Early Triassic peritidal carbonate sedimentation on a Panthalassan seamount : The Jesmond succession, Cache Creek Terrane, British Columbia, Canada

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Abstract The Jesmond succession of the Cache Creek Terrane in southern British Columbia records late Early Triassic peritidal carbonate sedimentation in a mudflat of a buildup resting upon a Panthalassan seamount. Conodont and foraminiferal biostratigraphy dates the succession as the uppermost Smithian to mid-Spathian. The study section (ca. 91 m thick) is dominated by fine-grained carbonates and organized into at least twelve shallowing-upward cycles, each consisting of shallow subtidal facies and overlying intertidal facies. The former includes peloidal and skeletal limestones, flat-pebble conglomerates, stromatolitic bindstones, and oolitic grainstone, whereas the latter consists mainly of dolomicrite. The scarcity of skeletal debris, prevalence of microbialite, and intermittent intercalation of flat-pebble conglomerate facies imply environmentally harsh conditions in the mudflat. The study section also records a rapid sea-level fall near the Smithian-Spathian boundary followed by a gradual sea-level rise in the early to mid-Spathian.

Keywords late Early Triassic, peritidal carbonates, seamount, Cache Creek Terrane Panthalassa Ocean, Canada

Introduction

The Permian-Triassic boundary (~252.3 Ma: Mundil et al. 2010) is known as an interval of the most profound collapse of marine and terrestrial ecosystems and drastic environmental changes in the Phanerozoic (Erwin 2006). Approximately 90 % of marine and terrestrial species became extinct at the end of Permian, resulting in the largest biotic turnover of the Phanerozoic (Sepkoski 1984). The recovery of the severely devastated marine ecosystems was much delayed in comparison with other major mass extinction events (Erwin 2006). It was early Middle Triassic when the marine ecosystems fully recovered (Payne et al. 2004; Pruss et al. 2005; Lehrmann et al. 2006), though unique and exceptionally diverse earliest Triassic faunas are reported (e.g., central Oman: Krystyn et al., 2003; South China: Hautmann et al., 2011 in press). Concurrent with the biotic crisis, many shallow-marine shelf seas suffered from euxinic to anoxic conditions in the Permian-Triassic boundary interval (e.g., Wignall and Hallam 1992; Wignall et al. 2005; Cao et al. 2009; Grasby and Beauchmap 2009; Bond and Wignall 2010), and unstable conditions continued throughout Early Triassic time (Payne et al. 2004).

A great deal of geological, paleontological, and geochemical work on the Permian-Triassic biotic turnover and environmental changes has been undertaken mainly in shallow-marine carbonate and siliciclastic sections on the Tethyan shelf basins and in a few, epicontinental seas at the Pangean margin in tropical to high latitudinal zones (e.g., Schubert and Bottjer 1995; Twitchett and Wignall 1996; Twitchett 1999, 2007; Payne et al. 2004; Payne 2005; Brayard et al. 2006; Shen et al. 2006; Angiolini et al. 2007; Galfetti et al. 2007a, 2007b, 2008; Lindström and McLaughlin 2007; Tong et al. 2007a, 2007b; Brühwiler et al. 2008; Korte and Kozur 2010). These studies contributed much to an increase of our knowledge on biotic and environmental crisis at the Permian-Triassic boundary and its aftermath during the Early Triassic time.

However, as suggested by Algeo et al. (2010), paleoenvironmental conditions in the Permian-Triassic Panthalassa Ocean, which was ~50% larger than the modern Pacific basin and covered an entire hemisphere of the Earth’s surface (Kiessling et al. 1999), have received little attention. This is chiefly due to the scarcity of reliable sections from this region. As the vast majority of the Permian-Triassic Panthalassan seafloor was subducted, only a few of seamounts (or oceanic plateaus) and associated sediments have survived as exotic slivers and blocks within accreted terranes of the circum-Pacific region (North America: Tozer 1982; Monger et al. 1991; Japan: Isozaki 1997; New Zealand: Aita and Spörli 2007), among which only a few have received detailed stratigraphic study to date (e.g., Permo-Triassic Kamura Formation, Takachiho, southwest Japan: Koike 1996; Sano and Nakashima 1997; Musashi et al. 2001; Payne et al. 2007; Horacek et al. 2009). The sedimentation, marine ecosystems, seawater geochemistry, sea levels, and climates at the Permian-Triassic boundary and during the Early Triassic time within the mid-Panthalassa Ocean remain poorly understood.

In order to gain insights into late Early Triassic (Smithian-Spathian) environmental conditions within the Panthalassa Ocean, we present the sedimentary facies and age of an upper Lower Triassic carbonate succession of the Cache Creek Terrane that is reconstructed as a shallow-marine buildup at the top of a seamount (or an oceanic plateau) in the mid-Panthalassan realm. Chosen for study is the Jesmond succession of the Cache Creek Terrane in the Marble Range of southern British Columbia, western Canada (Fig. 1). We present the second example of a stratigraphic and sedimentological study of the Lower Triassic carbonates on a mid-oceanic seamount in the Panthalassa Ocean: the first example from southwest Japan (Kamura Formation: Sano and Nakashima 1997).

