

Global correlation of the radiolarian faunal change across the Triassic–Jurassic boundary¹

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Abstract: Precise comparison of the change in radiolarian faunas 3.5 m above a U–Pb zircon dated 199.6 ± 0.3 Ma tuff and approximately coincident with a negative $\delta^{13}\text{C}$ anomaly in the Queen Charlotte Islands, B.C. (Canada) with Inuyama (Japan) sequences indicates that major global changes occurred across the Triassic–Jurassic (T–J) boundary. Nearly 20 genera and over 130 Rhaetian species disappeared at the end of the Triassic. The index genera *Betraccium* and *Risella* disappear and the final appearance of *Globolaxtorum tozeri*, *Livarella valida*, and *Pseudohagiastrum giganteum* sp. nov. are also diagnostic for the end of the Triassic. The low-diversity Hettangian survival fauna immediately above the boundary is composed mainly of small, primitive spumellarians with spongy or irregularly latticed meshwork and rod-like spines, and new genera *Charlottea*, *Udalia*, and *Parahsuum* s.l. first appear in the lowest Hettangian in both localities. Irrespective of different sedimentation rates and sedimentary environments, such as shelf to upper slope (Queen Charlotte Islands) and deep sea below carbonate compensation depth (CCD; Inuyama), radiolarians show a similar turnover pattern at the T–J boundary.

Résumé : Une comparaison précise du changement dans les faunes radiolaires à 3,5 m au-dessus d'un tuf daté à $199,6 \pm 0,3$ Ma, par U–Pb sur un zircon, et coïncidant approximativement à une anomalie négative $\delta^{13}\text{C}$, dans les îles de la Reine Charlotte, Colombie-Britannique (Canada), avec les séquences d'Inuyama (Japon), indique que de grands changements globaux se sont produits et ont traversé la limite Trias–Jurassique. Près de 20 genres et plus de 130 espèces datant du Rhétien ont disparu à la fin du Trias. Les genres index *Betraccium* et *Risella* disparaissent et l'apparition finale de *Globolaxtorum tozeri*, *Livarella valida* et *Pseudohagiastrum giganteum* sp. nov. est aussi caractéristique de la fin du Trias. La faune de survie, faiblement diversifiée, de l'Hettangien, immédiatement au-dessus de la limite, est composée surtout de petits spumellaires primitifs, avec un maillage spongieux ou à grille irrégulière et des épines en forme de tiges, ainsi que des nouveaux genres *Charlottea*, *Udalia* et *Parahsuum* s.l., faisant une première apparition dans le Hettangien de plus bas niveau dans les deux localités. Peu importe les différents taux de sédimentation et les environnements sédimentaires, tels qu'une plate-forme, un haut de pente (îles de la Reine Charlotte) et la mer profonde sous le niveau de compensation des carbonates (Inuyama), les radiolaires montrent un patron de renouvellement similaire à la limite Trias–Jurassique.

[Traduit par la Rédaction]

Introduction

The Triassic–Jurassic (T–J) boundary records one of the five largest mass extinctions during Phanerozoic time (Hallam 1990) with over 48% of marine invertebrate genera becoming extinct (Sepkoski 1986, 1989). Many studies document the extinction of marine life across the T–J boundary. Affected groups include cephalopods (Tozer 1981; Guex 1982, 2001; Taylor et al. 2000) and bivalves (Hallam 1981; Allasinaz 1992; McRoberts 1994; McRoberts et al. 1995). However, as Hallam and Wignall (1997) have postulated, the best evidence for catastrophic change at the end of the Triassic may come from microfossils. Final extinction has been recog-

nized amongst conodonts (Mostler et al. 1978), with exception of the claim by Kozur (1993) on the presence of a few survivors in the earliest Hettangian, and severe decline occurred amongst ostracods (Whatley 1988), coccoliths (Bown and Lord 1990), palynomorphs (Olsen et al. 1990), and radiolarians (Tipper and Carter 1990; Hori 1992; Carter 1993, 1994; Tipper et al. 1994, 1998).

Radiolarians have been diverse and widespread in the oceans from Cambrian to Recent (Anderson 1983; De Wever et al. 2001) and can be highly reflective of changing global conditions over long periods of time. Their siliceous remains are found in a wide range of sedimentary rocks of shallow to deep-sea origin. Their preservational potential frequently

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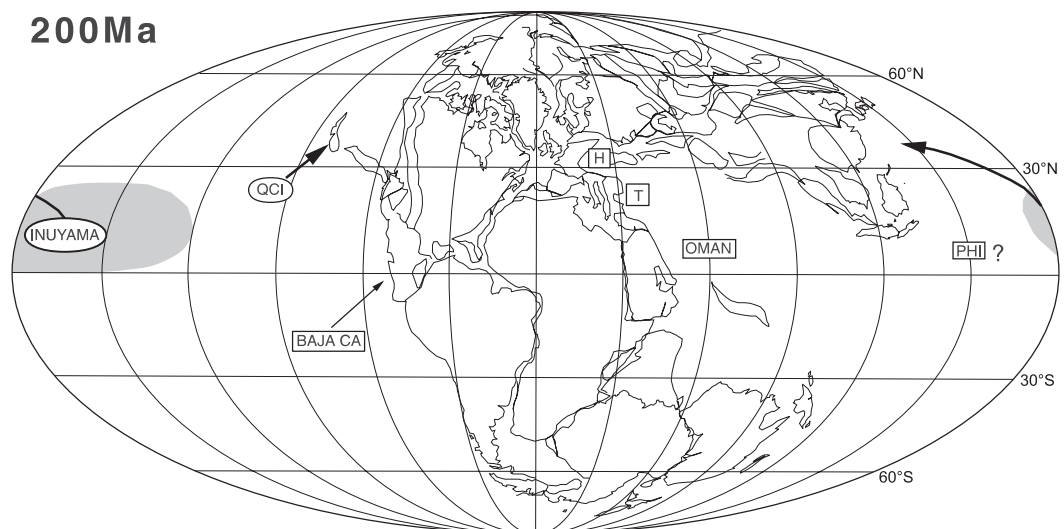
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Fig. 1. Localities in Queen Charlotte Islands (QCI), Canada, Inuyama, southwestern Japan, and other areas where uppermost Rhaetian and lowermost Hettangian radiolarian-bearing strata are present shown on a reconstructed map of the Early Jurassic; map modified from Bocharova and Golonka (1995). Other localities shown are (BAJA CA) Baja California, (H) Hungary, (T) Turkey, (PHI) Philippines, and Oman.



allows radiolarians to be present where other macro- or microfossils are absent.

Some studies have indicated that the end-Triassic extinction was not drastic amongst radiolarian families (De Wever et al. 2001). However, families are long ranging and our knowledge of family-level systematics is still in early stages. In time, ongoing studies of the inner structure of radiolarians are expected to attribute more genera to family level. In fact, many genera common to the uppermost Triassic and lowermost Jurassic have not been raised to a family, effectively eliminating them from consideration. We believe a more accurate assessment of the end-Triassic extinction and ensuing recovery can be made at the genus and species level. Detailed analysis of the radiolarian faunal succession in Queen Charlotte Islands (QCI) (Carter 1993; Carter et al. 1998; Haggart et al. 2002) and the Inuyama area of Japan (INY) (Hori 1992) indicates that many genera disappeared at the end of the Triassic and only a few species persisted into the Jurassic.

Radiolarian faunal change is correlated across the T–J boundary between marine sequences in Queen Charlotte Islands, British Columbia, Canada, and the Inuyama area of southwestern Japan (Fig. 1). These localities are thus unique because continuous sequences recording macro- and microfossils across the T–J boundary are rare and both contain radiometrically dated strata: QCI contains a tuff layer dated 199.6 ± 0.3 Ma (Pálffy et al. 2000), whereas INY has a whole rock chert date of 202.6 ± 13.0 Ma (Hori et al. 2000). Similar radiolarian faunas of Rhaetian and (or) Hettangian–Sinemurian age are recognized in Austria (Gawlik et al. 2001), Turkey (Tekin 1999, 2002a, 2002b), the Philippines (Yeh 1992; Yeh and Cheng 1996, 1998), New Zealand (Spörli and Aita 1988; Hori et al. 1996), Italy (Bertinelli et al. 2004), Peru (Suzuki et al. 2002), and Far East Asia, including Russia (Bragin 1991), China (Yang and Mizutani 1991), and Japan (e.g., Yao et al. 1980; Kishida and Hisada 1985; Igo and Nishimura 1984; Sato et al. 1986; Sugiyama 1997). Although the precise boundary interval is missing in each

area, published data fully support our observations on faunal extinction and recovery around the T–J boundary.

