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NEARING THE END: REEF BUILDING CORALS AND BIVALVES IN THE LATE TRIASSIC AND COMPARING CORALS AND BIVALVES BEFORE AND AFTER THE END-TRIASSIC MASS EXTINCTION USING A TAXONOMIC DATABASE

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TRIASSIC AND COMPARING CORALS AND BIVALVES BEFORE AND AFTER

THE END-TRIASSIC MASS EXTINCTION USING A TAXONOMIC DATABASE

By

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Nearing the End: Reef Building Corals and Bivalves in the Late Triassic and Comparing Corals and Bivalves before and after the end-Triassic Mass Extinction Using a Taxonomic Database

Chairperson: George D. Stanley, Jr.

   One of the most important tenants in geology is that the present is the key to the past, but it can also be said that the past is the key to the present. The five great extinction events are some of the key events that can help us to understand how changes in climate and sea chemistry can cause great changes in the ecology of our planet. Today the increase in atmospheric CO_2 is causing ocean acidification, which has also been proposed as part of the system that caused the end-Triassic mass extinction. Ocean acidification can be greatly detrimental to the skeletal structures of marine invertebrate such as reef building corals and bivalves. During the Norian and Rhaetian (Late Triassic), corals and bivalves had high diversity and abundance, but like many organisms involved in the mass extinction, quickly disappeared at the end of the Triassic. In the early Jurassic, very few surviving species of corals can be found, and almost no reefs. If this 'reef gap' was caused by a change in ocean chemistry, then how did these few species of corals survive? Were bivalves also affected by the changes?

   On Vancouver Island, rock units containing corals and bivalves can be found that represent both Norian and Rhaetian time intervals, but early Jurassic sedimentary units are found rarely, if ever. This creates a difficulty in looking for patterns in changes that happened after the mass extinction, but does allow for analysis of what reef communities looked like shortly before the end of the Triassic. In addition, by building upon data from the Paleobiology Database, changes in the global reef communities after the end-Triassic mass extinction can be examined.

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Part 1:   Nearing the End: Reef Building Corals and Bivalves in the Late Triassic

Chapter 1: Introduction

(1)   <u>The Big 5 Mass Extinctions</u>

One of the most important tenants in geology is that the present is the key to the past, but it can also be said that the past is the key to the present. Over the course of geologic history, there have been five events which are considered major mass extinctions, Late Ordovician (440 Ma), Late Devonian (370–350 Ma), End-Permian (250 Ma), End-Triassic (201 Ma) and End-Cretaceous (65 Ma) (Raup and Sepkoski, 1982, 1984). Although it is likely that these events have different causes, such as bolide impacts and magmatic provinces, it is also likely that they have common themes, such as the pattern of recovery (Erwin, 2001). Therefore in an effort to understand mass extinctions on the grand scale, we can study one mass extinction event and compare our findings to those studying other mass extinctions. We can also apply this to the world today, as we may be facing global extinctions with today's global climate change. Perhaps understanding extinctions and the recovery from them will help us prevent global extinctions of some animals. The five great extinction events are some of the key events that can help us to understand how changes in climate and sea chemistry can cause great changes in the ecology of our planet.

(2)   <u>Setting the scene: Late Triassic</u>

The end-Triassic mass extinction is unique among the big 5 extinctions in that the cause was unlikely to be external (no impact event) and it is the first of the great extinctions to primarily effect the "modern fauna" as described by Sepkoski (Raup and Sepkoski, 1982;

Sepkoski, 1982; Sepkoski et al., 2002). This 'modern fauna' actually got its start in the Early

Ordovician, but did not become the dominant marine life until after the Permian extinction.

Scleractinian corals (modern stony corals) first appear in the fossil record in the Triassic

(Roniewicz and Morycowa, 1993), The Triassic is also the time period in which bivalves began

to take over from brachiopods as the dominant benthic filter feeders (Fraiser and Bottjer, 2007).

Also beginning in the Triassic, predator-prey interactions increased the variety of predators and

defense strategies (Stanley, 1972; Vermeij, 1977; Fraiser and Bottjer, 2007), termed the

Mesozoic Marine Revolution.

This reef ecosystem modernization makes the Late Triassic an ideal time period for

studying how changes in water chemistry and atmospheric temperature could affect reef

organisms in terms of diversity, morphology, and abundance, and comparing these affects to the

affects of climate change on today's reefs. Today reefs are facing a crisis from the rise in

atmospheric CO_2 (Caldeira and Wickett, 2003; Orr et al., 2005; Hoegh-Guldberg et al., 2007;

Silverman et al., 2009), which is a factor that may have affected the reefs and the entire marine

environment of the Late Triassic (Hautmann, 2004; Hautmann et al., 2008a). Volcanic activity

from the Central Atlantic Magmatic Province (CAMP) (Marzoli et al., 1999) began shortly

before the end-Triassic mass extinction (White et al., 1987; Sebai et al., 1991; Hautmann et al.,

2008a, 2008b; Marzoli et al., 2008; Schoene et al., 2010; Whiteside et al., 2010).

