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Isotopic evidence bearing on Late Triassic extinction events, Queen Charlotte Islands, British Columbia, and implications for the duration and cause of the Triassic/Jurassic mass extinction

Peter D. Ward[a,*], Geoffrey H. Garrison[b], James W. Haggart[c], David A. Kring[d], Michael J. Beattie[e]

[a] *Department of Biology/Astrobiology Program, Box 351800, University of Washington, Seattle, WA 98195-1800, USA*
[b] *Department of Earth and Space Sciences/Astrobiology Program, University of Washington, Seattle, WA 98195, USA*
[c] *Geological Survey of Canada, Vancouver, Vancouver, BC V6B5J3, USA*
[d] *Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721, USA*
[e] *Anadarko Petroleum, The Woodlands, Texas 77380, USA*

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Abstract

Stable isotope analyses of Late Triassic to earliest Jurassic strata from Kennecott Point in the Queen Charlotte Islands, British Columbia, Canada shows the presence of two distinct and different organic carbon isotope anomalies at the Norian/Rhaetian and Rhaetian/Hettangian (= Triassic/Jurassic) stage boundaries. At the older of these boundaries, which is marked by the disappearance of the bivalve *Monotis*, the isotope record shows a series of short-lived positive excursions toward heavier values. Strata approaching this boundary show evidence of increasing anoxia. At the higher boundary, marked by the disappearance of the last remaining Triassic ammonites and over 50 species of radiolarians, the isotopic pattern consists of a series of short duration negative anomalies. The two events, separated by the duration of the Rhaetian age, comprise the end-Triassic mass extinction. While there is no definitive evidence as to cause, the isotopic record does not appear similar to that of the impact-caused Cretaceous/Tertiary boundary extinction.

Keywords: Triassic; Jurassic; Norian; Rhaetian; Hettangian; Monotis; extinctions; carbon isotopes

1. Introduction

The end-Triassic mass extinction remains enigmatic in terms of its cause, duration, and effect on the biota. Both short-term events (e.g. asteroid impact: [1]) and longer-term effects (e.g., sea level change: [2], volcanic-induced climate and oceanographic change: [3]) have been invoked. Testing these various hypotheses requires multiple lines of evidence that includes biostratigraphic and chemostratigraphic data from both marine and non-marine stratigraphic sections of latest Triassic and earliest Jurassic age.

While the magnitude of the end-Triassic mass extinction has long been known from the paleonto-

* Corresponding author.
E-mail address: argo@u.washington.edu (P.D. Ward).

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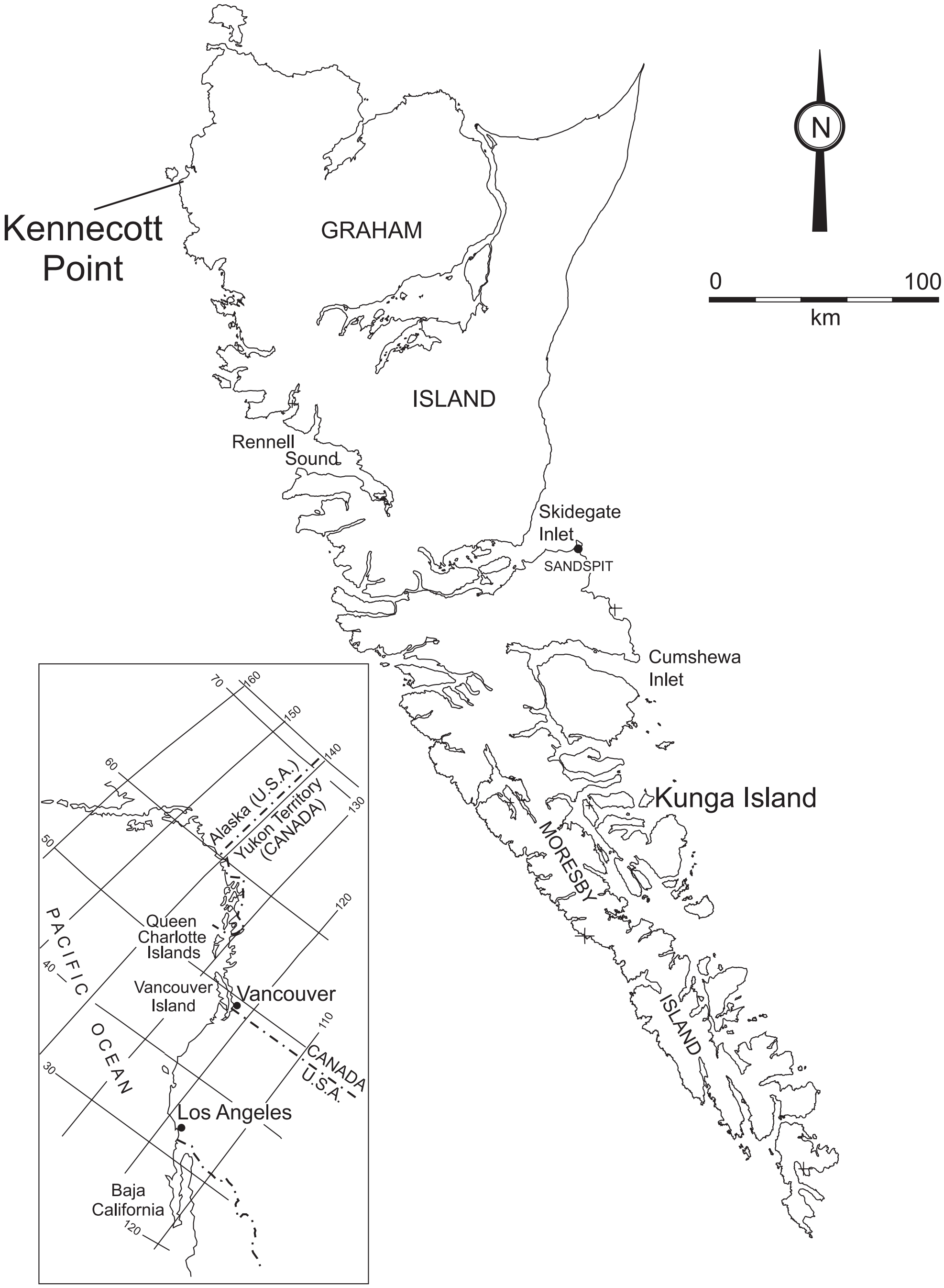