The purpose of this paper is to document major global change in radiolarian faunas across the Triassic–Jurassic boundary through comparing species from Queen Charlotte Islands (QCI) and Inuyama (INY), Japan. The study focuses closely on boundary sequences observing precise disappearance and appearance patterns of species (and species groups) just below and above the boundary to confirm the extinction event in the marine realm. Quantitative analysis of latest Rhaetian and earliest Hettangian samples presented in this study support these observations.

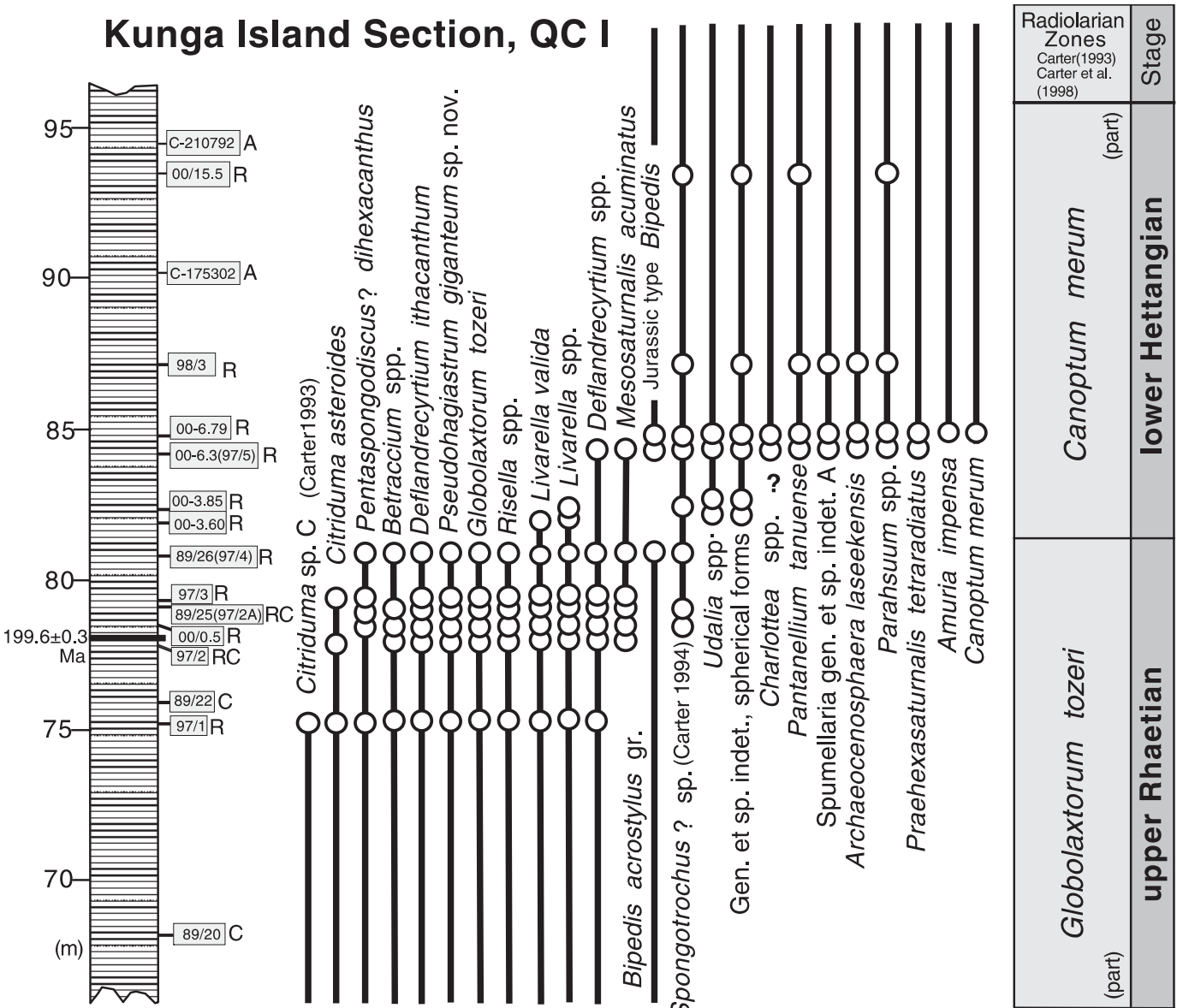
Geologic setting

Queen Charlotte Islands, Canada

The Queen Charlotte Islands are part of the Wrangellia terrane that docked in Middle Jurassic (Van der Heyden 1992) to Cretaceous (Irving et al. 1996) time alongside the North American craton. Continuous radiolarian-bearing sequences spanning the T–J boundary in QCI are present in thick clastic strata of the Sandilands Formation (lower Rhaetian to lowermost Pliensbachian) at Kennecott Point (Graham Island) and Kunga Island (Fig. 2). In each locality, the Rhaetian–Hettangian part of the formation is > 120 m thick and comprises interbedded light to dark gray sandstone, siltstone, shale, and limestone with thin tuffs and abundant calcareous concretions that contain well-preserved radiolarian faunas (Carter 1990, 1993; Carter et al. 1998). There is no facies change across the T–J boundary interval in either locality and no evidence for shallowing has been found. The formation was originally believed to be turbiditic (Desrochers and Orchard 1991); Haggart et al. (2002) have suggested that it was deposited in an outer shelf to upper slope setting.

The radiolarian succession is similar at both localities and in some respects complementary, but the more closely spaced, better preserved faunas in critical boundary beds at Kunga Island (Fig. 2) give a higher resolution radiolarian

Fig. 2. Triassic–Jurassic transition at Kunga Island, Queen Charlotte Islands, with the range of diagnostic radiolarian species. R, radiolarians; C, conodonts; A, Hettangian ammonites.



biochronology (Carter 1993; Carter et al. 1998). Based on these findings, the sequence at Kunga Island has been proposed as a candidate GSSP (Global Stratotype Section and Point) for the T–J boundary with the base of the Jurassic defined by the first occurrence of Hettangian radiolarians (Carter and Tipper 1999). Subsequently, this proposal has been strengthened by (1) dating of a tuff layer 6.3 m (herein revised to 3.55 m) below the prominent change in radiolarian faunas at Kunga Island that yielded a U–Pb zircon age of 199.6 ± 0.3 Ma (Pálffy et al. 2000); and (2) discovery of a negative $\delta^{13}\text{C}_{\text{org}}$ anomaly that appears to be coincident with the end-Triassic radiolarian extinction at Kennecott Point (Ward et al. 2001, 2004).