There is a growing scientific consensus that ocean acidification caused by CAMP is a

major cause of the end-Triassic mass extinction (Whiteside et al., 2010). There is some question

as to how long this acidification lasted, and how it affected organisms before, during, and after

the extinction interval. Following a mass extinction event, there is usually a "survival interval"

with an extremely low diversity of taxa (Erwin, 2001). Following the period of low diversity,

there is a recovery period in which the diversity of taxa is increasing. A taxon can be considered "recovered" when the diversity has returned to levels similar to those before the mass extinction event. In corals, the extinction and recovery intervals can also be assessed in terms of reefbuilding, as well as diversity. Reefs could be considered recovered after a mass extinction, when global reefbuilding returns to the same extent as it was before the extinction. In the case of the end-Triassic mass extinction, not only was the diversity of corals and bivalves extremely low through the entire Hettangian, approximately 2 Ma after the mass extinction (Gradstein, 2012), but only a few reefs from this period are found in the geologic record (Kiessling et al., 2009; Melnikova and Roniewicz, 2012).

(3)   Geologic Setting

(a)   Tectostratigraphic Terranes

As we know from plate tectonics, the shapes we currently think of as continents were not always the shape, size, and location they are today. A major portion of the North American continent is now made up of tectonostratigraphic terranes that are now accreted onto the North American Craton (Howell, 1989) (Fig. 1). The term tectonostratigraphic is used to describe terranes in terms of both structure and stratigraphy. These terranes are allochthonous blocks of rock that are distinct from the cratonic material on a continent, "area possessing unique tectonic assemblages (lithostratigraphic units representing a specific depositional or volcanic setting responding to a tectonic event), which differs from adjacent terranes and is bounded by faults" (Gabrielse et al., 1991). Terranes are by definition bounded by faults because a given terrane was once separate from the continental craton and subsequently was accreted onto the continent (Howell, 1989), however these faults may be a product of subsequent tectonics along the weak

terrane boundaries (Colpron et al., 2007). Terranes which are characterized by coherent

stratigraphic sequences represent the geologic history of that terrane and are distinct from

surrounding units are classified by Howell (1989) as stratigraphic terranes.

In western Canada and southeastern Alaska, there are several accreted terranes, including

Quesnellia, Stikinia, Wrangellia, and the Alexander terrane (Fig. 1). All four of these large

terranes are dominated by oceanic sedimentary and volcanic rocks, indicative of volcanic island

arcs and intra-arc plateaus (Monger et al., 1982; Price, 1994; Monger and Price, 2002; Greene et

al., 2005a, 2005b). Each of these allochthonous terranes has its own unique geologic history,

making them distinguishable from one another in the rock record. Starting in the late Paleozoic,

the western coast of Laurentia (North American craton) was a subduction zone, with the

Panthallasic plate being subducted under Laurentia. During the Devonian to Permian, this

subduction created a series of volcanic arcs, which formed the landmasses that are now known as

Quesnellia and Stikinia (Dickinson, 2004). Alexander and Wrangellia terranes both went

through periods of island arc volcanism and subsidence as oceanic basins. Both were formed

initially as volcanic arcs, Alexander in the Cambrian, Wrangellia in the Carboniferous to

Permian. Alexander may have been an oceanic plateau in the Carboniferous, and both went

through periods of subsidence in the Late Triassic becoming oceanic plateaus, followed by

another period of island-arc volcanism in the Jurassic (Monger et al., 1982; Richards et al., 1991;

Butler et al., 1997; Greene et al., 2005b). Gardner and others (1988) found that a Pennsylvanian

pluton stitched Wrangellia and Alexander terranes together, which is also supported by the two

terranes shared paleomagnetic history (Hillhouse and Gromme, 1984; Butler et al., 1997;

Dickinson, 2004). Others (Yarnell, 2000; Caruthers, 2005; Caruthers and Stanley, 2008a) assert

that the fossil evidence supports separate histories for these two terranes at least through the

Triassic. Paleomagnetic and fossil evidence shows that Wrangellia and Alexander were both

displaced much greater distances latiduninally than Stikinia and Quesnellia (Hillhouse and

