Deep-sea record of impact apparently unrelated to mass extinction in the Late Triassic

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The 34-million-year (My) interval of the Late Triassic is marked by the formation of several large impact structures on Earth. Late Triassic impact events have been considered a factor in biotic extinction events in the Late Triassic (e.g., end-Triassic extinction event), but this scenario remains controversial because of a lack of stratigraphic records of ejecta deposits. Here, we report evidence for an impact event (platinum group elements anomaly with nickel-rich magnetite and microspherules) from the middle Norian (Upper Triassic) deep-sea sediment in Japan. This includes anomalously high abundances of iridium, up to 41.5 parts per billion (ppb), in the ejecta deposit, which suggests that the iridium-enriched ejecta layers of the Late Triassic may be found on a global scale. The ejecta deposit is constrained by microfossils that suggest correlation with the 215.5-Mya, 100-km-wide Manicouagan impact crater in Canada. Our analysis of radiolarians shows no evidence of a mass extinction event across the impact event horizon, and no contemporaneous faunal turnover is seen in other marine planktons. However, such an event has been reported among marine faunas and terrestrial tetrapods and floras in North America. We, therefore, suggest that the Manicouagan impact triggered the extinction of terrestrial and marine organisms near the impact site but not within the pelagic marine realm.

chert | Panthalassa | Mino Terrane | pelagic sediments

The discoveries of an iridium-enriched clay layer at the Cretaceous/Paleogene (K/Pg) boundary and the 65-million-year (My)-old Chicxulub impact structure in Mexico have revealed the global environmental damage such impacts can cause and their association with mass extinction events (1, 2). Analysis of the K/Pg event has led to the assumption that other large extraterrestrial impacts also contributed to mass extinction events over the past 250 million years (3, 4). The Late Triassic, 236–201 million years ago (Mya), is marked by several large impact craters (5): the 100-km Manicouagan and the 40-km Saint Martin structures in Canada; the 25-km Rochechouart structure in France; the 10-km Paasselkä structure in Finland; and the 9-km Red Wing structure in the United States (Fig. 1). Previous researchers suggested that these Late Triassic impact craters could have resulted in the end-Triassic extinction event (6, 7) or earlier extinctions at the Norian/Rhaetian or Carnian/Norian boundaries (8, 9). To understand the causal link between the Late Triassic extinctions and the impact events, it is necessary to precisely date the age of crater formation and locate the geologic record of the impact ejecta layer within a well age-constrained stratigraphic sequence. Although the ages of the Late Triassic impact events have been constrained by radioisotopic dating (*SI Appendix, Table S1*), deposits containing their ejecta are known only from a nonmarine sequence in southwestern Britain (10–12).

Here, we report that Upper Triassic deep-sea sediment (bedded chert) at Sakahogi in the Inuyama area, Central Japan, contains

microspherules, nickel (Ni)-rich magnetite, and a platinum group element (PGE) anomaly, all of which suggest an extraterrestrial impact event (2, 13). A previous paleomagnetic study of the Sakahogi locality indicated that the bedded chert accumulated at low latitudes ($3.9^\circ \pm 3.3^\circ$ N or S) within a deep Paleo-Pacific (Panthalassa) basin (14, 15). We examine the high-resolution biostratigraphy of microfossils across the impact event horizon and discuss the relationship between the impact and extinction events in the Late Triassic deep-sea sediments.

Impact Ejecta Layer

Evidence of a Late Triassic impact event was discovered as a PGE anomaly from a claystone layer in an Upper Triassic bedded chert succession of the Sakahogi locality, Inuyama area, Central Japan (*SI Appendix, Fig. S1*). The claystone layer, which we call the “Sakahogi ejecta layer,” contains microspherules, Ni-rich magnetite, and a high abundance of PGEs, ranges in thickness from 4 to 5 cm, and extends laterally for at least 90 m at Sakahogi. We distinguish lower and upper sedimentary sublayers within the claystone (*SI Appendix, Fig. S3*). The lower sublayer (~8-mm-thick) contains 10–15% (by rock volume) microspherules in a matrix of clay minerals (mainly illite), cryptocrystalline quartz, and hematite. Our preliminary investigation reveals that this sublayer contains many small euhedral to subhedral crystals of oxidized Ni-rich magnetite (16). Geochemical mapping using a scanning X-ray analytical microscope also reveals a high concentration of nickel (*SI Appendix, Fig. S4*). The upper sublayer of the claystone is composed of undisturbed sediments of clay (illite) and cryptocrystalline quartz containing radiolarians, siliceous sponge spicules, and conodonts.

