Timing of Cache Creek Ocean closure: insights from new Jurassic radiolarian ages in British Columbia and Yukon and their significance for Canadian Cordillera tectonics

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1 *Title:* Timing of Cache Creek Ocean closure: insights from new Jurassic radiolarian ages in
2 British Columbia and Yukon, and their significance for Canadian Cordillera tectonics.

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Title: Timing of Cache Creek Ocean closure: insights from new Jurassic radiolarian ages in British Columbia and Yukon, and their significance for Canadian Cordillera tectonics.

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Abstract

The closure of the Cache Creek Ocean during the Jurassic led to the structuration of the Canadian Cordillera. To reassess the timing of this major tectonic event, this study proposes a biochronological review of all the youngest radiolarian-bearing localities of the Cache Creek Terrane in British Columbia and Yukon using updated radiolarian biozonations and taxonomy, complemented by new data from the type locality. The results show that all ages are Early Jurassic and fairly homogenous along the entire terrane. All the youngest siliceous rocks are restricted to the Late Sinemurian–Early Toarcian interval (~195–180 Ma). The youngest well-dated pelagic cherts are Early Pliensbachian, with slightly younger siliceous argillites of Pliensbachian and possibly Early Toarcian age. These results suggest that Cache Creek deep pelagic sedimentation ceased fairly synchronously along the entire belt, probably during the Pliensbachian (~191–183 Ma), predating the final closure of the basin when Cache Creek units were thrust over Stikinia and Quesnellia in the Middle and Late Jurassic. This apparent synchronicity should result in re-evaluating the tectonic mechanism of the Cache Creek “entrapment model” in its present form. The study also shows that pelagic sedimentation ceased 22 to 31 m.y. earlier in the Cache Creek Terrane than in the Bridge River Terrane, confirming the stratigraphic discrepancy between the two terranes during the Jurassic.

42 **Résumé**

43 La fermeture de l'océan Cache Creek au Jurassique a conduit à la structuration de la Cordillère
44 Canadienne. Afin de réévaluer la chronologie de cet événement tectonique majeur, l'étude
45 propose une synthèse biochronologique de toutes les plus jeunes localités à radiolaires du terrane
46 de Cache Creek en Colombie-Britannique et au Yukon grâce aux nouvelles biozonations et à une
47 taxonomie actualisée, avec en complément de nouvelles données pour la localité-type. Les
48 résultats montrent que tous les âges sont du Jurassique inférieur et sont homogènes pour
49 l'ensemble du terrane. Toutes les roches siliceuses les plus jeunes sont comprises dans l'intervalle
50 Sinémurien supérieur–Toarcien inférieur (~ 195–180 Ma). Les plus jeunes cherts pélagiques sont
51 du Pliensbachien inférieur, avec des argilites siliceuses légèrement plus jeunes du Pliensbachien
52 et peut-être du Toarcien inférieur. Ces résultats suggèrent que la sédimentation pélagique
53 profonde de l'océan Cache Creek a cessé de manière relativement synchrone sur toute sa
54 longueur, probablement pendant le Pliensbachien (~191–183 Ma), avant la fermeture finale du
55 bassin lorsque les unités de Cache Creek ont été charriées sur la Stikinia et la Quesnellia au
56 Jurassique moyen et supérieur. Ce synchronisme apparent devrait conduire à réévaluer les
57 modalités du modèle tectonique en ciseau sous sa forme actuelle. L'étude montre aussi que la
58 sédimentation pélagique a cessé 22 à 31 Ma plus tôt dans le terrane de Cache Creek que dans
59 celui de Bridge River, confirmant la différence stratigraphique entre les deux unités au
60 Jurassique.

61

62 *Mots-clés* : terrane de Cache Creek, Radiolaria, Jurassique, Cordillère canadienne, radiolarite,
63 terrane de Bridge River

64

Introduction

The Canadian Cordillera (Fig. 1) is a complex collage of arc and oceanic terranes which has been the subject of a vast amount of studies and literature in the past 50 years. Various models describing the tectonic history of the orogen are still debated (Monger & Gibson 2019 and references therein) but they all point to the importance of the Cache Creek Terrane, considered as one major evidence for a large Mesozoic ocean basin in the Canadian Cordillera. One important issue is the timing of the ocean closure during the Jurassic period which led to collision with Stikinia and Quesnellia volcanic arcs, contributing to the structuration of the Cordillera (Nelson and Mihalynuk 1993, Colpron et al. 2015, Monger & Gibson 2019).

To determine the age of the Cache Creek Terrane, radiolarian biostratigraphy has been applied over the last 40 years to its deep ocean strata with a particular focus on the youngest localities considered to predate the final stages of convergence. The youngest Jurassic unit of the Cache Creek Terrane was originally found in its type locality in southern British Columbia (Cordey et al. 1987). At the time, it contradicted the scenario in which amalgamation of the Cache Creek and Quesnellia terranes occurred in the Late Triassic (Monger 1981, Monger et al. 1982). Further investigations confirmed the occurrence of Jurassic radiolarian-bearing oceanic strata in all segments of the Cache Creek Terrane in British Columbia and Yukon (Fig. 2; Cordey et al. 1991, Cordey & Struik 1996, Cordey 1998, Orchard et al. 2001, Struik et al. 2001, Mihalynuk et al. 2004). Although most of these localities are Early Jurassic, some confusion remained due to the “Early or Middle Jurassic” age of the youngest Cache Creek rocks in the type locality. This question also led to conflicting interpretations in comparisons between the Cache Creek Terrane and other Paleozoic-Mesozoic oceanic units of the Canadian Cordillera such as the Bridge River and Hozameen terranes (Cordey et al. 1987, Cordey & Schiarizza 1993, Mihalynuk et al. 1994, Cordey 1998, Monger 2014).

To clarify the stratigraphy of the youngest Cache Creek strata, the goal of this study is to review all the youngest radiolarian localities and, when possible, improve and refine previous ages with new Jurassic radiolarian biozonations and taxonomy (Baumgartner et al. 1995, Carter et al. 1988, 1998, 2010, Goričan et al. 2006, 2018, O'Dogherty et al. 2009). The results reveal that the youngest ages are fairly homogenous along the entire Cache Creek belt, which provides some clues regarding the accuracy of current tectonic models such as the Cache Creek Terrane entrapment in its present form (Mihalynuk et al. 1994). Finally, the study provides some new elements for stratigraphic comparison of the Cache Creek Terrane with other main oceanic units of the Canadian Cordillera during the Jurassic (Cordey and Schiarizza 1993, Monger and Gibson 2019).