Gromme, 1984; Aberhan, 1999; Belasky et al., 2002). The specific history of the Wrangellia

terrane is discussed further herein.
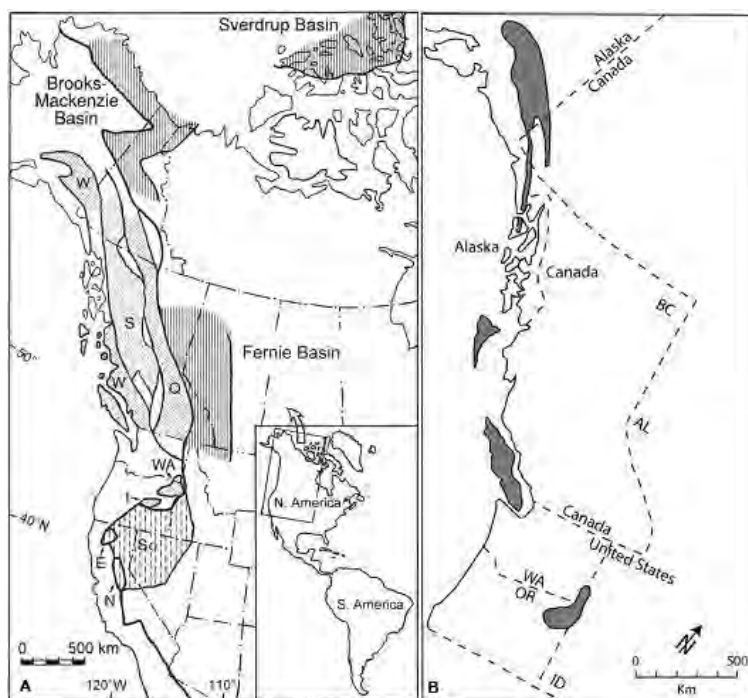
Figure 1: Terrane maps of North America, with major terranes (A) and Wrangellia only (B).
A. Present-day position of selected North American sedimentary basins. The dotted shading represents
allochthonous terranes, which were not accreted to the North American craton by Early Jurassic times;
I=Izee Terrane; Q=Quesnellia; S=Stikinia; W=Wrangellia; WA=Wallowa Terrane. The dashed hatching
represents terranes, which were already accreted to the craton by Early Jurassic times; E=Eastern Klamath
Terrane; N=Northern Sierra Terrane; So=Sonomia; the Kettle Rock Terrane (not shown) is situated
northeast of the Northern Sierra Terrane. The vertical hatching represents autochthonous sedimentary
basins of western Canada (Aberhan, 1999, modified from Aberhan, 1998b.) B. Areas (shaded) regarded as
parts of Wrangellia by Jones et al. (Jones et al., 1977; Stevens, 2008)

Another notable North American terrane is the Wallowa terrane (in older literature

known as the Seven Devils terrane) in Oregon, Idaho, and Washington, United States (Fig. 1).

The Wallowa terrane may have been an independent volcanic island during the Triassic (White

et al., 1992), or it may have been part of one of the other terranes, such as Wrangellia (Jones et

al., 1977; Hillhouse et al., 1982) or Stikinia (Mortimer, 1986). Sarewitz (1983) suggested that

Wallowa developed as an island arc with Wrangellia as a back arc farther west. Paleomagnetic evidence suggests that Wallowa terrane was at ~18° north or south of the equator during the Triassic (Hillhouse et al., 1982) and close to its current latitude of ~45°N by the Cretaceous, having also experienced substantial (~60°) rotation during the Cretaceous (Wilson and Cox, 1980; Housen and Dorsey, 2005). Faunal evidence seems to support associations between Wallowa and Wrangellia (Newton et al., 1987; Yancey and Stanley, 1999; Stanley et al., 2013) or Wallowa with Stikinia (Yarnell, 2000; Caruthers, 2005), but these faunal associations could also be explained by models that put these terranes in geographic proximity to one another during the Triassic.