The geochemical signals of the extraterrestrial impact are recorded in the lower sublayer of the claystone. Anomalies in iridium and other PGEs in the lower sublayer were identified based on analyses of nine claystone and two chert samples by instrumental neutron activation analysis (INAA) and inductively coupled plasma-mass spectrometry (ICP-MS). The anomalously high abundances of iridium, which is limited to the lower sublayer (Fig. 2), is defined by concentrations of up to 41.5 parts per billion (ppb), much greater than the background level of ~0.2

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Fig. 1. Late Triassic paleogeography and age of impact craters and ejecta deposits. (A) Approximate locations of five impact craters and ejecta sites plotted on a Late Triassic paleogeographic map modified from the original figure in ref. 5. The hatched area indicates the inferred depositional area of the bedded chert from the Mino Terrane in the low-latitude zone of the Panthalassa Ocean (14). See *B* for abbreviations for the craters and ejecta sites. (B) Radiometric and stratigraphic ages of the five impact craters based on the timescale proposed by ref. 27. Triassic radiolarian fossil zones (FZ) are from ref. 45. Note that the age of the ejecta deposit is constrained by conodonts and radiolarians (base of the 6B fossil zone) and is, therefore, given without an error range. The blue shading in the fossil zone column indicates the total age range of the section shown in Fig. 5.

ppb (*SI Appendix, Table S2*). The magnitude of this concentration is comparable to that measured at K/Pg sites (17), suggesting that the iridium-enriched ejecta layers of the Late Triassic may be found in sites worldwide (18). Anomalies in other PGEs are also seen in the lower sublayer of the claystone (Fig. 2). Fig. 3 shows the average elemental abundances of PGEs (relative to CI

carbonaceous chondrite) at four stratigraphic levels in the study section. In the lower sublayer, the concentrations of all of these elements are well above the background values in the underlying and overlying levels, and are enriched by up to three orders of magnitude compared with average terrestrial crustal abundances (19). The PGE anomaly was confirmed by an additional analysis of

Fig. 2. PGE abundances and biostratigraphy of radiolarians from the middle Norian section (Sakahogi) in Japan. Solid squares beside the lithologic section indicate the occurrence of conodonts and radiolarians in cherts and claystones. The radiolarian ranges are used to constrain the age of the ejecta deposit. Radiolarian (RZ) and conodont (CZ) zones are from refs. 45 and 22, respectively. See [S1 Appendix, Tables S2 and S3](#) for PGE data.

Fig. 3. CI chondrite-normalized PGE patterns of middle Norian samples at Sakahogi. Stratigraphic levels of samples are shown in Fig. 2. The concentrations of CI chondrites are from ref. 20. PGE patterns of the upper continental crust (19) and K/Pg boundary sediments (17) are shown for comparison. See *SI Appendix, Table S3* for data.

the second sample (NH-52R2) from the lower sublayer in the Sakahogi locality (*SI Appendix, Table S3*). Because PGEs are highly depleted in the Earth's crust relative to solar abundances (19, 20), the PGE anomaly reported here may have resulted from the accretion of a significant amount of siderophile elements from a large projectile. However, additional sampling for PGEs is needed to further test the origin of the projectile and to estimate its size.