Fig. 1. Location map showing the Kennecott Point and Kunga Island localities in the Queen Charlotte Islands, British Columbia, Canada. The T/J boundary is located at GPS N53.54.807; W133.09.296.

logical record [4], only recently have perturbations been recognized in the global carbon record associated with this event. Negative carbon isotope excursions are now recognized from both terrestrial [5] and marine sections of Rhaetian/Hettangian (=Triassic/Jurassic) age [3,6–11]. In addition to the recognition of a worldwide pattern of carbon isotope stratigraphy at the Rhaetian/Hettangian (R/H) stage boundary, there is mounting evidence that the preceding stage boundary, that of the Norian/Rhaetian (N/R), is also characterized by a carbon isotope anomaly. However, unlike the negative excursion now widely recognized at the R/H boundary, the N/R boundary may contain a positive excursion in $\delta^{13}C_{org}$ [10,12].

We report here results from new, high-resolution paleontological and chemostratigraphic sampling of upper Norian to lower Hettangian strata exposed at Kennecott Point, Queen Charlotte Islands, British Columbia, Canada (Fig. 1). These results amplify and expand on our previous work [10]. Our new data support the hypothesis that the Late Triassic mass extinction was actually two separate pulses of elevated extinction, one at the Norian/Rhaetian, and a larger pulse at the Rhaetian/Hettangian boundary.

2. Stratigraphy

We studied a continuous outcrop of the uppermost Peril (Triassic: upper Norian) and Sandilands (Rhaetian to Pliensbachian) formations at Kennecott Point. Integrated biostratigraphic studies previously carried out on this section [13,14] showed that the sequence contains both microfossils and macrofossils in sufficient abundance to allow refined biostratigraphic correlation. This sections exhibits some structural disruption; beds dip ~ 15–25° and are cut by numerous small-scale offsets that can be mapped and deconstructed on the outcrop. The Kennecott Point section exhibits minimal evidence of diagenetic alteration [15]. The section, located in proximity (ca. 5 km) to Tertiary plutons, is not intruded by igneous dikes.

At Kennecott Point, the uppermost Peril Formation consists of fossiliferous, black calcareous shale and siltstone, locally with occasional large calcareous concretions (Fig. 2). The most notable lithological feature in the uppermost portion of the Peril Formation is the presence of coquina beds with species of the bivalve genus *Monotis* (Fig. 3). The local extinction of these bivalves, which occurs at the top of the Peril Formation, is associated with a gradual transition from massive and bioturbated black calcareous mudstone and siltstone, with abundant bedding-plane concentrations of *Monotis* spp. in bituminous facies, to the thinly laminated black shale, interbedded with more massive turbiditic siltstone and sandstone of the overlying Sandilands Formation (Fig. 4). This lithological change extends over approximately 30m. Ammonoid diversity and abundance decreases significantly at this point, and their preservation changes from entire (but flattened) body fossils to impressions of shells with organic siphuncular structures preserved in three dimensions within the phragmocone outline.

Radiolarian fossils obtained from Kennecott Point have been the subject of numerous previous and ongoing studies [13,14,16]. It is the dramatic turnover of radiolarian taxa in the section that is used to define the Triassic/Jurassic boundary at Kennecott Point, and at coeval sections in the region. The Triassic/Jurassic boundary is placed at the base of the *Canoptum merum* Zone, which is superjacent to the Rhaetian *Globolaxtorum tozeri* radiolarian zone (equivalent to the Crickmayi Zone of the ammonoid standard zonal sequence [14]. The biostratigraphic distribution of radiolarian fossils clearly defines a significant (>90%) die-out of Rhaetian taxa, with replacement assemblages in the basal Lower Hettangian limited in both diversity and numbers of individuals [17]. At Kennecott Point, radiolarian biostratigraphy was only able to place the boundary within a 10-m-thick interval [10].

