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**Jurassic Foraminifera from the Queen Charlotte Islands, British Columbia:
biostratigraphy, paleoenvironments and paleogeographic implications**

By

Niranjala Kottachchi, B. Sc. (Hons. Earth Sciences)

**A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfillment of the
requirements for a degree of Masters of Science**

**Department of Earth Sciences
Carleton University
Ottawa, Ontario
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A handwritten signature in black ink, appearing to read 'J. W. Higgins', written over a horizontal line.

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Chair, Department of Earth Sciences

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January 19, 2001

ABSTRACT

Lower and Middle Jurassic (Sinemurian to Callovian) foraminifera were examined from 66 sections of the Queen Charlotte Islands, British Columbia, Canada. Over 200 species of well preserved benthic calcareous and agglutinated taxa belonging to 50 genera were identified. Foraminifera from the Lower Jurassic are represented by a predominantly abundant and diverse, Tethyan-derived calcareous assemblage with Boreally-derived agglutinated taxa becoming gradually more dominant in the late Lower Jurassic to early Middle Jurassic. Sedimentary strata and their faunal components and position of hiatuses correlate approximately with the Jurassic eustatic sea-level curve. Sea-level changes have resulted in a variety of depositional environments ranging from deep-water euxinic shales with abundant tuff beds, characterized by small pyritized foraminifera, to a well oxygenated outer shelf setting, characterized by a major faunal increase, to shoreface sandstones and conglomerates with absent to rare benthic foraminifera. A gradual shallowing from a slope- to a shelf-dominated deposition, with a magmatic arc provenance is suggested for the Lower Jurassic and a nearshore environment (i.e. inner shelf to upper shoreface) dominated by sedimentary strata of volcanoclastic origin is suggested for the Middle Jurassic. A marked faunal turnover is observed for the Lower Jurassic Whiteaves Formation (middle Toarcian) with the extinction of several earlier species and the appearance of a new diverse assemblage equating to 225 species. This turnover is also observed for the ammonite and radiolarian assemblages of the Queen Charlotte Islands. In comparison to the dominantly Tethyan-derived taxa of pre-middle Toarcian age, many of the species from the middle Toarcian are found in northern latitudes such as Alaska, Arctic Islands and the Northwest Territories. Hence, foraminifera, in conjunction with existing radiolarian and ammonite data, suggest a northward displacement of the Queen Charlotte Islands from low to mid-paleolatitudes by late Lower Jurassic (Toarcian) to early Middle Jurassic (Bajocian) time.

ACKNOWLEDGMENTS

I would first like to thank my supervisor, Dr. Claudia Schröder-Adams for providing me with invaluable support and advice along the way. Funding was provided by an N.S.E.R.C. Research Grant to Dr. Schröder-Adams.

Many thanks to my co-supervisor, Dr. Jim Haggart of the Geological Survey of Canada, Vancouver for providing me with the opportunity to work with the collection, numerous literature references, and countless e-mail contacts throughout the duration of this thesis. Having the opportunity to visit and conduct fieldwork in such a beautiful locality as the Queen Charlotte Islands was an experience I will never forget. Thank you for the wonderful memories. Thanks also to Jessica Page of the GSC, Vancouver for her many hours of volunteering in compiling all the necessary data required for this thesis.

Hugs and kisses to my husband and life partner, Steven, for all the love and support you've given me. You've been my backbone and sanity throughout and a great nurse during those rough ill-fated times. Thank you for the shoulder to cry on and the many laughs. I love you tons.

Last but not least, I would like to thank my family for their love and support. Thank you for saving me during times of crisis and for taking the weight off my shoulders when it was getting too heavy. I love you all.

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1. INTRODUCTION

The Queen Charlotte Islands archipelago includes more than 125 islands located off the west coast of British Columbia, Canada, between latitudes 52°N and 55°N (Fig. 1) (Lewis et al., 1991). The islands are part of the Wrangell terrane of the Insular Belt of western North America, or Wrangellia, and are composed of Mesozoic granitic, volcanic and sedimentary rocks; the latter include perhaps the most continuous and best preserved stratigraphic sections in the western Canadian Cordillera (Haggart et al., 1995). With their excellent fossil preservation, particularly of the mollusks, these strata serve as a Mesozoic reference section for the northeast Pacific region, and for correlation with European type sections.

Biostratigraphic analysis has proven of fundamental importance in interpreting the geological history of the Queen Charlotte Islands (Haggart et al., 1995). The islands, as part of Wrangellia, are interpreted to have been located at equatorial to low-temperate latitudes during Triassic time (Haggart et al., 1995). Migration of Wrangellia northward along the western margin of North America to its present position occurred during later Mesozoic time. Significant recent debate has centered on the precise time of arrival and amalgamation of Wrangellia with the rest of North America. Analysis of paleomagnetism of Cretaceous rocks from the western Cordillera has led to the conclusion that northward displacement of the terrane by as much as 3000 km occurred during mid-Cretaceous to early Tertiary time (Irving and Wynne, 1990; Irving et al., 1985; and Irving et al., 1996). On the other hand, paleobiogeographic data appear to contradict this model, as the Cretaceous ammonite, bivalve, and radiolarian faunas of Wrangellia are characteristic of high rather than low latitudes (Haggart et al., 1995).

Extensive work has been undertaken previously to develop biostratigraphic schemes for Upper Triassic, Jurassic and Cretaceous strata of the islands, primarily utilizing mollusks, radiolarians, and conodonts (summarized in Haggart et al., 1995). To date, such schemes for the Jurassic have emphasized macrofauna, primarily ammonites and trigonid bivalves (Poulton and Tipper, 1988; Tipper et al., 1988; Pálffy et al., 1994; Smith and Tipper, 1996), as well as radiolarians (Carter, 1988; Carter et al., 1988; Carter et al., 1998); little work has been done on the foraminifera of these strata (Cameron and Tipper, 1985; Tipper et al., 1991).

Foraminifera serve as important biostratigraphic indicators due to their abundance, diversity, and rapid evolution (Boltovskoy and Wright, 1976). The primary objective of this paper is to document biostratigraphic ranges for the Lower and Middle Jurassic foraminifera of the Queen Charlotte Islands and to assess these foraminiferal faunae in regards to their paleoecologic and paleobiogeographic implications. Our study utilizes a micropaleontological approach to analyze foraminiferal data from the Lower Jurassic upper Kunga and Maude groups, and the Middle Jurassic Yakoun and Moresby groups of the Queen Charlotte Islands (Table 1). A biostratigraphic framework from this region will allow for future circum-Pacific correlations as well as regional correlations of Jurassic sections of the Canadian Cordillera. Furthermore, benthic foraminiferal faunal changes add to existing paleoenvironmental and paleogeographic reconstructions based on other faunal groups.

Figure 1: Generalized locality and geologic map of the Queen Charlotte Islands (modified from Patterson, 1990 and Haggart et al., 1995, respectively)

	Stage	Group	Formation	Member
Middle Jurassic	Callovian			
		Moresby	Alliford	
			Newcombe	
	Robber Point			
	Bathonian	angular discordance		
	Bajocian	Yakoun	Richardson Bay	Volcanic Breccia
				Dark Sandstone
				Lapilli
			Volcanic Sandstone	
		Graham Island	Mottled Siltstone	
			Shale-Tuff	
	paraconformity			
Lower Jurassic	Aalenian	Maude	Phantom Creek	Belemnite Sandstone
	Toarcian			possible paraconformity
				Coquinoid Sandstone
				Concretionary Shale
			Septarian Shale	
	Pliensbachian		Fannin	
			Ghost Creek	
	Sinemurian	Kunga	Sandilands	

Table 1: Stratigraphic intervals under study, Queen Charlotte Islands (modified from Cameron and Tipper, 1985)

2. GEOLOGICAL SETTING

The Queen Charlotte Islands form part of the Insular Belt, composed of the Wrangell and Alexander terranes (Fig. 2), the westernmost morphogeological belts of the Canadian Cordillera. Wrangellia extends from southern Alaska to at least the southernmost part of Vancouver Island and includes a characteristic Upper Triassic to Jurassic stratigraphic succession (Jones et al., 1977; Yole and Irving, 1980; Yorath and Chase, 1981) observable throughout the extent of the terrane. Perhaps the most distinctive unit of this succession is the Upper Triassic island arc basalts of the Karmutsen Formation and equivalents, exceeding 2,500 meters in thickness on Queen Charlotte Islands. Basalts in the upper part of the Karmutsen Formation on Queen Charlotte Islands are interstratified with bioclastic limestones of Late Triassic (Carnian) age (Sadler Limestone), interpreted as tropical reef deposits which accumulated fringing the island-arc complex. Overlying Carnian to Hettangian (Lower Jurassic) strata record deepening of deposition to slope depths and corresponding loss of carbonate deposition during latest Triassic time (Desrochers and Orchard, 1991; Haggart and Orchard, 1999).

Jurassic strata of the islands show greater variation in sedimentary and volcanic facies than those of any other system (Haggart, 1990). Lower Jurassic strata reflect continuation of sedimentation that initiated in latest Triassic time and persisted through the earliest Aalenian (Middle Jurassic). These strata all include a volcanic component, principally siliceous tuffs that reflect episodes of distal volcanism, possibly exposed in the emerging Bonanza Volcanics arc complex of northern Vancouver Island. The latter part of Aalenian time is characterized by a regional unconformity, followed by renewed sedimentation and associated calc-alkaline volcanism and plutonism during Bajocian to Callovian time. This magmatic episode is inferred to represent the initiation of an active subduction system along the west coast of North America during Middle Jurassic time (Lewis et al., 1991).

Jurassic strata consist predominantly of clastic sediments and reflect a variety of sedimentary regimes and depositional environments, including deep-water anoxic shales, shallow-marine sandstones and conglomerates deposited in a back-arc basin, and epiclastics deposited in active volcanic centers (Cameron and Tipper, 1985). Lower Jurassic strata reflect

gradual shallowing in a magmatic arc provenance, from slope to shelf-dominated deposition. Middle Jurassic volcanoclastic units and associated, coeval magmatic-arc volcanic rocks are suggestive of a nearshore environment. Sea-level changes indicated by Jurassic sequences of the Queen Charlotte Islands are comparable with worldwide eustatic cycles (Hallam, 1978; Haq et al., 1988). Corresponding transgressive phases are recognized for the Sinemurian, lower Pliensbachian, middle Toarcian, lower Bajocian, and the lower Callovian. Corresponding regressive phases include the upper Toarcian to Aalenian and the lower Bathonian (Cameron and Tipper, 1985).

As noted above, the late Mesozoic tectonic history of Wrangellia and Queen Charlotte Islands is a matter of current debate. Geophysical models based on paleomagnetism suggest that Wrangellia migrated from its low-latitude, tropical position to its present location adjacent to western North America, during Cretaceous and early Tertiary time (the "Baja BC" hypothesis; see Umhoefer, 1987). A variety of geological and paleontological data (summarized in Haggart et al., 1995) suggest, however, that Queen Charlotte Islands achieved its approximate present relative position by Middle Jurassic time. Indeed, the most significant tectonic event recorded in the geological record of Queen Charlotte Islands is Aalenian (early Middle Jurassic) compression (Thompson et al., 1991; Lewis et al., 1991). Geologic evidence for an Aalenian compressional event is extensive in the western Cordillera (McLelland and Gehrels, 1990; Thompson et al., 1991; van der Heyden, 1992), reflecting its widespread nature and regional importance. In addition, the lack of extensive tectonism in the islands region during most of Cretaceous time further militates against a Cretaceous arrival for the terrane (Haggart et al., 1995). As alluded to above, paleobiogeographic analysis of Cretaceous fossil assemblages suggests that Cretaceous faunae are dominated by high-latitude, rather than low-latitude or tropical forms. The paleomagnetic model of northward Cretaceous translation of Wrangellia alongside western North America persists, however. Foraminiferal analysis of Jurassic strata of Queen Charlotte Islands, in conjunction with existing data on ammonites and radiolarians, has the potential to provide a significant key to resolving this controversy.

Figure 2: Position of Wrangell and Alexander terranes relative to the Queen Charlotte Islands (modified from Thompson et al., 1991)

3. PREVIOUS WORK

Geological and paleontological investigations of the Queen Charlotte Islands region date to the late 1800's, and Jurassic biostratigraphic and paleontologic investigations have been presented in numerous publications (summarized in Haggart et al., 1995). Recently, Geological Survey of Canada field parties have undertaken detailed field studies of Jurassic lithostratigraphy and biostratigraphy of the islands (Tipper and Cameron, 1979; Cameron and Tipper, 1985; Carter et al., 1988). The biostratigraphy and paleontology of Lower and Middle Jurassic ammonite faunae have been studied extensively (Poulton and Tipper, 1988; Tipper et al., 1988; Poulton et al., 1991; Tipper and Guex, 1994; Pálffy et al., 1994; Smith and Tipper, 1996) and the radiolarian faunae of these strata have received similar treatment (Pessagno and Whalen, 1982; Carter, 1988; Carter et al., 1988; Carter et al., 1998). Table 2 summarizes the existing ammonite and radiolarian biochronological scheme for the Jurassic of the Queen Charlotte Islands.