The discovery of microspherules and Ni-rich magnetite associated with the PGEs anomalies in the lower sublayer also suggests an impact event (2, 13, 21), although they are affected by secondary processes, including low-grade regional metamorphism of the study area [conditions below those of the prehnite pumpellyite facies (15)], which altered their chemical composition. Microspherules were only found in the lower sublayer and have never been reported in the Triassic bedded chert succession of the Inuyama area. The microspherules in the lower sublayer are dark green to dark gray and range in size from 200 to 300 μm (Fig. 4A). Synchrotron X-ray diffraction analysis indicates that the microspherules are pseudomorphs of clinocllore-rich chlorite (*SI Appendix, Fig. S5*). These microspherules preserve a pseudomorphic internal texture that comprises dendrites and spherulites radiating from the surface into the microspherules (Fig. 4B). Some microspherules contain a high proportion of small, euhedral to subhedral crystals of oxidized Ni-rich magnetite (Fig. 4C). The Ni-rich magnetite grains are 5–20 μm in size and commonly have skeletal or octahedral morphologies (Fig. 4D). Electron microprobe analysis shows large variations in the concentrations of Al, Fe, Cr, Ni, and Zn among the magnetite grains, along with minor amounts of Mg, Ti, and Mn (*SI Appendix, Table S4*). These magnetite grains are distinguished from typical igneous magnetite by high contents of Ni and Fe^{3+} and relatively low concentrations of Ti.

Age and Biostratigraphy

The depositional age of the claystone is constrained by radiolarians and conodonts (*SI Appendix, Table S6 and Fig. S6*). A detailed discussion of their biostratigraphy in the Sakahogi locality is given in *SI Appendix, SI Text*. The claystone layer lies between pelagic chert layers of the radiolarian zones TR6A and TR6B and is correlated with the upper middle Norian. A biostratigraphic analysis of conodonts also reveals that the ejecta deposit is embedded in the upper middle Norian (base of the *Epigondolella bidentata* zone of ref. 22). This age indicates that the impact event occurred well before the Rhaetian interval (*Epigondolella mosheri* and *Misikella posthernsteini* conodont zones), and, therefore, it has no

relevance to the extinction events at the end-Triassic and Norian/Rhaetian boundaries (7, 23, 24).

Our biostratigraphic analysis suggests that there was no mass extinction of radiolarians across the impact event horizon. Fig. 5 shows biostratigraphic ranges of 147 species in 62 genera of radiolarians from 331 horizons; the collection intensity was uniform without any sampling gaps (*SI Appendix, Fig. S2*). A significant faunal turnover is observed ~ 1 m above the impact ejecta horizon in the upper middle Norian. Given that the average sedimentation rate of the middle Norian chert succession, estimated from the measured thickness and the time interval of its deposition (*SI Appendix, Fig. S2*), is 1.0 mm per thousand years, this turnover occurred ~ 1 My after the impact event. Only one species became extinct at the ejecta horizon and the extinction rate of radiolarians (extinct species divided by total species at the same level) is estimated to be about 5% at the horizon. High-resolution radiolarian biostratigraphy across the impact ejecta layer also indicates that, of the 13 radiolarian species identified below this horizon, only one species, *Trialatus robustus*, disappears at the horizon (Fig. 2). The extinction of the genus *Trialatus* appears to have occurred synchronously across several regions in the middle Norian (*SI Appendix, SI Text*), meaning its last occurrence may be a good time indicator for the ejecta deposit.

Discussion

A biostratigraphic analysis of radiolarians and conodonts reveals that the ejecta deposit is embedded in the upper middle Norian. Recent magnetostratigraphic studies linked to conodont biostratigraphy (25–27) suggest that the stratigraphic position of the Sakahogi ejecta layer can be correlated with paleomagnetic chron PM9 to PM10 at the Pizzo Mondello section in Sicily (26) and with SB-9 at the Silická Brezová section in Slovakia (25). Although no radiometric age data are available, the magnetostratigraphic ages from these Norian sections have been assigned an age range of 216–212 Mya (*SI Appendix, Fig. S7*) based on the correlation with the astronomically tuned geomagnetic polarity time scale (Newark-APTS of refs. 28–30). These ages would seem to be consistent with the dating of an impact ejecta layer in southwestern Britain that has yielded a diagenetic age (from