Sandilands Formation strata of the Triassic/Jurassic boundary interval at Kennecott Point (Fig. 5) consist of silicified, organic-rich, laminated to massive dark-grey to black shale, alternating with siltstone to fine- to medium-grained sandstone. Sedimentary structures in coarser-grained units include low-angle planar cross-stratification, flame structures, ripple-laminated beds, rare hummocky cross-stratification, and graded bedding. Ichnofossils are rare in fine-grained facies but more common in coarser-grained facies and include both bedding plane grazing traces and infaunal burrowing traces. Thin tuff beds are common in the Kennecott Point section and include clay-rich tuffs as

Fig. 2. Black shale and limestone characteristic of the Peril Formation, Kennecott Point. At this locality, the darker shale units are composed of shell coquina made up of numerous compressed bivalve mollusk shells assignable to *Monotis* spp.

well as tuffaceous siltstone and fine-grained sandstone beds. The presence of abundant laminated black shale interbeds in the Kennecott Point section suggests anoxic bottom conditions, and this may account for the distinct lack of benthic fauna within these shales.

3. Materials and methods

Paleontological and geochemical sampling was conducted at Kennecott Point in 1999 and 2001 from a measured stratigraphic section. We used a 100-m

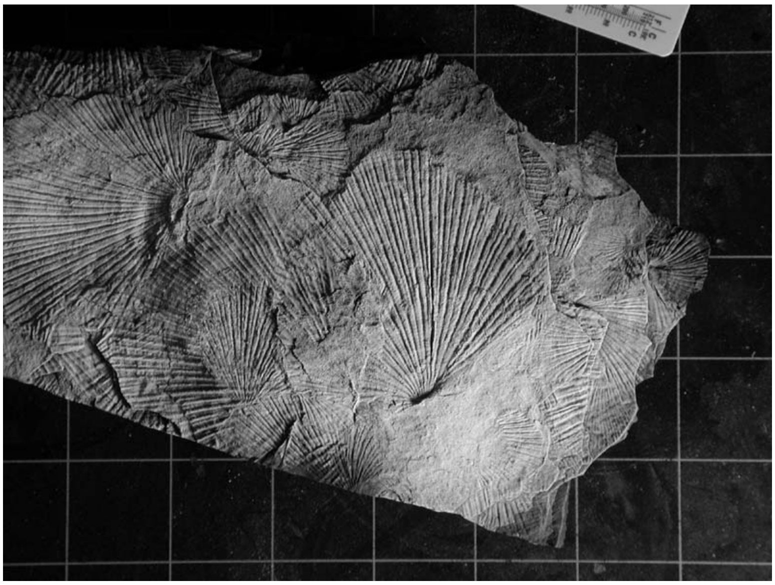

Fig. 3. Close up of *Monotis* coquina from Peril Formation, Kennecott Point. Grid lines are approximately 3 cm apart.

Fig. 4. Thinly laminated black shale interbedded with turbiditic siltstone and sandstone of the Sandilands Formation, Kennecott Point. T/J boundary lies in low shales beneath the thick sandstones on left side of photo.

steel tape affixed to a concrete cairn erected in basal Jurassic strata in 1999 to identify stratigraphic levels. Macrofossils were collected throughout the section, with concentrated collecting at the N/R and R/H stage boundaries. Below the N/R boundary, bulk samples of *Monotis* spp. coquina were collected in situ and returned to the laboratory for identification and measurement; these materials are reposited at the University of Washington, Seattle. Measurements of monotid shells were also made on selected well-preserved specimens observed on bedding planes in the field. At the R/H boundary, ammonites were collected from

Fig. 5. Stratigraphic interval of T/J boundary within the Sandilands Formation at Kennecott Point.

quarried pits; these fossils were returned to the Vancouver office of the Geological Survey of Canada, where they were identified to genus level and reposited in GSC collections. The systematic paleontology of these specimens at the species level will be published in subsequent paleontological monographs.

Bulk samples of sedimentary rock were collected at Kennecott Point for both organic carbon and inorganic carbonate analyses. Isotope ratios are reported in standard delta notation relative to Vienna PDB (VPDB), where $\delta^{13}C=[[(^{13}C/^{12}C)\ sample/(^{13}C/^{12}C)\ VPDB]-1]\times 1000$, and internal laboratory reference materials for $\delta^{13}C$ and $\delta^{18}O$ analyses have been calibrated against NBS-19 ($\delta^{13}C=+1.95$‰ $\delta^{18}O=-2.2$‰ VPDB). Samples for organic carbon ^{13}C:^{12}C analysis ($\delta^{13}C_{org}$) were first acidified with either 20 μl of 50% HCl or 50 μl of 6% H_2SO_3 and oven-dried at 50 °C to remove inorganic (carbonate) carbon. One of two methods was then used to measure $\delta^{13}C_{org}$. The first used the sealed vessel technique of Wedeking et al. [18], wherein samples were sealed in borosilicate ampoules with cupric oxide and combusted at 680 °C for at least 8 h. The ^{12}C:^{13}C ratio was then measured on cryogenically purified CO_2 via dual inlet isotope-ratio-mass-spectrometry (IRMS) on a ThermoFinnigan DELTAplus model mass spectrometer in the Stable Isotope Laboratory of the College of Ocean and Fishery Sciences at the University of Washington. Fifty-nine $\delta^{13}C_{org}$ samples from Kennecott Point were analyzed this way, and sample replicates had an average standard deviation (σ) of 0.15‰($n=140$). Analytical precision based on routine analyses of internal laboratory reference materials by this technique was 0.08‰The remaining 103 $\delta^{13}C_{org}$ samples from Kennecott Point were analyzed via elemental-analyzer-continuous-flow-IRMS (EA-CFIRMS). A Costech ECS 4010 Elemental Analyzer coupled to a ThermoFinnigan DELTAplus mass spectrometer via a ThermoFinnigan CONFLO III interface was used at the Stable Isotope Research Facility (SIRF) operated jointly by the Quaternary Research Center and the Astrobiology Program at the University of Washington. Sample replicates via CF-IRMS had an average σ of 0.17‰($n=208$), while analytical precision was 0.10‰ Finally, sedimentary carbonate mineral stable isotope ratios ($\delta^{13}C_{carb}$ and $\delta^{18}O_{carb}$) were analyzed on a MicroMass Isoprime model dual inlet mass spectrometer. Samples were prepared and introduced to the mass spectrometer via a MicroMass MultiPrep model autosampler in Multicarb mode. These samples were reacted with 103% phosphoric acid at 90 °C for 10 min. The system was calibrated using NBS-19, and has an analytical precision of 0.15‰ (VPDB); replicated sample analyses had a $\sigma=0.21$ ($n=25$).