(b)   Wrangellia and Vancouver Island

Vancouver Island, along with the Haida Gwaii (Queen Charlotte Islands) and parts of Alaska, make up the tectonostratigraphic terrane Wrangellia (Figs. 1 and 2), which is one of the largest and best known accreted terranes that runs north to south along Canada's and Alaska's western edge. This terrane consists of volcanic and sedimentary rocks that were Pacific Ocean island arcs during the Permian and Triassic time and subsequently were accreted to the North American Craton. Accretion of Wrangellia to the North American Craton may have taken place as early as the mid Jurassic (McClelland et al., 1992) or as late as after the Cretaceous (Panuska, 1985). Vancouver Island is the southern part of Wrangellia (Figs. 1 and 2). This terrane consists of a series of rocks that span the Cambrian through the Early Jurassic (Jones et al., 1977; Gardner et al., 1988). Of particular interest within Wrangellia, are the Late Triassic fossiliferous sedimentary units consisting in some localities of reef material (Caruthers and Stanley, 2008b).
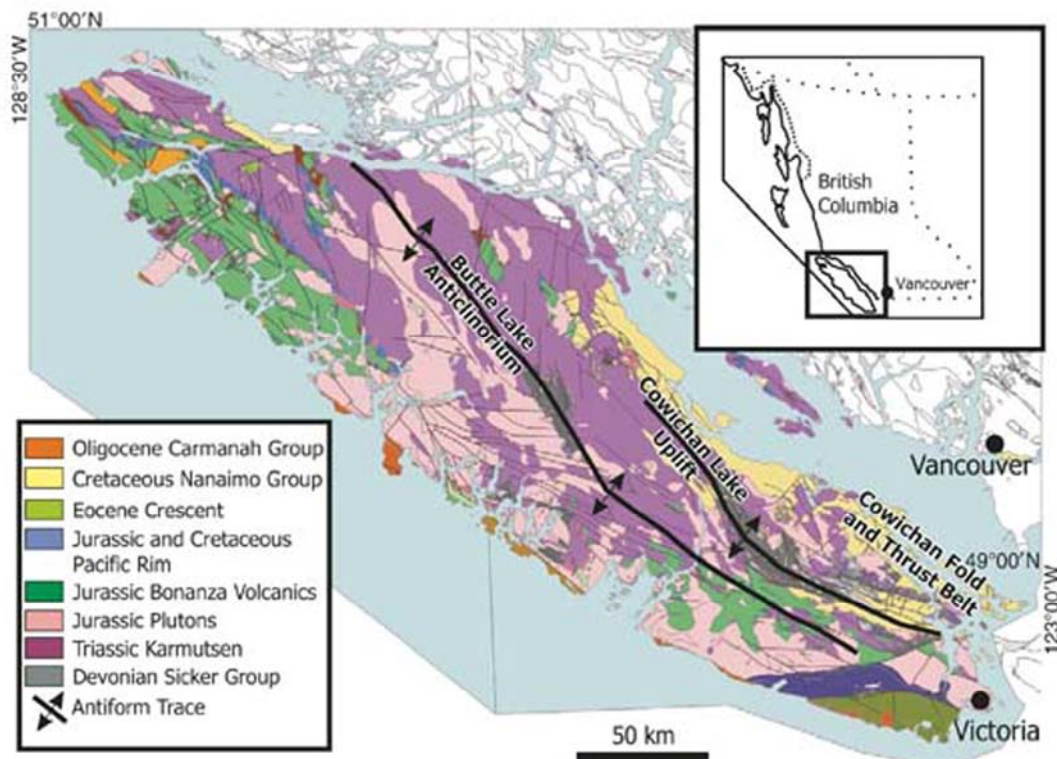
Figure 2: Geology of Vancouver Island compiled from BC Map-Place (http://www.em.gov.bc.ca/ Mining/Geolsurv/MapPlace/). Upper right inset shows map location within British Columbia. Also shown are the traces of the Buttle Lake and Cowichan Lake Anticlinoria, and the Cowichan Fold and Thrust Belt. (from Canil et al., 2010)

During the Paleozoic era, Wrangellia was likely an ocean seafloor characterized by volcanic island arcs. The Devonian rocks of Vancouver Island make up the Sicker Group (Figs. 2 and 3), a series of felsic volcanic, volcanoclastic, and sedimentary rocks that overly mafic volcanic rocks (Muller, 1977; Massey, 1995a, 1995b; Yorath and Nasmith, 1995; Nixon and Orr, 2007; Dostal et al., 2011). The Buttle Lake Group, a series of fossiliferous limestone (Mississippian to early Permian) overlies the Sicker Group. There is an unconformity representing more than 50 million years (Middle to Late Triassic) between the top of the Buttle Lake Group and the Vancouver Group (Massey, 1995a, 1995b; Yorath and Nasmith, 1995). The lower portion of the Vancouver Group consists of flood basalts known as the Karmutsen Formation (Nixon and Orr, 2007; Nixon et al., 2008; Dostal et al., 2011). Above this lies the

Quatsino Limestone (Carnian stage), which is a light weathering medium to dark micritic limestone with few fossils (Nixon and Orr, 2007). Above the Vancouver Group is the Bonanza Group (Late Triassic to Early Jurassic), which consists of Parson Bay Formation, Sutton Formation, and an unnamed volcanoclastic-sedimentary unit. The Parson Bay Formation consists of a series of volcanic and sedimentary units. The sedimentary units within Parson Bay are fine-grained micritic limestone, siltstone, and shale (Nixon and Orr, 2007). Near the top of the Parson Bay or possibly overlying the Parson Bay Formation, lie the fossiliferous reef limestones of the Sutton Formation, notably mapped and described at Cowichan Lake (Fyles, 1955; Stanley, 1989; Massey, 1995b; Yorath and Nasmith, 1995; Caruthers and Stanley, 2008b). Above these fossiliferous sedimentary units lie the Bonanza volcanics, which continue from the end of the Triassic into the Jurassic (Nixon and Orr, 2007).