Although many data have been generated on Jurassic ammonite and radiolarian biochronological schemes for Queen Charlotte Islands, few data exist on foraminiferal paleontology; Lower and Middle Jurassic foraminifera found on the islands have been documented briefly by Cameron and Tipper (1985), Tipper et al. (1991), Poulton et al. (1991), and Haggart et al. (1995).

While there is a minimal amount of published research on Jurassic foraminifera of the North Pacific region, an extensive body of literature exists for Jurassic foraminifera elsewhere in the Boreal region. Lower Jurassic foraminiferal faunae have been described from the North Slope of Alaska (Tappan, 1955), the Arctic Archipelago region of northern Canada (Souaya, 1976), and for the eastern Sverdrup Basin (Wall, 1983). Upper Jurassic foraminifera from the Aklavik Range, Northwest Territories, were described by Hedinger (1993), those of Saskatchewan by Wall (1960) and Brooke and Braun (1972), and those of the Black Hills region of South Dakota by Loeblich and Tappan (1950). Gradstein (1978) and Exton and Gradstein (1984) have studied Jurassic foraminifera from the Grand Banks of Newfoundland. Lower and Middle Jurassic foraminiferal studies from northwestern Europe (i.e., England) have been published by Copestake and Johnson (1981) and Coleman (1981), respectively.

In contrast, studies of Jurassic foraminifera from the Tethyan regions are comparatively few, and seem to be lacking for North America (i.e., Texas and Mexico). In the Mediterranean regions, Lower Jurassic foraminifera have been reported from Zambujal, Portugal (Exton, 1978), and Middle to Upper Jurassic faunae have been described from India (Bhalla and Abbas, 1978) and Sinai, Egypt (Said and Barakat, 1958).

Age	Stage	Ammonite Zonation Queen Charlotte Islands (Haggart et al., 1995)	Radiolarian Zonation Queen Charlotte Islands (Carter et al., 1988)
Middle Jurassic	Callovian		
		<i>Keppertes spinosum</i>	
		<i>Cadoceras doroschui</i>	
	Bathonian	<i>Oxyceres</i>	
		<i>Keppertes</i> spp	
		<i>Inskundes cepoides</i>	
Lower Jurassic	Bajocian		7
		<i>Chondroceras oblatum</i>	
		<i>Stephanoceras karschneri</i>	
	Aalenian	<i>Kumetostephanites, Sonnenids</i>	6
		<i>Sonnenids, Fontannesia (?)</i>	
	Toarcian	<i>Yakoune</i>	5
		<i>Hillebrandi</i>	4
		<i>Crassicoela</i>	3
		<i>Planulata</i>	2
	Pliensbachian	<i>Karense</i>	1
		<i>Carlottense</i>	
		<i>Kunze</i>	
		<i>Freiboldi</i>	
	Sinemurian	<i>Whiteavesi</i>	
		<i>Imlayi</i>	
		<i>Recognitum</i>	
		<i>Harbledownense</i>	
		<i>Vinens</i>	
		<i>Arnouldi</i>	
		<i>Coroniceras</i>	
		<i>Canadensis</i>	

Table 2: Ammonite and radiolarian faunal zones

4. MATERIALS AND METHODS

Samples from 66 localities spanning the Lower to Middle Jurassic were collected by field parties of the Geological Survey of Canada in the late 1970s and early 1980s from Maude Island in Skidegate Inlet, on northern Moresby Island, the central regions of Graham Island, and Cumshewa Inlet (Fig. 1). Of the 66 localities comprising the study, only 13 represent complete stratigraphic sections (sections 4, 5, 7-12, 14-17, 19). The remainder of the sample localities represent sites where samples were collected randomly (i.e., spot sampling) from stratigraphic sections or from isolated exposures, and these collections consequently lack precise interval data. A dual approach was therefore undertaken to utilize all samples in this study: first, biostratigraphic studies were based only on the collections from the 13 complete sections; second, samples lacking precise interval measurements were also studied, to gain a better understanding of Jurassic foraminiferal assemblages with respect to species diversity and composition.

Approximately 1020 microslides containing picked benthic foraminifera, radiolarians and ostracods form the base of this study. Where known, microfossil data have been incorporated with ammonite and other macrofaunal data, to obtain precise age control. Analysis of foraminifera included assessment of foraminiferal abundance, diversity and test composition (calcareous versus agglutinated); excellent foraminiferal preservation greatly facilitated the taxonomic work. Identifications are based primarily on references cited above, as well as Gordon (1967), Exton (1978), and Brooke and Braun (1981). Numerous taxa could not be assigned at species level, and hence have been identified with open nomenclature at the generic level. During the study, it became clear that a detailed taxonomic study is necessary to fully document the Jurassic foraminiferal diversities including intraspecific variability and possible description of new species. This shall be the focus of a future study.

Additional field study was conducted during the summer of 2000 to improve understanding of the Lower and Middle Jurassic formations and lithologies, and to document further observational data not addressed by earlier works. Although several of the sampled sections are now inaccessible, several others (i.e., sections 7, 8, 16, 17), including various type

sections (i.e., Richardson Bay), were visited (figure 3). Foraminifera are not represented in the existing collections from several Jurassic formations studied in the field, and we attribute this to the fact that these formations (i.e., sandstones of Newcombe Formation and Yakoun Group volcanics) are too coarse-grained for foraminiferal recovery, precluding sampling.

Electron micrograph images of foraminifera were produced on a JOEL 6400 scanning electron microscope (SEM) at the Carleton University Research Facility for Electron Microscopy. The specimens were mounted onto SEM stubs and coated with Au dust for SEM micrography. Images were then enhanced and in Photoshop 5.5.

Figure 3: Map showing section localities visited during summer 2000 field season (modified from Cameron and Tipper, 1985)

5. RESULTS

5.1. *Lithostratigraphy and Foraminiferal Biostratigraphy*

Lower and Middle Jurassic stratigraphic units of the Queen Charlotte Islands consist of four major groups; in ascending order these are the upper part of the Kunga Group, and the Maude, Yakoun, and Moresby groups (Table 1). Lithologies and thicknesses of the formations which comprise these units, and which are the subject of this study, are presented in detail in Table 3. Type sections for most formations of the Kunga and Maude groups are found on Maude Island, in Skidegate Inlet (Fig. 3). Lithological observations are based on fieldwork on sections exposed on Maude and Moresby islands (Fig. 3). A composite section for each island shows general lithology, paleoenvironmental interpretation and representative outcrop photographs (Figs. 4a and 4b).

Taxonomic studies were based on well-preserved foraminiferal assemblages from 66 localities on the islands, spanning the Lower to Middle Jurassic. Benthic calcareous and agglutinated taxa belonging to 50 genera and over 200 species were identified, of which taxa of both Tethyan and Boreal affinities are present. The relative dominance of both benthic calcareous and agglutinated taxa varies throughout the study interval (Fig. 5). Calcareous assemblages typically dominate, with the exception of the lower Middle Jurassic where agglutinated taxa are more abundant. Foraminiferal assemblages show significant variations in species abundance and diversity, notably throughout the Lower and Middle Jurassic interval (Fig. 5), but also within each formation (Figs. 6 a-d). In addition, species composition changes as well, with first and last appearance datums present. Two significant faunal changes have been recognized: the Lower Jurassic Whiteaves Formation (early to middle Toarcian) is characterized by a significant faunal increase (Fig. 6a); and the Middle Jurassic Graham Island Formation (early to middle Bajocian) shows a change to a dominance of agglutinated foraminifera (Fig. 6c).

5.1.1. *Upper Kunga Group*

The Sandilands Formation (late Norian to early Sinemurian in the type area, but ranging to the Toarcian elsewhere) consists of a heterogeneous, fining upward sequence of well bedded,

thin and finely laminated, fine sandstone, siltstone, shale and tuff (Fig. 7a). The tuffaceous layers are commonly found weathered to a white or green colour. Contacts between lithologies are sharp. Rare pyrite nodules occur at the base of the formation. Sediment load casts (Fig. 7b) are evident and are concentrated at the base of the coarse sandstone beds, which are interpreted as turbidite deposits (Cameron and Tipper, 1985). The upper contact to the Ghost Creek Formation is gradational.

Although macrofauna is abundant in the Sandilands Formation, microfossils are rare. Only a few, pyritized calcareous foraminiferal taxa including *Marginulina*, *Nodosaria* and *Lenticulina* were recovered from spot samples in sections without recorded sample intervals.

Figure 4a: Composite section for Maude Island

Figure 4b: Composite section for Moresby Island

Gp.	Fm.	Member	Thickness (m)	Lithology
Moresby	Alford		60	grey to grey-buff, poorly laminated siltstones, shales and minor sandstone
	Newcombe		30-45	well-bedded sandstones overlain by massive volcanic concretionary sands
	Robber Point		15-90	varies from siltstones, tuffaceous sandstones, volcanic breccia, coarse volcanic sandstones, and tuffs, volcanics may be derived from the underlying Yakoun Group
Yakoun	Richardson Bay	Volcanic Breccia	60-530	massive, poorly sorted, porphyritic andesite breccia and tuff
		Dark Sandstone	30-110	heterogeneous with dark, greenish grey sandstone, shale and siltstone
	Graham Island	volcanic sandstone/ lapilli	140-270 (volcanic sandstone member) 200 (lapilli member)	volcanic sandstone member (central Graham Island) - interbedded green to brown, fine to coarse-grained sandstone, argillaceous dark grey to brown siltstone with buff weathering fine-grained, partly calcareous sandstone, shales rare lapilli member (Skidegate Inlet) - lapilli tuff, tuff and minor andesitic agglomerates both members are stratigraphically equivalent to each other
		shale- tuff/ mottled siltstone	75-85 (shale-tuff) 30 (mottled siltstone)	shale-tuff member (central Graham Island) -well-bedded sandy shales, argillaceous, partly tuffaceous siltstones, and minor laminated and cross laminated buff-weathering sandstones. Lower shales are recessive and upper part coarser, more tuffaceous and resistant mottled siltstone member (Skidegate Inlet) - mottled, dark grey siltstone reflecting shallower marine environment both members are stratigraphically equivalent to each other
Maude	Phantom Creek	belemnite sandstone	3-5	massive, indurated sandstone, contains abundant belemnites
		coquinoid sandstone	5-25	fossiliferous, grey to greenish-brown well-bedded sequence containing concretions
	Whiteaves	concretionary shale	3-30	more sandy, lacks septanan nodules but contains calcareous nodules, less glauconitic
		septanan shale	15-55	grey-green weathering shale with pale grey weathering septanan nodules (sandy and somewhat carbonaceous)
	Fannin		75	a regressive, coarsening upward sequence from shales and sandstones near the base to coarser, more tuffaceous, calcareous sandstones with minor siltstones and shales near the top
	Ghost Creek		45-68	argillaceous unit of shales, mudstones, and siltstones
Upper Kunga	Sandilands		300+	well indurated and fissile, thick sequence of thinly bedded dark shale and siltstone containing thin interbeds of fine to medium-grained sandstone and tuff, calcareous nodules and limestone lenses present throughout

Table 3: Jurassic formations under study, Queen Charlotte Islands (modified from Cameron and Tipper, 1985; Haggart *et al.*, 1995)

Figure 5: Foraminiferal distribution (Lower to Middle Jurassic) with respect to total diversity (left column) and diversity with respect to total number of calcareous (o) and agglutinated (Δ) taxa within each formation (right column). No foraminifera were recovered from the Newcombe Formation. Striped bars denote unconformities. Note that each unit is represented by one composite data point, despite intraformational faunal variability

Figure 6a: Foraminiferal distribution for the lower Jurassic Ghost Creek, Fannin and Whiteaves formations

1-5 specimens • 6-10 specimens • 11-50 specimens • >50 specimens

Figure 6b: Foraminiferal distribution for the lower Jurassic Whiteaves and Phantom Creek formations

• 1-5 specimens • 6-10 specimens • 11-50 specimens • >50 specimens

Figure 6c: Foraminiferal distribution for the lower Jurassic Whiteaves and middle Jurassic Graham Island formations

Figure 6d: Foraminiferal distribution for the middle Jurassic Richardson Bay, Robber Point and Alliford formations

• 1-5 specimens • 6-10 specimens • 11-50 specimens • >50 specimens

Figure 7: Sandilands Formation : a) thinly bedded turbidite sequences; b) sediment load casts (arrow)

5.1.2. Maude Group

Lower Jurassic Maude Group strata conformably overlie the Kunga Group and are represented by four formations: Ghost Creek (early Pliensbachian), Fannin (middle Pliensbachian to early Toarcian), Whiteaves (middle Toarcian) and Phantom Creek formations (late Toarcian to Aalenian). The Phantom Creek Formation is not exposed in sections of Maude and Moresby islands, but is best represented in central Graham Island where it is found in stream and road cuts (Haggart, et al., 1995).