4. Results

Biostratigraphic sampling was limited to the stage boundary intervals. At the lower of these boundaries, the Norian/Rhaetian, we measured maximum valve size for monotid bivalves approaching the boundary, which in this section is defined by the last occurrence of *Monotis* spp. (Fig. 6). Maximum shell size remains approximately constant over approximately 10 m of section, then reduces markedly approaching the stage boundary. At this time, it is not known whether this marked size reduction approaching the boundary is related to a succession of ever-smaller *Monotis* species, or a single species undergoing size reduction approaching the extinction level. Coincident with this change is a gradual change in lithology that has been used to differentiate the Peril Formation from the overlying Sandilands Formation. In the last 10 m of beds containing *Monotis* the strata become finer-grained and noticeably darker. Trace fossils assignable to *Chondrites* appear for the first time, suggesting that this transition is marked by increasing anoxia of bottom waters, which we favor here as a cause of the bivalve extinction at this site.

Sampling for macrofossils near the R/H boundary (as defined by radiolarians) resulted in the recovery of seven specimens of the late Triassic zonal index ammonite *Choristoceras* sp. Previous work [10] reported the last specimens of this important upper Triassic zonal index at 17 m below the micropaleontologically defined R/H boundary (the first occurrence of the Merum radiolarian zone). Our new work now shows that this ammonite ranges up at least to within 4 m of the base of the Merum Zone.

The isotopic profiles measured results for C_{org}, C_{carb}, and O^{18}/O^{16} are shown in Fig. 7a–e. Our new results in $\delta^{13}C_{org}$ appear to confirm the prior discovery of a positive isotopic anomaly at Kennecott Point coincident with the Norian/Rhaetian stage boundary,

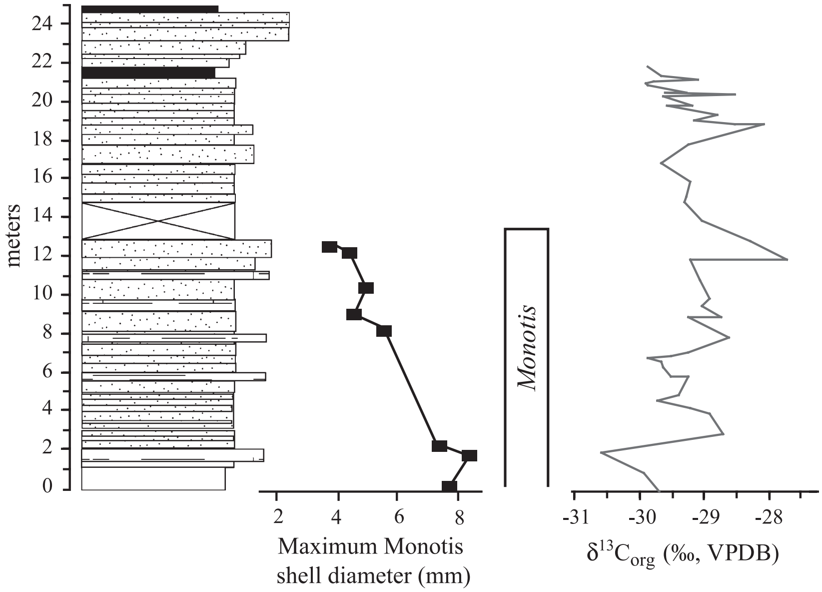

Fig. 6. Measured section of uppermost Peril Formation from Kennecott Point showing diminishing maximum shell size of Monotis specimens approaching their final extinction level. This pattern argues against a sudden or catastrophic extinction of these bivalves.

made by Ward et al. [10] and later observed at a correlative stratigraphic position at Williston Lake by Sephton et al. [12], which in British Columbia is coincident with the extinction of the bivalve *Monotis*. Our sampling across this interval (Fig. 7b) suggests that this anomaly is composed of multiple positive excursions away from the average baseline values, coincident with our observed reduction in the size of *Monotis* spp. in bedding-plane mass occurrences. The positive excursion might represent pulses of organic productivity prior to the extinction itself.