Geologic setting

The Cache Creek Terrane is a subduction-generated accretionary terrane of the Canadian Cordillera, allochthonous to the western margin of North America (Monger et al. 1991). It occupies the axial zone of the Canadian Cordillera and underlies large areas of its Intermontane Belt, extending from southernmost Yukon Territory to southern British Columbia (Fig. 1; Gabrielse et al. 1991). As a whole, the Cache Creek Terrane comprises an oceanic assemblage containing Mississippian to Upper Triassic carbonates, Pennsylvanian to Jurassic radiolarian ribbon-chert and basaltic rocks, and Permian to Middle Jurassic mudstone and graywacke, along with ultramafic rocks and blueschist (Monger et al. 1991; Struik et al. 2001; Orchard et al. 2001). All the terrane rocks have been severely sheared and contorted, and their stratigraphic continuity is commonly disrupted. The terrane was formed as an accretionary complex during the Early to Middle Jurassic, comprising structurally stacked thrust sheets of oceanic crusts, oceanic plateaus, and seamounts with shallow-marine limestone and deep-water chert, and trench-fill terrigenous sediments, which are tectonically sitting upon possibly arc-derived clastic sediments (Struik et al. 2001).

The Cache Creek carbonate rocks consist chiefly of Mississippian to Triassic shallow-marine limestones (e.g., Pope Succession in central British Columbia: Sano and Rui 2001). Commonly associated with basaltic rocks, these limestones are interpreted as atoll-type carbonates that accumulated on the tops of isolated mid-oceanic seamounts (Monger 1977; Tardy et al. 2001; Sano and Rui 2001). Fusulinids, conodonts, radiolarians, and corals show that the Cache Creek oceanic rocks remained located within the Panthalassa Ocean far from the North American Craton during Mississippian to Triassic time (Orchard et al. 2001).

Cache Creek Terrane rocks in southern British Columbia, including the type area of the terrane, are best exposed in the Cache Creek-Clinton-Jesmond area and are subdivided into NNW-SSE-trending eastern, central, and western belts (Fig. 1: Monger et al. 1991). The eastern belt comprises a tectonic mélange of intensely sheared Permian to Triassic siliceous argillites containing isolated blocks of pillow lava, gabbro, serpentinite, shallow-marine limestone, and ribbon-chert, informally named “Mr. Mike’s Melange” (Shannon 1981; Orchard and Danner 1991; Price and Monger 2000). The central belt consists dominantly of massive, light-gray shallow-marine skeletal limestones of largely Permian to Lower Triassic age with basaltic rocks and dolomitic facies (Trettin 1980) and minor Triassic limestones (Orchard 1981; Beyers and Orchard 1989, 1991). Limestones of the central belt are known to yield fusulinids of a Tethyan affinity (Thompson and Wheeler 1942; Monger and Ross 1971; Orchard and Danner 1991). The western belt also comprises a tectonic mélange of sheared argillites containing isolated blocks of ribbon-chert, limestone, and basaltic rocks, with minor graywacke. Cordey et al. (1987) extracted Jurassic radiolarians from the sheared argillites of the western belt and considered the timing of its accretion as the Jurassic.

Lower to Upper Triassic carbonates, though thinner and less conspicuous than their Permian counterparts, occur at several localities of the central belt of the Cache Creek Terrane in the Marble Range (Monger 1981; Orchard 1981; Orchard and Beyers 1988; Beyers and Orchard 1989, 1991; Monger and McMillan 1989). Beyers and Orchard (1989, 1991) described the upper Lower Triassic (Smithian to Spathian) conodont faunas from the carbonates at several localities in our study section. However, we also examined conodonts in the present study, because it is difficult to precisely relate the stratigraphic levels of the conodont-yielding samples by Beyers and Orchards (1989, 1991) to the stratigraphy measured in this study.

The examined carbonates crop out in a series of exposures along the Jesmond Road at the northern end of the Marble Range, about 72 km northwest of the town of Cache Creek (Fig. 2). We informally designate these Lower Triassic carbonates as the "Jesmond succession." Rocks of the Jesmond succession strike north-south to north-northwest-south-southeast and gently dip to the east. The Jesmond succession is underlain by polymictic limestone conglomerate, dolomite, and Middle to Upper Permian dark gray limestone (Fig. 2: Beyers and Orchard 1989, 1991).

Stratigraphy and age

Stratigraphy

The stratigraphy of the Jesmond succession was measured on a 1:100 scale at outcrops JE 1 to 14 and JE 17 along the Jesmond Road (Fig. 2). The lithology of the entire Jesmond succession was drawn by compilation of these measured sections.

The Jesmond succession consists almost entirely of carbonate rocks, mainly light gray and locally dark gray limestones and dolomites, with minor calcareous shale (Fig. 3). The carbonate rocks are usually bedded. Thickness of the beds range from a few to several tens of centimeters, and the bedding surfaces generally are wavy and undulating. Dolomite facies often occur as thick beds up to a few meters in thickness.

The Jesmond succession attains approximately 91 m in thickness and is lithologically divided into three units (Fig. 3). The lower unit is dominated by thick-bedded, light-gray lime-mudstone facies and contains thin calcareous shale beds in the upper part. The calcareous shale is irregularly mottled with pale pink to greenish gray, very fine-grained and clayey, fissile, and occurs as thin (less than 20 cm), lenticular beds within fenestral-laminated lime-mudstone facies of the lower unit (Fig. 4). The top and bottom surfaces of the calcareous shale beds are irregularly knobby due to intense stylolitization. The over- and underlying lime-mudstones are also pale pink- and greenish-mottled and include a lumpy to micro-nodular structure. The middle unit consists of thick-bedded, light gray, fine-grained dolomite (dolomicrite) with intermittent skeletal limestones, stromatolitic and fenestral-laminated bindstones, flat-pebble conglomerates at several levels, and oolitic grainstones at the top. The upper unit comprises mainly thick-bedded peloidal facies with subordinate skeletal limestones and flat-pebble conglomerates.

Age

Dating of the Jesmond succession is based upon the conodonts and foraminifers. We processed 42 samples of the Jesmond carbonates for conodonts. Age-diagnostic conodonts were extracted from 5 samples of the lower and middle units (Fig. 3).