Fig. 4. Microspherules and Ni-rich magnetite from a Norian ejecta deposit in Japan. (A) Photomicrographs of microspherules from the ejecta deposit. Plane-polarized light. (Scale bar: 500 μm .) (B) Microspherule showing the inward-radiating growth form of clinoclase pseudomorphs. (Scale bar: 100 μm .) (C) Scanning electron micrographs (backscattered mode) of a polished section of microspherule from the ejecta deposit. Ni-rich magnetite (bright grains) commonly occur as skeletal grains. (Scale bar: 100 μm .) (D) Close-up view of the microspherule in C illustrating skeletal crystal morphologies of Ni-rich magnetite in the microspherule. (Scale bar: 20 μm .)

in ammonoids, bivalves, and conodonts from western North America (40). It is possible that the Manicouagan impact may have triggered the extinctions of these marine faunas, at least in western North America, but this will require further biostratigraphic study at middle Norian sites globally.

Terrestrial records of Late Triassic vertebrates and plants have been well studied in the Chinle Formation of the Petrified Forest National Park in southwestern United States. Recent magnetostratigraphic and radioisotopic studies of the Chinle Formation suggest that a faunal turnover of terrestrial tetrapods, including the disappearance of herbivorous dicynodonts, occurred in the middle Norian (41–43). This turnover may coincide with a floral turnover in North America deduced from palynology studies (41, 42, 44). The depositional site of the Chinle Formation is relatively close to the Manicouagan crater (within ~3,500 km), raising the possibility that the effects of the impact [e.g., acid rain and wildfire on a regional scale (35)] triggered a catastrophic disruption of the terrestrial ecosystems in North America (42). However, it is uncertain whether the igneous and metamorphic target rocks of Manicouagan impact (8) could have produced catastrophic environmental effects (35), and a lack of age data prevents confirmation of the concurrence of the Manicouagan impact and floral and faunal turnovers in North America (41, 43). Detailed studies of terrestrial sections in the middle Norian are needed to determine whether the biotic turnover of terrestrial biotas at this time was caused by the Manicouagan impact.

Materials and Methods

For whole-rock analyses of PGEs, eleven samples were powdered in an agate mortar. Veins and strongly recrystallized zones were avoided to minimize the effects of diagenetic or metamorphic overprinting. PGE abundances were determined using inductively coupled plasma–mass spectrometry combined with a nickel sulfide fire assay (*SI Appendix, SI Materials and Methods*). Iridium was measured using a neutron activation technique. Powder samples were enclosed in small pure quartz vials and irradiated for 48 h in the JRR-3 reactor at the Japan Atomic Energy Agency (Ibaraki, Japan). Iridium was quantified with a gamma–gamma spectrometer detecting the 468- to 316-keV γ -ray coincidence resulting from the decay of ^{192}Ir .

We handpicked microspherules from the crushed rock powders (<500- μm grain size) of the ejecta deposit under a binocular microscope. To investigate the mineral composition of individual microspherules, synchrotron X-ray diffraction analysis was performed using a Gandolfi camera with synchrotron X rays of 2.165-Å wavelength at the High Energy Accelerator Research Organization (Tsukuba, Japan). After this analysis, microspherules were mounted in epoxy, sectioned, and polished to reveal their internal texture using a field-emission scanning electron microscope. Chemical compositions of Ni-rich magnetite were determined by electron microprobe with an electron acceleration voltage of 15 keV and a beam current of 10 nA. Details of our sample preparation and analytical methods can be found in *SI Appendix, SI Materials and Methods*.