Our new sampling at Kennecott Point yields new information about the structure of the higher isotopic excursion, at or near the level of the paleontologically defined Triassic/Jurassic boundary. This excursion is also composed of a series of vacillations, but in this case toward more negative rather than more positive values (Fig. 7c). We sampled continuously and analyzed homogenized centimeter-scale samples throughout the interval. While most values remain nearly 2‰ lighter than the rest of the section, significant swings toward heavier values also occur. The anomaly is composed of a complex series of swings toward heavier and lighter values, with the first of these clearly predating the extinction of Triassic ammonoids and microfauna in this section. The end of the isotopic excursion coincides with the appearance of earliest Jurassic radiolarians, and is 8 m below the lowest Hettangian ammonites yet recovered in this section.

We found that there was no significant correlation between $\delta^{13}C_{org}$ and weight percent organic C ($R^2 = 0.008$, Fig. 8). Furthermore, the similarity of the Kennecott Point $\delta^{13}C_{org}$ record to other published records (discussed later) is such that the trend of these data is considered to reflect their primary condition. There are three unique intervals within the Kennecott Point section as identified by the $\delta^{13}C_{org}$ record. The least variant interval of the section is between 16 and 113 m (Fig. 7). Within these strata, $\delta^{13}C_{org} = -29.4 \pm 0.5$ ‰ (VPDB; $n = 161$), which is considered a long-term average value for the section for comparative purposes. At the base of the section, there is a slight positive excursion away from this average between 7.2 and 16.0 m (Fig. 7c). Within these deposits, $\delta^{13}C_{org}$ has an average value of −28.9‰ (VPDB), with a maximum of −27.7‰ (VPDB) at 12.0 m. Furthermore, with the data available, as many as five individual relative maxima can be identified within the pattern of this positive excursion. There is a more dramatic and important excursion within the $\delta^{13}C_{org}$ data at the top of the section (Fig. 7b). Between 106 and 113 m, $\delta^{13}C_{org}$

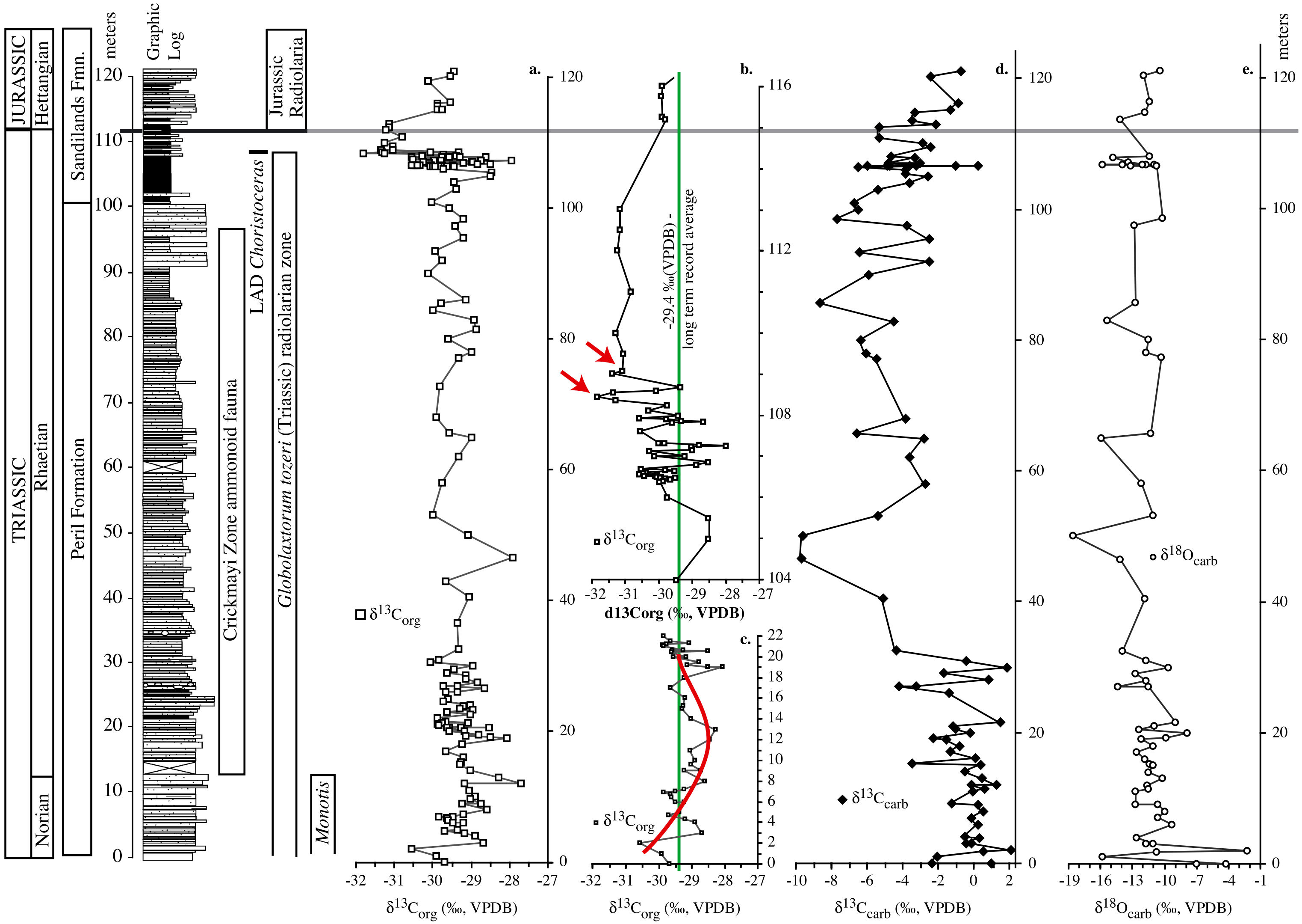

Fig. 7. (a–e) Isotopic profiles for $\delta^{13}C_{org}$, $\delta^{13}C_{carb}$, and $\delta^{18}O_{carb}$ from the Kennecott Point section.