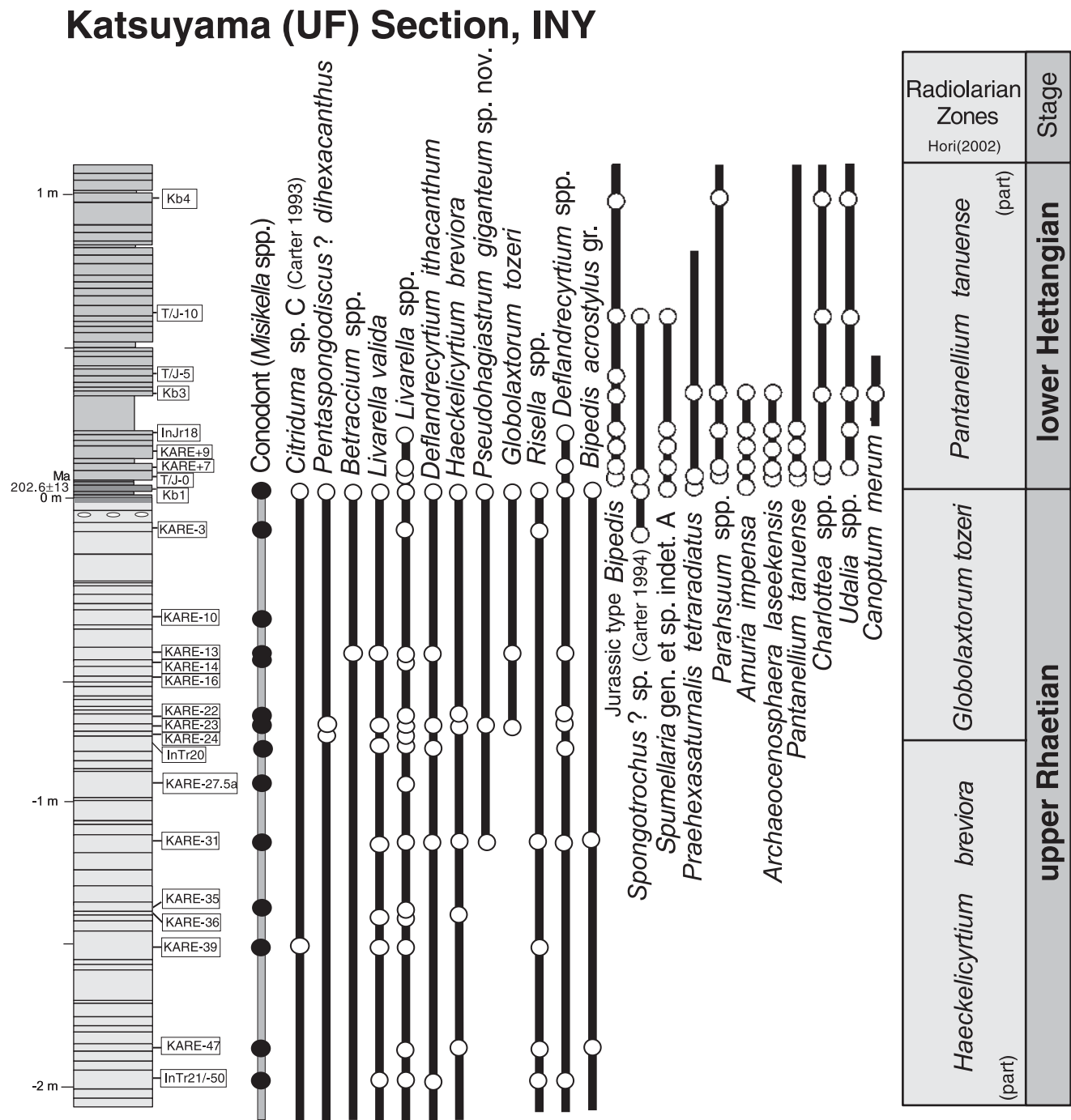
Inuyama, Japan

Two measured sections containing radiolarians of latest Triassic and earliest Jurassic age are present in the Inuyama area, southwestern Japan: the Kurusu section (KU) and the

Katsuyama section (UF). Both sections comprise bedded-chert sequences in the Jurassic accretionary complex (Kimura and Hori 1993) of the Mino-Tamba terrane, which is representative of deep-sea sedimentary rocks deposited below carbonate compensation depth (CCD; Matsuda and Isozaki 1991). Based on paleomagnetic studies (e.g., Shibuya and Sasajima 1986; Fujii et al. 1993; Oda and Suzuki 2000; Ando et al. 2001), the Inuyama sequence is considered to have moved from low to middle latitude pelagic areas of Panthalassa (Paleo-Pacific) from Middle Triassic to Early Jurassic time.

The Katsuyama section consists of a rhythmically alternating sequence of chert and shale beds 1–10 cm thick. The entire reconstructed sequence is ~100 m thick and spans the upper Lower Triassic to upper Lower Jurassic. The chert is mostly red-brown in colour, except for the Lower Triassic part, which is black to greenish-gray. The T–J boundary interval in the Katsuyama section is about 3 m thick (Fig. 3). A few thicker shale layers are developed within this interval,

Fig. 3. Triassic–Jurassic transition in the Katsuyama section (UF), Inuyama, Japan with the range of diagnostic radiolarian and conodont (*Misikella* spp.) species.



and a notable colour change is observed at the boundary. Rhaetian beds are a light red-brown colour, but the topmost Triassic bed (Kb1 in Fig. 3) is a distinctive dusty red. The Rb–Sr age of whole rock chert is 202.6 ± 13.0 Ma at Kb1 (Hori et al. 2000). The Rb–Sr age of Inuyama chert dates the closing of the Rb–Sr system in siliceous deposits. This probably occurred during diagenetic processes over a period of 6–26 million years (Shibata and Mizutani 1982; Mizutani 1983). Therefore, the sedimentary age of Kb1 is considered relatively older than the Rb–Sr age, that is, at least before

195.6 (189.9 + 6) Ma. The Kurusu section is a rhythmically bedded ~40 m-thick sequence of mostly gray and green to partly red chert. Thicker shales are not developed in latest Triassic beds nor is a remarkable colour change observed. Geochemical analysis (e.g., Platinum group element (PGE) and Rare-earth element (REE) patterns) of this section suggests that an extraordinary event such as a bolide impact and (or) volcanic eruption occurred in Late Triassic time (Fujiki et al. 2002). The same radiolarian faunal sequence is present in both sections but the Katsuyama section yields more precise

data. Hori (1992, 2002) and Sugiyama (1997) have studied Rhaetian and Hettangian radiolarian faunas from these sections.

Biostratigraphy

Rhaetian

Rhaetian strata at Kennecott Point, QCI are dated by the ammonoid *Choristoceras* and the conodont *Misikella posthernsteini* (Carter et al. 1989; Orchard in Carter 1993; Tipper et al. 1994), whereas coeval strata at Kunga Island contain conodonts but totally lack macrofossils, suggesting deposition in deeper waters. Early Hettangian ammonites date overlying strata at both Kennecott Point and Kunga Island (Tipper and Guex 1994; Tipper et al. 1994; Carter et al. 1998), but radiolarians are the only fossil group with a continuous record across the T–J boundary. In Japan, the Rhaetian conodonts *Misikella hernsteini* and *M. posthernsteini* occur in both sections. No macrofossils are present. Isozaki and Matsuda (1982, 1983) and Matsuda and Isozaki (1991) have shown that the conodont zones of the Inuyama area agree with the radiolarian biozones of Yao et al. (1980).

The diverse, well-preserved Rhaetian radiolarian fauna of QCI contains over 140 described species (>42 genera) and still many undescribed forms (Carter 1993). Radiolarian zonation for the Rhaetian, based on the Unitary Associations (UA) method (Guex 1991), established 27 UA distributed over two zones, whose age is correlated with the Late Triassic ammonoid biochronology of Tozer (1979). The *Proparvicungula moniliformis* Zone is lower Rhaetian and correlates approximately with the Amoenum Zone; the *Globolaxtorum tozeri* Zone is upper Rhaetian, equivalent to the Crickmayi Zone (Carter 1993). *Globolaxtorum tozeri* has also been found in Japan (Hori 2002), Baja California (Whalen et al. 2003), Hungary (Pálffy et al. 2001), Oman (Carter 1993), Turkey (Tekin 1999, 2002a), the Philippines (Yeh and Cheng 1996), and appears to be an excellent global indicator for the latest Triassic.

Radiolarian diversity increased rapidly in the Rhaetian following extinction of the Capnuchosphaeridae and Capnodocinae in the late middle Norian (Pessagno et al. 1979), and the *Betraccium deweveri* fauna in the late Norian or earliest Rhaetian (Blome 1984; Carter 1993). Diversification was particularly noticeable amongst hat-shaped genera, such as *Deflandrecyrtium* Kozur and Mostler, *Squinabolella* Pessagno, and *Haekelicyrtium* Kozur and Mostler (Carter 1993; Sugiyama 1997; Taishi 1997) in QCI and INY, and in the rise of other architecturally complex genera, such as *Citriduma* De Wever, *Praecitriduma* Kozur, *Kungalaria* Dumitrica and Carter, and the *Risella* and *Laxtorum*–*Globolaxtorum* lineages of Carter and Guex (1999). More than 65 described or informal species are documented in uppermost Rhaetian beds (Carter 1993; Haggart et al. 2002) and even in the highest samples, new species or forms considerably different from described species first appear. Over 15 genera and 130 species disappeared near the end of the Triassic, over half of these in uppermost beds of the Rhaetian. Rare specimens of *Deflandrecyrtium*, *Fontinella* Carter, *Icrioma* De Wever, *Kahlerosphaera* Kozur and Mostler, and *Livarella* Kozur and Mostler persist into the basal Jurassic but all disappear before the end of the Hettangian.