It has been suggested that starting sometime in the late Jurassic, Wrangellia amalgamated to the Alexander Terrane to become a composite terrane, known as the Insular Composite Terrane (Monger et al., 1982). Gardner et al. (1988) and Bacon et al. (2011) have suggested that Alexander and Wrangellia amalgamated as early as the Pennsylvanian, based on plutons and xenoliths shared by the two terranes in Alaska. This amalgamation likely occurred prior to accretion to continental North America in the Cretaceous, based on geologic work by Nokleberg et al (Nokleberg et al., 1985). Fossil analysis by Yarnell (2000) and Caruthers and Stanley (2008a) indicate that at least through the Triassic, Alexander and Wrangellia were separate island arcs. Paleomagnetic data suggest that during the late Paleozoic and early Mesozoic eras, Wrangellia existed at a much lower paleolatitude (10°-20°N) than Vancouver Island does today (49°N) (Hillhouse, 1977; Jones et al., 1977; Panuska, 1984).
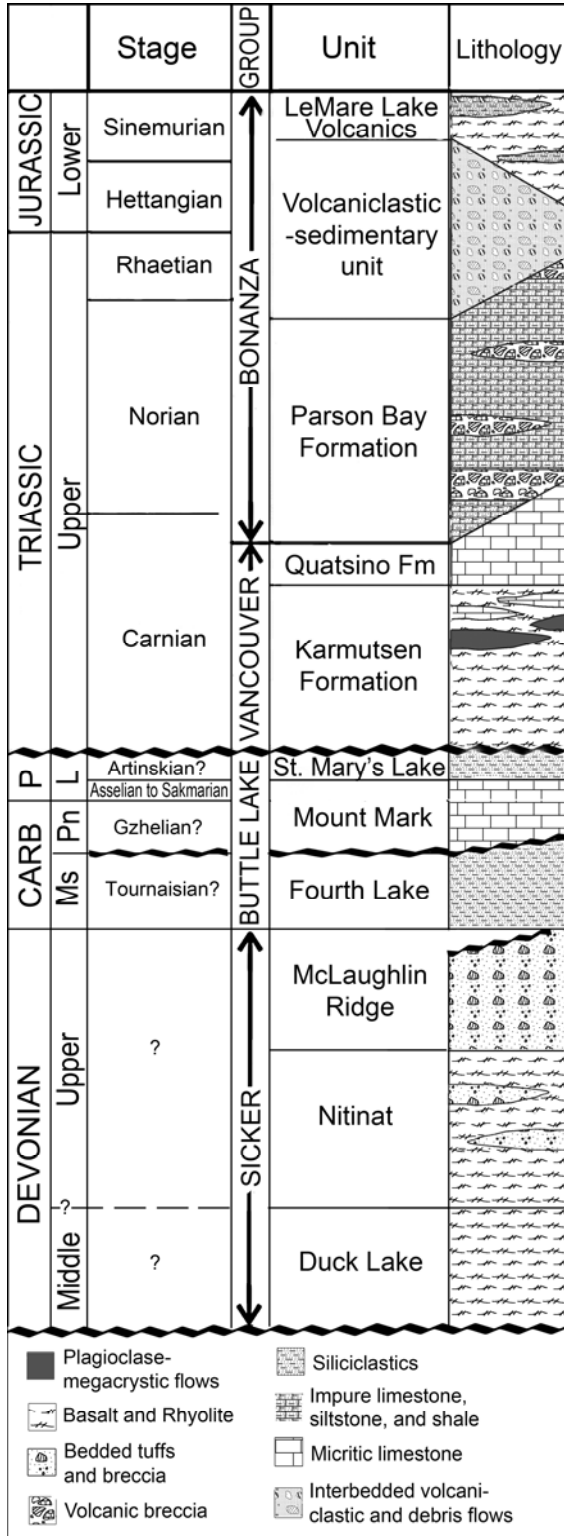
Figure 3: Stratigraphic section of Vancouver Island formations. (based on Massey, 1995a, 1995b; modified from Nixon and Orr, 2007 and Stanley et al., 2013)

(c)   Northern Vancouver Island

On the northern portion of Vancouver Island, near Port Alice, British Columbia there are

outcrops of Late Triassic fossiliferous limestone, interbedded with volcanic units. Graham

Nixon and others (2007-2011) have recently revised the maps and stratigraphy for the region

near Port Alice (figs. 4-6), which were formerly mapped (Dawson, 1887; Gunning, 1930;

Jeletzky, 1950, 1970, 1976; Hoadley, 1953; Muller and Carson, 1969; Muller, 1977). Table 1

below outlines major geologic findings and research conducted on northern Vancouver Island.