Material and Methods

The radiolarian assemblages presented in this paper are part of a large dataset of Devonian to Jurassic radiolarian samples collected and studied in several terranes of the Canadian Cordillera since the 1980s. Among them, the youngest Jurassic assemblages of the Cache Creek Terrane were found at eight localities from southern British Columbia to southern Yukon (Fig. 2: J1, Pavilion; J2, Alkali Lake; J3, Blackwater; J4, Pinchi Lake; J5, French Range; J6-J8, Teslin Plateau). The geological setting and lithostratigraphy of these localities are described in detail in former publications (J1: Mortimer 1987, Cordey et al. 1987, Cordey 1998; J2: Read 1993, Cordey, unpub. data; J3: Cordey and Struik 1996, Orchard et al. 2001; J4: Orchard et al. 2001, Struik et al. 2001; J5: Mihalynuk et al. 2004; J6-J8: Cordey et al. 1991). The radiolarian faunas from the Cache Creek Terrane are usually poorly or moderately preserved due to silica recrystallization as a result of diagenesis associated with P/T conditions during

tectonic emplacement and local magmatic intrusions. To maximize the quality of the
 microfossils, the samples were selected with specific field detection techniques applied to pelagic
 strata from orogenic belts, using a strong hand lens and investigating specific microfacies such as
 argillaceous layers within chert beds (Cordey & Krauss 1990, Cordey 1998). Radiolarians were
 then extracted by repetitive leaching of samples with low-concentration hydrofluoric acid (HF)
 and then hand-picked and mounted on aluminum stubs for SEM observation and taxonomical
 identifications (Tabletop SEM Phenom ProX, Laboratoire de Géologie de Lyon).
 Although most radiolarian assemblages presented here are described in previous publications,
 new SEM images have been obtained for a selection of samples to improve the quality of
 previous illustrations and complement former studies with new taxa.
 When microfossil assemblages are not well-preserved, radiolarians are usually identified at the
 genus level only (J1, J2, J5, J7, J8; Table 1). In this case, the age is established from overlapping
 ranges of genera (O'Dogherty et al. 2009). Other assemblages show a better state of preservation
 with radiolarians identified at the species level (J3, J4, J6), allowing correlations to more precise
 biozones (Carter et al. 1988, Cordey 1998, Whalen and Carter 2002, Goričan et al. 2006, Carter
 et al. 2010). A selection of biostratigraphically-significant radiolarians is presented in Figures 5
 and 6. Radiolarian assemblages and ages are synthesized in Table 1.

Results

New radiolarian assemblage from the type locality

In southern British Columbia, the Cache Creek Terrane is divided into three belts (Figs. 3, 4)
 (Duffell and McTaggart 1952, Trettin 1980, Shannon 1981, Monger and McMillan 1984, Monger
 1985, Mortimer 1987). The central belt is composed of massive limestone and marble of the

Marble Canyon Formation where schwagerinid fusulinids of Late Permian age (*Colania* assemblage) belong to a Tethyan faunal province and are cited as evidence that carbonate units of the Cache Creek Terrane are far-travelled (Monger and Ross 1971; Monger et al. 1982; Danner 1985; Orchard et al. 2001). To the west of Marble Canyon, the western belt contains the youngest strata of the type locality as shown by Early or Middle Jurassic radiolarians found in siliceous argillites above Hambrook Creek (“R2”, Cordey et al. 1987, Cordey 1998).

With the aim of improving this previous radiolarian dating, this locality was resampled (NEO-R2, Figs. 3, 4). A new radiolarian assemblage J1 (Table 1) is composed of the following taxa:

Archaeodictyomitra sp., *Homoeoparonaella* sp. cf. *reciproqua* Carter, *Hsuum* sp., *Pseudocrucella*? sp., *Thurstonia* sp., *Trillus* sp., *Xiphostylus*? sp., *Triactoma* sp., and *Zartus* sp..

The previous collection was dated as Pliensbachian–Bajocian based on the age range of *Zartus* sp. (Cordey et al. 1987). In the new sample NEO-R2, the co-occurrence of *Thurstonia* sp., *Trillus* sp. and *Zartus* sp. provides an age restricted to the Early Pliensbachian–Early Toarcian interval (O’Dogherty et al. 2009). Although the preservation of the assemblage is poor, the specimens of *Thurstonia* sp. display well-developed nodes at pore frame intersections (Fig. 5, no. 1), showing affinities with *Thurstonia* specimens from the northern part of the Cache Creek Terrane (J6, Fig. 5, no. 3) as well as *Thurstonia* sp. B documented in Early Jurassic radiolarian assemblages from the Bridge River and Hozameen terranes (Cordey 1998).

Refined Jurassic radiolarian ages

Southern British Columbia

An Early Jurassic radiolarian assemblage was found in gray-green radiolarian chert of the Riske Creek Formation in the Alkali Lake map area (locality J2, Fig. 2) as a result of mapping and sampling by Read (1993). Such as J1, it is located within the western belt of the terrane. This assemblage is composed of *Canutus* sp., *Lantus* sp., *Orbiculiformella* sp., *Parahsuum* sp. and

Praeconocaryomma sp. (Table 1). Originally dated as Sinemurian or Pliensbachian, its age is refined to the Early Pliensbachian–Early Toarcian interval (Table 1) based on co-occurrence of the genera *Canutus* sp. and *Lantus* sp.. (O’Dogherty et al. 2009). It is noteworthy that the age ranges of J1 and J2 assemblages are identical, although based on different radiolarian taxa.