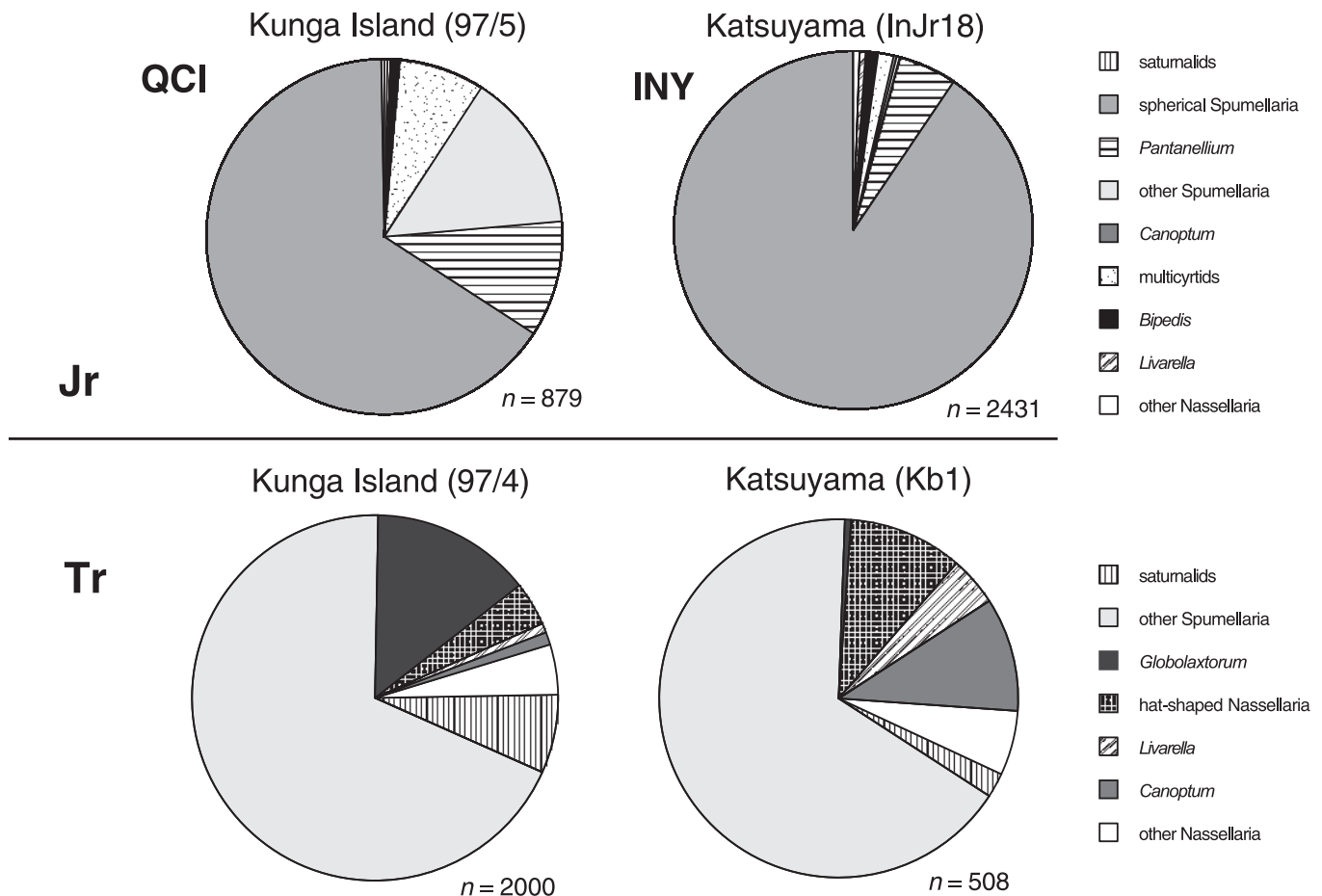
Hettangian

The Hettangian and Sinemurian fauna of QCI comprise over 120 species of at least 54 genera (Carter et al. 1998). Radiolarian zonation for this interval established 25 UA divided into seven zones, with the lower Hettangian *Canoptum merum* Zone being the oldest. All Hettangian and Sinemurian Radiolaria are associated with ammonites, and zones are correlated with the ammonite biochronology of Tipper and Guex (1994) and Pálffy et al. (1994). Earliest Hettangian radiolarians are abundant but easily distinguished from Rhaetian ones by their low diversity, small size, primitive appearance, and the absence of all distinctive uppermost Triassic taxa (Carter 1994). These faunas are characterized by latticed irregularly spinose forms with poorly organized meshwork, spongy forms with or without spines, and rare nassellarians (Carter 1994, 1998). There are few recognizable genera amongst this fauna and rarely is more than one species per genus present. In contrast to the highly twisted triradial spines of many Late Triassic species, earliest Hettangian radiolarians have simple, straight, rod-like spines; the more advanced triradial morphology does not reappear until the middle to upper Hettangian. Blooms of *Archaeocenosphaera laseekensis* Pessagno and Yang, a smooth, spherical spumellarian composed of small, densely packed hexagonal pore frames, dominate the lower Hettangian fauna as well. This primitive morphology is similar to some found around the Permo-Triassic boundary, as mentioned by Kakuwa (1997) and Yao and Kuwahara (1997).

It is important to emphasize that earliest Hettangian radiolarians represent a survival phase. Amongst more than 25 genera that survived the T–J boundary, most were widespread conservative forms that were possibly more tolerant of changing ecological conditions than those with more complex morphologies. This survival fauna was composed mainly of primitive forms almost impossible to describe even at generic level. A few Rhaetian species survived the boundary but most are extremely rare in our collections and disappear by the end of the Hettangian. Except for these, the extinction of Rhaetian species at the boundary was essentially complete. True radiolarian recovery did not begin until the middle to upper Hettangian when new spumellarian and entactiniid species appeared and nassellarians became increasingly abundant and diverse (Carter et al. 1998).

Earliest Jurassic radiolarians from Inuyama sections in southwestern Japan have been studied by Yao et al. (1980), Hori (1990, 1992) and Sugiyama (1997). Hori (1992) recognized a faunal transition between the final occurrence of the conodont *Misikella posthernsteini* and the first occurrence of *Parahsuum simplum* higher in the sequence. This interval is characterized by the first occurrence of primitive forms of *Parahsuum*, Jurassic-type *Bipedis*, *Gorgansium* aff. *gongyloideum* Kishida and Hisada (= *Charlottea amurensis* Whalen and Carter), *Xenorum* sp. A (= *Charlottea* sp.), *Pantanellium* aff. *klunense* Pessagno and Blome, and *Syringocapsa coliforme* Hori (= *Protokatroma* sp. A of Whalen and Carter 1998) together with unnamed spumellarians, and corresponds well with Hettangian and early Sinemurian radiolarians in QCI. This interval does not include *Parahsuum simplum*, which heretofore has been associated with the base of the Jurassic in Japan. Based on more recent study, Hori (2002) tentatively proposed the *Pantanellium tanuense* Zone for this interval, which is defined

Fig. 4. Faunal composition below and above the Triassic (Tr) – Jurassic (Jr) boundary at Kunga Island, Queen Charlotte Islands (QCI), and Inuyama (INY), Japan. See Figs. 2 and 3 for sample position in respective sequences. For the Triassic, other Spumellaria include *Archaeocenosphaera*, *Crucella*, *Entactinosphaera*, *Ferresium*, *Fontinella*, *Haliomma*, *Loupanus*, *Orbiculiformella*, *Paratriassostrum*, *Plafterium*, *Pseudohagiastrum*, *Risella*, Spumellarian indet. D (Carter 1993), all pantanelliids, and other indeterminate genera; other Nassellaria include *Bipedis*, *Canutus*, *Laxtorum*, and indeterminate nassellarians. For the Jurassic, other Spumellaria include *Paronaella*, disk-shaped forms, and flattened spumellarians with 3–4 long spines; amongst nassellarians, multicyrtids include mainly *Atalanta*, *Droltus*, *Proparvicingula*, *Laxtorum*, *Relanus*, and all parahsuuids. Hat-shaped Nassellaria include *Deflandrecyrtium*, *Haeckelicyrtium*, *Squinabolella* and are similar for both the Triassic and Jurassic. All single genus categories are self-explanatory.



as the interval between the first occurrence of *Pantanellium tanuense* and the first occurrence of *Parahsuum simplum*. In Japan, *Pantanellium tanuense* is recognized in bedded chert from the Inuyama, Kuzuu and Ikuno areas (e.g., Hori and Goto 1994), where it is associated with undetermined species of *Canoptum*, *Charlottea* and *Udalia*. *Pantanellium* and spherical spumellarians are very abundant in the lower part of this interval, but species diversity is very low, as in Queen Charlotte Islands. For example, *Pantanellium* represents ca. 5% of the total fauna from the *Pantanellium tanuense* Zone in the Ikuno area, but only two species are recognized.