The Ghost Creek Formation consists of interbedded shale, siltstone (Fig. 8a) and sandstone showing an overall coarsening-upward trend. The formation differs from the Sandilands Formation by reduced frequency of sandstone and tuff beds, indicating the absence of turbidites and a greater distance from volcanic sources. In the upper part of the formation, channels filled with sandstone cut into shales, and basal contacts are marked by sandstone clasts reworked into the shale (Fig. 8b). Calcareous concretions occur throughout the formation.

The formation contains a predominantly calcareous foraminiferal assemblage of low species diversity. The genus *Frondicularia* dominates the assemblage (Fig. 6a). Calcareous specimens are small, pyritized forms within the lower siltstone and shale units (Figs. 4a, 4b). Rare agglutinated taxa are present near the top of the formation within sandstones (Figs. 4a, 4b) and are represented by *Trochammina*, *Ammobaculites multiformis*, *Arenoturrspirilina waltoni*, and *Haplophragmoides* sp. C. Taxa restricted to the Ghost Creek Formation include *Ramulina* sp. A, *Lingulina tenera*, *Lingulina camerata*, and *Frondicularia squamosa*. Ammonite faunae occur within the siltstone units. Benthic macrofossils and bioturbation are absent within the shale beds but are abundant in thicker sandstone beds near the top of the formation.

The conformable contact between the Ghost Creek Formation and the overlying Fannin Formation is gradational. The Fannin Formation is blockier and more resistant than the underlying Ghost Creek Formation and is represented dominantly by tuffaceous, calcareous sandstone interbedded with siltstone. The tuff is less abundant than in the underlying Sandilands and Ghost Creek formations. On Maude Island, large channel structures were observed that pinch out laterally within the sandstone (Fig. 9a). Towards the top of the formation, silty shale

units are found with sharp lower and upper contacts within sandstone (Fig. 9b), indicating phases of quiet energy conditions. At Whiteaves Bay, the sandstones contain load casts, calcareous concretions and cross-stratification. Bioturbation, represented by predominantly large sand-filled vertical burrows (Fig. 9c) is present throughout the formation.

The coarse-clastic nature of the Fannin Formation is reflected in a change in foraminiferal assemblage from diverse, predominantly calcareous faunae at the base of the formation to a less diverse, dominantly agglutinated assemblage at the top (Fig. 6a). The abundant species of *Fronicularia* in the Ghost Creek Formation also range into the Fannin Formation. Genera such as *Neobulimina*, *Brizalina*, *Bigenerina* and *Conorbina* are restricted to the Fannin Formation. Ammonites are particularly abundant in the middle and upper Fannin Formation, and are randomly oriented on bedding surfaces (Fig. 9d). Shell fragments occur near the base of the formation.

The overlying middle Toarcian Whiteaves Formation is not well exposed on Maude Island (Fig. 4a) where it is only represented by loose beach debris consisting of septarian and calcareous nodules, some of the latter containing ammonites. At Whiteaves Bay on Moresby Island (Figs. 3, 4a), this unit conformably overlies the Fannin Formation. Although poorly exposed along the beach, both the lower septarian shale member and upper concretionary shale member may be observed. The formation on Moresby Island is a predominantly homogeneous unit of shales interbedded with thin, sandstone layers and in association with abundant glauconite. The Whiteaves Formation becomes more sandy and calcareous up section. Here, the lower septarian shale member dominated by septarian nodules, is replaced by concretionary nodules.

The transition from a generally shallow-water marine environment (i.e. Ghost Creek and Fannin formations) to a deeper-water environment (i.e. Whiteaves Formation) in the Lower Jurassic of Queen Charlotte Islands is reflected in a large increase in foraminiferal abundance and species diversity. Approximately 225 taxa have been distinguished in the Whiteaves Formation, in comparison to 125 taxa observed in the Ghost Creek and Fannin formations. Most of the taxa characterizing the Whiteaves Formation have their first appearance within this

formation. Only a few species such as *Fron dicularia* sp. A and *Fron dicularia* sp. B are ranging up from the underlying strata.

In comparison to underlying formations, agglutinated taxa become increasingly more abundant towards the top of the Whiteaves Formation. The lower, septarian shale member is dominated by calcareous taxa of *Lenticulina d'orbignyi*, *Astacolus pediacus* and various species of *Citharina*, *Nodosaria*, *Eoguttulina* and *Dentalina* (Fig. 6c). Dominant agglutinated species of the upper concretionary member include *Ammobaculites lunaris*, *Ammobaculites* sp. E, *Ammodiscus orbis*, and *Verneuillinoides graciosus* (Fig. 6a). Abundant calcareous species in the upper concretionary member are *Lenticulina audax*, *Lenticulina toarcense*, *Lenticulina excavata* and *Dentalina vulgata* (Fig. 6a).

The late Toarcian to Aalenian Phantom Creek Formation is best exposed in central Graham Island, where its lower coquinooid sandstone member is represented by a well-bedded sandstone unit containing calcareous concretions, bivalves and ammonites (Jakobs, 1990; Haggart et al., 1995). Friable, volcanoclastic-rich layers are typically interbedded within sandstones. The upper belemnite sandstone member of the formation is more massive and indurated than the underlying coquinooid member and contains more belemnites, bivalves, and rare ammonites (Haggart et al., 1995).

The foraminiferal fauna of the Phantom Creek Formation differs from that of the Whiteaves assemblage in its reduced diversity and dominance of calcareous species (Fig. 5). Typical species such as *Lenticulina audax*, *Lenticulina prima*, *Lenticulina excavata*, *Lenticulina toarcense*, *Falsopalmula antrorsa* and *Astacolus pediacus* (Fig. 6b) of the Phantom Creek Formation first appear in the underlying Whiteaves Formation. *Lenticulina d'orbignyi*, found abundantly in the Whiteaves Formation, is no longer present. Distinctive taxa restricted to the Phantom Creek Formation include rare occurrences of *Epistomina parastelligera*, *Vaginulina kochi* and *Dentalina* sp. K (Fig. 6b).

Figure 8: Ghost Creek Formation: a) siltstone interlaminated with shales; b) channel scour (arrow)

Figure 9: Fannin Formation: a) channel structure; b) shale unit representing a flooding surface (arrow); c) sand-filled burrow (arrow); d) ammonite impressions

5.1.3. Yakoun Group

The Yakoun Group disconformably overlies the Maude Group and is of Middle Jurassic age. In comparison to the Lower Jurassic Maude Group, the Yakoun Group is composed primarily of tuffaceous shales, siltstones and agglomerates suggesting nearshore environments in close proximity to volcanic sources. The Yakoun group is composed of two formations, the lower Graham Island and the upper Richardson Bay formations (Cameron and Tipper, 1985).

The lower Bajocian Graham Island Formation is not exposed on Maude and Moresby islands, but is represented on central Graham Island where it is divided into the lower shale-tuff/mottled siltstone member and the upper volcanic sandstone/lapilli member (Table 3). The lower member is composed of a well-bedded sequence of sandy shales, tuffaceous siltstones with laminated sandstones. The upper member consists of interbedded sandstone and siltstones containing abundant lapilli with occasional calcareous sandstone and minor shale (Haggart et al., 1995).

The significant facies change seen between the Maude and Yakoun groups is reflected in a foraminiferal biofacies change, to a dominantly agglutinated assemblage (Fig. 5, 6c) in the Graham Island Formation. *Ammobaculites* dominates this assemblage and is accompanied by rare occurrences of *Bulbobaculites*, *Haplophragmoides*, *Trochammina*, *Ammodiscus*, *Bathysiphon* and *Reophax* (Fig. 6c). Numerous *Ammobaculites* species are unique to the Graham Island Formation. Rare occurrences of calcareous taxa spanning from the Lower Jurassic include *Pseudolamarckina liapinensis*, *Pseudonodosaria statuta*, *Falsopalmula antrorsa*, *Citharina entypomatus*, *Eoguttulina liassica*, *Eoguttulina metensis*, *Astacolus varians*, *Astacolus pediacus* and *Lenticulina audax* (Fig. 6c). Several of these species, however, are restricted to the lower part of the formation.

The overlying lower Bajocian Richardson Bay Formation is subdivided into the lower dark sandstone and upper volcanic breccia members (Cameron and Tipper, 1985). Both members are best represented at the type section on Maude Island (Fig. 3). Here, large, poorly sorted breccia nodules and abundant lapilli (Fig. 10a) characterize the lower sandstone member. The lower sandstone member was not documented on Moresby Island, although it is believed to exist

between Alliford Bay and Whiteaves Bay. The upper volcanic breccia or agglomerate member is massive on Maude Island, but is not as well exposed on Moresby Island. The unit is a coarse porphyritic andesitic breccia and tuff dominated by large-scale hummocky cross-stratification (Fig. 10b), coalified wood (Fig. 10c) and breccia nodules (Fig. 10d). The top of the member is characterized by a facies change to a dominantly silty shale bed containing large nodules (Fig. 10e) and bioturbation (Fig. 10f).

Foraminifera recovered from the Richardson Bay Formation were derived only from near the top of the sandstone member. A distinct drop in abundance and diversity to 11 species is noted for the Richardson Bay Formation (Fig. 5, 6d). Rare taxa, new to the formation and to the Middle Jurassic include *Ammobaculites toughenoughensis* and *Triloculina*, whereas *Eoguttulina liassica* and *Bulbobaculites willowensis* were also found in the underlying Graham Island Formation.

Figure 10: Richardson Bay Formation: a) lapilli; b) hummocky cross-stratification; c) coalified wood; d) breccia nodules; e) concretionary nodules; f) bioturbated sand-shale interval

5.1.4. Moresby Group

The Moresby Group (Middle Jurassic) disconformably overlies the Yakoun Group and consists of the Robber Point (late Bathonian), Newcombe (early Callovian) and Alliford formations (early Callovian) (Cameron and Tipper, 1985) (Table 1). Relative to the underlying Yakoun Group, volcanic-derived sediments are a lesser component of the Moresby Group.

The base of the Robber Point is defined by two thin units (< 1m thick) of pebble conglomerate containing well-sorted, well-rounded pebbles separated by a 20 cm thick silty sand layer (Fig. 11a). On Maude Island, Robber Point strata above the pebble layers are poorly exposed (Fig. 4a). Only the upper part of the formation, close to the boundary with the overlying Newcombe Formation, is exposed on the island, and is characterized by friable shales containing a rich and diverse assemblage of bivalves, particularly trigoniid bivalves (i.e. shell hash) (Fig. 11b). Foraminifera from this shale unit consist of a diverse, dominantly calcareous assemblage. The dominant genus is *Reinholdella* accompanied by abundant specimens of *Eoguttulina liassica* and *Pseudonodosaria statuta* and various species of *Lenticulina* and *Astacolus*.

On Moresby Island (Fig. 4b) the base of the Robber Point Formation is also characterized by two pebble conglomerate beds, here overlain by sandstone fining upwards into silty shale towards the top of the formation. Foraminifera abundance and diversity is low and dominated by *Globulina alexandrae*. The assemblage contains a completely silicified component of foraminifera, ostracods and possibly thecamoebians, considered here as reworked from underlying and now missing coastal plain deposits.

On Maude Island, the overlying Newcombe Formation is composed entirely of coarse sandstone, whereas on Moresby Island, where only the upper part of the formation is exposed, it is characterized by siltstone. Large concretionary nodules are abundant on bedding surfaces (Fig. 12) and, on Maude Island, are found concentrated along the basal contact with the Robber Point Formation. Newcombe Formation strata on Moresby Island are abundant in trigoniid bivalves and belemnites and shell fragments of various bivalves are common near the base of the formation. No foraminifera were recovered from the only two samples collected from the sandstone on Maude Island.

The Alliford Formation conformably overlies the Newcombe Formation and is exposed only at Alliford Bay on Moresby Island (type section) (Figs. 3, 4b), where it is defined by friable, poorly laminated shales and siltstones. The Alliford Formation is characterized by the presence of abundant bioturbation (Fig. 13a) and *in situ* trioniid bivalves (Fig. 13b). Bioturbation is more commonly found in the siltstone units where the burrows occur both horizontally on the bedding surface as well as oblique to bedding (e.g. *Zoophycus* structures). U-shaped burrows are also present (Fig. 13c). Shell fragments of bivalves occur throughout the formation. Foraminifera in the Alliford Formation on Moresby Island include more than 40 taxa (Figs. 5, 6d) and calcareous species slightly outnumber agglutinated taxa. Dominant calcareous species are *Reinholdella dreheri*, *Pseudolamarckina liapinensis* and *Astacolus pediacus*, whereas agglutinated taxa include *Haplophragmoides barrowensis*, *Haplophragmoides kingakensis* and *Haplophragmoides* sp. G. The Alliford Formation is not exposed on Maude Island.