These rocks have been dated as spanning from Norian to late Rhaetian, occurring very close to

the Triassic-Jurassic boundary (Nixon and Orr, 2007). According to the most recent geologic

time scale (Gradstein, 2012), the Norian stage spans from 228.4 Ma to 209.5 Ma, and the

Rhaetian stage spans from 209.5 to 201.3 Ma. Specifically, conodont dating of the Yreka

outcrop, completed by M. J. Orchard (Nixon et al., 2011b), found them to be Rhaetian in age. In

addition there also are absolute dates, the Re-Os (determined by R. A. Creasor) dating found the

outcrop to be 202.4 (+/- 1.7) Ma and the detrital zircon (determined by R. M. Friedman) has a

date of 206-212 (+/- 2) Ma. There are also Early Jurassic rocks, but these are volcanic units, thus

not containing fossil material. The most recent compilation of radiometric dating puts the

Triassic Jurassic boundary at 201.3 Ma (Gradstein, 2012).

Figure 4: Outline map (left) and satellite image (right) of Vancouver Island, showing locations of study areas used in research. (Satellite image modified from Google Earth earth.google.com)

(d)   Previous research on Northern Vancouver Island Geology and Paleontology

Many researchers have done basic mapping of geology and mineral resources on

Vancouver Island (Table 1). Beginning with basic mapping of Northern Vancouver Island by

Dawson (1887), geological surveyors have continued to add to the detail and understanding of

the geologic history of the island through mapping and stratigraphy (Gunning, 1930; Jeletzky,

1950, 1970, 1976; Hoadley, 1953; Fyles, 1955; Muller and Carson, 1969; Muller, 1977; Muller

et al., 1999). Of particular note are the studies of the Sutton member of the Parson Bay

Formation on Southern Vancouver Island (originally called the Sutton Formation by Dawson),

which found extensive corals, bivalve, and other marine fossils (Clapp and Shimer, 1911; Fyles,

1955; Stanley, 1989). The Sutton member at Lake Cowichan was initially interpreted as a coral

reef (Clapp and Shimer, 1911), but later reinterpreted as small scale bioherms (Stanley, 1989).

Recently Nixon, of the BC Geological Survey, and others have embarked on a detailed mapping

project on Northern Vancouver Island (Nixon et al., 2000, 2006, 2008, 2011a, 2011b, 2011c,

2011d, 2011e; Nixon and Orr, 2007). The Parson Bay Formation is also found on Northern

Vancouver Island, and Nixon found that some deposits are likely part of the Sutton member of

the formation. As part of this mapping project, Mike Orchard and Tim Tozer identified fossils as

part of finding accurate geologic ages for the sedimentary rocks (Nixon et al., 2000, 2006).

Nixon himself has as part of this mapping project worked toward a better understanding of the

mineral resources and igneous petrology of Wrangellia (Greene et al., 2009). These

researchers have found that Vancouver Island, as part of Wrangellia, went through periods of

volcanism and limestone deposition throughout the Triassic and into the Jurassic.

Table 1: Previous research on Vancouver Island Geology

Author	Year	Research
G. M. Dawson	1887	Mapping and stratigraphy of Northern Vancouver Island; named the "Vancouver Series" and the Sutton Formation
Clapp and Shimer	1911	Fossil descriptions, recognized and described "coral reef" in the Sutton member of the Parson Bay Formation
Gunning, H. C.	1930	Survey of geology and mineralogy of Quatsino-Nimpkish area
J. W. Hoadley	1953	Survey of geology and mineralogy of the Zeballos Nimpkish Area
J. Fyles	1955	Mapping and stratigraphy of the Cowichan Lake area, Paleozoic to Cenozoic rocks
J. E. Muller and D. Carson	1969, 1977, 1999	Mapping, stratigraphy, analysis of the tectonic history of Vancouver Island in relation to the Corillera
Jeletzky, J. A.	1950, 1970, 1976	Mapping, stratigraphy, fossil descriptions and dating; subdivided the "Vancouver Group" into Karmutsen and Bonanza subgroups, divided Bonanza into lower sedimentary and upper volcanic.
Stanley, G. D., Jr	1989	Fossil and lithologic descriptions of Sutton Limestone at Lake Cowichan, interpretation as carbonate platform, but not a reef.
Orchard, M. J. and Tozer, T.	(Nixon et al., 2000, 2006)	Contributed fossil descriptions and dating to mapping and geologic descriptions for papers with Nixon and others.
Caruthers, A.	(Caruthers, 2005; Caruthers and Stanley, 2008a, 2008b)	Fossil coral descriptions, paleobiogeography, comparing Wrangellia and Alexander terranes, found that Wrangellia and Alexander to be faunally different.
Nixon and Orr	(2007, 2010, 2011)	Field mapping, fossil dating (Macrofossils, conodonts), absolute dating (U-Pb zircon, Ar40/Ar39, Re-Os) of areas near Port Alice