Conodonts detected from the lower unit (JE 2-1 and 2-5 in Fig. 3) include elements of *Pachycladina obliqua* Staesche, *Parapachycladina peculiaris* (Zhang), and *Pachycladina* sp. (Fig. 5). These are characteristic of a Smithian assemblage described from the shallow-water limestone in the Thaynes Formation of Utah (Solien 1979), Guangxi Province, China (Zhang and Yang 1991), and Israel (Hirsch 1975). The limestone of the middle unit (JE 11-1, 11-5, and 12-2 in Fig. 3) yields P elements of *Triassospathodus homeri* (Bender), *T. symmetricus* (Orchard), and *Neospathodus* sp. (Fig. 5), collectively assigned to the *T. homeri* group. These conodonts are widespread, being known from Spathian limestones in, for example, Chios Island, Greece (Bender 1970), Salt Range (Sweet 1970), Nevada (Orchard 1994), Oman (Orchard 1995), Romania (Orchard et al. 2007a), and China (Orchard et al. 2007b). The conodont assemblage indicates an upper Smithian to Spathian age for the Jesmond succession. The Smithian-Spathian boundary is marked by the transition from the late Smithian *Pachycladina* Assemblage to the early Spathian *Neospathodus* Assemblage (Fig. 3).

The results of our conodont biostratigraphic analysis are in agreement with the results of previous studies (Orchard and Beyers 1988; Beyers and Orchard 1991). Beyers and Orchard (1991) recognized two conodont faunas in their “sect. 4” which corresponds to the Jesmond succession. The older fauna (their Fauna 5), collected 13 m above the base of “sect. 4” , includes *“Lonchodina” nevadensis* (Müller) and *Pachicladina obliqua* (Staesche), which are indicative of Smithian age. The younger fauna (their Fauna 7), collected in the stratigraphic interval from 10.5 m to 64 m above the base of “sect. 4” and also near the fire-lookout (Fig. 2), cons

Mists of *Neospathodus triangularis* (Bender) and *Triassospathodus homeri* (Bender), which are indicative of Spathian age.

Biostratigraphically significant foraminifers were found at four levels of the middle and upper units (Fig. 3). These include three genera and three species (Fig. 6) that have been reported from many shallow-marine platforms of the Tethys Ocean (Rettori, 1995). *Hoyenella sinensis* (Ho) and *Meandrospira pusilla* (Ho) are characteristic species of the *H. sinensis-M. cheni* Assemblage (Maurer et al. 2008) and have been reported from many carbonate successions of the Tethyan realm from Sicily to China (Transdanubian Central Range: Oravecz-Scheffer 1987; Internal Hellenides, Greece: Baroz et al., 1990; Hydra, Greece: Rettori et al. 1994; northern United Arab Emirates: Maurer et al. 2008; South China: Ho 1959). This assemblage is considered to be indicative of Early Triassic age (Maurer et al. 2008). Márquez (2005) showed the markedly abundant occurrence of *M. pusilla* in the lower part of the Spathian. *Pilammina praedensa* (Urošević) is reported from the Spathian of east Serbia (Urošević 1988).

Microfacies of the Jesmond carbonate rocks

For the microfacies analysis, we collected oriented samples of the lower unit at outcrops JE 17 and JE 1 to 3 (in stratigraphically ascending order), middle unit at outcrops JE 4 to JE 12, and upper unit at outcrops JE 13 and 14 (Fig. 2). Approximately 250 thin-sections (ca. 50×70 mm size) were examined.

Microfacies description

Jesmond succession carbonate rocks are mostly fine-grained and dominated by peloidal limestone and dolomite (Fig. 3). These fine-grained facies contains multiple, thin and densely spaced, spar-filled, laterally continuous laminoid-type fenestrae. No skeletal debris are discernible in the field, except for microgastropods scattered in lime-mudstone facies (Fig. 7A). Bioturbation is recognized only at a few stratigraphic levels as burrows a few millimeters in diameter.

Flat-pebble conglomerate in the middle and upper units is the coarser-grained facies of the Jesmond succession (Fig. 3). It consists of flat-lying, angular, elongated and tabular-shaped pebble-sized limestone debris, with well-defined top and bottom surfaces (Figs. 7B, 8A-B), and often occur in a close association with dark gray and carbonaceous stromatolitic peloidal bindstone rich in laminoid to tabular, bedding-parallel fenestrae (Figs. 7C-D, 8C-D). Oolitic grainstone occurs as a 0.5-m-thick bed at the top of the middle unit (Fig. 3).

We classified the Jesmond carbonate rocks into six microfacies types (Fig. 3; Table 1). They are peloidal limestone, including peloidal bindstone of various types, dolomite, skeletal limestone, flat-pebble conglomerate, microproblematica-rich facies, and oolitic grainstone. The former two types are abundant, while the latter four are minor.

Peloidal limestone facies

Peloidal limestones include peloidal lime-mudstone, wackestone, packstone, grainstone and various types of bindstone (Table 1). Peloidal lime-mudstone and wackestone occur as thin layers (less than 10 millimeters) alternating with peloidal grainstone (Fig. 9A). The lime-mudstone layers have poorly defined top surfaces. Rocks of this microfacies type contain scattered peloids with ostracods and microproblematica in the predominant lime-mud matrix. Local intercalation of thin (0.2 to 1 mm thick), laterally discrete patches and lenses of densely packed and micritized peloidal particles is recognized. Peloidal grainstone consists mostly of well-sorted and fine-grained peloidal grains, most commonly 200 to 300 μm in diameter (Fig. 9B), occasionally with larger aggregated peloidal grains, intraclasts, microgastropods, bivalves, and ostracods. The intraclasts are locally flat with rounded edges and aligned nearly parallel to bedding surfaces. Peloidal packstone is characterized by dense accumulation of fine-grained peloidal particles with subordinate microgastropods, bivalves, ostracods, smaller foraminifers, and microproblematica. These particles are cemented by microspar and embedded in a sparse matrix of micrite. Short, irregularly twisted and curved, laminoid-type fenestrae are locally abundant in this facies (Fig. 10A).