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- Alvarez LW, Alvarez W, Asaro F, Michel HV (1980) Extraterrestrial cause for the cretaceous-tertiary extinction. *Science* 208(4448):1095–1108.
- Schulte P, et al. (2010) The Chicxulub asteroid impact and mass extinction at the Cretaceous–Paleogene boundary. *Science* 327(5970):1214–1218.
- Alvarez W, Muller RA (1984) Evidence from crater ages for periodic impacts on the Earth. *Nature* 308(5961):718–720.
- Raup DM, Sepkoski JJ, Jr. (1984) Periodicity of extinctions in the geologic past. *Proc Natl Acad Sci USA* 81(3):801–805.
- Spray JG, Kelley SP, Rowley DB (1998) Evidence for a late Triassic multiple impact event on Earth. *Nature* 392(6672):171–173.
- Bice DM, Newton CR, McCauley S, Reiners PW, McRoberts CA (1992) Shocked quartz at the triassic-jurassic boundary in Italy. *Science* 255(5043):443–446.
- Olsen PE, et al. (2002) Ascent of dinosaurs linked to an iridium anomaly at the Triassic–Jurassic boundary. *Science* 296(5571):1305–1307.
- Hodych JP, Dunning GR (1992) Did the Manicouagan impact trigger end-of-Triassic mass extinction? *Geology* 20(1):51–54.
- Tanner LH, Lucas SG, Chapman MG (2004) Assessing the record and causes of Late Triassic extinctions. *Earth Sci Rev* 65(1–2):103–139.
- Kirkham A (2003) Glauconitic spherules from the Triassic of the Bristol area, SW England: Probable microtektite pseudomorphs. *Proc Geol Assoc* 114:11–21.
- Walkden G, Parker J, Kelley S (2002) A late Triassic impact ejecta layer in southwestern Britain. *Science* 298(5601):2185–2188.
- Thackrey S, et al. (2009) The use of heavy mineral correlation for determining the source of impact ejecta: A Manicouagan distal ejecta case study. *Earth Planet Sci Lett* 285(1–2):163–172.
- Koeberl C (2001) The sedimentary record of impact events. *Accretion of Extraterrestrial Matter Throughout Earth's History*, eds Peucker-Ehrenbrink B, Schmitz B (Kluwer Academic, New York), pp 333–378.
- Ando A, Kodama K, Kojima S (2001) Low-latitude and Southern Hemisphere origin of Anisian (Triassic) bedded chert in the Inuyama area, Mino terrane, central Japan. *J Geophys Res* 106(B2):1973–1986.
- Matsuda T, Isozaki Y (1991) Well-documented travel history of Mesozoic pelagic chert in Japan: From remote ocean to subduction zone. *Tectonics* 10(2):475–499.
- Sato H, Onoue T (2010) Discovery of Ni-rich spinels in Upper Triassic chert of the Mino Terrane, central Japan. *J Geol Soc Jpn* 116(10):575–578.
- Ganapathy R (1980) A major meteorite impact on the Earth 65 million years ago: Evidence from the cretaceous-tertiary boundary clay. *Science* 209(4459):921–923.
- Claeys P, Kiessling W, Alvarez W (2002) Distribution of Chicxulub ejecta at the Cretaceous–Tertiary boundary. *Spec Pap Geol Soc Am* 356:55–69.
- Peucker-Ehrenbrink B, Jahn BM (2001) Rhenium–osmium isotope systematics and platinum group element concentrations: Loess and the upper continental crust. *Geochim Geophys Geosyst* 2:2001GC000172.
- Anders E, Grevesse N (1989) Abundances of the elements: Meteoritic and solar. *Geochim Cosmochim Acta* 53(1):197–214.
- Glass BP, Simonson BM (2012) Distal impact ejecta layers: Spherules and more. *Elements* 8(1):43–48.
- Orchard MJ (1991) Upper Triassic conodont biochronology and new index species from the Canadian Cordillera. *Geol Surv Can Bull* 417:299–335.
- Olsen PE, Shubin NH, Anders MH (1987) New early Jurassic tetrapod assemblages constrain Triassic–Jurassic tetrapod extinction event. *Science* 237(4818):1025–1029.