Central British Columbia

Geological mapping of the Cache Creek Terrane in central British Columbia (Struik et al. 2007 and references therein) resulted in an important number of Paleozoic and Mesozoic radiolarian collections (Cordey and Struik 1996, Struik 1998, Orchard et al. 2001). The youngest radiolarian chert succession of this region is exposed along the Blackwater River in Punchaw Lake map area (J3, Fig. 2), 25 km to the south-southwest of the town of Prince George (Cordey and Struik 1996, Orchard et al. 2001, Struik et al. 2001). This succession is broadly continuous and contains Middle Triassic, Late Triassic, and Early Jurassic radiolarians. The youngest radiolarian assemblage found near the top of the section was initially dated as Pliensbachian (Cordey and Struik 1996, Orchard et al. 2001). Complementary chemical processing and new SEM images reveal an abundant and well-preserved assemblage (Table 1) composed of *Atalantria* sp., *Beatricea?* *argescens* Cordey, *Bipedis japonicus* Hori, *Broctus* sp., *Canoptum rugosum* Pessagno & Poisson, *Canoptum* sp. cf. *dixoni* Pessagno & Whalen, *Charlottea* sp., *Katroma* sp. cf. *elongata* Carter, *Lantus* sp. cf. *praeobesus* Carter, *Laxtorum* sp., *Orbiculiformella?* *trispina* s.l. (Yeh), *Orbiculiformella* sp., *Palaeosaturnalis* sp., *Parahsuum simplum* Yao, *Parahsuum vizcainoense* Whalen & Carter, *Praeconocaryomma* sp. cf. *sarahae* Carter, *Thurstonia* sp. and *Spumellaria* gen. sp. indet. (Figs. 5, 6). This assemblage corresponds to the interval from the middle part of the *Canutus tipperi* – *Katroma clara* Zone to the base of the *Gigi fustis* – *Lantus sixi* Zone of Early Pliensbachian age (Carter et al. 2010).

In the Fort-St-James area, the Tezzeron succession (originally called the Pinchi succession by Struik et al. (1996) and Cordey and Struik (1996)) is exposed to the north of Stuart and Pinchi lakes and bears some similarities with clastic assemblages from the upper part of the Cache Creek Terrane in southern British Columbia (Shannon 1981, Monger 1985) and in Yukon (Cordey et al. 1991, Cordey and Stevens 1994). It is interpreted as belonging to the Cache Creek Terrane (Bellefontaine et al. 1995, Struik et al. 1996, Orchard et al. 2001, Struik et al. 2001).

Within the Tezzeron succession, a limy siltstone unit located near the south end of Pinchi Lake contains an Early Jurassic radiolarian assemblage (J4, Fig. 2, Table 1) previously reported by Orchard et al. (2001) and Struik et al. (2001). It is composed of *Emiluvia?* sp. A (Carter et al. 1988), *Hsuum lucidum* Yeh (formerly interpreted as *H. sp. cf. optimum* Carter), *Paronaella grahamensis* Carter, *Praeconocaryomma decora* gr. Yeh (formerly *P. sp. A*), and *Praeparvicingula tlellensis* Carter (formerly *Parvicingula sp. E*, Carter et al. 1988). This assemblage was originally assigned to the biozones 2 to 5 of Carter et al. (1988). It correlates with the *Elodium pessagnoii* – *Hexasaturnalis hexagonus* Zone of Carter et al. (2010) of Middle-Late Toarcian age. The corresponding sample, which is a limy siltstone, cannot be considered part of “deep ocean” Cache Creek strata. It shows, however, that radiolarian pelagic input lasted until the Toarcian, at least locally.

Northern British Columbia

In the French Range to the west of the Dease Lake area, a unit belonging to the Cache Creek Terrane is composed of cherty argillites with local tuffaceous layers that contain Middle Triassic and Early Jurassic radiolarians (Mihalynuk et al. 2004). This succession is correlative to the rocks on the Teslin Plateau, ~200 km to the north (Cordey et al. 1991). One Early Jurassic radiolarian assemblage (J5, Fig. 2, Table 1) was extracted from a black cherty argillite exposure located 2.5 km to the north of Slate Creek. It is from blueschists, and therefore places a maximum age limit

on blueschist mineral formation ((Mihalynuk et al. 2004). The assemblage is composed of *Parahsuum izeense* (Pessagno & Whalen) (formerly *Canutus izeensis* Pessagno & Whalen), *Orbiculiformella? trispina* s.l. (Yeh) (formerly *Orbiculiforma silicatilis* Cordey), *Praeconocaryomma* sp. cf. *sarahae* Carter (formerly *P. aff. media* Pessagno & Poisson), *Praeconocaryomma* sp., and *Thurstonia* sp. (Table 1). Initially, the radiolarian assemblage was dated as Pliensbachian–Toarcian (Mihalynuk et al. 2004). The age is revised to the Pliensbachian–Early Toarcian based on the occurrence of *Parahsuum izeense* Pessagno & Whalen and the refined range of *Thurstonia* (Table 1). The presence of *Praeconocaryomma* sp. cf. *sarahae* Carter suggests that this assemblage could be restricted to the Pliensbachian (Carter et al. 2010), but this cannot be confirmed due to the incomplete nature of the specimen.

Yukon

An assemblage composed of radiolarian cherts and fine-grained clastic rocks is exposed on the Teslin Plateau, ~20 km to the north of the British Columbia-Yukon border (Gordey 1991). This succession has previously been called the Lewes River assemblage (Wheeler et al. 1991, Gordey 1991) or Teenah Lake assemblage (Jackson 1992), and is equivalent in part to the Kedahda Formation of Monger (1975). Several localities with Middle Triassic, Late Triassic, and Early Jurassic radiolarian assemblages were discovered along a five-kilometre-long ridge north of Mount Bryde and Sterlin Lake (Gordey 1991, Cordey et al. 1991). The ridge consists of successive outcrops and isolated sections of stacked radiolarian chert, argillite and graywacke previously described and discussed in detail (Cordey et al. 1991).

The first Early Jurassic radiolarian assemblage J6 (Fig. 2, Table 1) is from siliceous argillite interbedded with graywacke that contain *Bipedis* sp., *Broctus* sp., *Canoptum anulatum* Pessagno & Poisson, *Canoptum* sp., *Hagiastrum majusculum* Whalen & Carter (formerly called *H. sp. A*, Cordey 1998), *Homoeoparonaella* sp., *Lantus sixi* Yeh, *Napora cerromesaensis* Pessagno,

240 Whalen & Yeh, *Pantanellium cumshewaense* Pessagno & Blome, *Parahsuum izeense* (Pessagno
 241 & Whalen) (formerly described as *Canutus giganteus* Pessagno & Whalen), *Praeconocaryomma?*
 242 sp. cf. *yakounensis* Carter (formerly interpreted as *Praeconocaryomma*. sp. aff. *P.* sp. B Yeh),
 243 *Thurstonia* sp., and *Wrangellium* sp.. This assemblage was originally dated as
 244 Pliensbachian–Early Toarcian (Table 1). It is now correlated with the base of the *Gigi fustis* –
 245 *Lantus sixi* Zone to the middle part of the *Eucyrtidiellum nagaiae* – *Praeparvicingula tllellensis*
 246 Zone (Unitary associations UA 12-22) (Carter et al. 2010), establishing a late Early Pliensbachian
 247 to Late Pliensbachian age.