Several textural varieties of the peloidal bindstone, including layered, domal, and stromatolitic structures, are formed by accumulation of presumably microbially bound and clotted peloidal particles, yielding peloidal bindstone (Fig. 9C-D, F; Table 1). Peloidal bindstone with laminated structures is often carbonaceous (Figs. 7D, 8C) and consists of thin (a few to several millimeters thick), alternating layers of densely micritized, microbial-peloidal micritic mats and peloidal grainstone-packstone (Fig. 9C-D). These micritic layers and mats are gently undulated and often have a small, low-relief domal structure in which peloidal particles are densely packed and interconnected by micrite and skeletal debris are incorporated (Fig. 9E). Bedding-parallel laminoid- to sheet-shaped fenestrae are common. Stromatolitic bindstone is characterized by columnar to domal growth of thin alternation of microbial peloidal bindstone layers and dilute micrite to microsparitic layers, including abundant bedding-parallel lenticular-shaped fenestrae (Figs. 8D, 9F). These alternating layers are a few hundreds of microns thick and locally crinkled.

Dolomite facies

Dolomite facies mostly comprises very fine-grained dolomite composed mainly of light brown, anhedral dolomite crystals (Fig. 10B). They are mostly equant, commonly less than 10 μm in size, and exhibit an equigranular and xenotopic fabric. An inequigranular fabric composed of coarser dolomite grains, usually 50 μm in size, is recognized as a minor variety of this facies. Poorly defined parallel laminae are present (Fig. 10B). Faint vestiges of peloidal grains, gastropods, bivalves, ostracods, and microproblematica debris are discerned in some samples.

Skeletal limestone facies

Skeletal limestones are recognized at a few stratigraphic levels of the middle and upper units of the Jesmond succession (Fig. 3; Table 1). Skeletal grains seen in the Jesmond succession include microgastropods, bivalves, ostracods, crinoids, and smaller foraminifers (Fig. 3). Of these skeletal components, the former two are abundant.

Microgastropods are particularly widespread in the succession (Fig. 3). Their shells range in size from 0.5 or less up to 5 mm, most commonly 1 to 2 mm, and are invariably thin and sometimes covered by thin micritic envelopes (Fig. 10C). Bivalve shells are also small and thin, and mostly fragmented (Fig. 10C-D).

The lowest stratigraphic occurrence of crinoids is recognized in the upper part of the middle unit (Fig. 3). Crinoid oscicles are fine-grained, commonly less than 2 mm in diameter, and occurs along with microgastropods and bivalves in skeletal limestones (Fig. 10D).

Smaller foraminifers, including encrusting forms, are recognized at several levels of the succession, but in most cases are poorly preserved (Fig. 6). Ostracods are common throughout the entire succession (Fig. 3).

Microgastropods and bivalves are dominant components of skeletal limestones, which usually have wackestone and packstone fabrics with a matrix of poorly sorted peloidal lime-mud and silt (Fig. 10C-D). This type of microfacies also contains smaller amounts of crinoids, ostracods, and small foraminifers. These skeletal debris are locally cemented by blocky spars and also nearly isopachous rims of short, bladed to pyramidal calcite.

Flat-pebble conglomerate facies

Flat-pebble conglomerates consist of elongated tabular-shaped limestone clasts set in a poorly sorted lime-mud and silt matrix and cemented by blocky spar along with minor skeletal debris (Fig. 10E). The limestone clasts are poorly sorted, ranging in size from minute clasts (<0.5 mm) up to clasts 1 cm thick and 4 cm long. They also widely vary in shape, including flat and tabular, elongated, lenticular, and rectangular to blocky shapes. Their edges are usually sharp and outlines are smooth, but clasts with rounded edges and irregularly rugged outlines are also seen. The limestone clasts are oriented nearly parallel to bedding surfaces and slightly imbricated in many cases (Fig. 10E). Randomly oriented clasts are, however, also recognized, where the rocks include finer-grained, subrounded intraclasts and the lime-mud matrix.

The clast association of flat-pebble conglomerates is polymictic. Dominant clast types include peloidal lime-mudstone, bivalve-bearing peloidal wackestone, microproblematica-bearing wackestone, peloidal bindstone, and fenestral lime-mudstone. Minor clasts of volcanic rocks are also recognized (Fig. 8B).

Bottom surfaces of flat-pebble conglomerate beds are sharp both in the field and under the microscope (Figs. 7B) and are locally erosional, clearly cutting laminae of underlying beds (Fig. 10F). Top surfaces are usually flat and sharp (Fig. 8B), or gradational where the limestone clasts are small and scattered in a dominant micritic matrix.

Limestone conglomerates are locally associated with flat-pebble conglomerates.

They consist of poorly sorted, subangular to subrounded, poorly oriented to unoriented, often densely packed limestone clasts randomly set in the poorly sorted lime-mud and silt matrix with minor skeletal debris and are cemented by isopachous rims of bladed to dogtooth spars. The limestone clasts range in size from 1 to 3 mm, smaller than those of flat-pebble conglomerates, and are polymictic, dominated by lime-mudstone facies.