Radiolarian faunal change

To assess faunal similarity between QCI and INY, we counted the total number of known and previously unrecognized species in samples 97/4(89/26) and 00-6.3(97/5) from QCI and samples Kb1 and InJr18 from INY. For the Rhaetian, 92 species are present in the Kunga Island section, 51 species in Katsuyama section; of the latter, 20 species (39%) of the INY fauna are in common with QCI. For the Hettangian, 37 species are present in the Kunga Island section, 27 in the Katsuyama

section and of these, nine species (33%) of INY fauna are in common with QCI. Over 30% of the INY fauna is identical to the QCI fauna around the T–J boundary. This value is presumably much higher (closer to 40%), because other horizons near Kb1 and InJr18 contain additional common species not counted. Considering the high similarity of species in both areas, we compared these common and diagnostic species to illustrate radiolarian faunal change across the T–J boundary.

Kunga section, QCI

The Rhaetian sequence at Kunga Island is over 85 m thick, with the upper 22 m yielding radiolarians of the *Globolaxtorum tozeri* Zone (Carter 1993). This is overlain, without visible break, by an interval of nearly 45 m, which encompasses most of the Hettangian (Tipper et al. 1994; Carter et al. 1998).

Triassic radiolarians continue to diversify into uppermost beds of the Rhaetian (Carter 1993; Carter and Guex 1999), where over 70 species are present. *Citriduma* sp. C (Carter 1993) disappears at 75.2 m; a tuff sample dated at 199.6 ± 0.3 Ma occurs at 77.95 m (Pálffy et al. 2000); conodonts disappear above 79.1 m; *Citriduma asteroides* vanishes above 79.3 m;

and *Deflandrecyrtium* aff. *ithacanthum* Sugiyama (Pl. 1A, fig. 8), *Globolaxtorum tozeri* Carter (Pl. 1A, fig. 7), *Livarella valida* Yoshida (Pl. 1A, fig. 10), *Pentaspogonodiscus? dihexacanthus* Carter (Pl. 1A, fig. 9), and *Pseudohagiastrum giganteum* sp. nov. (Pl. 1A, fig. 6) together with all species of *Betraccium* Pessagno, *Risella* Carter and other indeterminate species disappear above 80.75 m. The first occurrence of Hettangian radiolarians occurs 3.55 m above the dated tuff bed.

Samples 00-3.60 and 00-3.85 (at 81.55 and 81.8 m, respectively) contain an enigmatic fauna. The radiolarians are abundant but moderately preserved and, apart from rare specimens of *Livarella*, the assemblages appear to be Jurassic rather than Triassic. Both samples contain some but not all forms typical of the earliest Hettangian fauna seen just a few metres higher. The most likely explanation is that these faunas represent the transition into the Jurassic. This means that basal Hettangian beds at Kunga Island begin 3.55 m above the dated tuff bed rather than 6.3 m, as reported by Haggart et al. (2002). The presence of a transitional interval with a mixed fauna, such as found at Kennecott Point, had long been expected at Kunga Island; it has now been identified. Typical early Hettangian radiolarians characteristic of the *Canoptum merum* Zone begin at 84.25 m. By far the most abundant forms are small, primitive indeterminate spherical spumellarians, *Spongostrochus?* sp. (Carter 1994) (Pl. 1A, fig. 4), *Archaeocenosphaera laseekensis* Pessagno and Yang (Pl. 1A, fig. 5), and *Pantanelium tanuense* Pessagno and Blome (Pl. 1A, fig. 1). Less common are *Praehexasaturnalis tetraradiatus* Kozur and Mostler, *Amuria impensa* Whalen and Carter (Pl. 1A, fig. 2), Spumellaria gen. et sp. indet. A (Whalen and Carter) (Pl. 1A, fig. 3), and rare species of *Charlottea*, *Tozerium*, and *Udalia* (Hettangian genera described by Whalen and Carter 1998). Nassellarians are extremely rare in the lower Hettangian and are limited to *Bipedis elizabethae* Whalen and Carter, *Canoptum merum* Pessagno and Whalen, *Droltus hecatensis* Pessagno and Whalen and a few primitive species of *Parahsuum*.

Katsuyama section, INY

The faunal change in Inuyama (section UF; see Fig. 3) occurs over ~1.0 m. In bedded cherts beginning about the –1.0 m level, Late Triassic radiolarian species gradually become less abundant and some disappear, including *Canoptum*, *Livarella*, *Haekelicyrtium*, and *Archaeocenosphaera*. At 0.0 m, the transitional sample (Kb1) contains some latest Rhaetian taxa together with the first representatives of the earliest Jurassic fauna. Recorded here are the final occurrence of *Globolaxtorum tozeri* (Pl. 1B, fig. 6), *Bipedis acrostylus*, *Livarella valida* (Pl. 1B, fig. 9), *Pentaspogonodiscus? dihexacanthus* (Pl. 1B, fig. 8), *Deflandrecyrtium ithacanthum* (Pl. 1B, fig. 7), *Haekelicyrtium breviora*, *Citriduma* sp. C, and *Pseudohagiastrum giganteum* sp. nov. (Pl. 1B, fig. 5), together with terminal species of *Betraccium*, *Risella*, and the conodont *Misikella posthernsteini*. *Globolaxtorum tozeri* occurs at several levels in the Rhaetian sequence, but its multi-shell mode is difficult to identify in poorly preserved material. Earliest Hettangian forms co-occurring in this same sample include *Amuria impensa* (Pl. 1B, fig. 2), *Praehexasaturnalis tetraradiatus*, *Spongostrochus?* sp. (Carter 1994) (Pl. 1B, fig. 4) and Spumellaria gen. et sp. indet. A (Pl. 1B, fig. 3) together with abundant spherical spumellarians. Slightly higher in the sequence (sample T/J-0), the first Jurassic *Bipedis* (as opposed to Triassic

forms with flat bladed horn and feet such as *Bipedis acrostylus*) appears, as well as *Archaeocenosphaera laseekensis*, *Pantanelium tanuense* (Pl. 1B, fig. 1), and primitive species of *Charlottea*, *Parashuum*, *Udalia*, and other undescribed spumellarians; 0.2 m higher, sample InJr18 marks the final occurrence of Triassic *Deflandrecyrtium* and *Livarella*, and higher still at 0.34 m *Canoptum merum* first appears. The presence of a mixed fauna in this transitional red chert sample is not unusual considering the condensed nature of the chert sequence; similar faunas have been recognized in New Zealand (Spörl and Aita 1988) and the Philippines (Yeh and Cheng 1998). The length of time from the first record of extinctions to the transitional level that records the final appearance of most Triassic species together with the first appearance of Jurassic species is estimated at < 1 million years based on sedimentation rate. Sedimentation rates in the Inuyama area were calculated at ~1 m/million years for Lower Jurassic chert (Hori et al. 1993) and ~2.8 million years for the Upper Triassic chert (Matsuda et al. 1980). These data suggest that the faunal change from uppermost Triassic (Rhaetian) to lowest Jurassic (Hettangian) in this section occurred within a short period of time.

In summary, the similarity of species in T–J boundary strata of western North American and Japanese terranes, and the manner in which certain species vanish at the end of the Rhaetian and new and completely different species arise in the earliest Hettangian, argue against these being random regional events. Both localities have low latitude characters and originated in areas ~5000 km distant from each other. Thereafter both areas moved in opposite directions about 3000 km before accretion or docking. The radiolarian extinction is apparently related to a global event that controlled the oceanic productivity in the latest Triassic and earliest Jurassic.