248 The second youngest Early Jurassic sample on the Teslin Plateau (J7, Fig. 2, Table 1) is from a
 249 radiolarian chert succession located 4 km to the south of J6 (Cordey et al. 1991). It was
 250 previously dated as Sinemurian–Toarcian (Cordey et al. 1991). It is composed of *Beatricea?*
 251 *argescens* Cordey, *Canoptum* sp. cf. *anulatum* Pessagno & Poisson (previously interpreted as
 252 *Wrangellium* sp. cf. *thurstonense* Pessagno & Whalen), *Canoptum* sp., *Praeconocaryomma* sp.
 253 cf. *immodica* Pessagno & Poisson, and *Wrangellium* sp. (Table 1). The age is here refined to the
 254 Late Sinemurian–Late Pliensbachian interval based on the co-occurrence of *Beatricea* sp. and
 255 *Wrangellium* sp..

256 The third sample (J8, Fig. 2, Table 1) is part of the same radiolarian chert succession and location
 257 as J7. The radiolarian assemblage is composed of *Beatricea? argescens* Cordey, *Bipedis* sp.,
 258 *Canoptum* sp. cf. *dixonii* Pessagno & Whalen, *Gorgansium* sp., *Pantanellium* sp., *Parahsuum* sp.,
 259 *Praeconocaryomma* sp., and *Wrangellium* sp.. It was previously dated as Sinemurian–Toarcian
 260 (Cordey et al. 1991). It is here refined to the Late Sinemurian–Late Pliensbachian interval, based
 261 on the co-occurrence and refined ranges of *Beatricea* sp., *Bipedis* sp. and *Wrangellium* sp. (Table
 262 1).

263

264

Discussion

Homogeneity of youngest Cache Creek ages

Revised Jurassic radiolarian ages reveal that the youngest Cache Creek ages are fairly homogenous along the entire Canadian Cordillera (Fig. 7). These ages are comprised within the Late Sinemurian–Late Toarcian interval (~195–174 Ma, Cohen et al. 2013). The siliceous rocks (radiolarian chert and siliceous argillite) are restricted to the Late Sinemurian–Early Toarcian interval (~195–180 Ma), including error margins. The most precise age determinations from central British Columbia and Yukon (Fig. 7) indicate that the youngest true radiolarian cherts (= devoid of clastic intercalations) are Pliensbachian in age (J3), and the youngest siliceous argillites may also be Pliensbachian in age, possibly reaching the Early Toarcian (J1, J5, J6). The youngest Jurassic age obtained on a limy siltstone in the Tezzeron succession (J4) suggests that radiolarian pelagic input possibly lasted until the Middle or Late Toarcian in central British Columbia, although chert sedimentation might have ceased. To date, no pelagic sedimentary strata of Middle Jurassic age have been found in the Cache Creek Terrane.

Cache Creek Terrane and overlap assemblages

Some of the youngest Cache Creek strata have locally been interpreted as overlap assemblages, for instance the chert-argillite-graywacke successions exposed on the Teslin Plateau (Lewes River assemblage, Wheeler et al. 1991, Gordey 1991; Teenah Lake assemblage, Jackson 1992). More recently, all post-Middle Triassic sequences were proposed to represent overlap assemblages on top of already assembled terranes including the Paleozoic units of the Cache Creek Terrane (Zagorevski et al. 2017). The notion of an “overlap assemblage” implies that marine sedimentation ceased prior to the deposition of clastic sediments on top of exhumed oceanic units. Regarding the Cache Creek

290 Terrane, this view is not consistent with the occurrence of radiolarian chert sedimentation as
 291 young as Pliensbachian or of Middle Jurassic blueschists with in part Early Jurassic sedimentary
 292 protoliths (Mihalynuk et al. 2004), which demonstrate that deep ocean sedimentation persisted
 293 between Stikinia and Quesnellia until the end of the Early Jurassic. In central British Columbia
 294 (Blackwater; Figs. 7, 8), a Triassic–Early Jurassic chert succession also suggests that Cache
 295 Creek marine sedimentation was continuous prior to the closure of the basin. However, pelagic
 296 and clastic regimes are interrelated: in the northern part of the Cache Creek Terrane, the argillites
 297 and graywackes are locally intercalated with Late Triassic radiolarian cherts (Cordey et al. 1991).
 298 More recently, a Hettangian age (199.5 ± 2.0 Ma) was obtained on detrital zircons from a Cache
 299 Creek graywacke east of Carcross (Colpron et al. 2015) and interpreted as a probable distal
 300 equivalent of the Richtofen Formation (Laberge Group), showing a probable link between the
 301 Cache Creek Terrane and the Whitehorse trough as early as the end of the Triassic or the
 302 beginning of the Jurassic. The input of clastic sediments within Cache Creek pelagic strata may
 303 be a result of the geometry of the terrane at this time, flanking the Yukon-Tanana Terrane to the
 304 north during the counterclockwise rotation of Stikinia (“isolation stage” of Mihalynuk et al. 1994;
 305 Colpron et al. 2015). These transitional regimes evolved towards a narrowing Cache Creek basin
 306 incorporating thicker and coarser siliciclastic sediments associated with tectonic convergence in
 307 the form of synorogenic piggyback basins (Colpron et al. 2015, Bickerton et al. 2020).
 308 Numerous examples of pelagic to clastic successions are found in other segments of the circum-
 309 Pacific ranges such as in Japan and Siberia where the Permian-Jurassic oceanic terranes display
 310 Jurassic intercalations of radiolarian chert, siliceous argillite and sandstone interpreted as ocean
 311 environments within the depositional influence of one continental margin or flanking sources
 312 (Isozaki et al. 1990, Matsuoka et al. 1996). In general, the intercalations and lateral facies
 313 changes between pelagic and clastic rocks make it difficult to delineate a clear boundary where
 314 oceanic terrane sedimentation ends and where clastic assemblages begin. This is true for the

Cache Creek Terrane in the Yukon, but also in southern British Columbia (Mortimer 1987, Cordey et al. 1987). The composite nature of Cordilleran oceanic terranes, i.e. the likelihood for these terranes to be the end-result of juxtaposed basinal entities, has previously been suggested for the Bridge River Terrane (Cordey and Schiarizza 1993, Cordey 1998) and the Cache Creek Terrane (Golding 2018) but these hypotheses do not challenge the interpretation that these terranes were dominantly oceanic until the final stages of convergence.