Microproblematica-rich facies

We recognized microproblematica of at least three forms, termed A, B, and C, in the Jesmond succession carbonates. Type A is far more common than the types B and C.

Microproblematicum A varies in morphology, including thin, gently curved and twisted tubular (Fig. 11A); oval, spherical to subspherical (Fig. 11C); thick, barrel- to cylindrical; and irregularly bifurcated to digitate forms with knobby surfaces. The tubular to cylindrical form partly has poorly defined segmentation and constriction (Fig. 11A). Microproblematicum A has coarse blocky spar-filled interiors and thin, micritic outer walls.

Microproblematicum B has a bulbous to massive shape and is much larger than microproblematica A and C (Fig. 11B). The outline is irregularly digitate, rugged and knobby, and has small, protruding humps. The outer wall is thin and micritized. The interior is filled with blocky spar and includes much smaller, spar-filled bulbous to irregularly digitate forms with thin micritic outer walls, which are densely packed and interconnected to form small clusters (Fig. 11B).

Microproblematicum C has short and thick, barrel to cylindrical shapes with spar-filled interiors and micritic outer walls (Fig. 11C). Its outline is usually smooth. Micritization is seen along the periphery. The interior includes tiny filamentous tubes (Fig. 11C).

These microproblematica occur as scattered debris in various facies of the Jesmond succession, but also form grainstone, packstone, and bindstones in the middle to upper units (Fig. 3; Table 1). Microproblematicum A grainstone-packstone consists exclusively of various shapes of microproblematicum A cemented by blocky spar and locally by micrite cements (Fig. 11D). Microproblematicum A bindstones form thin micritic layers that are laterally discrete, gently undulating, and locally domal. Bedding-parallel and elongated, laminoid-shaped fenestrae locally containing the vadose silt are common.

Oolitic grainstone facies

Oolitic grainstone chiefly comprises ooids with subordinate intraclasts and peloids (Fig. 11E). Ooids are moderately to poorly sorted, and up to 1.5 mm in diameter, occasionally abraded and broken, and irregularly coated by micrite presumably of a microbial origin. Intraclasts are rounded to subrounded and 2 to 6 mm in size, and consist of oolitic packstone, fine peloidal packstone, and stromatolitic bindstone. All the particles of this microfacies type have a grain-supported fabric and are cemented by nearly equigranular microspar. A micritic matrix is locally present.

Discussion

Depositional conditions

The Lower Triassic carbonate rocks of the Jesmond succession contain no coarse terrigenous clastic grains. Also, no terrigenous clastic units that grade laterally or vertically into the Jesmond succession are known to date. Thus, the succession is thought to have accumulated in a mid-oceanic setting beyond the reach of land-derived materials.

The Jesmond succession crop out underlain by the Middle to Upper Permian carbonate rocks (Fig. 2), which comprise a part of the dominantly Permian carbonate rock mass with basaltic rocks of the Cache Creek Terrane in southern British Columbia (Fig. 1). We consider that the deposition of the Jesmond carbonates successively occurred following the Middle to Late Permian carbonate sedimentation in a mid-oceanic environment.

With an emphasis upon these sedimentological and stratigraphic features, following the estimated paleogeographic setting of the Mississippian to Triassic carbonate rocks of the Cache Creek Terrane (Monger 1977; Struik et al. 2001; Tardy et al. 2001; Sano and Rui 2001), we consider the Lower Triassic carbonate rocks of the Jesmond succession as a carbonate buildup at the top of an isolated mid-oceanic seamount or oceanic plateau (Jesmond buildup). On the basis of the paleobiogeographic reconstruction (Orchard et al. 2001), the Jesmond buildup was located in the Panthalassa Ocean, far removed from the cratonic margin of North America.

Based upon the dominance of fine-grained peloidal facies containing stromatolitic bindstone, and microbial peloidal bindstone and related micritic mats and laminae, and fine-grained dolomite (dolomicrite) facies, we interpret the Jesmond carbonate rocks to have accumulated in a peritidal mudflat (Table 1) (Wilson 1975; Demicco and Hardie 1994; Flügel 2004). The prevalence of fenestrae in the succession agrees with a peritidal origin. Oolitic grainstone at the top of the middle unit represents a sand bar facies formed during a temporary shift of the depositional site to an open subtidal setting. The scarcity of vertical burrows indicates low infaunal activity, probably due to local, environmentally stressed conditions in the peritidal setting. Also, the general scarcity of benthic faunas in the aftermath of the end-Permian biotic crisis may have been a factor for the low diversity assemblage (Twitchett 1999).

The dominance of fine-grained peloidal lime-mudstone facies indicates low-energy conditions of the peritidal mudflat of the Jesmond buildup. The quiet conditions were, however, intermittently disturbed by storms, resulting in deposition of flat-pebble conglomerates at several levels of the middle and upper units, though non-storm origins of this facies are also possible (Myrow et al. 2004). Flat-pebble conglomerate is a common facies especially on Cambro-Ordovician carbonate platforms, but is much rarer in younger sediments (Sepkoski 1991; Kuznetzov and Suchy 1992; Friedman 1994; Wignall and Twitchett 1999) before exhibiting an “anachronistic” resurgence in Lower Triassic carbonate platform successions (Wignall and Twitchett 1999; Lehrmann et al.

2001; Pruss et al. 2005, 2006). The deposition of flat-pebble conglomerates on the Jesmond buildup is thought to be related to the limited infaunal bioturbation that reflects the Early Triassic stressed environmental conditions that followed the end-Permian crisis (Wignall and Twitchett 1999; Pruss et al. 2005, 2006). The enhanced storm activity on the Jesmond buildup may have been induced by warmer climatic conditions as suggested by Kidder and Worsley (2004).