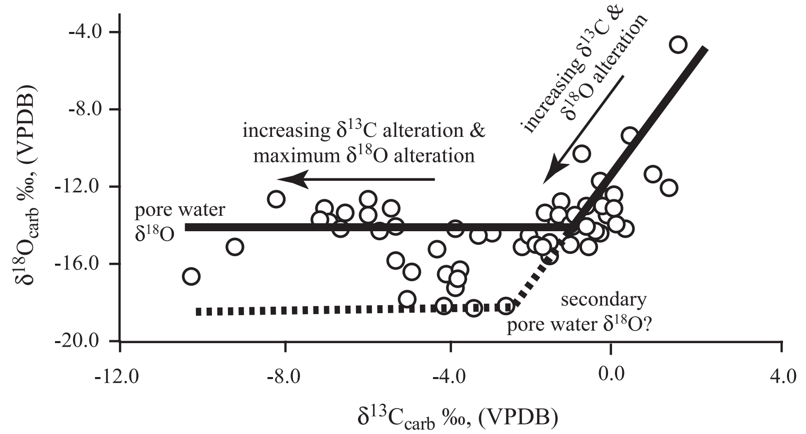

Fig. 8. The graph of $\delta^{18}O_{carb}$ vs. $\delta^{13}C_{carb}$ of the samples from the Kennecott Point section.

falls to an average value of -30.0‰(VPDB), with a nadir of -31.9‰(VPDB) measured at 108.45 m. Again, there is a toothy pattern to the excursion, with as many as six relative minima identifiable from these data.

The graph of $\delta^{18}O_{carb}$ vs. $\delta^{13}C_{carb}$ in Fig. 8 reveals that the sedimentary carbonate material in the Kennecott Point section have been affected by diagenesis. The positive correlation among the data on the right side of the graph reflects recrystallization of carbonate material in waters that were more depleted in $\delta^{13}C$ and $\delta^{18}O$ than the original mineral [19]. The farther data plot to the left the greater their degree of alteration from primary isotopic values. The samples which plot along the plateau in $\delta^{18}O_{carb}$ values (~ -14‰VPDB) on the left are interpreted as having reached isotopic equilibrium with the ^{18}O:^{16}O ratio, but not the ^{13}C:^{12}C ratio, of the pore waters. The second group of more depleted $\delta^{18}O_{carb}$ values (~ -18.5‰VPDB) may have resulted from an additional, probably earlier, period of recrystallization within different pore waters with an even lower ^{18}O:^{16}O ratio. Furthermore, the absence of calcareous shell material in the upper parts of the section (i.e., only fossil impressions remain) is additional evidence of carbonate mineral diagenesis. However, the lack of any correlation between $\delta^{13}C_{org}$ and $\delta^{13}C_{carb}$ (Fig. 9) indicates that the diagenesis that has altered the carbonate isotopic values did not have an effect on the $\delta^{13}C_{org}$, which supports the interpretation that these $\delta^{13}C_{org}$ data are primary. This interpretation is further reinforced by the agreement in shape and magnitude of the Kennecott Point $\delta^{13}C_{org}$ profile with sections from Hungary [3], the United Kingdom [11], Nevada and Italy (unpublished data from Ward et al.). Thus we conclude that the sedimentary organic carbon isotope values from the Kennecott Point section (and the others) reflect the primary isotope signature during the T/J boundary period.

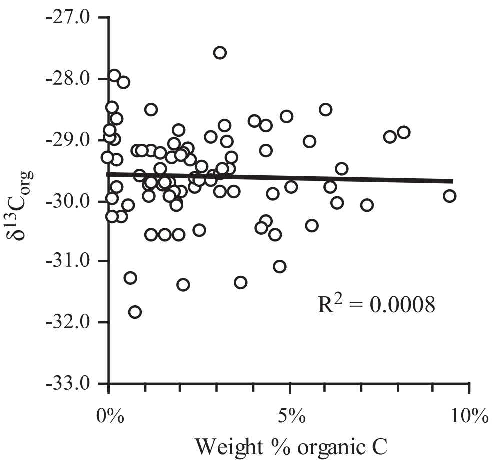

Fig. 9. The graph of $\delta^{13}C_{org}$ vs. weight percent organic carbon of the samples from the Kennecott Point section.