Cache Creek closure: fast entrapment?

Several models have been proposed for the tectonic mechanism of Cache Creek Ocean closure (see Golding 2018 for a recent review). The consensus model of Cache Creek “entrapment” from Nelson and Mihalynuk (1993) and Mihalynuk et al. (1994) proposes that the terrane became enclosed between the Stikinia and Quesnellia terranes leading to Cache Creek oceanic crust being subducted during an oroclinal bending event, with a progressive “scissor-like” closure from north to south, and the Yukon-Tanana Terrane acting as the hinge. In this scenario, the Whitehorse trough is considered a northern precursor to the Bowser Basin (Ricketts et al. 1992, Evenchick et al. 2010) accompanying the final stages of convergence and closure (Colpron et al. 2015).

The entrapment model implies a diachronous closure of the Cache Creek Ocean, with the youngest oceanic sedimentary rocks progressively younging to the south (basin isolation followed by closure, Mihalynuk et al. 1994). The updated radiolarian ages suggest instead a relative synchronicity in the cessation of pelagic sedimentation along the entire Cache Creek Terrane. While Yukon hemipelagic rocks (J6) are Pliensbachian in age, a similar age (Pliensbachian–Early Toarcian) is obtained on siliceous argillites 1200 km to the south in the type locality (J1). Additionally, radiolarian cherts from central British Columbia (J3) and Yukon (J8) could have a common Pliensbachian age, even though they are ~1000 km apart.

One could argue that the speed and geometry of the counterclockwise oroclinal bending of

Stikinia towards Quesnellia are not precisely known. One way to reconcile the entrapment model with the relative synchronicity of the youngest Cache Creek oceanic strata is through very rapid tectonic rotation. In northern British Columbia, Mihalynuk et al. (1994, 2004) assessed that the final closure of the Cache Creek Terrane in the north occurred before 171 Ma (late Aalenian or early Bajocian, Cohen et al. 2013), the age of the post-kinematic Fourth of July batholith that intrudes deformed Cache Creek units in the Atlin Lake area (Mihalynuk et al. 1992). The minimum age of Cache Creek extrusion in the French Range was constrained to ~174.5–172 Ma (latest Toarcian or Aalenian, Cohen et al. 2013), using the interval between the youngest blueschists and the oldest intrusions (Mihalynuk et al. 2004). In the south, the Cache Creek Terrane was thrust eastward over Quesnellia in the Late Jurassic (≤ 160 Ma) (Travers 1978). The most precise ages of the youngest Cache Creek Terrane strata are Pliensbachian and found in central British Columbia (J3) and Yukon (J6). The Early Pliensbachian chert J3 (Figs. 7, 8) found at the top of a Triassic-Early Jurassic succession along the Blackwater River in central British Columbia is a good time proxy for the age of the youngest and still truly oceanic Cache Creek sedimentation at the center of the Cache Creek belt, suggesting that the youngest sustained hemipelagic sedimentation in southern British Columbia could be slightly younger, possibly Late Pliensbachian or Early Toarcian, predating the final closure of the Cache Creek Ocean. In this case, the final phase of the counterclockwise rotation of Stikinia must have occurred within 8 m.y. (the interval between late Early Pliensbachian and Early Toarcian, ~188–180 Ma, Cohen et al. 2013).

Comparison between youngest Cache Creek and Bridge River ages

Since the 1980s, geological and paleontological studies have established that the oceanic strata of the Cache Creek and the Bridge River terranes (Fig. 1) share fairly similar Carboniferous-Jurassic stratigraphic ages (Cordey et al. 1987, Mihalynuk et al. 1994, Monger 2014). The Hozameen

Terrane exposed in southern British Columbia and northern Washington (Fig. 1) is considered as a southern continuation of the Bridge River Terrane (Monger 1985).

Early Jurassic radiolarian assemblages found in the Cache Creek Terrane are also present in the Bridge River and Hozameen terranes which contain Pliensbachian and Toarcian radiolarian cherts (Cordey and Schiarizza 1993, Cordey 1998). However, the cherts of the Bridge River Terrane document a pelagic sedimentation that lasted significantly longer: the youngest radiolarian assemblages are from the Noaxe Creek area (Cordey and Schiarizza 1993, Cordey 1998) where six localities are Middle Jurassic (Aalenian–Bajocian, Early–Middle Bathonian, Late Bathonian–Middle Callovian, Late Bathonian–Late Callovian), and one locality is Middle or Late Jurassic (Late Callovian–?Middle Oxfordian) based on biozonations for the Middle-Late Jurassic (Baumgartner et al. 1995, Matsuoka 1995, Goričan et al. 2018). This Bridge River radiolarian chert succession probably grades into Late Jurassic and earliest Cretaceous clastic rocks of the Tyaughton-Methow basin (Mahoney and Journeay 1993, Cordey 1996, Monger 2014, Monger and Gibson 2019).

It is hypothesized here that the youngest radiolarian chert of the Cache Creek Terrane is Early Pliensbachian in age (~191–187 Ma, Cohen et al. 2013) based on the well-constrained assemblage at the Blackwater section in central British Columbia (J3, Figs. 7-8). In the Bridge River Terrane, the youngest age for a radiolarian chert is within the “Late Callovian – Middle Oxfordian” interval (~165–160 Ma, Cohen et al. 2013). These ages imply that the Cache Creek Terrane oceanic sedimentation had ceased since 22 to 31 m.y. (minimum and maximum possible durations due to the error margins of biostratigraphic data, corresponding to “Late Pliensbachian–Late Callovian” and “Early Pliensbachian–Middle Oxfordian” intervals, respectively) while the Bridge River Ocean was still recording pelagic sedimentation in the Middle Jurassic and possibly the early Late Jurassic.