Although a few beds of the fenestral-peloidal bindstone facies in the lower part of the middle unit (lowest Spathian) are dark gray to black (Figs. 7D, 8C) and may have been moderately organic-rich prior to burial, most of the Jesmond carbonate rocks are light gray and appear to be poor in carbonaceous matter. No pyrite grains are recognized in the Jesmond succession. In addition, the Jesmond carbonates exhibit generally low contents of total organic carbon (ca. 0.15 % in average) and total sulfur (ca. 0. 05 % in average) (unpublished data by T. J. Algeo). Thus, we infer uniformly well-oxygenated conditions within the peritidal flat on the Jesmond buildup. Although shallow-water anoxic conditions are reported to persist into the Dienerian in a peri-Gondwana shelf setting (Wignall and Twitchett 2002) and into the late Smithian in the Nanpanjiang Basin of South China (Galfetti et al. 2008), the Jesmond succession provides no positive evidence for anoxia in the mid-Panthalassa Ocean during the late Early Triassic.

Calcareous shale in the lower unit is an exceptional facies within the carbonate rocks of the Jesmond succession (Fig. 3). On the basis of the irregular color-mottling and clayey facies as well as the lumpy and micro-nodular structure in the immediately over- and underlying lime-mudstone beds, the calcareous shale may possibly be of paleosol origin. We hypothesize that the stratigraphic level of the calcareous shale represents a probably short-lived episode of subaerial exposure of the Jesmond buildup near the Smithian-Spathian boundary interval.

Sea-level changes

Various microfacies types of the Jesmond succession are grouped into intertidal and shallow subtidal facies (Fig. 3). With an emphasis upon the subtidal affinity of major skeletal debris including microgastropods, bivalves, ostracods, and crinoids (e.g., Fraiser et al. 2005), we interpret rocks containing these skeletal debris as shallow subtidal facies. It comprises skeletal limestones, some peloidal limestones, flat-pebble conglomerates, microproblematica-rich limestones, and oolitic grainstone (Table 1).

On the other hand, we interpret rocks having no or very few skeletal debris as intertidal facies. It is represented dominantly by dolomite facies and subordinately by some of peloidal grainstone, mudstone, and wackestone. According to Ye and Mazzullo (1993), fine-grained dolomite (dolomicrite) is thought to have been formed by the syngenetic growth of finely crystalline dolomite in a shallow subtidal to supratidal zone under normal seawater conditions. It is noted that dolomite facies includes microgastropods, though very few. Nevertheless, no sedimentary features diagnostic of the supratidal sedimentation, including evaporitic facies, teepees, desiccation cracks (cf. McKenzie et al. 1980; Flügel 2004) are recognized in association with the dolomite facies. We favor an intertidal depositional environment for the Jesmond dolomicrite rather than a supratidal origin. As microbial-laminated carbonates, including stromatolites and microbial mats, are common facies in a supratidal flat (e.g., Demicco and Hardie 1994), we do not rule out the possibility that peloidal bindstone and related microbial-peloidal micritic mats of the Jesmond succession are supratidal sediments. However, as noted above, the no positive indicators for the supratidal sedimentation are recognized through the Jesmond succession. We presume peloidal bindstone and related microbial-peloidal micritic mats of the Jesmond succession to be an intertidal facies.

Stratigraphic distribution of the shallow subtidal and intertidal facies shows that the latter is slightly dominant over the former in the lower and middle units, while the former gradually increases up-section within the middle unit and then constitutes the larger parts of the upper unit (Fig. 3). The Jesmond succession in the whole seems to record a gradually upward-deepening sedimentation within a peritidal zone. As the Jesmond buildup rest upon a constantly subsiding mid-oceanic seamount due to the thermal subsidence of an oceanic crust, the upward-deepening sedimentation possibly resulted from a slight relative sea-level rise in late Early Triassic time. According to the recent estimation by Ovtcharova et al. (2006), this sea-level rise is considered to have occurred for approximately 1.5 Myr, the time-span of the Jesmond carbonate sedimentation from the latest Smithian to mid-Spathian.

We organized the peritidal carbonate rocks of the Jesmond succession into cyclically stacked, at least twelve shallowing-upward cycles (Fig. 3). Individual cycles range in thickness from 2 to 20 m and consists of shallow subtidal facies overlain by intertidal facies (Fig. 3). With an emphasis upon the lack of clear evidence for the supratidal sedimentation or prolonged subaerial exposure in the Jesmond succession, the amplitude of the sea-level fluctuation indicated by each of these cycles is presumably limited to a few meters. This is consistent with the absence of evidence for continental glaciation during the Early Triassic (Frakes et al. 1992). Larger amplitude sea-level fluctuations have been inferred from other Lower Triassic sections (e.g., Lehrmann et al. 2001). However, the Jesmond succession provides a probably better record of the contemporaneous eustatic fluctuation, for the Jesmond buildup rest on a tectonically stable and constantly, thermally subsiding mid-ocean seamount.

We infer a significant change of the water depths around the Smithian-Spathian boundary on the basis of the stratigraphic distribution pattern of the shallow subtidal-intertidal cycles of the Jesmond succession. Below the Smithian-Spathian boundary, cycle 2 contains a particularly thick shallow subtidal facies (Fig. 3). This suggests a sea-level highstand near the end of the Smithian. We postulate that the end-Smithian highstand was followed possibly by a short-lived episode of subaerial exposure, indicated by intercalation of thin calcareous shale beds near the Smithian-Spathian boundary. Cycles immediately above the exposure horizon are dominated by intertidal facies (cycles 4 and 5 in Fig. 3), whereas subsequent cycles consist predominantly of subtidal facies in the lower to middle Smithian section. The change in the stacking pattern of the shallow subtidal-intertidal cycles across the exposure horizon reflect an early to mid-Spathian deepening trend.