5. Discussion

Previous chemostratigraphic studies of the Kennecott Point site showed that extinctions recognizable among macro- and microfossils at both the Norian/

Rhaetian and Rhaetian/Hettangian boundaries were co-incident with excursions in $\delta^{13}C_{org}$ values away from average values of about $+29.5 \pm 0.5$‰ (VPDB). The lower of these excursions, coincident with the extinction of the bivalve *Monotis*, showed a +2‰ rise and occurred over about 10m of section, but was defined by few sampled sites. The upper excursion was a −2‰ drop that follows a similar positive excursion, with the entire event extending over approximately 10 m of section (10 samples) that spanned the position of the paleontologically defined T/J boundary. The new $\delta^{13}C_{org}$ data presented above confirm the presence of a positive isotopic anomaly at the Norian/Rhaetian stage boundary, first noted at Kennecott Point by Ward et al. [10]. The paucity of samples across the N/R boundary in that earlier study made conclusions problematical. Sephton et al. [12] also recognized a ~ +1.5‰ positive $\delta^{13}C_{org}$ excursion at the same stratigraphic position within the classic section at Black Bear Ridge near Williston Lake, British Columbia. These results were later challenged by [20], who suggested that the isotope record obtained near the top of the Williston Lake Triassic section were not from end-Norian strata, but from end-Rhaetian beds in a condensed sequence. Thus the Sephton et al. [12] results recorded the R/H rather than N/R stage boundary. However, as noted by these authors, the presence of a pronounced positive, rather than negative excursion, argues against this conclusion. Furthermore, Sephton et al. [12] recognized a coincident rise then fall in nitrogen isotope rations of sedimentary organic matter ($^{15}N/^{14}N$) consistent with oceanic torpor and compartmentalization. In such a scenario, stagnation leads to nutrient limitation in surface waters and an eventual change to planktonic populations dominated by nitrogen-fixing bacteria.

In both Williston Lake and Kennecott Point, the positive excursion is coincident with the final extinction of the bivalve *Monotis*, as well as in a dramatic reduction in ammonite diversity from the highest Norian ammonite zone (Cordilleranus Zone) to that of the lowest Rhaetian (Amoenum Zone). As noted above, lithological and trace fossil evidence is suggestive of increasingly anaerobic bottom conditions across this interval, which is consistent with the conclusion [12] that the positive $\delta^{13}C_{org}$ excursion and the *Monotis* crisis resulted from increased stagnation in ocean circulation. Unfortunately, the Rhaetian deposits in the Black Bear Ridge section are either incomplete or had very low accumulation rates; Sephton et al. [12] report the Rhaetian strata at Williston Lake to be only 10 m thick as compared to 120 m thick at Kennecott Point. Thus, comparing the detailed structure of the $\delta^{13}C_{org}$ data from both sections is problematical. Nevertheless, the Sephton et al. study clearly shows the presence of a significant, positive excursion co-incident (or related to) the extinction of *Monotis*; consequently, they concluded that the $\delta^{13}C_{org}$ values are primary and could prove a new and useful correlation tool for comparing sections across the Norian/Rhaetian boundary, a view that we endorse.

The second pulse of extinction occurs in the uppermost Rhaetian, and is observed in both micro- and macrofossils. The negative excursion in the $\delta^{13}C_{org}$ record begins 8 m below the first appearance of earliest Jurassic radiolarians. There is a series of $\delta^{13}C$ record perturbations associated with this event, which more closely resemble the $\delta^{13}C$ record across the Permian/Triassic boundary mass extinction event than the $\delta^{13}C$ record measured across the Cretaceous/Tertiary (K/T) mass extinction event. While there has been recent evidence that the T/J mass extinction was the result of a large-body impact on the Earth [1], the pattern of isotopes does not conform to the pattern observed at the K/T event [21], the only widely accepted impact-induced mass extinction. Pálfy et al. [3,9] have argued that the isotopic record across the T/J boundary is best explained through some combination of productivity collapse associated with gas hydrate release into the biosphere. Presumably in this scenario, there are multiple events over hundreds of thousands of years that cumulatively produce that mass extinction. The isotopic record reported from Hungary [3], the United Kingdom [11] and in British Columbia, reported here, shows a repeated series of both positive and negative excursions away from a background mean.

The isotopic record from Kennecott Point suggests further that quite different environmental conditions may have characterized N/R and R/H boundary time. Our own view is that the biosphere from about 260 to at least 180 million years ago underwent a series of crises brought about by a series of terrestrial and endogenous events: sudden rises in global temperature accompanied by increased atmospheric CO_2 and decreased oxygen content. This category of events may also have been the cause of the P/T, Carnian, end-Norian, end-Rhaetian, and Pliensbachian extinction events. In this hypothesis, the ultimate cause of extinction was the unification and disintegration of the global supercontinent Pangea, and such long-term biotic crises are likely a characteristic of this phase of the Wilson Supercycle of continents. In each case, however, differences in biota, continental position, and climate led to different results and characteristic isotopic patterns.

There is now an emerging view of the carbon isotope record across the Triassic/Jurassic (Rhaetian/Hettangian) boundary. Disparate geographic sites with varying lithologies have similar sedimentary stable carbon isotope profiles. The T/J event was not a single "reversible" anomaly, that is, a short-term deviation from a steady state with return to values of the pre-event environment; the K/T event seems to be characterized by such reversible δ^{13}C anomalies. While the T/J event was also transient, the anomaly pattern now seen globally is of two or more negative excursions in succession. From this evidence alone, it seems unlikely that the T/J event was largely or entirely the consequence of large body impact with the Earth in the manner of the K/T event.

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References

[1] P.E. Olsen, D.V. Kent, H.-D. Sues, C. Koeberl, H. Huber, A. Montanari, E.C. Rainforth, S.J. Fowell, M.J. Szajna, B.W. Hartline, Ascent of dinosaurs linked to an iridium anomaly at the Triassic–Jurassic boundary, Earth-Sci. Rev. 296 (2002) 1305–1307.

