}$) values, typically 5–10‰ or more, in marine carbonate successions that are mostly between c. 2.3 and 2.1 Ga in age^{1–3} and has played a central role in ideas regarding the oxygenation of Earth's surface environments^{4–17}. Conventional thinking has adopted a scenario in which, following the Great Oxidation Event, a biogeochemical feedback was established such that atmospheric O_2 rose and fell in concert with increasing and decreasing marine primary productivity as a consequence of postulated co-varying fluctuations in nutrient fluxes and intensities in the oxidative weathering of continental landmasses⁷. Crucial to this thinking is a key underpinning assumption about the LJE, namely, that its highly positive $\delta^{13}\text{C}_{\text{carb}}$ values are representative of the isotope composition of the dissolved inorganic carbon (DIC) reservoir of the global ocean. Thus, a view that has become accepted widely is that the LJE archives an unprecedented perturbation of the global C cycle related to wholesale changes in the redox state of the Palaeoproterozoic ocean-atmosphere system and in atmospheric oxygenation.

Here we evaluate the key underlying assumption of the LJE (i.e. that it is a global perturbation to the C cycle) by analysing judiciously the relationship between C-isotope composition and facies (i.e. palaeoenvironment) of carbonate rocks. To do so, and place the LJE into context, we constructed a database linking $\delta^{13}\text{C}_{\text{carb}}$ values to facies that spans the 3.0–1.0 Ga time interval and for apropos times during the Phanerozoic. The database totals 14,943 $\delta^{13}\text{C}_{\text{carb}}$ values (N=11,557 for the Neoarchaean-Proterozoic rocks; N=3,386 for the Phanerozoic data) and we included only those data that record primary depositional (or nearly so) conditions, as per original authors' reporting of petrographic features, C-O isotope cross-plots and key element ratios. We disregarded data from rocks that experienced significant post-depositional isotopic resetting and from features of clearly later diagenetic origin (e.g. concretions, cements), as well as data from carbonate rocks associated with banded-iron formations. See supplemental information for C-isotope data and sources (see Supplementary Information Figure S1, Tables S1–S5 and Data S1).

Lje In The Kola-karelia Region And Francevillian Basin

Our work focused initially on two areas in which we have extensive first-hand knowledge of the geology: the archetypal LJE-bearing successions in the Francevillian Basin of Gabon¹⁸⁻²⁰ and the Onega Basin and Pechenga and Imandra-Varzuga Belts of Kola-Karelia Russia²¹⁻²⁷ (see Supplementary Information Fig. S1 for locations), particularly the latter region via the International Continental Scientific Drilling Program's Fennoscandia-Arctic Russia Deep Early Earth Project (FARDEEP)²⁷. In both regions, distinct lithological characteristics enable placing the LJE-bearing rocks into three facies associations that are representative of intertidal and sabkha settings, nearshore marine–inner shelf settings, and open and deeper marine settings.

The LJE-bearing succession in the Onega Basin represented by the Tulomozero and overlying Zaonega Formations offer a good example of these facies associations (Fig. 1). The lower part of that succession consists of many tens to several hundreds of metres of interbedded variegated pale grey to pink dolostone and red-brown-grey mudstone. Sedimentary features include stromatolites, desiccation cracks and evaporite fabrics ranging from individual bladed and nodular carbonate-pseudomorphed former sulphate crystals to enterolithic bedding and chicken-wire textures (Fig. 1a). There are also (palaeo)karst and tepee structures and various small- and large-scale ripple forms, including herring-bone cross-lamination with reactivation surfaces and mud drapes (Fig. 1b). These facies are overlain by an upper interval many tens of metres thick that is transitional from the upper Tulomozero Formation into the lower part of the Zaonega Formation. This interval consists of interbedded very fine dolostone, dolomarl and mudstone marked by small current ripples, co-sets of low-angle to plane-parallel lamination (Fig. 1c) and mm- to cm-thick fine graded beds; colours vary from medium to dark grey excepting one 10–30 m thick variegated dolomicrite unit known locally as 'krivozerite'. The Tulomozero-Zaonega facies motif also typifies the LJE-bearing Francevillian succession in Gabon²⁰. There, the succession consists of many tens of metres of pastel and grey coloured dolostone replete with desiccation cracks, evaporite fabrics, (palaeo)karst, oolites and dm-scale cross-bedded dolograinstones overlain by interbedded, dark grey to black, very fine-grained dolostone, dolomarl and mudstone displaying mm-scale current ripples, low-angle to plane-parallel laminations and thin fine graded beds.