Figure 11: Robber Point Formation: a) basal pebbly conglomerate; b) shell debris of bivalves near top of formation (arrows)

Figure 12: Newcombe Formation; concretionary nodules

**Figure 13: Alliford Formation: a) bioturbation;
b) trioniid bivalve; c) U-shaped burrow (arrow)**

6. DISCUSSION

6.1. *Paleoenvironmental Interpretation*

The Jurassic stratigraphy and paleontology of the Queen Charlotte Islands represent a variety of depositional environments ranging from deep-water euxinic shales (upper Kunga and lower Maude groups) to shallow marine sandstones and conglomerates (Yakoun Group) to shelfal mudstones (Moresby Group). A gradual shallowing from a slope- to a shelf-dominated deposition with a magmatic arc provenance is suggested for the Lower Jurassic. Nearshore environments, dominated by sedimentary strata of volcanoclastic origin and associated coeval magmatic arc volcanic and plutonic rocks, characterize Middle Jurassic strata (Haggart et al., 1995). Foraminiferal abundance and diversity are strongly reflected in these lithologies, with greater numbers associated with finer sediments (transgressive phases) and absence or reduced abundances associated with coarser clastic facies (regressive phases) and volcanic strata.

6.1.1. *Upper Kunga Group*

The depositional environment of the Sandilands Formation is interpreted as a deep, partly euxinic back-arc basin (Cameron and Tipper, 1985; Haggart et al., 1995). Fine-grained deposits suggest a low energy environment of continental slope or rise origin. Presence of load casts and graded bedding in sandstone beds reflect episodic proximal and distal turbidity current deposition, possibly in close proximity to the continental slope (Bustin and Mastalerz, 1995; Tipper et al., 1998). Euxinic environmental conditions are inferred by thin, relatively undisturbed laminations and pyrite nodules found near the base of the formation. The scarcity of benthic macrofossils and bioturbation, and rare occurrences of benthic foraminifera, further attest to deep-water, euxinic conditions (Cameron and Tipper, 1985). The light coloured tuff beds interbedded within the turbidites represent possible air-fall deposits from a nearby volcanic source; frequent ash layers would have produced an inhospitable benthic environment (Cameron and Tipper, 1985; Tipper et al., 1991). Silica-rich ashes may also have contributed to enhanced preservation of siliceous pelagic organisms such as radiolarians, which are found in large

numbers in the Sandilands Formation (Cameron and Tipper, 1985), also supporting an offshore setting.

6.1.2. Maude Group

The Maude Group represents various paleodepths from deep to shallow marine environments (Cameron and Hamilton, 1988) linked to eustatic sea-level changes for the Early Jurassic (Cameron and Tipper, 1985). Absence of turbidite beds in the Ghost Creek Formation implies a position on the outer shelf as a result of a slight sea-level fall during the early Pliensbachian (Fig. 14) (Haq et al., 1988). Low energy, offshore conditions are indicated by the presence of ammonites and shale laminae within the siltstone beds (Bustin and Mastalerz, 1995). Partly euxinic conditions most likely prevailed as evident from the scarcity of bioturbation and benthic macrofossils. Depleted oxygen conditions are also reflected in the low diverse assemblage of predominantly small and simple, pyritized calcareous foraminifera (Cameron and Tipper, 1985). Low levels of O_2 inhibit $CaCO_3$ precipitation and result in stunted growth of calcareous foraminifera (Copestake and Johnson, 1981; Boltovskoy et al., 1991), such as seen in species from the Ghost Creek Formation. Oxygen availability increased towards the top of the formation, with continued basin shallowing resulting in thick sandstone beds containing bioturbation and shell fragments (Fig. 4b). Agglutinated foraminiferal taxa also make their first appearance at the top of the formation and appear to be related to regressive phases, corresponding to the influx of coarser clastic sedimentation. Tuff is rare to absent in the Ghost Creek Formation, suggesting deposition more distant from volcanic sources.

The Fannin Formation straddles the Pliensbachian/Toarcian boundary, which is marked by another global sea-level drop (Haq et al., 1988); resultant environments of the Queen Charlotte Islands were middle to inner shelf (Cameron and Tipper, 1985). A shallow, inner shelf environment is inferred by the presence of bioturbation and chamosite oolites. Although chamosite was not observed on Maude and Moresby islands, it is characteristic of the upper beds of the Fannin Formation and is indicative of a shallow marine, high-energy environment such as on the inner shelf (Cameron and Tipper, 1985). Tuffaceous clastics in the Fannin Formation

attest to the presence of distal volcanic sources. Presence of soft-sediment deformation (i.e. load casts) and cross-stratification suggest fast deposition and a high energy regime for the Fannin Formation (Haggart et al., 1995).

Foraminiferal tests remain relatively small in the Fannin Formation, such as observed in the underlying Ghost Creek Formation. Calcareous benthic foraminifera dominate the assemblage, although the number of agglutinated species is greater than in underlying strata (Fig. 5). Species such as *Reophax densa*, and taxa including *Trochammina* and *Ammodiscus*, are also found in Jurassic sections of the Boreal realm, such as in Alaska (Tappan, 1955) and Northwest Territories (Hedinger, 1993); their occurrence on the Queen Charlotte Islands may indicate the southernmost limit of their distribution.

As global sea-level rose again throughout the middle Toarcian (Fig. 14) (Haq et al., 1988), deep-water basinal shales of the Whiteaves Formation were deposited (Cameron and Tipper, 1985; Tipper et al., 1991). The Whiteaves Formation differs from the deep water facies of the Sinemurian Sandilands Formation in that the environment is no longer that of a restricted, partly euxinic basin, but rather, a well-oxygenated one. Volcanic activity is assumed to have ceased at this time, based on the absence of volcanic ash beds (Cameron and Tipper, 1985). The presence of abundant glauconite in the shales is indicative of low sedimentation rates, typical of the middle to outer shelf, with water depths of 200-300 m (Bhalla and Abbas, 1978; Cameron and Tipper, 1985; Boersma, 1998). The highly abundant and diverse foraminiferal assemblage present in the formation, particularly of calcareous taxa, attests to a significant rise in sea-level: times of marine transgression are characterized by new appearances of taxa (i.e. due either to evolutionary and/or migration) as well as an increase in diversity of calcareous species (Copestake and Johnson, 1981). Taxa such as *Ammodiscus orbis*, *Ammobaculites lunaris*, *Nodosaria daedala* and *Dentalina ectadia* are ranging upwards from the underlying Fannin Formation and may indicate species of greater environmental tolerance, in contrast to shorter ranging species, which may be less environmentally adaptable.

The top of the Whiteaves Formation is characterized by an overall foraminiferal decrease, and the appearance and dominance of agglutinated taxa such as *Ammobaculites* (Fig. 6a). In

recent marine sediments, this genus occurs in shallow, brackish waters but may also be found in deep, open marine environments (i.e. continental shelf) in small abundances (Exton, 1978). These changes signal the initial phase of a major sea-level drop recognized during the early Aalenian (Haq et al., 1988), as reflected in the sandstones of the overlying Phantom Creek Formation (Fig. 14).

The late Toarcian to Aalenian Phantom Creek Formation straddles the Lower to Middle Jurassic boundary. Its depositional environment is interpreted as shallow inner shelf as indicated by the coarse nature of the sandstone and the presence of a rich and diverse benthic macrofaunal assemblage (Haggart et al., 1995). Poor foraminiferal representation in comparison to the macrofauna of the Phantom Creek Formation is due either to the difficulty associated with disintegrating the hard sandstones or to the shallow depositional environment leading to the poor development of the microfauna (Cameron and Tipper, 1985).

6.1.3. *Yakoun Group*

The Middle Jurassic (Bajocian) Yakoun Group is characterized by predominantly volcanic rocks deposited in an island arc system (Cameron and Tipper, 1985). Strata are lithologically heterogeneous and were deposited in large part in marine environments, as evident from the interfingering of volcanics with marine clastics (Hunt, 1958). The overall environment of the Middle Jurassic differs from that of the Lower Jurassic in that deposition took place within a fore-arc basin rather than a back-arc basin, as suggested for the Lower Jurassic (Cameron and Tipper, 1985). Global sea-level during the Bajocian was generally higher as compared to the early Aalenian (Fig. 14), a phase of major erosion, although the early Bajocian experienced a renewed sea-level drop (Haq et al., 1988). Sediments of the Graham Island and Richardson Bay formations reflect resulting shoreface deposits.

The transition from the lower shale-tuff/mottled siltstone member to the upper volcanic sandstone/lapilli member of the Graham Island Formation (Table 1) indicates a shallowing upward succession from a deep marine to a shallow marine shelf environment (Cameron and Tipper, 1985; Haggart et al., 1995). The renewal of active volcanism is evident by the presence

of tuff and lapilli. The drop in abundance and diversity of foraminifera across the Lower-Middle Jurassic boundary is a reflection of stressed inner-shelf paleoenvironments, and agglutinated foraminifera resume dominance (Figs. 5, 6c), as seen in the upper volcanic sandstone/lapilli member.

Inhospitable paleoecological conditions are even more evident in the Richardson Bay Formation. Deposition took place in close proximity to a series of volcanic vents as seen by the large breccia nodules and lapilli (Haggart et al., 1995). Sedimentation had to be rapid in order to preserve the lapilli. A shallow, upper shoreface environment is indicated by the presence of large-scale hummocky cross-stratification, coalified wood and bioturbation at the top of the volcanic breccia member. The high-energy regime and coarse-grained and volcanic nature of the Richardson Bay Formation, likely reflecting toxic conditions, results in a poor foraminiferal assemblage (Figs. 5, 6d).

6.1.4. Moresby Group

The late Bathonian to Callovian Moresby Group unconformably overlies the Yakoun Group. Missing strata might have been eroded during a major drop in sea level during late Bathonian time (Haq et al., 1988). As sea level rose again, deposition of the Robber Point, Newcombe and Alliford formations took place, overall indicating a shallow marine basin ranging from upper shoreface to inner shelf environments (Cameron and Tipper, 1985). Initial marine transgression is documented in a pebbly conglomeratic lag at the base of the Robber Point Formation derived from the erosion and reworking of the underlying Yakoun Group (Cameron and Tipper, 1985).

A rich and diverse assemblage of bivalves, pelecypods, and gastropods in the upper shale unit of the Robber Point Formation may reflect a brief transgressive phase establishing favourable conditions for macroorganisms. Periodic storm events produced accumulations of chaotically-oriented benthic macrofauna at the base of the shale units. Sandstones of the Newcombe Formation on Maude Island were deposited under shallow marine conditions within the upper to middle shoreface; the presence of trioniid bivalves and belemnites in these strata

further attests to the shallow environmental conditions. Siltstones of the Newcombe Formation on Moresby Island might reflect a slightly deeper part of the basin. Increased numbers of foraminifera and newly appearing species in the overlying Alliford Formation, well exposed on Moresby Island, also suggest improving marine conditions. The environment was well-oxygenated as evident from the abundant bioturbation, although still of shallow-marine depths, as indicated by an abundance of trioniid bivalves. The presence of common U-shaped burrows and *Zoophycus* structures further confirms this paleo water depth (Collinson and Thompson, 1989).

Integrated paleontological and sedimentological data suggest a variable Early to Middle Jurassic sea-level history for the Queen Charlotte Islands region. Comparisons of the local sea-level curve with the eustatic sea-level curve of Haq et al. (1988) shows a remarkable similarity of the Queen Charlotte Islands region with global sea-level changes, despite its active tectonic history. Foraminiferal faunae in these basins were influenced not only by sea-level changes, but also by local environmental and ecological conditions, driven by volcanic activity and oxygen supply related to various degrees of basin restriction.

6.2. *Paleogeographical Interpretation*

Numerous paleomagnetic studies have been cited to suggest that the Wrangell terrane, including the Queen Charlotte Islands, was situated at equatorial to low temperate latitudes (i.e. near present-day Mexico) during the late Triassic (summarized in Haggart et al., 1995): paleomagnetism of Triassic Nikolai Greenstone basalts in south-central Alaska, a part of the Wrangell terrane, indicates a southern origin within 15°E of the paleoequator (Hillhouse, 1977; Jones et al., 1977).