- Sephton MA, et al. (2002) Carbon and nitrogen isotope disturbances and an end-Norian (Late Triassic) extinction event. *Geology* 30(12):1119–1122.
- Channell JET, et al. (2003) Carnian–Norian biomagnetostratigraphy at Silicka Brezova (Slovakia): Correlation to other Tethyan sections and to the Newark Basin. *Palaeogeogr Palaeoclimatol Palaeoecol* 191(2):65–109.
- Muttoni G, et al. (2004) Tethyan magnetostratigraphy from Pizzo Mondello (Sicily) and correlation to the Late Triassic Newark astrochronological polarity time scale. *Geol Soc Am Bull* 116(9–10):1043–1058.
- Hüsing SK, Deenen MHL, Koopmans JG, Krijgsman W (2011) Magnetostratigraphic dating of the proposed Rhaetian GSSP at Steinbergkogel (Upper Triassic, Austria): Implications for the Late Triassic time scale. *Earth Planet Sci Lett* 302(1–2):203–216.
- Kent DV, Olsen PE (1999) Astronomically tuned geomagnetic polarity time scale for the Late Triassic. *J Geophys Res* 104(B6):12831–12841.
- Olsen PE, Kent DV (1999) Long-period Milankovitch cycles from the Late Triassic and Early Jurassic of eastern North America and their implications for the calibration of the Early Mesozoic time-scale and the long-term behaviour of the planets. *Phil Trans Royal Soc London Ser A* 357(1757):1761–1786.
- Olsen PE, Kent DV, Whiteside H (2010) Implications of the Newark Supergroup-based astrochronology and geomagnetic polarity time scale (Newark–APTS) for the tempo and mode of the early diversification of the Dinosauria. *Earth Environ Sci Trans R Soc* 101:201–229.
- Renne PR, Mundil R, Balco G, Min K, Ludwig KR (2010) Joint determination of ^{40}K decay constants and $^{40}\text{Ar}^*/^{40}\text{K}$ for the Fish Canyon sanidine standard, and improved accuracy for $^{40}\text{Ar}^{39}\text{Ar}$ geochronology. *Geochim Cosmochim Acta* 74(18):5349–5367.
- Renne PR, Balco G, Ludwig KR, Mundil R, Min K (2011) Response to the comment by W.H. Schwarz et al. on “Joint determination of ^{40}K decay constants and $^{40}\text{Ar}^*/^{40}\text{K}$ for the Fish Canyon sanidine standard, and improved accuracy for $^{40}\text{Ar}^{39}\text{Ar}$ geochronology” by P.R. Renne et al. (2010). *Geochim Cosmochim Acta* 75(17):5097–5100.
- French BM, Koeberl C (2010) The convincing identification of terrestrial meteorite impact structures: What works, what doesn't, and why. *Earth Sci Rev* 98(1–2):123–170.
- Ramezani J, Bowring SA, Pringle MS, Winslow FD III, Rasbury ET (2005) The Manicouagan impact melt rock: A proposed standard for the intercalibration of U–Pb and $^{40}\text{Ar}^{39}\text{Ar}$ isotopic system. *Geochim Cosmochim Acta* 60(10):A321.
- Kring DA (2007) The Chicxulub impact event and its environmental consequences at the Cretaceous–Tertiary boundary. *Palaeogeogr Palaeoclimatol Palaeoecol* 255(1–2):4–21.
- Bown PR (1992) Late Triassic–Early Jurassic calcareous nannofossils of the Queen Charlotte Islands, British Columbia. *J Micropalaeontol* 11(2):177–188.
- Riding JB, Mantle DJ, Backhouse J (2010) A review of the chronostratigraphical ages of Middle Triassic to Late Jurassic dinoflagellate cyst biozones of the North West Shelf of Australia. *Rev Palaeobot Palynol* 162(4):543–575.
- Benton MJ (1986) More than one event in the late Triassic mass extinction. *Nature* 321(6073):857–861.
- Simms MJ, Ruffell AH (1990) Climatic and biotic change in the late Triassic. *J Geol Soc London* 147(2):321–327.
- Orchard MJ, et al. (2001) The Upper Triassic of Black Bear Ridge, Williston Lake, northeast British Columbia: An integrated biochronology. *Geol Surv Can Curr Res* A6: 1–21.