In both the Francevillian and Onega Basins, the facies characteristics associated with the lower intervals of pink-grey dolostone are unambiguous sedimentological evidence of tidal currents, evaporitic processes and episodic exposure occurring in nearshore marine, intertidal and sabkha settings, whereas the facies features of the overlying darker-grey fine dolostone-dolomarl-mudstone intervals are indicative of lower energy, more open and deeper marine settings; note that deeper here refers to depths near or below storm-wave base, an interpretation supported by the notable absence of features attributable to strong storm-, wave- or tide-generated currents. These interpretations are in-line with those of all previous workers^{12, 18-28}.

Global Analysis Of The Lje

What is salient about the Francevillian and Kola-Karelia successions is that $d^{13}C_{carb}$ data exhibit a spread of values between c. -5‰ and c. 15‰ but the values are entirely facies dependent (Fig. 2a, Table 1; see Ref. 20). Classifying C-isotope data by their respective facies shows clear differentiation and a systematic decrease in $d^{13}C_{carb}$ values from the shoreline through to more open-marine settings: intertidal-sabkha facies have a mean value of 9.3‰, nearshore marine-inner shelf facies have a mean value of 6.8‰ whereas open and deeper marine facies have a mean value of 2.0‰ which is a value consistent with normal marine seawater. This co-dependent relationship between facies and $d^{13}C_{carb}$ values from two hallmark LJE-bearing successions implies that conventional thinking about the LJE as a global ocean phenomenon is incorrect.

To assess this further and determine if the co-variation between $d^{13}C_{carb}$ values and facies exhibited by the Francevillian and Kola-Karelia strata is not merely a coincidence but indicative of other Palaeoproterozoic successions, we expanded our analysis to encompass available published data for LJE-bearing successions worldwide. Of central relevance is that the facies characteristics described above are present in LJE-bearing successions elsewhere such that, where original authors provided sufficient sedimentological details, facies interpretations and $d^{13}C_{carb}$ data could be assigned to our three main facies categories: intertidal-sabkha, nearshore marine-inner shelf, and open and deeper marine. This analysis confirmed the co-dependence between facies and $d^{13}C_{carb}$ as seen in the Francevillian and Kola-Karelia successions (Fig. 2b, Table 1): the $d^{13}C_{carb}$ are spread between c. -10‰ and c. 25‰ yet the open marine realm remained undisturbed during the LJE, having a mean $d^{13}C_{carb}$ value of 1.5‰, whereas high $d^{13}C_{carb}$ values that are the hallmark signature of the LJE were restricted entirely to nearshore marine-inner shelf and intertidal-sabkha settings, with mean values of 6.2‰ and 8.1‰, respectively.

We extended our analysis further to include marine carbonate rocks from c. 3.0 to 1.0 Ga (Fig. 2c) and, to have a comparator for the Neoarchaeon and Proterozoic rocks, we also examined times of major evaporite and open-marine deposition during the Phanerozoic (Permian-Triassic, Messinian, Recent sabkhas; Fig. 2d). This analysis corroborated our key finding, namely, that $d^{13}C_{carb}$ values of open and deeper marine carbonates for all assessed time periods, *including* LJE-bearing successions, were consistently within 0 ± 4 ‰ and comparable to that for the modern open ocean DIC reservoir (Fig. 2d). The clear conclusion is that the highly positive $d^{13}C_{carb}$ values of the LJE are unequivocally facies dependent and are not representative of either the global DIC pool or global C cycle.

The Lje: A New Understanding

Can it be that the highest amplitude, longest-lived deviation from what is considered to be 'normal' C-cycle functioning in 4 billion years is largely due to facies-dependent isotopic effects rather than an extraordinary disturbance of the global C-cycle? We apply uniformitarianism *sensu lato* as a means of addressing that question. No evidence for major depositional breaks (i.e. unconformities) in LJE-bearing successions has been reported in the literature, in fact successions that record a declining trend in

$\delta^{13}\text{C}_{\text{carb}}$ values are commonly emphasised as evidence of the steady transition to cessation of the LJE^{11, 19}. Consequently, the underpinning concept of stratigraphy, Golovkinsky's–Walther's Law (successions without a significant hiatus were formed in *co-existing* laterally adjacent depositional environments), is applicable to LJE-bearing successions and yields another key insight: the C-isotope pattern of the LJE is a record of *contemporaneous* lateral gradients in the isotopic compositions of DIC pools as a function of their depositional setting, i.e. these patterns are generated, preserved and become superposed during sedimentation that occurs concurrently during the lateral migration of coeval environments (Fig. 3a).