Significant displacement of terranes along the west coast of North America has also been inferred from fossil biogeographic data. Large-scale tectonic displacements have been invoked to explain the observed juxtaposition of Permian warm water and cool water fusulinid foraminiferal faunae of southwest British Columbia (Monger and Irving, 1980). Triassic ammonites and radiolarians from the Queen Charlotte Islands and from the western Cordillera

(i.e. Vancouver Island) display a Tethyan influence and are indicative of warm water conditions in close proximity to the paleoequator, in contrast to contemporary faunae of cratonic North America (Cameron and Tipper, 1985). On the Queen Charlotte Islands, Early Jurassic macrofauna and radiolarians of both Tethyan and Boreal affinities have been found in the same beds (Smith and Tipper, 1996) and Lower Jurassic ammonite faunae of the islands are more closely related to faunae from southern Europe, North Africa and South America than to those from northern Europe and cratonic North America, where boreal species dominate (Carter et al., 1988). Lower Jurassic radiolarians are similar to Tethyan assemblages from west-central coastal North America (i.e. California, east-central Oregon) and the Mediterranean (Pessagno and Whalen, 1982; Carter et al., 1988).

Interpretations of Cordilleran history based on paleomagnetic and paleobiogeographic data diverge after the Early Jurassic, however. Several distinct paleomagnetic data sets, from plutonic, volcanic and sedimentary rocks of the western Canadian Cordillera, suggest that the Wrangell terrane, and Queen Charlotte Islands, were still situated in Tethyan latitudes during mid-Cretaceous time, as much as 3000 km south of their present position (Irving et al., 1985; Umhoefer, 1987; Irving and Wynne, 1990; Irving et al., 1996; Ward et al., 1997).

In contrast to the paleomagnetic evidence, however, late Early Jurassic to early Middle Jurassic ammonite and radiolarian faunae from the Queen Charlotte Islands show a gradual change from predominantly Tethyan to Boreal compositions (Smith and Tipper, 1986; Poulton et al., 1991). Furthermore, Lower Cretaceous ammonite, radiolarian and foraminiferal faunae of the islands display temperate to boreal affinities, suggesting that the Wrangell terrane had already arrived at approximately its present position prior to the Cretaceous (Haggart and Carter, 1993; Dalby, 1997).

Jurassic foraminiferal faunae of the Queen Charlotte Islands can contribute to an improved and refined understanding of biogeographic affinities of Mesozoic faunae of the Wrangell terrane. Planktonic foraminifera are the most reliable foraminiferal types useful for paleolatitude determination. Unfortunately, such types are lacking in the Queen Charlotte Islands foraminiferal assemblages and comparisons must be based on benthic taxa, which tend to be

more dependant on facies and bottom water oxygen conditions. Another constraint is the limited number of taxonomic studies for Jurassic foraminifera of the western Tethyan region. This study also has yielded a considerable number of unidentified species, which may represent taxa endemic to this region. Although further work is clearly needed to examine Jurassic foraminiferal assemblages in adjacent regions, several important biogeographic trends are evident from this initial study of Queen Charlotte Islands faunae.

Significant changes in Jurassic benthic foraminiferal assemblages of the Queen Charlotte Islands, as indicated by numerous first appearance datums, occur within: 1) the middle Toarcian (middle Whiteaves Formation); 2) the late Toarcian to Aalenian (basal Phantom Creek Formation); 3) the lower Bajocian (within the Graham Island Formation); and 4) in the upper Bajocian to lower Callovian (basal Alliford Formation) (Figs. 6a-6d). These faunal changes correlate roughly with facies changes, which are closely linked to the sea-level history of the region, as well as other paleoenvironmental factors, such as volcanic input (Fig. 14). For example, the dominance of agglutinated foraminifera in the Graham Island Formation (Fig. 5) appears to be correlated with basin shallowing, resulting in deposition of sandstones. Owing to these problems, it is difficult to link the faunal changes solely to change in paleolatitudes.

Still, Lower Jurassic foraminiferal assemblages found in the Ghost Creek, Fannin and Whiteaves formations show strong similarities with foraminiferal assemblages from the Tethyan region (e.g. Portugal, Egypt and India; Exton, 1978; Said and Barakat, 1958; Bhalla and Abbas, 1978, respectively). Species common to all these areas include *Nodosaria mitis*, *Dentalina pseudocommunis*, *Nodosaria simplex* and *Lenticulina muensteri*, suggesting a significant Tethyan influence on the Queen Charlotte Islands faunae during the Early Jurassic, and confirming interpretations derived from ammonites and radiolarians. In contrast, latest Early Jurassic (Toarcian) foraminiferal assemblages of the Whiteaves Formation include numerous species reported from Sinemurian to Pliensbachian strata of Alaska, as reported by Tappan (1955) (Fig. 15). There, many species seem to disappear in the earliest Toarcian, although core coverage was poor. The presence of these species suggest an additional faunal component, typical of the

Boreal realm, at the time of Whiteaves Formation deposition and the formation consequently includes a mixed foraminiferal faunae of both Boreal and Tethyan indicators.

Biogeographic studies of ammonites of Alaska and other regions of the globe indicate that significant differentiation of Jurassic faunae into Tethyan and Boreal associations developed during the late Pliensbachian, suggesting that faunal change was gradational and spanned a considerable amount of time (Smith and Tipper, 1986; Imlay and Detterman, 1973). Indeed, Middle Jurassic ammonite faunae of the Queen Charlotte Islands suggest a gradual change to boreally-influenced assemblages (Smith and Tipper, 1986; Poulton et al., 1991). Middle Jurassic foraminiferal faunae of the islands show significant decreases in both specimen abundance and species diversity, as seen in the assemblages from the Phantom Creek and Graham Island formations. These observed foraminiferal changes could result from transport of the Wrangell terrane to high latitudes during Early Jurassic time; alternatively, they could result from the change to a shoreface depositional environment, as such environments are somewhat inhospitable to benthic foraminifera, as noted above. Although the general trends are significant, accurate dating of the time of amalgamation of the Wrangell terrane with cratonic North America based on analysis of foraminiferal assemblages remains questionable.

Figure 14: Simplified composite section for the Queen Charlotte Islands depicting relations of facies changes with respect to eustatic sea-level changes (sea-level curve modified after Haq et al., 1988)

Figure 15: Biostratigraphic ranges of selected foraminifera from the Queen Charlotte Islands (black) and Arctic Slope of Alaska (grey) (after Tappan, 1955)

6.3. Comparative Biostratigraphic Studies with other Jurassic Localities

Abundant literature exists on Jurassic foraminiferal assemblages of various regions; most of these studies, however, concentrate on the Upper Jurassic whereas little is known of the Lower and Middle Jurassic. Comparisons between the Lower to Middle Jurassic foraminiferal assemblages of the Queen Charlotte Islands and selected other areas show that numerous benthic species have long biostratigraphic ranges, spanning the entire Jurassic, and had cosmopolitan distributions.

6.3.1. Grand Banks, Newfoundland

Gradstein (1978) and Exton and Gradstein (1984) studied Jurassic foraminifera from the Grand Banks region of Newfoundland; these assemblages have distinct similarities with those of the Queen Charlotte Islands, particularly of the Lower Jurassic. Taxa in common between the two areas include *Lenticulina tricarinella*, *Lenticulina d'orbignyi*, *Lingulina tenera* and *Eoguttulina liassica*. *Lenticulina d'orbignyi*, for example, is restricted to the Lower Jurassic Toarcian-Aalenian on the Grand Banks and to the middle Toarcian (Whiteaves Formation) in this study. These species have also been reported from Jurassic sections of Portugal, suggesting a Tethyan influence on both margins of the initial Atlantic basin (Exton and Gradstein, 1984), and confirming the Tethyan influence on the Queen Charlotte Islands during the Early Jurassic.

6.3.2. Tethyan Region

Jurassic Tethyan foraminiferal studies for Callovian-Oxfordian (Middle to Upper Jurassic) strata of India (Bhalla and Abbas, 1978), Bajocian-Kimmeridgian (Middle-Upper Jurassic) strata of Egypt (Said and Barakat, 1958) and Pliensbachian-Toarcian (Lower Jurassic) strata of Portugal (Exton, 1978) document dominantly calcareous taxa, many of which are found in the Lower Jurassic of the Queen Charlotte Islands. These include:

Nodosaria hortensis
Nodosaria mitis
Nodosaria simplex
Nodosaria regularis
Astacolus varians
Astacolus stillus
Astacolus dubius
Marginulina prima

Dentalina pseudocommunis
Dentalina sinemuriensis
Dentalina exilis
Dentalina terquemi
Lenticulina prima
Lenticulina d'orbignyi
Lenticulina toarcense
Eoguttulina liassica

Lingulina tenera

Species such as *Lenticulina muensteri*, *Lenticulina varians*, *Dentalina pseudocommunis*, and *Eoguttulina liassica* appear to be cosmopolitan, as they have also been found in the Boreal realm of northwestern Europe (Copestake and Johnson, 1981) and Alaska (Tappan, 1955).

In the Lower Jurassic of Portugal, a distinct change in taxa is evident between the Pliensbachian and Toarcian intervals and has been attributed to a faunal extinction and renewal event at the Pliensbachian-Toarcian boundary, resultant from a worldwide transgressive event (Exton, 1978). This event correlates with the major increase in foraminiferal diversity and abundance within the middle Toarcian Whiteaves Formation on the Queen Charlotte Islands.

6.3.3. Northwestern Europe

Callovia (Middle Jurassic) foraminifera of Scotland were studied by Gordon (1967), and Copestake and Johnson (1981) and Coleman (1981) have presented a detailed study of Lower and Middle Jurassic foraminifera of England, respectively. A comparison between Jurassic assemblages of Scotland and England shows that Middle Jurassic faunas from Scotland resemble Upper Jurassic faunas from England. Many of the taxa which are shared by the Jurassic of England and the Queen Charlotte Islands are cosmopolitan, and over 90% of the common taxa between England and the Queen Charlotte Islands are comprised of calcareous species, of which a majority belongs to the Nodosariidae family.

6.3.4. Arctic region

Mesozoic foraminiferal studies have been conducted for the eastern Sverdrup Basin (Wall, 1983) and for the Linckens Island, Canadian Arctic Archipelago (Souaya, 1976). Although Boreal taxa dominate at both localities, their Jurassic foraminiferal successions differ significantly (Wall, 1983). Several of the shared taxa (i.e. *Haplophragmoides barrowensis*, *Haplophragmoides tryssa*, *Ammobaculites vetusta*, *Ammodiscus cheradospirus*) are also characteristic of the Middle Jurassic of the Queen Charlotte Islands. Assemblages from the Queen Charlotte Islands and Linckens Island have a large number of species in common, including:

<i>Lenticulina muensteri</i>	<i>Haplophragmoides topagorukensis</i>
<i>Lenticulina audax</i>	<i>Haplophragmoides barrowensis</i>
<i>Vaginulinopsis enodis</i>	<i>Haplophragmoides tryssa</i>
<i>Marginulina utricula</i>	<i>Trochammina sablei</i>
<i>Marginulina pletha</i>	<i>Saccammina lathrami</i>
<i>Eoguttulina liassica</i>	<i>Ammobaculites alaskensis</i>
<i>Dentalina subtenuicollis</i>	<i>Ammobaculites barrowensis</i>
<i>Dentalina pseudocommunis</i>	<i>Ammobaculites venustus</i>
<i>Dentalina exilis</i>	<i>Ammobaculites vetustus</i>
<i>Nodosaria setulosa</i>	<i>Ammodiscus cheradospirus</i>
<i>Nodosaria regularis</i>	<i>Ammodiscus orbis</i>
<i>Vaginulina sherboni</i>	<i>Lituotuba irregularis</i>
<i>Astacolus pediacus</i>	<i>Bathysiphon anomalocoelia</i>
<i>Astacolus dubius</i>	
<i>Pseudonodosaria brandi</i>	

6.3.5. Alaska

Tappan (1955) examined Lower Jurassic (Sinemurian to Toarcian) foraminifera from the northern Arctic slope of Alaska, among which 41 species occur also on the Queen Charlotte Islands. The Boreal assemblage contains a predominantly diverse, agglutinated foraminiferal assemblage. The late Pliensbachian to early Toarcian is characterized by a dominance of calcareous species. This faunal change in Alaska is comparable to a slightly younger change within the middle Toarcian Whiteaves Formation.

6.3.6. Northwest Territories

Late Jurassic (Oxfordian-Volgian) foraminifera of the Aklavik Range, Northwest Territories, were examined by Hedinger (1993), who recognized a predominance of agglutinated taxa. Several species, found in the Lower to Middle Jurassic of the Queen Charlotte Islands, range into the Upper Jurassic in the Aklavik Range, indicating long biostratigraphic ranges for these species (Fig. 16).

6.3.7. Western Interior of North America

Jurassic foraminifera from the Western Interior of North America have been reported from northeastern British Columbia and Alberta (Brooke and Braun, 1981), the Oxfordian Redwater Shale of South Dakota (Upper Jurassic) (Loeblich and Tappan, 1950) and from Saskatchewan (Middle to Upper Jurassic) (Wall, 1960; Brooke and Braun, 1972). South Dakota and Saskatchewan have a few calcareous taxa such as *Citharinella exarata*, *Citharinella rhomboidea*,

Citharina entypomatus, *Vaginulina compsa*, *Nodosaria daedala* and *Lingulina micida* in common with the Queen Charlotte Islands. Their ranges span over the entire Jurassic.