(e)   Statement of problem

The main focus of my research on Vancouver Island was initially examine the Triassic-Jurassic boundary and test the sediments for evidence for or against ocean acidification, and to compare fossils before and after the end-Triassic mass extinction to find out more about how the extinction happened. The main forms of evidence for ocean acidification are dissolution surfaces in sedimentary rock and loss of diversity in calcifying marine organisms (Hinojosa et al., 2012; Kershaw et al., 2012). However, the Triassic-Jurassic boundary at the sites near Port Alice is not well defined, since the volcanoclastic sedimentary unit crosses the Triassic-Jurassic boundary without apparent changes to the lithology (Fig. 3). In addition, all the earliest Jurassic material with definite Jurassic dates are volcanic igneous rocks. Although the Early Jurassic units were located on Vancouver Island, it was not possible to compare fossils to Late Triassic fossils, and no dissolution surfaces were found. Although there is no Triassic-Jurassic boundary that we could put our finger on near Port Alice, we do know that we were looking at upper Rhaetian sediments, so there may have been dissolution within these, even without a definite boundary surface. My first hypothesis is that if ocean acidification occurred, there will be evidence of dissolution in the uppermost units of the sections I studied (Yreka-1 and Pulp Mill Hill). This would add to the growing evidence that ocean acidification is the cause of the marine extinction in the end-Triassic.

Since the sedimentary rocks I found on northern Vancouver Island are comparable to those recognized from other Vancouver Island sites, I sought to interpret the depositional environment of these formations and to determine if the formations found near Port Alice can be correlated stratigraphically, lithologically, and faunally to the formations at Tahsis and Lake Cowichan on Vancouver Island (Fig. 4). I did this by visually comparing rocks and identifying

fossils found in all these localities. My second hypothesis is that if the Yreka-1 and Pulp Mill Hill sections are the same units as those found at Lutes Creek near Tahsis, BC, they will be similar lithologically and faunally.

I also studied the black limestone found near Port Alice and compared it to that found at Black Marble Quarry in the Wallowa Terrane, Oregon (Fig. 1). The black limestone at Port Alice is younger (Rhaetian) than the Black Marble Quarry (Carnian-Norian), but they have a similar appearance, seemingly indicating a similar post-depositional history to the unusually black limestone. My third hypothesis is that the black limestone found at Yreka-1 and Pulp Mill Hill is similar lithologically to the Black Marble Quarry in Wallowa Terrane, but not the same unit because it is of different age.

Figure 5: Satellite image of area near Port Alice, British Columbia, showing general localities (modified from Google Earth earth.google.com).
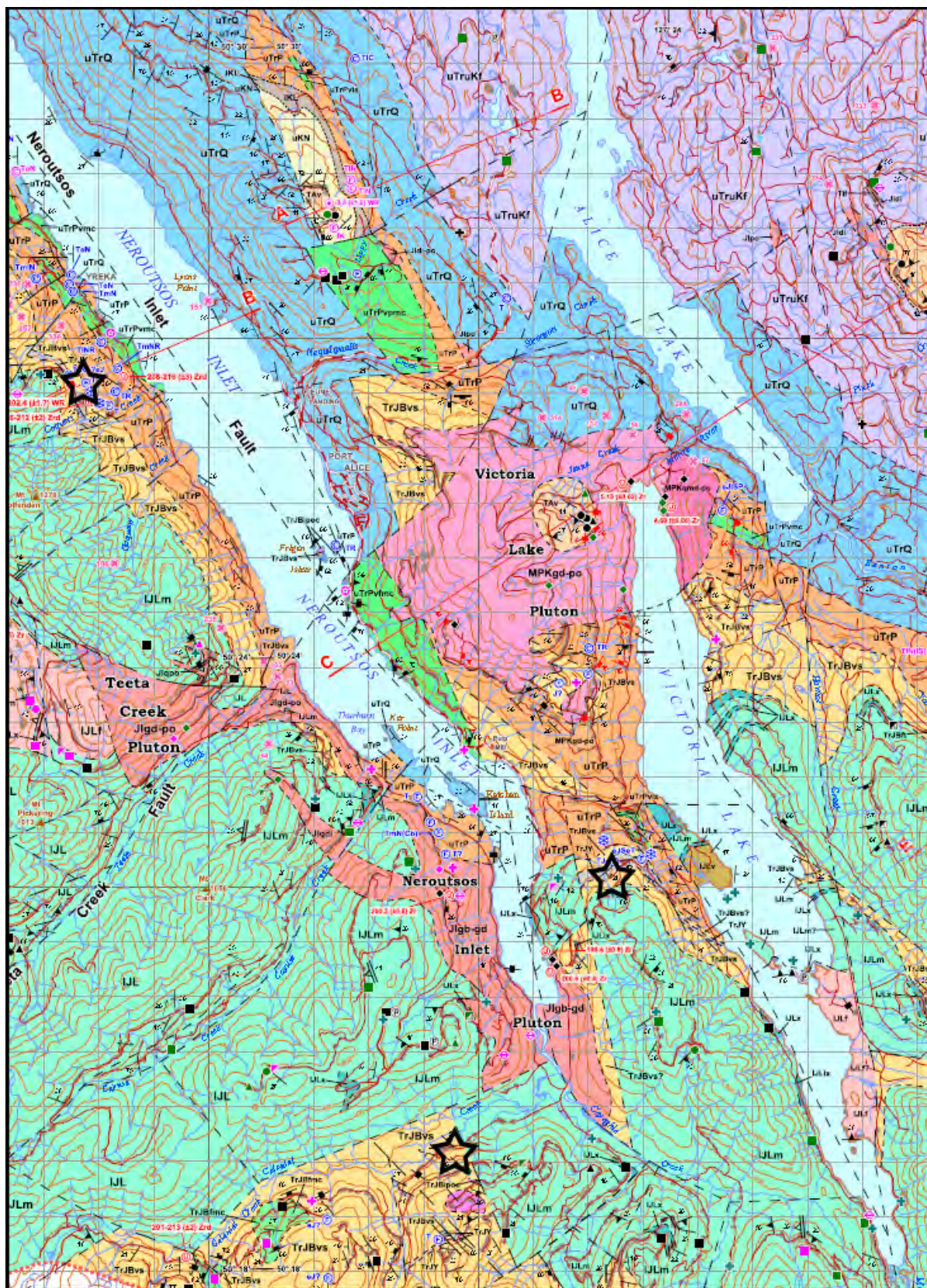
Figure 6: Geologic Map of area near Port Alice, British Columbia. Stars indicate localities (see Fig. 5 for locality names). Key on next page. Modified from GM2011-3 and GM2011-4 (Nixon et al., 2011a, 2011d).