Studies of C-isotope process-response for carbonate precipitation from marine DIC pools in recent and modern depositional environments offer credence to that scenario. These studies show that shallow-marine settings may have $\delta^{13}\text{C}_{\text{carb}}$ differences of 2–4‰ or more relative to the coeval encompassing global ocean²⁹, in some instances occurring diurnally via C-cycling in shallow-water photic zones with high productivity³⁰. These findings are apropos to the LJE in that they are consistent with and substantiate the interconnectedness between facies and $\delta^{13}\text{C}_{\text{carb}}$ values. Modern examples, though, do not explain why carbonate precipitated in nearshore marine and evaporative settings during the LJE reached such high enrichments in ^{13}C . For this, we do not yet have an answer. It is noteworthy, though, that many LJE-bearing successions are typified by widespread deposition of shallow-marine carbonate rocks associated with evaporitic and sabkha-like features. It is known from evaporation ponds that ^{13}C -rich brines can have $\delta^{13}\text{C}$ values of 8–16‰ and brine-evaporation experiments have generated values of 16–35‰³¹. Both sets of values overlap with those of the LJE. This hints at an intriguing possibility to investigate, namely, that a heretofore unrecognised relationship existed between Palaeoproterozoic microbial ecosystems and coastal-marine and evaporite settings.

By establishing that LJE-bearing successions are typified everywhere by facies marked by both normal and elevated $\delta^{13}\text{C}_{\text{carb}}$ values, it becomes apparent that the canonical image of the LJE as a high-amplitude C-isotope bulge punctuating an otherwise undisturbed 2-billion-year continuum of relatively normal marine C-isotope values is misleading (Fig. 3b). Instead, our new understanding shows that there is a spectrum of values that occurred during the LJE, ranging from normal open-marine values of c. 0‰ to extremely high values of 16‰ and even higher, and that these co-vary as a function of facies (Fig. 3c). Consequently, the highly positive $\delta^{13}\text{C}_{\text{carb}}$ values taken as the fingerprint of the LJE are, in fact, a biogeochemical phenomenon restricted almost entirely to the coastal interface between the marine and non-marine realms.

The Lje And Earth's Oxygenation

The LJE is not a global ocean perturbation of the global C-cycle. Rather, careful sedimentological assessment of the relationship between facies and C-isotope composition of carbonate rocks shows that ^{13}C enrichment during the LJE was restricted to nearshore marine-inner shelf and intertidal-sabkha settings with mean $\delta^{13}\text{C}_{\text{carb}}$ values of 6.2‰ and 8.1‰, respectively. In contrast, carbonate sediments

deposited in open and deeper marine settings are marked by $\delta^{13}\text{C}_{\text{carb}}$ values averaging 1.5‰, consistent with the mean C-isotope composition of oceans throughout most of geological time. Discovering this key relationship eliminates having to invoke complex biogeochemical scenarios to explain $^{13}\text{C}/^{12}\text{C}$ of the oceanic DIC pool during the LJE. It reveals that the LJE is an archive of the C-isotopic composition of *contemporaneous* DIC pools associated with *coeval* depositional settings with *specific* environmental conditions. The significance of our findings carries substantial implications regarding concepts about oxygenation of the Earth system following the postulated Great Oxidation Event and oblige re-evaluation of models that emphasise the LJE as a proxy for assessing fluctuating atmospheric oxygen levels. Our findings also highlight an overarching question that remains to be answered: why did coastal-marine and evaporite settings acquire uniquely positive $\delta^{13}\text{C}_{\text{carb}}$ values only during the middle part of the Palaeoproterozoic Era?

Declarations

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Competing Interests. There are no competing interests.

Author contributions. A.P., A.L., K.K. and A.F. wrote the manuscript. All authors contributed equally to the science, sampling, analyses and interpretations.

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Table

Table 1. Summary $\delta^{13}\text{C}_{\text{carb}}$ data for Lomagundi-Jatuli Event (LJE)-bearing successions (data in Supplementary Information Table S5 and Data S1). C.I. – Confidence Interval.