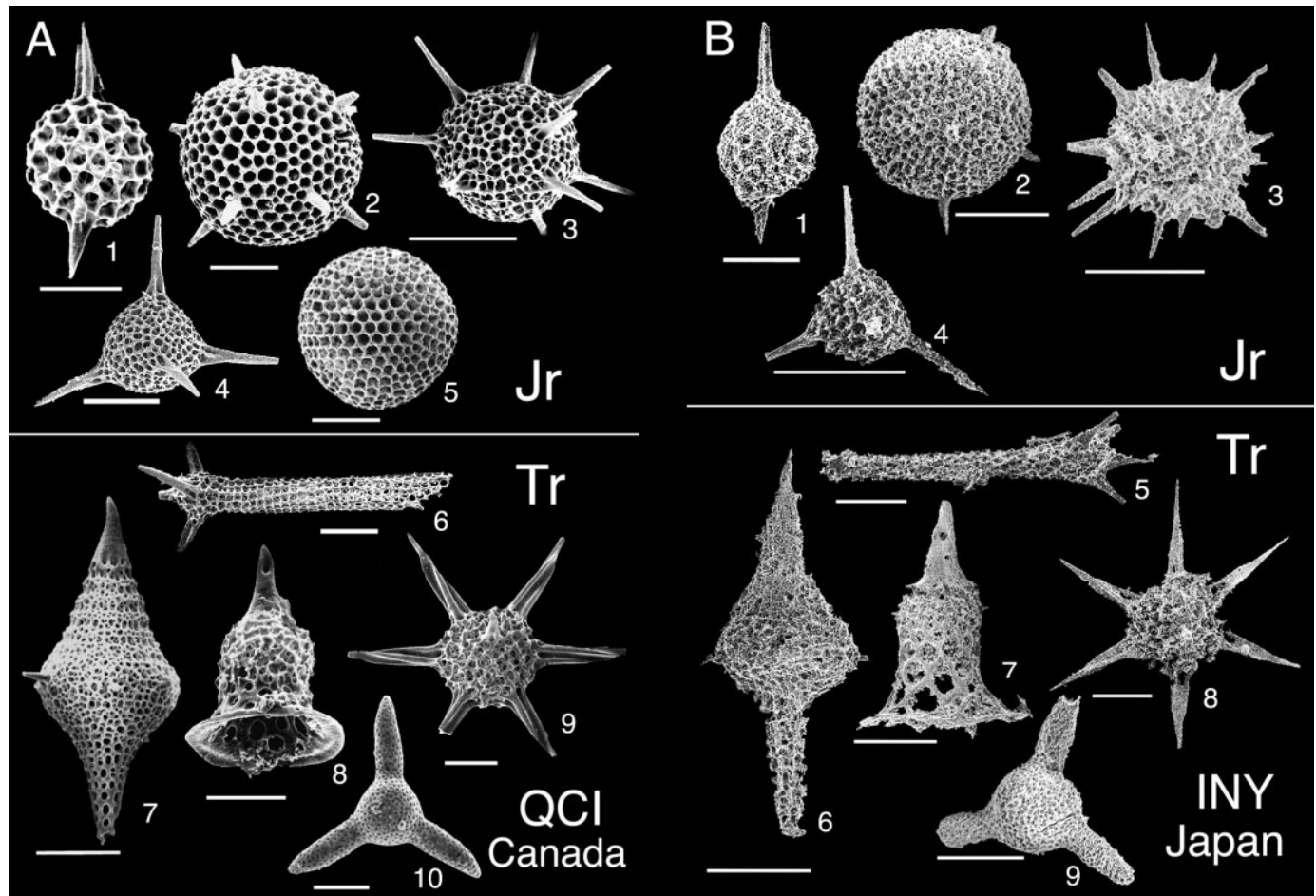
Comparative quantitative analysis

Methods

In an effort to quantify faunal similarities and differences on either side of the T–J boundary, we counted specimens from an uppermost Rhaetian and lowermost Hettangian sample from sections in QCI and INY. The two samples from Kunga Island, shown as 97/4(89/26) and 00-6.3(97/5), respectively, on Fig. 2 are ~3 m apart; those from INY, Japan (Kb1 and InJr18) are 20 cm apart, again emphasizing the condensed nature of Japanese chert sections. The counting process was carried out by splitting off a small portion of dry residue and, using a binocular microscope, counting all determinable specimens (>50% complete) in the 75–250 µm size range until the numbers (*n*) shown on Fig. 4 were reached. Results were first tabulated to genus, then later (depending on abundance) certain genera were combined into groups. In some cases, < 2000 specimens per sample were counted, but in less productive samples genus or group composition appeared to be relatively consistent even with fewer specimens counted.

Categories of Rhaetian radiolarians discriminated during the counting process include genera such as *Globolaxtorum*, *Livarella*, and *Canoptum*, while other genera are grouped together as saturnalids, other Spumellaria, hat-shaped Nassellaria, and other Nassellaria (see Fig. 4). Other Spumellaria are mainly *Ferresium*, *Risella*, Spumellarian indet. D (Carter 1993),

Plate 1A. Characteristic Radiolarians from the T–J boundary interval of Queen Charlotte Islands, Canada. 1–5 are earliest Hettangian, 6–10 are latest Rhaetian. **fig. 1.** *Pantanellium tanuense* Pessagno and Blome, GSC 107689. **fig. 2.** *Amuria impensa* Whalen and Carter, GSC 107804. **fig. 3.** *Spumellaria* gen. et sp. A (Whalen and Carter 1998), GSC 11697. **fig. 4.** *Spongostrochus?* sp. (Carter 1994), GSC 11698. **fig. 5.** *Archaeocenosphaera laseekensis* Pessagno and Yang, GSC 107801. **fig. 6.** *Pseudohagiastrum giganteum* sp. nov., Holotype, GSC 11696. **fig. 7.** *Globolaxtorum tozeri* Carter, GSC 85927. **fig. 8.** *Deflandrecyrtium* aff. *ihacathum* Sugiyama, GSC 102049. **fig. 9.** *Pentaspogonodiscus?* *dihexacanthus* Carter, GSC 102020. **fig. 10.** *Livarella valida* Yoshida, GSC 101930. Scale bars for each specimen = 100 μ m. **Plate 1B.** Characteristic Radiolarians from the T–J boundary interval of Inuyama, Japan. 1–4 are earliest Hettangian, 5–9 are latest Rhaetian. **fig. 1.** *Pantanellium tanuense* Pessagno and Blome, RH431. **fig. 2.** *Amuria impensa* Whalen and Carter, RH432. **fig. 3.** *Spumellaria* gen. et sp. A (Whalen and Carter 1998), RH429. **fig. 4.** *Spongostrochus?* sp. (Carter 1994), RH433. **fig. 5.** *Pseudohagiastrum giganteum* sp. nov., RH429. **fig. 6.** *Globolaxtorum tozeri* Carter, RH35. **fig. 7.** *Deflandrecyrtium ihacathum* (Sugiyama), RH40. **fig. 8.** *Pentaspogonodiscus?* *dihexacanthus* Carter, RH38. **fig. 9.** *Livarella valida* Yoshida, RH436. Scale bars for each specimen = 100 μ m.



and, in decreasing order of abundance, *Plafkerium*, *Icrioma*, *Loupanus*, *Fontinella*, pantanelliids, *Orbiculiformella*, hagiastriids, *Entactinosphaera*, and other indeterminate forms; hat-shaped Nassellaria include *Deflandrecyrtium*, *Squinabolella*, and *Haecelicyrtium*; other Nassellaria are mainly *Canutus?* and *Laxtorum*. Amongst Hettangian spumellarians, we include spherical *Spumellaria* (primitive indeterminate spumellarians), *Pantanellium*, other *Spumellaria* (*Spongostrochus?* sp. (Carter 1994), *Paronaella*, *Udalia*, and *Charlottea*), and saturnalids. Hettangian nassellarians consist of multicyrtids, such as *Droltus* and primitive parahsuuids, a few discrete genera (*Bipedis*, *Canoptum*, and *Livarella*), and other Nassellaria (e.g., *Farcus*).

Results

Triassic results indicate that saturnalids and other *Spumellaria* dominate the fauna in both localities (Fig. 3). In QCI, this

group represents 75% of the fauna, in INY slightly less. Earlier data from QCI indicates that for most of Rhaetian time, the ratio of spumellarians to nassellarians is 2:1 (Carter 1993). We suggest that the increasing ratio of spumellarians in highest beds of the Triassic is probably due to the loss of nassellarian species rather than to an actualized increase in spumellarians. Other *Spumellaria* (the largest group) are about equally abundant in each locality, while saturnalids are more common in QCI. This may be due to lithology as saturnalids are fragile forms and may survive processing in limestone more easily than in chert. Greater differences are noted amongst nassellarians (Fig. 4). Other Nassellaria are about equally abundant in each locality, but more variation exists in *Globolaxtorum*, hat-shaped Nassellaria, *Livarella*, and *Canoptum*. *Globolaxtorum* is extremely abundant in QCI suggesting environmental conditions (upwelling?) must have been highly

favorable to allow such dramatic proliferation; the species is rare in Japan. Differing abundance in *Canoptum* can probably be attributed to the fact that *Laxtorum*, rather than *Canoptum*, is the dominant multicyrtyd in the uppermost Rhaetian in QCI. The genus *Livarella* is certainly more common in Japan (see Fig. 3), the Philippines (Yeh 1992), and Far East Asia (e.g., Kojima and Mizutani 1987; Kametaka et al. 1997); this could be due to the greater preservation of sturdy forms (over fragile forms) in chert facies or, alternately, may reflect latitudinal variations in the latest Triassic fauna.