Rising global sea level during the Middle Jurassic allowed the cratonic Sundance Sea to locally breach the western North America Cordillera (Lemon, 1993), allowing faunal exchange between the Pacific margin and the interior. The Sundance Sea is believed to have extended as far east as Saskatchewan and South Dakota (Lemon, 1993) after the subsidence of the Sweetgrass Arch during the late Middle Jurassic (Brooke and Braun, 1972). This shallow marine basin extended as far north as Alaska, explaining the wide distribution of Jurassic foraminifera in western North America.

Figure 16: Biostratigraphic ranges of selected foraminifera from the Queen Charlotte Islands (black) and Aklavik Range, Northwest Territories (grey) (after Hedinger, 1993)

7. CONCLUSIONS

The Queen Charlotte Islands, British Columbia, are an important cornerstone of circum-Pacific correlations due to their unique biogeographical assemblages. Paleontological work in Jurassic strata to date has focused primarily on macrofossil (e.g. ammonites and trigoniid bivalves) and radiolarian assemblages, with only minor contributions from foraminiferal studies. Integration of Lower and Middle Jurassic foraminiferal studies of the Queen Charlotte Islands with existing data has resulted in the following conclusions:

1. The Jurassic sections on the Queen Charlotte Islands expose marine sedimentation associated with an island arc system. Basins experienced various degrees of restriction and volcanic input influencing benthic foraminiferal faunae. A variety of depositional environments ranging from deep-water euxinic shales to shallow marine sandstones and conglomerates are represented by the Jurassic strata and their faunal components. A gradual shallowing from a slope- to a shelf-dominated deposition, with a magmatic arc provenance is suggested for the Lower Jurassic and a nearshore environment (i.e. inner shelf to upper shoreface) dominated by sedimentary strata of volcanoclastic origin is suggested for the Middle Jurassic.
2. Over 200 species of well preserved benthic calcareous and agglutinated foraminifera representing both Tethyan and Boreal affinities were identified from Sinemurian to Callovian aged strata. The Lower Jurassic contains a highly abundant and diverse assemblage of predominantly calcareous taxa dominated by Nodosariids, with diverse agglutinated taxa becoming dominant in the late Lower Jurassic to early Middle Jurassic.
3. Foraminiferal abundances and composition are related to paleoenvironmental changes depending on sea level, input of volcanic material and basin restriction. Open distal shelf conditions without volcanic influence, as reflected in the middle Toarcian Whiteaves Formation, experience a significant increase in foraminiferal faunae (over 200 species) as response to a eustatic sea-level rise. Reduced numbers are observed in shoreface settings of the lower Bajocian Richardson Bay and upper Bajocian to lower Callovian Robber Point

formations. Deep water settings with considerable input of ash falls (tuff beds) as seen in the Sinemurian Sandilands Formation, seem to be inhospitable for benthic foraminifera.

4. Jurassic foraminiferal assemblages of the Queen Charlotte Islands are composed of: a) cosmopolitan species; b) taxa typical of Boreal and Tethyan regions; and c) a number of species left in open nomenclature, possibly of endemic nature. Based on comparisons to other regions, certain species are long-ranging throughout the entire Jurassic. A detailed taxonomic approach is needed to revisit this material to identify all existing taxa and describe new species. Future establishment of a biostratigraphic zonation for the west coast will then facilitate regional correlations along the Jurassic Cordillera.
5. Numerous Lower Jurassic foraminifera (Pliensbachian to lower Toarcian) of the Queen Charlotte Islands are widespread within the Tethyan region. Boreally derived taxa, as found in Alaska and Northwest Territories, gradually enter the assemblage during the middle Toarcian supporting macrofossil and radiolarian evidence for a northward displacement of the Wrangell terrain at that time. Faunal response, however, to changing paleolatitudes may be overprinted by sea-level change as global sea-level significantly dropped at the beginning of the Middle Jurassic.

FORAMINIFERAL REFERENCE LIST

The following list includes original references and, in some cases, a more recent reference of each identified species. Several genera were highly diverse and specimens were distinguished on a basis of open nomenclature by marking the species with a letter (see Appendices 3 and 4). These taxa include *Ammobaculites*, *Ammodiscus*, *Astacolus*, *Bathysiphon*, *Citharina*, *Citharinella*, *Dentalina*, *Eoguttulina*, *Fronicularia*, *Globulina*, *Haplophragmoides*, *Lenticulina*, *Lingulina*, *Marginulina*, *Miliammina*, *Nodosaria*, *Pseudonodosaria*, *Reinholdella*, *Trochammina*, *Vaginulina* and *Vaginulinopsis*. This method allows for a more detailed taxonomic approach in the future with descriptions of possibly new species.

Ammobaculites aklavikensis Hedinger, 1993, p. 51-52, pl. 13, figs. 1-10

Ammobaculites alaskensis Tappan subsp., 1955, p. 45, pl. 12, figs. 1, 4, 5, 8, 9
Hedinger, 1993, p. 52-53, pl. 11, figs. 1-4, 7-10

Ammobaculites barrowensis Tappan, 1955, p. 45, pl. 11, figs. 7-12

Ammobaculites canoensis Hedinger, 1993, p. 55, pl. 14, figs. 16-19

Ammobaculites lunaris Hedinger, 1993, p. 55-56, pl. 11, figs. 15-26
= *Ammobaculites* cf. *A. alaskensis* Tappan in: Brooke and Braun, 1981, p. 16, pl. 4, figs. 9-11

Ammobaculites magnus Hedinger, 1993, p. 56, pl. 13, figs. 17-20
= *Ammobaculites* sp. A Souaya, 1976, p. 269, pl. 7, fig. 7; pl. 12, fig. 10

Ammobaculites multiformis Dain in : Dain et al., 1972, p. 63, pl. XVI, figs. 5-8
Hedinger, 1993, p. 58, pl. 12, figs. 7-20

Ammobaculites toughenoughensis Hedinger, 1993, p. 56-57, pl. 13, figs. 11-16
= *Ammobaculites* sp. cf. Souaya, 1976, p. 268, pl. 10, fig. 11

Ammobaculites venustus Loeblich and Tappan, 1950, p. 42, pl. 11, figs. 7, 8
Hedinger, 1993, p. 59, pl. 16, figs. 1-6

Ammobaculites vetusta (Terquem and Berthelin) = *Haplophragmium vetustum* Terquem and Berthelin, 1875, p. 53, pl. 4, figs. 16a-d
Tappan, 1955, p. 45-46, pl. 13, figs. 1-3

Ammobaculoides rickyouni Hedinger, 1993, p. 60-61, pl. 16, figs. 13-18

Ammodiscus cheradospirus Loeblich and Tappan, 1950, p. 6, pl. 1, figs. 1, 2
Hedinger, 1993, p. 25-26, pl. 2, figs. 1-4

Ammodiscus francisi (Wall) = *Involutina francisi* Wall, 1960
Hedinger, 1993, p. 27, pl. 1, figs. 12-18

- Ammodiscus orbis* Lalicker, 1950, p. 11, pl. 1, fig. 2
Hedinger, 1993, p. 27-28, pl. 1, figs. 19-24
- Ammodiscus richardsonensis* Hedinger, 1993, p. 28-29, pl. 2, figs. 8-12; pl. 3, fig. 1
=*Involutina silicea* Terquem in: Loeblich and Tappan, 1953, p. 310, fig. 2
- Arenoturrispirillina waltoni* Chamney, 1971, p. 104, pl. 17, fig. 7; pl. 18, fig. 1
Hedinger, 1993, p. 29, pl. 3, figs. 2-6
- Astacolus agalmatus* Loeblich and Tappan, 1950, p. 44, pl. 12, figs. 5a-7
- Astacolus aphrastus* Loeblich and Tappan, 1950, p. 45, pl. 12, figs. 1-4
- Astacolus arietis* (Terquem) = *Cristellaria arietis* Terquem, 1866, p. 510, pl. 21, fig. 30
Tappan, 1955, p. 55, pl. 19, figs. 1-5
- Astacolus calliopsis* Tappan, 1955, p. 55, pl. 17, figs. 12-17
- Astacolus dubius* (Franke) = *Cristellaria dubia* Franke, 1936, p. 107, pl. 10, fig. 17
Tappan, 1955, p. 56, pl. 18, figs. 5-9
- Astacolus pauperatus* (Jones and Parker) = *Planularia pauperata* Jones and Parker, 1860, p. 454, pl. 20, fig. 39
Bhalla and Abbas, 1978, p. 176, pl. 5, figs. 3-4
- Astacolus pediacus* Tappan, 1955, p. 56-57, pl. 17, figs. 1-10
- Astacolus pellucida* Said and Barakat, 1958, p. 247, pl. 3, fig. 18; pl. 5, fig. 36
- Astacolus stillus* (Terquem) = *Cristellaria stilla* Terquem, 1866, p. 517, pl. 22, fig. 7
Exton, 1978, p. 164-166, pl. 2, fig. 7; pl. 4, figs. 14-16
- Astacolus varians* (Bornemann) = *Cristellaria varians* Bornemann, 1854, p. 41, pl. 4, figs. 32, 34
Exton, 1978, p. 166-169, pl. 2, fig. 4; pl. 4, fig. 12
- Bathysiphon anomalocoelia* Tappan, 1955, p. 35, pl. 7, figs. 1-3
- Bigenerina* sp. A
- Brizalina* sp. A
- Bulbobaculites pokrovkaensis* (Kosyrev) = *Haplophragmium pokrovkaensis* Kosyrev in: Dain et al., 1972, p. 68, pl. XVIII, figs. 1-5
Hedinger, 1993, p. 62, pl. 15, figs. 18-24
- Bulbobaculites willowensis* Hedinger, 1993, p. 62-63, pl. 15, figs. 1-6
- Bulbobaculites* sp. A
- Bullopora globulata* Barnard, 1950, p. 378, fig. 1e
Exton, 1978, p. 238, pl. 5, fig. 16
- Citharina callomoni* Hedinger, 1993, p. 84, pl. 24, figs. 17-23
- Citharina entypomatus* Loeblich and Tappan, 1950, p. 57, pl. 15, figs. 1-12

- Citharina fallax* (Payard) = *Pseudocitharina fallax* Payard. 1947. pl. 5. figs. 1-4
Tappan, 1955, p. 79, pl. 28, figs. 1-10
- Citharina flabellata* (Gümbel) = *Marginulina flabellata* Gümbel, 1862, p. 223, pl. 3, fig. 24
Gordon, 1967, p. 454, pl. 2, figs. 19-22
- Citharinella exarata* Loeblich and Tappan, 1950, p. 58, pl. 16, figs. 4-8
- Citharinella rhomboidea* Loeblich and Tappan, 1950, p. 58, pl. 16, figs. 1-3b
- Conorbina* sp. A
- Dentalina bartensteini* Tappan, 1955, p. 65-66, pl. 21, fig. 28
- Dentalina ectadia* Loeblich and Tappan, 1950, p. 47, pl. 13, figs. 3-5
Tappan, 1955, p. 66, pl. 21, fig. 11
- Dentalina ejuncida* Loeblich and Tappan, 1950, p. 48, pl. 13, figs. 9-11
Hedinger, 1993, p. 85-86, pl. 26, figs. 13, 32
- Dentalina exilis* Franke, 1936, p. 31, pl. 2, fig. 25
Tappan, 1955, p. 66, pl. 23, figs. 5-7
- Dentalina guembeli* Schwager, 1865, p. 101, pl. 2, fig. 2
Bhalla and Abbas, 1978, p. 178-179, pl. 7, fig. 4
- Dentalina pseudocommunis* Franke, 1936, p. 30, pl. 2, figs. 20a-b
Tappan, 1955, p. 66-67, pl. 21, figs. 29-33
- Dentalina sinemuriensis* Terquem, 1866, p. 405, pl. 15, figs. 6a-d
Said and Barakat, 1958, p. 254, pl. 2, fig. 23; pl. 5, fig. 8
- Dentalina subtenuicollis* Franke, 1936, p. 32, pl. 2, figs. 29a-b
Tappan, 1955, p. 67, pl. 21, figs. 26-27
- Dentalina terquemi* d'Orbigny, 1850, p. 242
Tappan, 1955, p. 68, pl. 23, figs. 1-4
- Dentalina vetustissima* d'Orbigny in : Terquem, 1858, p. 600, pl. 2, fig. 8
Said and Barakat, 1958, p. 254, pl. 3, fig. 28; pl. 5, fig. 6
- Dentalina vulgata* Hedinger, 1993, p. 85, pl. 26, figs. 24-29
- Eoguttulina liassica* Strickland, 1846
Brooke and Braun, 1981, p. 32, pl. 8, figs. 4-6
- Eoguttulina metensis* (Terquem) = *Polymorphina metensis* Terquem, 1864, p. 301, pl. 13, figs. 38a-b
Tappan, 1955, p. 83, pl. 28, figs. 15-16
- Epistomina parastelligera* Hofker, 1954, p. 180, text-figs. 4-6
Said and Barakat, 1958, p. 267, pl. 3, fig. 43; pl. 5, figs. 35a-c
- Falsopalmula antrorsa* Loeblich and Tappan, 1950, p. 57, pl. 15, figs. 13a-b