Summary

The Jesmond succession of the Cache Creek Terrane in the Marble Range of southern British Columbia records the late Early Triassic environmental conditions within a mid-oceanic realm of the Panthalassa Ocean. We examined the sedimentary facies and age of the Jesmond succession reconstructed as a shallow-marine buildup (Jesmond buildup) at the top of a Panthalassan seamount (or an oceanic plateau).

The approximately 91 m-thick succession comprises shallow subtidal facies of peloidal limestones, skeletal limestones, flat-pebble conglomerates, microproblematica-rich limestones, and oolitic grainstone and intertidal facies mainly of dolomicrite and subordinately of peloidal-microbial limestones. Discerned skeletal grains are only microgastropods, bivalves, ostracods, and crinoids, all are scarce, scattered, and small in size. Bedding-parallel fenestral voids are common thoroughout the succession. Conodonts and foraminifers date the Jesmond succession as ranging from the uppermost Smithian to the mid-Spathian.

We interpret the Jesmond succession as peritidal carbonates in a mudflat under generally quiet conditions, which was punctuated by episodic storms. The low diversity, scarcity, and small size of skeletal organisms, as well as the prevalence of microbialites and intermittent intercalation of flat-pebble conglomerate suggest persistently harsh environmental conditions on the Jesmond buildup. The general impoverishment of marine biotas following the Permian-Triassic boundary crisis may have been an additional factor. The Jesmond succession provides no positive evidence for anoxic conditions in the mid-Panthalassa Ocean during the late Early Triassic time.

We recognized at least twelve shallowing-upward cycles within the succession. Individual cycles range in thickness from 2 to 20 m and consist of shallow subtidal facies and overlying intertidal facies. The amplitude of the sea-level fluctuation indicated by each of these cycles must have been limited to a few meters. On the basis of the stratigraphic distribution of the cycles, we inferred that the Jesmond succession in the whole represents a gradually upward-deepening sedimentation within a peritidal zone in the latest Smithian to mid-Spathian. Also, we postulate that the Jesmond peritidal carbonates record highstands of sea-level at the latest Smithian, which is followed by a possible emergence episode near the Smithian-Spathian boundary and by a sea-level rise during the early to middle Spathian. This deepening trend is an important record found outside the Tethyan realm.

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Explanation for Text-figures 1 to 11

Fig. 1 Geologic map of the Clinton-Cache Creek area of southern British Columbia, simplified after Trettin (1980) and Monger et al. (1991). Approximate location of the Jesmond succession at the northern end of Marble Range is indicated by *star*. Location of main panel is shown in inset map at the upper right. Abbreviations: *CC* = eastern limit of deformation in the Canadian Cordillera, *BC* = British Columbia, *AB* = Alberta, *YT* = Yukon Territory, and *V* = Vancouver.

Fig. 2 Map showing locations of measured sections JE 1 to 14 and JE 17 and sites of field photos in Figs. 4 and 6. Inset map shows locality of the study section in the northern end of Marble Range.

Fig. 3 Columnar section showing stratigraphic distribution of representative microfacies types, major skeletal debris (*G* microgastropods, *B* bivalves, *O* ostracods, *C* crinoids), and shallow subtidal-intertidal cycles of the Jesmond succession. Stratigraphic levels of conodonts, foraminifers, and samples shown in Figs. 5, 6, 8, 9, 10 and 11 are indicated.

Fig. 4 Calcareous shale (*sh*) intercalated in fenestral-laminated lime-mudstone beds (m) of the lower unit. JE 2-2. See Fig. 2 for the locality of the outcrop.

Fig. 5 Lower Triassic conodonts from the Jesmond succession. See Figure 3 for stratigraphic levels of samples.

1a-b *Triassospathodus homeri* (Bender). **a** lateral view; **b** lower view. JE 11-1. **2a-b** *Neospathodus* sp. **a** lateral view; **b** lower view. JE 11-1. **3a-c** *Triassospathodus symmetricus* (Orchard). **a** lateral view; **b** lower-lateral view; **c** lower view. JE 11-5. **4-7** *Pachycladina obliqua* Staesche. **4, 5** Posterior view of S element; **6, 7** Posterior view of S elements. JE 2-1.

8-9 *Parapachycladina peculiaris* (Zhang). **8** Posterior view of S element; **9** Posterior view of P element. JE 2-1. **10** *Pachycladina* sp. Posterior view of S element. JE 2-1. **11** *Pachycladina* sp. Posterior view of S element. JE 2-1.

Fig. 6 Thin-section photomicrographs of smaller foraminifers from the Jesmond succession. Plane light. See Figure 3 for stratigraphic levels of samples.

A *Hoyenella* gr. *sinensis* Ho. JE 4-7. Scale bar = 0.5 mm. **B** Possibly encrusting foraminifer referable to the genus *Nubecularia*. JE 8-1. Scale bar = 0.5 mm. **C** Possible encrusting foraminifer. JE 8-1. Scale bar = 0.5 mm. **D** *Hoyenella* gr. *sinensis* Ho. JE 14-8. Scale bar = 0.25 mm.

Fig. 7 Outcrop views of representative facies of the Jesmond succession. See Figure 2 for outcrop locations.

A Microgastropods scattered in weakly dolomitized lime-mudstone. JE 9-12. **B** Flat-pebble conglomerate intercalated in finely laminated lime-mudstone. JE 6-8. **C** Stromatolitic-laminated bindstone. JE 9-2. **D** *Dark gray* well-laminated bindstone rich in thin, laminoid-shaped fenestral voids filled with calcite. JE 9-9.