[2] A. Hallam, P.B. Wignall, Mass extinctions and sea-level changes, Science 48 (1999) 217–250.

[3] J. Pálfy, A. Demény, J. Haas, M. Hetényi, M.J. Orchard, I. Vetö, Carbon isotope anomaly and other geochemical changes at the Triassic–Jurassic boundary from a marine section in Hungary, Geology 29 (2001) 1047–1050.

[4] A. Hallam, P.B. Wingall, Mass Extinctions and Their Aftermath, Oxford Univ. Press, 1997, p. 320.

[5] J.C. Mcelwain, D.J. Beerling, F.I. Woodward, Fossil plants and global warming at the Triassic–Jurassic boundary, Science 285 (1999) 1386–1390.

[6] A. Hallam, W.D. Goodfellow, Facies and geochemical evidence bearing on the end-Triassic disappearance of the Alpine reef ecosystem, Hist. Biol. 4 (1990) 131–138.

[7] R. Morante, A. Hallam, Organic carbon isotopic record across the Triassic–Jurassic boundary in Austria and its bearing on the cause of the mass extinction, Geology 24 (1996) 391–394.

[8] C.A. Mcroberts, H. Furrer, D.S. Jones, Palaeoenvironmental interpretation of a Triassic–Jurassic boundary section from Western Australia based on palaeoecological and geochemical data, Palaeoecol. Paleogeogr. Palaeoclimatol. 136 (1997) 79–95.

[9] J. Pálfy, J.K. Mortensen, E.S. Carter, P.L. Smith, R.M. Friedman, H.W. Tipper, Timing the end-Triassic mass extinction: first on land, then in the sea? Geology 28 (2000) 39–42.

[10] P.D. Ward, J.W. Haggart, E.S. Carter, D. Wilbur, H.W. Tipper, T. Evans, Sudden productivity collapse associated with the Triassic–Jurassic boundary mass extinction, Science, 292 (2001) 1148.

[11] S.P. Hesselbo, S.A. Robinson, F. Surlyk, S. Piasecki, Terrestrial and marine extinction at the Triassic–Jurassic boundary synchronized with major carbon-cycle perturbation: a link to initiation of massive volcanism, Geology 30 (2002) 251–254.

[12] M.A. Sephton, K. Amor, I.A. Franchi, P.B. Wignall, R. Newton, J.-P. Zonneveld, Carbon and nitrogen isotope disturbances and an end-Norian (Late Triassic) extinction event, Geology 30 (2002) 1119–1122.

[13] H.W. Tipper, J.W. Haggart, E.S. Carter, R.L. Hall, G.K. Jakobs, J. Pálfy, Field Trip B1: Haida Gwaii (Queen Charlotte Islands, in: P.L. Smith (Ed.), Field Trip B1: Haida Gwaii (Queen Charlotte Islands), International Union of Geological Sciences, Vancouver, 1998, pp. 127–229.

[14] E.S. Carter, Proposal of Kunga Island, Queen Charlotte Islands, British Columbia, Canada as Triassic/Jurassic global boundary stratotype, Geology 27 (1999).

[15] J.W. Haggart, E.S. Carter, M.J. Beattie, P.S. Bown, R.J. Enkin, D.A. Kring, M.J. Johns, V.J. Mcnicoll, M.J. Orchard, R. Perry, C.J. Schröder-Adams, P.L. Smith, L.B. Suneby, H.W. Tipper, P.D. Ward, Stratigraphy of Triassic/Jurassic boundary strata, Queen Charlotte Islands, British Columbia: potential global system stratotype boundary. IGCP #458 (Triassic–Jurassic Events), Southwest England Field Workshop, 2001, pp. 10–13.

[16] E.S. Carter, Biochronology and Paleontology of Uppermost Triassic (Rhaetian) Radiolarians, Queen Charlotte Islands, British Columbia, Canada, 1993, 175 pp.

[17] E.S. Carter, R.S. Hori, Radiolarian Faunal Turnover at the T/J Boundary: Western Canada and Japan.

[18] K.W. Wedeking, J.M. Hayes, U. Matzigkeit, Procedure of

organic geochemical analysis, in: J.W. Schopf (Ed.), Procedure of Organic Geochemical Analysis, Princeton Univ. Press, Princeton, 1983, pp. 428–441.

[19] J.D. Marshall, Climatic and oceanographic isotopic signals from the carbonate rock record and their preservation, Geol. Mag. 129 (1992) 143–160.

[20] R.L. Hall, S. Pitaru, Carbon and nitrogen disturbances and an end-Norian (late Triassic) extinction event: Comment, in press.

[21] K.J. Hsü, J.A. Mckenzie, Carbon-isotope anomalies at era boundaries; global catastrophes and their ultimate cause Global catastrophes in Earth history; an interdisciplinary conference on impacts, volcanism, and mass mortality, in: V.L. Sharpton, P.D. Ward (Eds.), Carbon-Isotope Anomalies at Era Boundaries; Global Catastrophes and Their Ultimate Cause Global Catastrophes in Earth History; An Interdisciplinary Conference On Impacts, Volcanism, and Mass Mortality, 1990, pp. 61–70.