Jurassic results indicate that spumellarians make up about 90% of radiolarian assemblages in low-diversity Hettangian faunas of both QCI and INY. Primitive indeterminate spherical spumellarians with spongy or irregularly latticed meshwork with or without randomly directed spines, referred to above as spherical Spumellaria, are by far the most abundant group (~65% in QCI, nearly 90% in INY), followed by pantanelliids (mainly *Pantanellium tanuense*). Other Spumellaria, such as *Amuria impensa*, *Spongotrochus*? sp. (Carter 1994), and Spumellaria gen. et sp. indet. A (Whalen and Carter 1998), allow correlation but are more abundant in QCI than INY. *Archaeocenosphaera laseekensis* is extremely abundant in the QCI fauna but not in INY. This phenomenon suggests the actions of opportunistic species possibly coupled with environmentally induced blooms of radiolarians. In both QCI and INY, nassellarians are rare in the lowest Hettangian; multicyrtyds are more common in QCI than INY, whilst the genus *Livarella* survives into the lower Hettangian in Japan and the Philippines (Yeh and Cheng 1998).

Morphological change at the T–J boundary

Little is known of the functional morphology in radiolarians related to extinction events. The most notable change observed in radiolarians crossing the T–J boundary is the transformation from diverse complex morphologies in the Rhaetian to very small, simplified, and primitive morphologies in the base of the Hettangian.

Similar morphological changes have been noted in ammonites (Guex 1992), particularly in Rhaetian faunas (Guex 1982) and those crossing the T–J boundary (Guex 2001). These changes involving a reduction in complexity of the shell geometry and suture line may have been caused by increasing ecological stress. Guex (1993) subsequently recognized the same simplification process in silicoflagellates and radiolarians based mainly on works of Deflandre (1950) and Dumitrica (1967, 1972, 1982, 1985). It seems clear that under conditions of extreme stress, complexification in protists breaks down and symmetry is reduced leading to unspecialized forms that are more apt to survive major ecological stresses (Guex 2001). In the case of radiolarians, the small, opportunistic forms (spumellarians and entactiniids) at the base of the Hettangian survived the extinction and may have given rise to more complex genera appearing in the upper Hettangian and Sinemurian.

We suggest the end-Triassic extinction of radiolarians was caused by stress resulting from extreme ecological conditions produced by causes, such as major volcanic eruptions, anoxic episodes related to climatic variation, etc.

Conclusions

The continuous radiolarian record provided by sections in Queen Charlotte Islands, Canada and Inuyama, Japan clearly demonstrates the abrupt change that occurred in radiolarians across the T–J boundary. Nearly 20 genera and 130 species of the diverse Rhaetian fauna disappeared at this time, almost half in uppermost beds of the Rhaetian. Surviving genera are mainly conservative forms possibly with more tolerance for environmental change. Very few species survived the boundary; those persisting are extremely rare in our collections and all disappeared by the end of the Hettangian. Radiolarian recovery in the Lower Jurassic is gradual with the earliest Hettangian fauna representing merely a survival phase. True recovery does not begin until the mid upper Hettangian when spumellarians and entactiniids diversify and nassellarians (especially multicyrtyds) become more dominant.

Comparative quantitative analysis of faunas just below and above the T–J boundary in each locality corroborates the greater faunal diversity in the topmost Rhaetian as opposed to the lowermost Hettangian. It also reveals the increasing dominance of spumellarians through the Rhaetian and Hettangian: ~75% in the upper Rhaetian, >90% in the lowest Hettangian. Amongst Rhaetian nassellarians, *Globolaxtorum* and *Laxtorum* dominate in QCI, whereas *Livarella* and *Canoptum* are more common in INY. Hettangian faunas in QCI contain more *Archaeocenosphaera* and multicyrtyds than in INY. Possible causal differences include preservation, the influence of upwelling, and latitudinal variation.

Faunal composition and the pattern of radiolarian change both below and above the T–J boundary are nearly identical in QCI and INY. Minor differences are believed to reflect different sedimentary environments, whereas differences in the timing of extinctions among a few species are likely related to stratal thickness and (or) faunal preservation in facies. Close inspection of first and last appearances in thick sequences of QCI indicates that, with rare exceptions, Rhaetian and Hettangian species are mutually exclusive. Conversely in INY, condensed bedded chert sequences spanning the same interval of time contain a mixed fauna of latest Triassic and earliest Jurassic species. Although sedimentation rates between Queen Charlotte Islands and Japan are highly different, radiolarian faunas show a similar turnover pattern at the T–J Boundary, arguing strongly that the event was global in nature.

Systematic paleontology

The systematics of radiolarians illustrated on Plates 1A and 1B follows. All illustrated specimens from Queen Charlotte Islands are deposited with the Geological Survey of Canada (GSC), Vancouver, B.C. Radiolarians from Japan are stored in the R.S. Hori collections at Ehime University, Matsuyama, Japan.

Phylum Protozoa

Class Actinopoda

Subclass Radiolaria Müller, 1858

Order Polycystina Ehrenberg, 1838, emend. Riedel, 1967

Genus *Amuria* Whalen and Carter, 1998

TYPE SPECIES: *Amuria impensa* Whalen and Carter, 1998, p. 56.
Amuria impensa Whalen and Carter, 1998
 (Pl. 1A, fig. 2; Pl. 1B, fig. 2)

SYNONYMY: *Archaeocenosphaera* sp., Carter, 1994, pl. 1, fig. 8
Amuria impensa Whalen and Carter, in Carter et al. 1998, p. 56; pl. 11, figs. 2, 3, 6, 23.

RANGE AND OCCURRENCE: Lower Jurassic; lowermost Hettangian to upper Hettangian – lower Sinemurian. Queen Charlotte Islands, Canada; Inuyama, Japan.

Genus *Archaeocenosphaera* Pessagno and Yang, in Pessagno et al. 1989

TYPE SPECIES: *Archaeocenosphaera ruesti* Pessagno and Yang, 1989, p. 203
Archaeocenosphaera laseekensis Pessagno and Yang, 1989
 (Pl. 1A, fig. 5)

SYNONYMY: *Archaeocenosphaera laseekensis* Pessagno and Yang, in Pessagno et al. 1989, p. 203; pl. 2, figs. 18, 21, 22, 25; Carter 1994, pl. 1, fig. 6; Carter et al. 1998, p. 57; pl. 11, figs. 1, 5, 9, 21.

RANGE AND OCCURRENCE: Lower Jurassic; lowermost Hettangian – lower Sinemurian. Queen Charlotte Islands, Canada; Inuyama, Japan.

Genus *Deflandrecyrtium* Kozur and Mostler, 1979

TYPE SPECIES: *Deflandrecyrtium popofskyi* Kozur and Mostler, 1979, p. 96
Deflandrecyrtium ithacanthum (Sugiyama), 1997
 (Pl. 1B, fig. 7)

SYNONYMY: *Dreyericyrtium* sp. A, Yao et al. 1982, pl. 2, fig. 2
Dreyericyrtium (?) sp., Yoshida 1986, pl. 8, figs. 5–6
 ?*Deflandrecyrtium* sp. A, Hori 1990, p. 581, fig. 8-1
Dreyericyrtium ithacanthum Sugiyama, 1997, p. 151; figs. 40-8, 10
Deflandrecyrtium ithacanthum (Sugiyama); Tekin 1999, p. 141; pl. 30, figs. 7–8; Tekin 2002a, p. 432; pl. 4, fig. 6

RANGE AND OCCURRENCE: Upper Triassic; upper Norian – Rhaetian. Queen Charlotte Islands, Canada; Central Japan; Turkey.

Deflandrecyrtium sp. aff. *D. ithacanthum* (Sugiyama), 1997
 (Pl. 1A, fig. 8)

SYNONYMY: aff. *Dreyericyrtium ithacanthum* Sugiyama, 1997, p. 151; figs. 40-8, 10

REMARKS: This species has a slightly shorter thorax than *D. ithacanthum*, and lacks a three-bladed apical spine.