390 **Cache Creek and Bridge River terranes: one or two sutures?**

391 The question whether the Cache Creek and Bridge River terranes mark two distinct sutures or are
 392 the remnants of a single oceanic domain has long been debated (Monger et al. 1972, Coney et al.
 393 1980, Monger et al. 1982, Monger 1985, Cordey 1986, Cordey et al. 1987, Monger et al. 1994,
 394 Nokleberg et al. 2000, Dickinson 2004, Johnston and Borel 2006, Gehrels et al. 2009). This issue
 395 has been revived by Sigloch and Mihalynuk (2013, 2017) who combined high-resolution
 396 tomography, plate reconstructions and the concept of vertical slab walls. Their analysis of the
 397 North American Cordillera implies that a cryptic suture zone existed between the Insular and
 398 Intermontane superterrane. In this model, the Bridge River Terrane corresponds to the land
 399 remnant of an intraoceanic domain identified in the subducted Mezcalera slab wall (named from
 400 the Mezcalera oceanic plate hypothesized in Mexico by Dickinson and Lawton 2001).

401 However, some authors question the accuracy of this “two-sutures” model which also implies a
 402 west-dipping subduction zone inboard of Wrangellia (see the recent discussion by Pavlis et al.
 403 2019). Monger (2014) and Monger and Brown (2016) have proposed instead that the Bridge
 404 River and Hozameen terranes are the southern continuation of the Cache Creek Terrane, prior to
 405 dextral displacements of ~115 km on the latest Cretaceous–Paleocene Yalakom Fault (Umhoefer
 406 and Schiarizza 1996) and ~140 km of Eocene movement on the Fraser-Straight Fault (Monger
 407 and Brown 2016). The age discrepancy between the two terranes is interpreted by implying that
 408 the Bridge River Terrane faced open ocean to the west until it was trapped in the Early
 409 Cretaceous (≤ 130 Ma) behind the arc rocks in the southwestern Coast Mountains, whereas in
 410 northern British Columbia, the Cache Creek Terrane was thrust southwestward over Stikinia in
 411 the earliest Middle Jurassic (~174 Ma) (Mihalynuk et al. 2004), and in southern British Columbia
 412 was thrust eastward over Quesnellia probably in the Late Jurassic (≤ 160 Ma) (Travers 1978).

413 The likelihood of differentiating the two terranes based on provincial radiolarian signatures has
 414 been discussed by Cordey (1998) and Orchard et al. (2001) and present some limitations. Some

elements of correlation with Tethyan assemblages may be found in older Paleozoic and Triassic assemblages of the Cache Creek Terrane (Cordey 1998, Orchard et al. 2001), but also in the Bridge River Terrane (Cordey and Schiarizza 1993, Cordey 1996, Cordey 1998). During the Jurassic, one can only demonstrate that the Bridge River Terrane has a longer record of chert sedimentation than the Cache Creek Terrane.

Conclusions

So far as known, all the youngest radiolarian assemblages of the Cache Creek Terrane are Early Jurassic in age, including in the type locality in southern British Columbia. All refined ages of the youngest radiolarian cherts and siliceous argillites are within the Late Sinemurian–Early Toarcian interval (~195–180 Ma) with a possible Pliensbachian common age (~191–183 Ma). Well-dated Early Pliensbachian radiolarian cherts are exposed in the central part of the terrane and may correspond to the youngest pelagic strata. These results suggest that Cache Creek deep pelagic “true chert” sedimentation ceased fairly synchronously along the entire belt, probably during the Pliensbachian, followed by hemipelagic sedimentation in the Pliensbachian and/or the Toarcian, predating the final closure of the basin that occurred by tectonic thrusting of Cache Creek units over Stikinia and Quesnellia in the Middle and Late Jurassic.

These results should lead to re-evaluating the tectonic mechanism of the Cache Creek entrapment model in its present form, either in speed or geometry. In addition, the study shows that pelagic sedimentation ceased ~22 to 31 m.y. earlier in the Cache Creek Terrane than in the Bridge River Terrane, confirming the stratigraphic discrepancy between the two terranes during the Jurassic. These refined chronological data now need to be more precisely taken into account by the current tectonic models which integrate the two terranes and the suture(s) they represent at the core of the

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755 Stikinia bedrock report of activities, British Columbia and Yukon: GEM 2 Cordillera. Geological