Fronicularia lustrata Tappan, 1951, p. 2, pl. 1, figs. 3-4
Tappan, 1955, p. 80-81, pl. 27, figs. 11-19

Fronicularia squamosa Terquem and Berthelin, 1875, p. 37, pl. 3, figs. 3a-b
Tappan, 1955, p. 81, pl. 27, figs. 8-9

Geinitzinita sp. A

Globulina alexandrae Dain, 1972, p. 148, pl. 44, figs. 7, 8
Brooke and Braun, 1981, p. 32, pl. 8, figs. 7-18

Glomospira sp. A

Haplophragmoides barrowensis Tappan, 1951, p. 1, pl. 1, figs. 5a-b
Tappan, 1955, p. 42, pl. 11, figs. 1-5

Haplophragmoides kingakensis Tappan, 1955, p. 43, pl. 10, figs. 1-6

Haplophragmoides tryssa Loeblich and Tappan, 1950, p. 41, pl. 11, figs. 2a-b
Tappan, 1955, p. 38-39, pl. 6, figs. 4-17

Heterohelix sp. A

Involutina silicea Terquem, 1862, p. 450, pl. 6, figs. 11a, b
Tappan, 1955, p. 39, pl. 9, figs. 1-4

Involutina sp. A

Labrospira freboldi Hedinger, 1993, p. 41, pl. 8, figs. 1-9, 13, 14

Labrospira sp. A

Lenticulina audax Loeblich and Tappan, 1950, p. 53, pl. 11, figs. 18-21
Hedinger, 1993, p. 89, pl. 25, figs. 6-8

Lenticulina d'orbignyi (Roemer) = *Peneroplis d'orbignyi* Roemer, 1839, p. 47, pl. 20, fig. 31
Exton, 1978, p. 201-202, pl. 6, fig. 10

Lenticulina excavata (Terquem) = *Cristellaria excavata* Terquem, 1864, p. 418, pl. 10, figs. 2a-b
Tappan, 1955, p. 52, pl. 16, figs. 4-7

Lenticulina lauta Dain, 1972, p. 122, pl. XXXVII, fig. 1
Hedinger, 1993, p. 89-90, pl. 25, figs. 20-23

Lenticulina muensteri (Roemer) = *Robulina muensteri* Roemer, 1839, p. 48, pl. 20, fig. 29
Said and Barakat, 1958, p. 248, pl. 1, fig. 10; pl. 3, fig. 25; pl. 4, fig. 35

Lenticulina prima (d'Orbigny) = *Cristellaria prima* d'Orbigny, 1850, p. 242
Tappan, 1955, p. 52-53, pl. 16, figs. 8-11

Lenticulina subalata (Reuss) = *Cristellaria subalata* Reuss in : Bartenstein and Brand, 1937, p. 176, pl. 6, fig. 35a-c; pl. 9, fig. 54a-c; pl. 10, fig. 41a-b; pl. 11A, fig. 15a-b; pl. 11B, fig. 22a-b; pl. 12A, fig. 18a-c; pl. 12B, fig. 16; pl. 13, fig. 38a-c; pl. 14B, fig. 16a-b; pl. 15A, fig. 35a-b
Said and Barakat, 1958, p. 250, pl. 1, fig. 11; pl. 2, fig. 18; pl. 3, fig. 22; pl. 4, fig. 26

- Lenticulina suturifusus* Bhalla and Abbas, 1978, p. 181, pl. 6, figs. 7-8; pl. 10, figs. 5-10
- Lenticulina toarcense* Payard, 1947, p. 88, pl. 7, fig. 1
Tappan, 1955, p. 53, pl. 15, figs. 1-9
- Lenticulina tricarinnella* (Reuss) = *Cristellaria tricarinnella* Reuss, 1863, p. 68, pl. 7, fig. 9; pl. 12, figs. 2-4
Bhalla and Abbas, 1978, p. 181-182, pl. 6, fig. 9; pl. 11, figs. 1-6
- Lenticulina varians* (Bornemann) = *Cristellaria varians* Bornemann, 1854, p. 41, pl. 4, figs. 32-34
Tappan, 1955, p. 53-54, pl. 18, fig. 1
- Lingulina ampliata* Loeblich and Tappan, 1950, p. 50, pl. 13, figs. 25a-26b
- Lingulina camerata* Loeblich and Tappan, 1950, p. 50, pl. 13, figs. 28a-b
- Lingulina lanceolata* (Haeüßler) = *Fronicularia lanceolata* Haeüßler, 1881, p. 18, pl. 2, fig. 3
Tappan, 1955, p. 75-76, pl. 27, figs. 5-6
- Lingulina polita* Tappan, 1955, p. 76, pl. 27, figs. 1-2
- Lingulina tenera* Bornemann, in: Macfadyen, 1941, p. 51, pl. 3, figs. 52a-b
Exton, 1978, p. 227-228, pl. 5, fig. 10
- Lituotuba irregularis* Tappan, 1955, p. 41, pl. 9, figs. 5-9
- Marginulina demissa* (Terquem and Berthelin) = *Nodosaria variabilis* Terquem and Berthelin, 1875, p. 20, pl. 1, figs. 19a-f
Tappan, 1955, p. 59, pl. 18, figs. 15-20
- Marginulina haynesi* Bhalla and Abbas, 1978, p. 182-183, pl. 7, figs. 5-6, pl. 11, figs. 7-9
- Marginulina interrupta* Terquem, 1866, p. 426, pl. 17, figs. 4a-c
Tappan, 1955, p. 59-60, pl. 20, figs. 17-25
- Marginulina pletha* Tappan, 1955, p. 60, pl. 18, figs. 10-11
- Marginulina prima* d'Orbigny, 1850, p. 242
Tappan, 1955, p. 60-61, pl. 20, figs. 1-13
- Marginulina thuringica* (Franke) = *Cristellaria thuringica* Franke, 1936, p. 103, pl. 10, figs. 7a-b
Tappan, 1955, p. 63, pl. 21, figs. 12-22
- Marginulina utricula* Terquem and Berthelin, 1875, p. 55, pl. 4, fig. 20
Tappan, 1955, p. 63-64, pl. 21, figs. 1-10
- Marginulina woodi* Bhalla and Abbas, 1978, p. 183, pl. 7, figs. 8-9
- Mesodentalina* sp. A
- Neobulimina* sp. A
- Nodosaria daedala* Loeblich and Tappan, 1950, p. 45, pl. 13, figs. 18-19
Bhalla and Abbas, 1978, p. 174, pl. 4, fig. 9

- Nodosaria detruncata* Schwager, 1867, p. 656, pl. 34, fig. 7
Tappan, 1955, p. 69-70, pl. 26, figs. 19-20
- Nodosaria hortensis* Terquem, 1866, p. 476, pl. 19, fig. 13
Exton, 1978, p. 145-146, pl. 1, fig. 8
- Nodosaria marginata* Marsson, 1878, p. 126, pl. 1, figs. 5a-b
Bhalla and Abbas, 1978, p. 175, pl. 4, fig. 13
- Nodosaria mecista* Loeblich and Tappan, 1950, p. 49-50, pl. 13, figs. 17, 20-22
- Nodosaria metensis* Terquem in: Franke, 1936, p. 74, pl. 4, fig. 15a-c
Said and Barakat, 1958, p. 255, pl. 1, fig. 30; pl. 5, fig. 20
- Nodosaria mitis* (Terquem and Berthelin) = *Dentalina mitis* Terquem and Berthelin, 1875, p. 28, pl. 2, figs. 9a-c
Tappan, 1955, p. 70, pl. 24, figs. 11-18
- Nodosaria phobytica* Tappan, 1955, p. 71-72, pl. 24, figs. 8-10
- Nodosaria radiata* (Terquem) = *Dentalina radiata* Terquem, 1866, p. 490, pl. 20, figs. 5a-b
Tappan, 1955, p. 72, pl. 25, figs. 1-5
- Nodosaria regularis* Terquem, 1862, p. 436, pl. 5, fig. 12
Tappan, 1955, p. 72-73, pl. 26, figs. 7-9
- Nodosaria setulosa* Tappan, 1955, p. 73, pl. 24, figs. 1-5
- Nodosaria simplex* Terquem in: Franke, 1936, p. 44, pl. 4, fig. 6
Said and Barakat, 1958, p. 255, pl. 2, fig. 29; pl. 5, fig. 9
- Planularia anceps* (Terquem) = *Cristellaria anceps* Terquem, 1870, p. 428, pl. 9, figs. 11-21
Gordon, 1967, p. 452, pl. 4, figs. 15-20
- Planularia fraasi* Schwager in: Gordon, 1961, p. 529, text fig. 2 (7a, b)
Hedinger, 1993, p. 94, pl. 24, figs. 12-16
- Planularia striata* (Issler) = *Cristellaria crepidula* Issler, 1908, p. 82, pl. 5, fig. 265; pl. 6, figs. 266-268
Tappan, 1955, p. 78, pl. 26, fig. 21
- Pseudolamarckina liapinensis* Dain, 1972, p. 169, pl. LII, figs. 1-6; pl. LIII, figs. 1, 2; pl. LV, figs. 1, 9
Hedinger, 1993, p. 103, pl. 28, figs. 1-8
- Pseudonodosaria brandi* (Tappan) = *Rectoglandulina brandi* Tappan, 1955, p. 74, pl. 26, fig. 12
Hedinger, 1993, p. 94-95, pl. 26, figs. 9, 10
- Pseudonodosaria sowerbyi* (Schwager) = *Nodosaria sowerbyi* Schwager, 1867, p. 656, pl. 34, fig. 8
Gordon, 1967, p. 453-454, pl. 4, figs. 9-11
- Pseudonodosaria statuta* Hedinger, 1993, p. 95, pl. 26, figs. 1-6
- Ramulina* sp. A

Rectoglandulina oviformis (Terquem) = *Glandulina oviformis* Terquem, 1864, p. 378, pl. 7, figs. 4a-b

Tappan, 1955, p. 74-75, pl. 26, fig. 13

Recurvoides decoris Hedinger, 1993, p. 46, pl. 9, figs. 23, 24

Reinholdella dreheri Brotzen, 1948, p. 126, *241

Leoblich and Tappan, 1964, p. C776, fig. 637

Reophax densa Tappan, 1955, p. 35-36, pl. 8, figs. 1-6

Reophax suevica Franke, 1936, p. 19, pl. 1, fig. 19

Tappan, 1955, p. 37-38, pl. 7, figs. 7-10

Reophax sp. A

Saccammina lathrami Tappan, 1960, p. 289, pl. 1, figs. 1, 2; pl. 29, figs. 9-12

Hedinger, 1993, p. 22-24, pl. 1, figs. 7-10

Saccammina sp. A

Saturnella brookeae Hedinger, 1993, p. 33-34, pl. 4, figs. 24-31, 34-38

= *Glomospirella* sp. 174 Brooke and Braun in: Wall, 1983, pl. 3, figs. 27-29

Saturnella sp. A

Spiroplectammina cuneata Hedinger, 1993, p. 64-65, pl. 17, figs. 1-4

Textularia aeroplecta Tappan, 1955, p. 47, pl. 13, figs. 13-16

Triloculina sp. A

Trochammina elevata Kosyreva subsp. A, in: Dain et al., 1972, p. 88, pl. XXIII, figs. 8-11, 13

Hedinger, 1993, p. 71, pl. 18, figs. 4, 8, 12

Trochammina sablei Tappan, 1955, p. 50-51, pl. 14, figs. 6-9

Trochammina scotti Hedinger, 1993, p. 74, pl. 20, figs. 22-30

Trochammina topagorukensis Tappan, 1955, p. 51, pl. 14, figs. 10-11

Vaginulina anomala Blake, 1876, p. 464, pl. 17, figs. 23-23a

Tappan, 1955, p. 76, pl. 26, fig. 1

Vaginulina curva Franke, 1936, p. 85, pl. 8, fig. 39

Tappan, 1955, p. 76-77, pl. 22, figs. 9-19

Vaginulina kochi Roemer, 1840-1841, p. 96, pl. 15, fig. 10

Bhalla and Abbas, 1978, p. 186, pl. 8, fig. 4; pl. 12, figs. 5-9

Vaginulina sherboni (Franke) = *Marginulina sherboni* Franke, 1936, p. 74, pl. 7, figs. 18a-b