Lomagundi-Jatuli Event $d^{13}C_{carb}$ (‰ V-PDB) summary data					
LJE-bearing successions	palaeoenvironmental setting	N	bootstrapped mean	Bootst. mean 95% C.I. low.	Bootst. mean 95% C.I. upr.
Kola-Karelia-Francevillian data	intertidal-sabkha (evaporitic)	273	9.3	9.1	9.5
	nearshore marine-inner shelf	325	6.8	6.6	6.9
	open and deeper marine	130	2.0	1.6	2.3
worldwide data	intertidal-sabkha (evaporitic)	562	8.1	7.8	8.4
	nearshore marine-inner shelf	705	6.2	6.1	6.4
	open and deeper marine	771	1.5	1.3	1.7

Figures

Figure 1

LJE-bearing succession and associated $\delta^{13}\text{C}_{\text{carb}}$ profile, Onega Basin (N=188; see Supplementary Information Table S5 for data). Photos of representative rock types are shown to the left of the stratigraphic column (scale bars = 2 cm): (a) layered dolostone cut by palaeokarst doloarenite (OPH core depth 2327 m); (b) dark mudstone with chicken-wire evaporitic fabric (OPH core depth 2309 m); (c) herring-bone cross-bedding with mud drapes and reactivation surfaces (OPH core depth 2104 m), (c)

planar- to wavy-laminated and small-scale ripple cross-laminated dolomicrite and dolomarl (OPH core depth 2050 m), (d) wavy- to planar-laminated and small-scale rippled pastel-coloured dolomicrite ('krivozerite', OPH core depth 2004 m), (e) planar-laminated dolomicrite and dark grey dolomarl, bright grains are pyrite (OPH core depth 1902 m). OPH – Onega Parametric Hole; R-S – Raiguba and Shunga outcrop localities (see Supplemental Information for locations).

Figure 1

LJE-bearing succession and associated $\delta^{13}\text{C}_{\text{carb}}$ profile, Onega Basin (N=188; see Supplementary Information Table S5 for data). Photos of representative rock types are shown to the left of the stratigraphic column (scale bars = 2 cm): (a) layered dolostone cut by palaeokarst dolarenite (OPH core depth 2327 m); (b) dark mudstone with chicken-wire evaporitic fabric (OPH core depth 2309 m); (c) herring-bone cross-bedding with mud drapes and reactivation surfaces (OPH core depth 2104 m), (c) planar- to wavy-laminated and small-scale ripple cross-laminated dolomicrite and dolomarl (OPH core depth 2050 m), (d) wavy- to planar-laminated and small-scale rippled pastel-coloured dolomicrite ('krivozerite', OPH core depth 2004 m), (e) planar-laminated dolomicrite and dark grey dolomarl, bright grains are pyrite (OPH core depth 1902 m). OPH – Onega Parametric Hole; R-S – Raiguba and Shunga outcrop localities (see Supplemental Information for locations).

Figure 2

Summary $\delta^{13}\text{C}_{\text{carb}}$ data differentiated by palaeoenvironmental setting (see Supplementary Information Table S5 and Data S1 for data). Data from LJE-bearing successions in (a) NW Russia and Gabon and (b) from LJE-bearing successions worldwide. (c) $\delta^{13}\text{C}_{\text{carb}}$ data for marine carbonate rocks between 3.0–1.0 Ga in age (age bins are 100 Myr); LJE-bearing successions are shown in red and those recording the purported decline of the LJE in light red. (d) Box-and-whisker plots (note that outliers are omitted)

revealing timeline trend of the mean C-isotope value of palaeoenvironmental settings spanning from the Neoproterozoic through to specific Phanerozoic time periods (Rec – Recent; Mess – Messinian; Perm – Permian; Trias – Triassic).

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Figure 3

The new understanding of the Lomagundi-Jatuli Event (LJE). (a) Golovkinsky's–Walther's Law of Facies as a means to envisage generating the LJE: as sediment accumulation occurs concurrently with environments migrating laterally by allo- and auto-cyclic processes, a vertical succession of facies is created, i.e. a stratigraphy (right-hand panel) that records the C-isotope composition of each different yet contemporaneous setting (mean values from Table 1). (c) Canonical view of the direct one-to-one linkage between the LJE and postulated rise in atmospheric pO₂ (PAL–present atmospheric level; adapted from Ref. 12). (d) LJE excursion as a consequence of palaeoenvironmental setting; canonical view is shown by the dashed outline; the deeply negative $\delta^{13}\text{C}_{\text{carb}}$ values that post-date the LJE are due to post-depositional overprinting^{33, 34}. Light-grey bar highlights the LJE.

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Supplementary Files

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