756 Survey of Canada, Open File 8329, pp. 1–15. doi.org/10.4095/306144

757 Table 1. Jurassic radiolarian taxa and ages from the Cache Creek Terrane

Locality, Region	Subterranean unit, map area & UTM coordinates	Lithology, Sample, GSC locality number when available	Radiolarian assemblage	Original age, Reference(s)	New or revised age	Generic assemblage or correlation to biozones (when applicable)
J1 southern British Columbia	western belt Pavilion NTS 092113 UTM zone 10 581045E 5646753N	siliceous argillite NEO-R2 GSC C-300438 (previously R2, Cordey et al. 1987, Cordey 1998)	<i>Archaeodictyomitra</i> sp., <i>Homoeoparonaella</i> sp. cf. <i>reciproqua</i> , <i>Hsuum</i> sp., <i>Pseudocrucella</i> ? sp., <i>Thurstonia</i> sp., <i>Trillus</i> sp., <i>Xiphostylus</i> ? sp., <i>Zartus</i> sp.	Early Jurassic (Pliensbachian- Bajocian) (Cordey et al. 1987, Cordey 1998)	Early Jurassic (Early Pliensbachian - Early Toarcian)	Co-occurrence of <i>Thurstonia</i> , <i>Trillus</i> and <i>Zartus</i> (O'Dogherty et al. 2009)
J2 southern British Columbia	western belt Alkali Lake NTS 092016 UTM zone 10 548240E 5749410N	gray-green radiolarian chert 92-PBR-C92-78F GSC C-210033	<i>Canutus</i> sp., <i>Lantus</i> sp., <i>Orbiculiformella</i> sp., <i>Parahsuum</i> sp., <i>Praeconocaryomma</i> sp.	Early Jurassic (Sinemurian- Pliensbachian) (Cordey, unp. data; Read 1993)	Early Jurassic (Early Pliensbachian - Early Toarcian)	Co-occurrence of <i>Canutus</i> and <i>Lantus</i> (O'Dogherty et al. 2009)
J3 central British Columbia	Blackwater River Punchaw Lake NTS 093G6 UTM zone 10 490750E 5904150N	gray radiolarian chert 95FC-21-4 GSC C-303032	<i>Atalantria</i> sp., <i>Beatricea</i> ? <i>argescens</i> , <i>Bipedis japonicus</i> , <i>Broctus</i> sp., <i>Broctus</i> ? sp., <i>Canoptum rugosum</i> , <i>Canoptum</i> sp. cf. <i>dixonii</i> , <i>Charlottea</i> sp., <i>Katroma</i> sp. cf. <i>elongata</i> , <i>Lantus</i> sp. cf. <i>praeobesus</i> , <i>Laxtorum</i> sp., <i>Orbiculiformella</i> ? <i>trispina</i> s.l. (Yeh), <i>Orbiculiformella</i> sp., <i>Palaeosaturmalis</i> sp., <i>Parahsuum</i> <i>simplum</i> , <i>Parahsuum vizcainoense</i> , <i>Praeconocaryomma</i> sp. cf. <i>sarahae</i> , <i>Thurstonia</i> sp., <i>Spumellaria</i> gen. sp. indet.	Early Jurassic (Pliensbachian) (Cordey and Struik 1996, Orchard et al. 2001)	Early Jurassic (Early Pliensbachian)	Interval from the middle part of the <i>Canutus tipperi</i> – <i>Katroma clara</i> Zone to the base of the <i>Gigi fustis</i> – <i>Lantus sixi</i> Zone (Unitary associations UA 04-12) (Carter et al. 2010).
J4 central British Columbia	Tezzeron succession Pinchi Lake NTS 093K9 UTM zone 10, 418200E 6049406N	limy siltstone 97-SCB-3602 GSC C-209935	<i>Emiluvia</i> ? sp. A, <i>Hsuum lucidum</i> , <i>Paronaella grahamensis</i> , <i>Praeconocaryomma decora</i> gr., <i>Praeparvicingula tiellensis</i>	Early Jurassic (Toarcian) (Struik et al. 2001, Orchard et al. 2001)	Early Jurassic (Middle - Late Toarcian)	Interval represented by the <i>Elodium pessagno</i> – <i>Hexasaturmalis</i> <i>hexagonus</i> Zone (Carter et al. 2010)
J5 northern British Columbia	French Range Little Dease Lake NTS 104J09 UTM zone 10, 419000E 6508000N	siliceous argillite MMI99-34-12	<i>Parahsuum izeense</i> , <i>Orbiculiformella</i> ? <i>trispina</i> s.l., <i>Praeconocaryomma</i> sp. cf. <i>sarahae</i> , <i>Praeconocaryomma</i> sp., <i>Thurstonia</i> sp.	Early Jurassic (Pliensbachian- Toarcian) (Mihalynuk et al. 2004)	Early Jurassic (Pliensbachian - Early Toarcian)	Co-occurrence of <i>Parahsuum izeense</i> and <i>Thurstonia</i> (Carter et al. 2010, O'Dogherty et al. 2009).
J6 Yukon	Teslin Plateau Mount Bryde NTS 105C03 UTM zone 10, 599028E 6676847N	siliceous argillite interbedded with sandstone 90FC-56-6 GSC C-177569	<i>Bipedis</i> sp., <i>Broctus</i> sp., <i>Canoptum</i> <i>anulatum</i> , <i>Canoptum</i> sp., <i>Hagiastrum majusculum</i> , <i>Homoeoparonaella</i> sp., <i>Lantus sixi</i> , <i>Napora cerromesaensis</i> , <i>Pantanellium cumshewaense</i> , <i>Parahsuum izeense</i> , <i>Praeconocaryomma</i> ? sp. cf. <i>yakounensis</i> , <i>Thurstonia</i> sp., <i>Wrangellium</i> sp.	Early Jurassic (Pliensbachian- Early Toarcian) (Cordey et al. 1991)	Early Jurassic (late Early Pliensbachian - Late Pliensbachian)	Interval from the base of the <i>Gigi fustis</i> – <i>Lantus</i> <i>sixi</i> Zone to the middle part of the <i>Eucyrtidiellum</i> <i>nagaiae</i> – <i>Praeparvicingula tiellensis</i> Zone (Unitary associations UA 12-22; Carter et al. 2010)
J7 Yukon	Teslin Plateau Mount Bryde NTS 105C03 UTM zone 10, 600094E 6673025N	black radiolarian chert 90FC-63-2 GSC C-177580	<i>Beatricea</i> ? <i>argescens</i> , <i>Canoptum</i> sp. cf. <i>anulatum</i> , <i>Canoptum</i> sp., <i>Praeconocaryomma</i> sp. cf. <i>immodica</i> , <i>Wrangellium</i> sp.	Early Jurassic (Sinemurian- Toarcian) (Cordey et al. 1991)	Early Jurassic (Late Sinemurian - Late Pliensbachian)	Co-occurrence of <i>Beatricea</i> and <i>Wrangellium</i> (O'Dogherty et al. 2009)
J8 Yukon	Teslin Plateau Mount Bryde NTS 105C03 UTM zone 10, 600094E 6673025N	dark gray radiolarian chert 90FC-63-9 GSC C-177587	<i>Beatricea</i> ? <i>argescens</i> , <i>Bipedis</i> sp., <i>Canoptum</i> sp. cf. <i>dixonii</i> , <i>Gorgansium</i> sp., <i>Pantanellium</i> sp., <i>Parahsuum</i> sp., <i>Praeconocaryomma</i> sp., <i>Wrangellium</i> sp.	Early Jurassic (Sinemurian- Toarcian) (Cordey et al. 1991)	Early Jurassic (Late Sinemurian - Late Pliensbachian)	Co-occurrence of <i>Beatricea</i> , <i>Bipedis</i> , and <i>Wrangellium</i> (O'Dogherty et al. 2009)

759 **Figure captions**

760 Figure 1 (colour online and printed). Paleozoic to early Mesozoic terranes of the Canadian
761 Cordillera and location of the Cache Creek Terrane. Modified from Piercey and Colpron (2009).

762
763 Figure 2. Geographic location of Jurassic radiolarian assemblages from the Cache Creek Terrane
764 (J1 to J8, Table 1). Black frame: Fig. 3a (type locality of the terrane).

765
766 Figure 3. a: Distribution of Paleozoic and Mesozoic rock units in the type locality of the Cache
767 Creek Terrane and position of the study area for locality J1 (Fig. 2). Geology from Monger
768 (1985). b: Geological map of the Pavilion area and location of the Early Jurassic radiolarian
769 sample NEO-R2. Geology from Monger and McMillan (1984), Mortimer (1987), and Cordey et
770 al. (1987).