RANGE AND OCCURRENCE: Upper Triassic; Rhaetian. Queen Charlotte Islands, Canada; Baja California Sur, Mexico.

Genus *Globolaxtorum* Carter, 1993

TYPE SPECIES: *Globolaxtorum tozeri* Carter, 1993, p. 111
Globolaxtorum tozeri Carter, 1993
 (Pl. 1A, fig. 7; Pl. 1B, fig. 6)

SYNONYMY: *Syringocapsa* sp. B, Yoshida 1986, p. 17; pl. 6, figs. 13–14

Podocapsa? sp. 1, Carter 1990, pl. 2, fig. 5

Katroma sp. A, Yeh 1992, p. 68; pl. 5, fig. 12

Globolaxtorum tozeri Carter, 1993, p. 111; pl. 19, figs. 14–16, 18–19; Bragin 1997, p. 28; Tipper et al. 1998, pl. 4.1, fig. 24; Carter and Guex 1999, p. 192; pl. 2, figs. 14–15

Globolaxtorum sp. C, Tekin 1999, p. 179; pl. 44, fig. 5

RANGE AND OCCURRENCE: Upper Triassic; upper Rhaetian. Queen Charlotte Islands, Canada; Inuyama, Japan; Uson Island, Philippines; Far East Russia; Hungary; Oman; Turkey; Baja California Sur, Mexico.

Genus *Livarella* Kozur and Mostler, 1981

TYPE SPECIES: *Livarella densiporata* Kozur and Mostler, 1981, p. 115
Livarella valida Yoshida, 1986
 (Pl. 1A, fig. 10; Pl. 1B, fig. 9)

SYNONYMY: *Livarella validus* Yoshida, 1986, p. 14; pl. 3, figs. 1–3; Kojima and Mizutani 1987, fig. 3, no. 18a, 18b. 1–3; Mizutani and Kojima 1992, pl. 1, figs. 3a, 3b; Fuji et al. 1993, pl. II, fig. 11; Carter 1993, p. 117; pl. 21, figs. 2–4, 6–7, 14.

Livarella validus Yoshida group; Sugiyama 1997, p. 183; fig. 50, 18-19.

Livarella valida Yoshida; Tekin 1999, p. 149; pl. 33, fig. 7; Tekin 2002a, p. 433, pl. 4, figs. 13–14.

RANGE AND OCCURRENCE: Upper Triassic; ?upper Norian, Rhaetian. Nanhada Range, Northeast China; Queen Charlotte Islands, Canada; Central Japan; Turkey; Baja California Sur, Mexico; Waipapa terrane, New Zealand.

Genus *Pantanellium* Pessagno, 1977

TYPE SPECIES: *Pantanellium riedeli* Pessagno, 1977, p. 78
Pantanellium tanuense Pessagno and Blome, 1980
 (Pl. 1A, fig. 1; Pl. 1B, fig. 1)

SYNONYMY: *Pantanellium tanuense* Pessagno and Blome, 1980, p. 259; pl. 4, figs. 3–4, 24; Tipper et al. 1991, pl. 8, fig. 5; Carter 1994, pl. 1, fig. 10; Carter et al. 1998, p. 49; pl. 1, figs. 4, 11, 26; Gorican 1994, pl. 1, figs. 14–18.

Pantanellium sp. aff. *tanuense* Pessagno and Blome; Spörli and Aita 1988, pl. 4, fig. 2; Spörli et al. 1989, fig. 5, no. 6.

RANGE AND OCCURRENCE: Lower Jurassic; Hettangian. Queen Charlotte Islands, Canada; Inuyama, Kuzuu and Ikuno, Japan; New Zealand; Montenegro.

Genus *Pentaspongodiscus* Kozur and Mostler, 1979; emend Dumitrica, Kozur and Mostler, 1980

TYPE SPECIES: *Pentaspongodiscus tortillus* Kozur and Mostler, 1979, p. 80
Pentaspongodiscus? dihexacanthus Carter, 1993
 (Pl. 1A, fig. 9; Pl. 1B, fig. 8)

SYNONYMY: *Pentaspogonodiscus? dihexacanthus* Carter, 1993, pp. 87–88; pl. 13, figs. 1–3; Sugiyama 1997, p. 184; fig. 15–9; Tekin 1999, p. 121; pl. 22, figs. 2–4

Pentaspogonodiscus? dihexacanthus Carter group; Tekin 2002a, p. 428; pl. 3, figs. 9–10

RANGE AND OCCURRENCE: Upper Triassic; Rhaetian. Queen Charlotte Islands, Canada; Inuyama, Japan; Turkey; Baja California Sur, Mexico.

Genus *Pseudohagiastrum* Pessagno, 1979

TYPE SPECIES: *Pseudohagiastrum monstuosum* Pessagno, in Pessagno et al. 1979, p. 165

Pseudohagiastrum giganteum sp. nov.
(Pl. 1A, fig. 6; Pl. 1B, fig. 5)

ETYMOLOGY: From the Latin (adj.) *Giganteus-a-um* = giant

TYPE MATERIAL: GSC 11696 (Holotype) from GSC locality C-305402 (sample 00-CNA-1.35), equivalent to samples 97/3 and 87/11 at 79.3 m in the Kunga Island section.

TYPE LOCALITY: Section SKUD (Carter 1993), southeast side of Kunga Island, Queen Charlotte Islands, British Columbia, Canada.

DESCRIPTION: Test as with genus, large. Rays very long and slender, not in the same plane; Rays approximately equal in length, maintaining equal circumference throughout length. Rays circular in cross-section, composed of 10–12 longitudinal beams. Square to rectangular pore frames aligned between adjacent beams; pores round. Rays terminate with four stout spines, one in the center and three lateral spines oblique to the axis and angled at ~120°.

REMARKS: The long distinctive rays of *Pseudohagiastrum giganteum* sp. nov., are abundant in well preserved uppermost Rhaetian samples of Queen Charlotte Islands and are common in Japan. No complete specimens have been found, but it seems evident this form probably has four arms not in the same plane, possibly arranged tetrahedrally. This species differs from *Pseudohagiastrum monstuosum* Pessagno in possessing rays that are at least twice as long, and meshwork is latticed and linearly arranged, rather than spongy and irregular.

MEASUREMENTS (μm):

	Holotype	Maximum	Minimum	Average
Length of rays:	483	488	316	393 (12 specimens)
Diameter of rays at tip:	79	94	56	72.5 (12 specimens)
Length of longest spine:	117	198	82	138 (10 specimens)

RANGE: Upper Triassic; uppermost Rhaetian, so far as known.

OCCURRENCE: Queen Charlotte Islands, British Columbia, Canada; Inuyama, Japan.

Genus *Spongotrochus* Haeckel, 1860

TYPE SPECIES: *Spongotrochus brevispinus* Haeckel, 1860, p. 844
Spongotrochus? sp. in Carter 1994
(Pl. 1A, fig. 4; Pl. 1B, fig. 4)

SYNONYMY: *Spongotrochus* sp., Carter 1994, pl. 1, fig. 7

Tozerium nascens Whalen and Carter, 1998; Tekin 2002b, p. 189; pl. 4, fig. 1

REMARKS: The genus *Spongotrochus* is Cenozoic in age and its range does not likely extend down to the Lower Jurassic. This species is tetrahedral in shape with four long, rod-like spines, one extending from each apex of the test. It has a thick spongy outer wall, and the inner part appears to be hollow. This taxon is basically similar through the Rhaetian and into the basal Hettangian (across the T–J boundary) except that in the Rhaetian the spines are triradial and highly twisted (see *Spumellaria* gen., and sp. indet. D, Carter 1993, p. 92; pl. 13, figs. 9–10), whereas in the basal Hettangian, the spines are straight and rod-like. The changing morphology of the spines makes this species a good index for the base of the Jurassic. It will be described as a new genus in the near future.

RANGE AND OCCURRENCE: Lower Jurassic; Hettangian. Queen Charlotte Islands, Canada; Inuyama, Japan; Turkey.

Spumellaria gen. et sp. A in Whalen and Carter 1998
(Pl. 1A, fig. 3; Pl. 1B, fig. 3)

SYNONYMY: *Spumellaria* indet. A, Whalen and Carter, in Carter et al. 1998, p. 61; pl. 11, figs. 10–11, 15.

RANGE AND OCCURRENCE: Lower Jurassic; Hettangian. Queen Charlotte Islands, Canada; Inuyama, Japan.

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