Fig. 8 Flat-pebble conglomerate and peloidal bindstone of the Jesmond succession. Polished slabs. All scale bars=5 cm. See Fig. 3 for approximate stratigraphic levels of samples.

A Flat-pebble conglomerate comprising mostly parallel-aligned and locally imbricated, poorly sorted, elongated and plate-shaped, angular limestone debris of polymictic association, set in poorly sorted peloidal mud with smaller intraclastic debris. JE 6-8. **B** Poorly defined boundary between slightly greenish flat-pebble conglomerate having much finer limestone debris and presumable volcaniclastic lithic fragments, indicated by *arrows*, and overlying lime-mudstone (*m*). JE 6-4. **C** *Dark gray*, thinly laminated, fenestral peloidal bindstone containing bedding-parallel laminoid- to lenticular-shaped fenestral voids and highly carbonaceous layers. Note a flat-lying and low, small-scale domal structure, indicated by *arrows*. JE 9-9. **D** Stromatolitic-laminated peloidal bindstone. JE 9-2.

Fig. 9 Thin-section photomicrographs of peloidal facies of the Jesmond succession. Plane light. See Fig. 3 for stratigraphic levels of samples.

A Millimeter-scale alternation of fine-grained peloidal grainstone (*g*) and lime-mudstone (*m*). Most of layers are gently undulating and have poorly defined top and bottom surfaces. Lime-mudstone layers are laterally discrete. JE 2-5. Scale bar = 2 mm. **B** Peloidal grainstone composed mostly of sorted and fine-grained peloidal particles and minor intraclastic debris (*d*), all cemented by microspar. JE 17-4. Scale bar = 5 mm. **C** Laminated peloidal bindstone chiefly consisting of finely alternating micritic mats (*m*) with peloidal grainstone-packstone layers (*g*). Note laterally discrete and lenticular, elongated fenestral voids (*f*). JE 6-6. Scale bar = 5 mm. **D** Enlarged view of peloidal bindstone patch (*p*) comprising densely micritized and interconnected peloidal particles. JE 9-9. Scale bar = 2 mm. **E** Peloidal bindstone layer, in which gastropods (*g*), peloidal particles, and intraclastic debris are bound with one another. Note undulating, gently domal top surface (*d*) of boundstone layer, fenestral structures (*f*), and micritized peloidal lime-mudstone (*m*). JE 2-4. Scale bar = 5 mm. **F** Domal structure of stromatolitic bindstone including thin and elongated laminoid fenestrae. JE 9-10. Scale bar = 2.5 mm.

Fig. 10 Thin-section photomicrographs of various facies of the Jesmond succession. Plane light. See Figure 3 for stratigraphic levels of samples.

A Laminoid-type fenestrae in peloidal packstone-wackestone. Fenestrae are mostly filled with nearly isopachous rims of bladed, light brown sparry calcite with blocky spar. Note the stromatactis structure (*s*) with digitate roof and fine-grained lime-silts at bottom. JE 7-3. Scale bar = 2 mm. **B** Homogenous and aphanitic dolomite (dolomicrite) with faint laminae, indicated by *arrows*. JE 10-7. Scale bar = 2 mm. **C** Gastropod-rich peloidal packstone intercalated in peloidal wackestone-mudstone with laminoid- and lenticular-shaped fenestrae, nearly parallel to bedding surface. JE 6-5. Scale bar = 6 mm. **D** Bivalve shell-rich skeletal packstone with gastropods (*g*) and crinoids (*c*), set in poorly sorted peloidal matrix with abundant tiny skeletal debris. JE 11-2. Scale bar = 8 mm. **E** Flat-pebble conglomerate comprising unsorted, oriented, flattened and elongated limestone clasts having sharp edges (*p*), with smaller, rectangular- to block-shaped limestone clasts (*c*), all set in matrix of peloidal grainstone with admixture of much finer intraclastic limestone debris. JE 6-8. Scale bar = 5 mm. **F** Erosional contact, traced from *a* to *c*, between flat-pebble conglomerate and underlying peloidal grainstone-wackestone with micritic mats (*m*). JE 6-8. Scale bar = 4 mm.

Fig. 11 Thin-section photomicrographs of three types of microproblematica and oolitic limestone of the Jesmond succession. Plane light. See Fig. 3 for stratigraphic levels of samples. **A** Microproblematicum A, indicated as *a*, comprising gently curved, poorly segmented, thin and elongated tube with spar-filled interior and thin, smooth micritic outer wall. JE 6-5. Scale bar = 0.5 mm. **B** Microproblematicum B, indicated as *b*, characterized by large, bulbous to massive shape with irregularly protruding, knobby to digitate outline, micritized periphery, and spar-filled interior including much smaller, irregularly digitate, curved, interconnected and chained tubular forms with micritic walls (*s*). JE 9-6. Scale bar = 1 mm. **C** Microproblematicum C, indicated as *c*, having a bulbous to massive form, sparry to locally micrite-filled interior containing tiny and short tubular filaments, and micritized periphery. *a* = oval- to barrel-shaped microproblematicum A. JE 7-3. Scale bar = 1 mm. **D** Microproblematicum A grainstone-packstone, composed exclusively of oval to cylindrical forms of microproblematicum A, locally bound with one another by micrite. Their interstices are mostly cemented by microspars, and locally filled with micrite. JE 10-8. Scale bar = 1 mm.

E Poorly sorted oolitic grainstone having sparry cements and minor fine-grained peloidal particles. JE 12-6. Scale bar = 5 mm.