771
772 Figure 4. Synthetic lithostratigraphic successions of the Cache Creek Terrane in its type locality
773 (southern British Columbia). The locality numbers (C-) refer to the Geological Survey of Canada
774 database and the radiolarian localities from Cordey (1998). Black lines (eastern belt): age of
775 blocks (Cache Creek mélange). Conodont data from Orchard (1981, 1984), Beyers and Orchard
776 (1989, 1991); fusulinid data from Monger and Ross (1971). Geological time scale from Cohen et
777 al. (2013). G: Guadalupian; L: Lopingian. LO: Lower.

778
779 Figure 5. Early Jurassic radiolarians from the Cache Creek Terrane. For each picture: taxon,
780 sample, locality (Table 1), length of scale bar. 1. *Thurstonia* sp., NEO-R2, J1, 150 µm. White
781 arrows point to fifth and sixth spines. 2. *Thurstonia?* sp., NEO-R2, J1, 170 µm. 3-7: *Thurstonia*
782 sp.; 3-5: 90FC-56-6, J6, 160 µm; 6: MMI99-34-12, J5, 110 µm; 7: 90FC-56-6, J6, 180 µm. White

783 arrows point to sixth spine. 8-9. *Spumellaria* gen. sp. indet., 95FC-21-4, J3, 165 and 140 μ m. 10.
 784 *Pantanellium cumshewaense* Pessagno & Blome, 90FC-56-6, J6, 110 μ m. 11-12. *Trillus* spp.,
 785 NEO-R2, J1, 120 μ m. 13. *Zartus* sp., NEO-R2, J1, 115 μ m. 14. *Charlottea* sp., 95FC-21-4, J3,
 786 115 μ m. 15. *Palaeosaturnalis* sp., 95FC-21-4, J3, 160 μ m. 16. *Hagiastrum majusculum* Whalen
 787 & Carter, 90FC-56-6, J6, 170 μ m. 17. *Homoeoparonaella* sp. cf. *reciproqua* Carter, NEO-R2, J1,
 788 220 μ m. 18. *Homoeoparonaella* sp., 90FC-56-6, J6, 140 μ m. 19. *Orbiculiformella* sp., 95FC-21-
 789 4, J3, 170 μ m. 20. *Orbiculiformella?* *trispina* s.l. (Yeh), 95FC-21-4, J3, 150 μ m. 21. *Beatricea?*
 790 *argescens* Cordey, 90FC-63-2, J7, 160 μ m. 22. *Praeconocaryomma?* sp. cf. *yakounensis* Carter,
 791 90FC-56-6, J6, 150 μ m. 23-24. *Praeconocaryomma* sp. cf. *sarahae* Carter; 23: 95FC-21-4, J3,
 792 130 μ m; 24: MMI99-34-12, J5, 160 μ m.

793
 794 Figure 6. Early Jurassic radiolarians from the Cache Creek Terrane. For each picture: taxon,
 795 sample, locality (Table 1), length of scale bar. 1. *Lantus sixi* Yeh, 90FC-56-6, J6, 110 μ m. 2.
 796 *Lantus* sp. cf. *praeobesus* Carter, 95FC-21-4, J3, 110 μ m. 3. *Broctus* sp., 95FC-21-4, J3, 100 μ m.
 797 4. *Broctus* sp., 90FC-56-6, J6, 130 μ m. 5. *Xiphostylus?* sp., NEO-R2, J1, 140 μ m. 6. *Katroma* sp.
 798 cf. *elongata* Carter, 95FC-21-4, J3, 150 μ m. 7. *Parahsuum vizcainoense* Whalen & Carter, 95FC-
 799 21-4, J3, 90 μ m. 8. *Parahsuum izeense* (Pessagno & Whalen), 90FC-56-6, J6, 140 μ m. 9.
 800 *Canoptum* sp., 95FC-21-4, J3, 100 μ m. 10. *Canoptum rugosum* Pessagno & Poisson, 95FC-21-4,
 801 J3, 90 μ m. 11-12. *Canoptum* spp., 90FC-56-6, J6, 120 μ m. 13. *Broctus?* sp., 95FC-21-4, J3, 110
 802 μ m. 14. *Canoptum* sp. cf. *anulatum* Pessagno & Poisson, 90FC-63-2, J7, 120 μ m. 15. *Canoptum*
 803 sp. cf. *dixonii* Pessagno & Whalen, 95FC-21-4, J3, 120 μ m. 16. *Atalantria* sp., 95FC-21-4, J3, 120
 804 μ m. 17. *Laxtorum* sp., 95FC-21-4, J3, 130 μ m. 18. *Wrangellium* sp., 90FC-56-6, J6, 120 μ m. 19.
 805 *Hsuum* sp., NEO-R2, J1, 110 μ m. 20. *Archaeodictyomitra* sp., NEO-R2, J1, 130 μ m. 21. *Bipedis*
 806 sp., 90FC-56-6, J6, 110 μ m. 22. *Bipedis japonicus* Hori, 95FC-21-4, J3, 130 μ m. 23. *Napora*
 807 *cerromesaensis* Pessagno, Whalen & Yeh, 90FC-56-6, J6, 105 μ m.

808

809 Figure 7. Synthesis of the youngest Jurassic radiolarian ages of the Cache Creek Terrane.

810 Previous age determinations: J1: Cordey et al. (1987), Cordey (1998); J2: Read (1993), Cordey

811 (unpub. data); J3: Cordey and Struik (1996), Orchard et al. (2001); J4: Struik et al. (2001),

812 Orchard et al. (2001) ; J5 : Mihalynuk et al. (2004) ; J6-J8 : Cordey et al. (1991).

813

814 Figure 8. Radiolarian age ranges and correlations of youngest Cache Creek strata in British

815 Columbia and Yukon. The hatched band materializes the youngest common age range of

816 siliceous rocks (radiolarian cherts and siliceous argillites); limy siltstones at J4 are not included in

817 the correlation. The gray band shows the hypothetical age range of the youngest siliceous

818 argillites overlying the youngest well-dated radiolarian cherts (J3, Early Pliensbachian). The

819 oblique line represents the maximum age difference of the youngest well-dated hemipelagic

820 rocks (siliceous argillites) between southern British Columbia (J1) and Yukon (J6); this interval

821 (late Early Pliensbachian to Early Toarcian) is ~8 m.y. (~188–180 Ma, Cohen et al. 2013).

822

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8