Tappan, 1955, p. 77, pl. 23, figs. 16-22

Vaginulinopsis enodis Loeblich and Tappan, 1950, p. 46, pl. 12, figs. 11a-16b

Verneuillinoides graciosus Kosyрева in: Dain et al., 1972, p. 98, pl. XXX, figs. 2-4
Hedinger, 1993, p. 78, pl. 21, figs. 1-9

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Plate 1

PLATE 1 FORAMINIFERA

1. *Bathysiphon* sp. B, section 5 (C-172521)
2. *Saccamina lathrami*, section 9 (C-172526)
3. *Ammodiscus orbis*, section 10 (C- 127887)
4. *Ammodiscus richardsonensis*, section 14 (C- 172412)
5. *Saturnella brookeae*, section 15 (C- 127900)
6. *Lituotuba irregularis*, section 16 (C- 172735)
7. *Reophax densa*, sections 69-74 (C- 164864)
8. *Reophax suevica*, section 15 (C- 127900)
9. *Miliammina* sp. B, section 14 (C- 172402)
10. *Miliammina* sp. C, section 19 (C- 164805)
11. *Haplophragmoides tryssa*, section 15 (C- 172476)
12. *Haplophragmoides* sp. D, section 14 (C- 172337)
13. *Haplophragmoides* sp. F, section 10 (C- 127825)
14. *Labrospira* sp. A, section 16 (C- 172735)
15. *Spiroplectammina cuneata*, section 8 (172607)
16. *Ammobaculites alaskensis*, section 10 (C- 127887)
17. *Ammobaculites lunaris*, section 12 (C- 172645)
18. *Ammobaculites multiformis*, section 15 (C- 172481)
19. *Ammobaculites toughenoughensis*, section 14 (C- 172337)
20. *Ammobaculites* sp. H, section 10 (C- 127887)

Plate 2

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PLATE 2 FORAMINIFERA

1. *Ammobaculites* sp. J, section 84 (C-164829)
2. *Bulbobaculites willowensis*, sections 59-68 (C- 172494)
3. *Textularia aeroplecta*, section 8 (C- 172605)
4. *Bigenerina* sp. A, section 8 (C-172596)
5. *Trochammina* sp. A, section 8 (C-172781)
6. *Neobulimina* sp. A, section 8 (C- 172608)
7. *Heterohelix* sp. A, section 15 (C-127836)
8. Unknown sp. S (aggl.), section 16 (C-172736)
9. Unknown sp. (aggl.), section 84 (C-164827)
10. *Geinitzinita* sp. A, section 8 (C-172574)
11. *Nodosaria detruncata*, section 5 (C- 172506)
12. *Nodosaria marginata*, section 62 (C- 172811)
13. *Nodosaria mitis*, section 7 (C- 172775)
14. *Nodosaria radiata*, section 15 (C- 127837)
15. *Nodosaria regularis*, section 10 (C- 127887)
16. *Nodosaria setulosa*, sections 69-74 (C-164866)
17. *Nodosaria* sp. A, section 11 (C- 172319)
18. *Astacolus agalmatus*, section 62 (C- 172812)
19. *Astacolus calliopsis*, section 14 (C- 172386)
20. *Astacolus dubius*, section 62 (C- 172811)

Plate 3

PLATE 3 FORAMINIFERA

1. *Astacolus pediacus*, section 16 (C-172735)
2. *Astacolus varians*, section 15 (C- 172481)
3. *Astacolus* sp. H, section 7 (C-172793)
4. *Citharina callomoni*, section 14 (C- 172376)
5. *Citharina entypomatus*, section 10 (C- 127887)
6. *Citharina fallax*, section 10 (C- 127887)
7. *Citharinella exarata*, section 84 (C- 164827)
8. *Citharinella rhomboidea*, section 15 (C- 172481)
9. *Citharinella* sp. A, section 12 (C- 172655)
10. *Citharinella* sp. E, section 15 (C- 172477)
11. *Dentalina ectadia*, section 93 (C- 164839)
12. *Dentalina exilis*, section 15 (C- 172746)
13. *Dentalina guembeli*, section 15 (C- 172423)
14. *Dentalina pseudocommunis*, section 62 (C- 172811)
15. *Dentalina terquemi*, section 38 (C- 172712)
16. *Dentalina vulgata*, sections 31-33 (C- 172823)
17. *Dentalina* sp. B, section 15 (C- 172478)
18. *Frondicularia lustrata*, section 8 (C- 172584)
19. *Frondicularia* sp. A, section 8 (C- 172559)
20. *Frondicularia* sp. B, section 8 (C- 172559)

Plate 4

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— 100 μ m

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— 100 μ m

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— 100 μ m

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— 100 μ m

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— 100 μ m

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— 100 μ m

8

— 100 μ m

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— 100 μ m

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— 100 μ m

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— 100 μ m

14

— 100 μ m

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— 100 μ m

PLATE 4 FORAMINIFERA

1. *Frondicularia* sp. C, section 8 (C- 172559)
2. *Frondicularia* sp. G, section 17 (C- 303044)
3. *Lenticulina audax*, section 7 (C- 172781)
4. *Lenticulina d'orbignyi*, section 7 (C-172791)
5. *Lenticulina excavata*, section 19 (C-164811)
6. *Lenticulina muensteri*, section 16 (C- 172735)
7. *Lenticulina toarcense*, section 16 (C- 172733)
8. *Lenticulina varians*, section 17 (C-172746)
9. *Lenticulina* sp. C, section 14 (C- 172388)
10. *Lenticulina* sp. E, section 7 (C- 172522)
11. *Lenticulina* sp. L, section 14 (C- 172376)
12. *Lenticulina* sp. O, section 10 (C- 127829)
13. *Lenticulina* sp. Q, section 15 (C-172423)
14. *Lenticulina* sp. S, section 10 (C-127887)
15. *Lenticulina* sp. T, section 15 (C- 172477)
16. *Lenticulina* sp. Z, section 16 (C- 172724)
17. *Marginulina demissa*, section 84 (C- 164827)
18. *Marginulina interrupta*, section 7 (C- 172793)
19. *Marginulina* sp. B, section 10 (C- 127818)
20. *Falsopalmula antrorsa*, section 15 (C- 172481)

Plate 5

PLATE 5 FORAMINIFERA

1. *Planularia anceps*, section 6 (C- 172706)
2. *Planularia fraasi*, section 11 (C- 172326)
3. *Pseudonodosaria brandi*, section 7 (C-172781)
4. *Pseudonodosaria statuta*, section 10 (C- 127818)
5. *Vaginulina sherboni*, section 16 (C- 172735)
6. *Eoguttulina liassica*, section 5 (C- 172517)
7. *Eoguttulina metensis*, section 16 (C-172732)
8. *Globulina alexandrae*, section 16 (C- 172736)
9. *Bullopore* sp. A, section 14 (C-172378)
10. *Brizalina* sp. A, section 8 (C-172587)
11. *Conorbina* sp. A, section 8 (C-172608)
12. *Pseudolamarckina liapinensis*, section 10 (C- 127825)
13. *Reinholdella* sp. B, section 17 (C-303044)

APPENDIX I

GSC data spreadsheets

(see CD in back pocket)

APPENDIX II

Lithostratigraphic columns for each of the studied sections

LEGEND

	shale		load cast		belemnite
	siltstone		sandstone lense		coalified wood
	silty shale		sandy lense pod		trigonal bivalve
	sandstone		cross bedding		coral
	sandstone and siltstone		convolute bedding		gastropod
	sandstone interbedded with shale		volcanic sandstone blocks		calcareous nodule
	sandstone with pebbles		tuff bed		septarian nodule
	agglomerate		dyke		glauconite
	lapilli tuff		fault		sample number
	covered interval		syncline		unconformity
	limestone lense		plant		
	breccia nodules		brachiopod		
	shale rip-up clast		ammonite

Appendix II. Lithostratigraphic column of section 4

Appendix II. Lithostratigraphic column of section 5

Appendix II. Lithostratigraphic column of section 7

Appendix II. Lithostratigraphic column of section 9

Appendix II. Lithostratigraphic column of section 10

Appendix II. Lithostratigraphic column of section 11

Appendix II. Lithostratigraphic column of section 12

Appendix II. Lithostratigraphic column of section 14

Appendix II. Lithostratigraphic column of section 15

Appendix II. Lithostratigraphic column of section 16

Appendix II. Lithostratigraphic column of section 17

Appendix II. Lithostratigraphic column of section 19

APPENDIX III

**Range charts depicting foraminiferal distribution, abundance and diversity
for each of the studied sections**

Period	Stage	Formation	Section 4 species	
			Interval (m)	
Lower Jurassic	Middle Toarcian	Whiteaves	156.35-157.88	Lenticulina d'orbignyi
			151.78-155.75	Astacolus pediacus
			148.74-151.48	Lenticulina varians
			145.69-148.43	Ammobaculites sp. A
			142.64-145.38	Labrospira freboldi
			139.90-142.33	Lenticulina toarcense
			138.37-130.45	Rectoglandulina oviformis
			128.92-130.45	Ammobaculites multiformis
			126.79-128.62	Dentalina sp. A
	M. Pliens.- L. Toarc.	Fannin	92.35-93.87	Astacolus sp. A
			40.54-41.76	Falsopalmula antrorsa
				Ammobaculites lunaris
	L. Pliens- bachian	Ghost Cr.	7.01-8.23	Ammobaculites sp. B
			3.05-3.96	Astacolus sp. B

• 1-5 specimens

● 6-10 specimens

Appendix III. Foraminiferal distribution in section 4

• 1-5 specimens

• 6-10 specimens

• 11-50 specimens

• >50 specimens

Appendix III. Foraminiferal distribution in section 5

1-5 specimens • 6-10 specimens • 11-50 specimens • >50 specimens

Appendix III. Foraminiferal distribution in section 7

Period	Stage	Formation	Section 9 species
L. Jurassic			Interval (m)
	M. Pliens.- L. Toarcian		
	Fannin	34.14-35.66	Lenticulina sp. K
		31.09-32.00	Lenticulina sp. E
		30.17	Frondicularia sp. A
		21.94	Lenticulina sp. D
		21.64	Planularia striata
			Marginulina sp. A
			Textularia aeroplecta
			Frondicularia lustrata
			Lenticulina sp. L
			Astacolus sp. K
			Nodosaria sp. C
			Ammodiscus sp. B
			Lingulina polita
			Citharinella sp. B
			Unknown sp. F (aggl.)
			Dentalina sp. E
			Eoguttulina liassica
			Reinholdella sp. A
			Unknown sp. G (aggl.)

• 1-5 specimens • 6-10 specimens ● 11-50 specimens ● >50 specimens

Appendix III. Foraminiferal distribution in section 9

• 1-5 specimens • 6-10 specimens • 11-50 specimens • >50 specimens

Appendix III. Foraminiferal distribution in section 11

● >50 specimens

● 11-50 specimens

● 6-10 specimens

● 1-5 specimens

Appendix III. Foraminiferal distribution in section 12

1-5 specimens 6-10 specimens 11-50 specimens >50 specimens

Appendix III. Foraminiferal distribution in section 14

Appendix III. Foraminiferal distribution in section 15

• 1-5 specimens • 6-10 specimens • 11-50 specimens • >50 specimens

Appendix III. Foraminiferal distribution in section 16

• 1-5 specimens • 6-10 specimens • 11-50 specimens • >50 specimens

Appendix III. Foraminiferal distribution in section 17

Period	Stage	Formation	Section 19 species
Lower Jurassic	Middle Toarcian	Whiteaves	Interval (m)
			210.30-212.44
			205.73-208.17
			201.16-203.90
			198.11-200.24
			194.76-197.20
	M. Pliensbachian-Lower Toarcian	Fannin	192.01-193.84
			186.83-188.36
			176.17-177.69
			153.92-155.75
			152.39-153.61
			148.74-150.26
			147.52-148.13
			140.20-141.73
			118.26-120.09
			86.56-88.39
	Lower Pliensbachian	Ghost Creek	74.67-76.20
			73.15-74.67
			57.91-60.04
			48.16-49.68
			45.72-47.24
			38.40-40.54
			34.44-36.57

Bathysiphon sp. B
Astacolus varians
Ammodiscus orbis
Miliammina sp. C
Pseudolamarcina liapinensis
Ammobaculites sp. D
Fronicularia sp. H
Lenticulina toarcense
Lenticulina prima
Lenticulina sp. Z
Nodosaria radiata
Lenticulina audax
Lenticulina sp. S
Fronicularia lustrata
Arenoturrispirulina waltoni

• 1-5 specimens

● 11-50 specimens

● >50 specimens

Appendix III. Foraminiferal distribution in section 19

APPENDIX IV

Foraminiferal distribution and abundances for each of the studied sections

(see CD in back pocket)