Layered Geologic Units

uKN	Upper Cretaceous (Campanian to ?Maastrichtian) Nanaimo Group Equivalents
lKL	Lower Cretaceous (Upper Valanginian to Barremian) Longarm Formation Equivalents

Bonanza Group

lJL	Lower Jurassic (Hettangian to Upper Sinemurian) Le Mare Lake Volcanic Unit

lJLm	**lJLx**	**lJLv**	Le Mare Lake Volcanics
lJLmf	**+**	**lJLs**	
lJLf		**lJLvs**	

TrJBvs	Upper Triassic (Rhaetian) to possibly Lower Jurassic (Hettangian) Volcaniclastic-Sedimentary Unit
TrJY	Yreka shale-limestone unit
TrJBfmc	Basaltic flows and minor volcaniclastic breccia and tuff
uTrP	Upper Triassic (Carnian to Rhaetian) Parson Bay Formation
❄	Sutton limestone equivalent

uTrPvmc	Parson Bay volcanics
uTrPfvmc	
uTrPvfmc	

Vancouver Group

uTrQ	Upper Triassic (Carnian to Lower Norian) Quatsino Formation
uTruKf	Upper Triassic (Carnian; possible Middle Triassic (Ladinian) at the base Karmutsen Formation
uTrmKh	

Intrusive Rocks

MPKgd-g	Tertiary (Late Miocene) Klaskish Plutonic Suite
Jl	Early Jurassic Island Plutonic Suite
Jlgd-g	
+	Late Triassic to Early Jurassic Minor Intrusions
✪	

Chapter 2: Methods

(1)   Field Methods

During the summers of 2010 and 2011, I conducted fieldwork on Vancouver Island, British Columbia. During August 2010 and August 2011, I collected fossils, described geology, and measured sections from the Port Alice, BC area (Fig. 6). Graham Nixon, of the British Columbia Geological Survey, and my supervisor, George D. Stanley, Jr., provided locality information and field assistance during the 2010 field season in the Port Alice area. During August 2011, I visited the Tahsis, BC area, near Tahsis Inlet (Fig. 4), looking for field localities previously described by Ken Paisley, my supervisor, and Andrew Caruthers (former UM graduate student). Since I was unable to locate the Tahsis localities I relied on substantial collections made by Stanley and Kenneth Paisley in the University of Montana Paleontology Center collections.

In the Port Alice area, I described and collected fossils from five localities from the Late Triassic Parsons Bay and the Jurassic Harbledown formations. The Triassic localities include Yreka-1, Yreka-2, Yreka-3, Pulp Mill Hill, and Colonial Creek (Fig. 5). The Jurassic locality is Cayeghie Creek (Fig. 5). In addition to describing and collecting fossils, I also measured 3 sections, Yreka-1, Yreka-3, and Pulp Mill Hill (Figs. 7 and 8). All localities were accessed by truck and/or on foot, via established logging roads. In 2010 latitude and longitude were estimated using a Magellan Triton 400 GPS, and in 2011 latitude, longitude, and elevation were collected using a Garmin eTrex Vista HCX GPS. All points were collected in the NAD83 coordinate system, using both UTM (zone 09U) and degree minutes seconds. Coordinates and

descriptions of each locality can be found in the results. Field photographs were taken with three

compact digital cameras, a Cannon, Sony, and a Nikon Coolpix S6000.
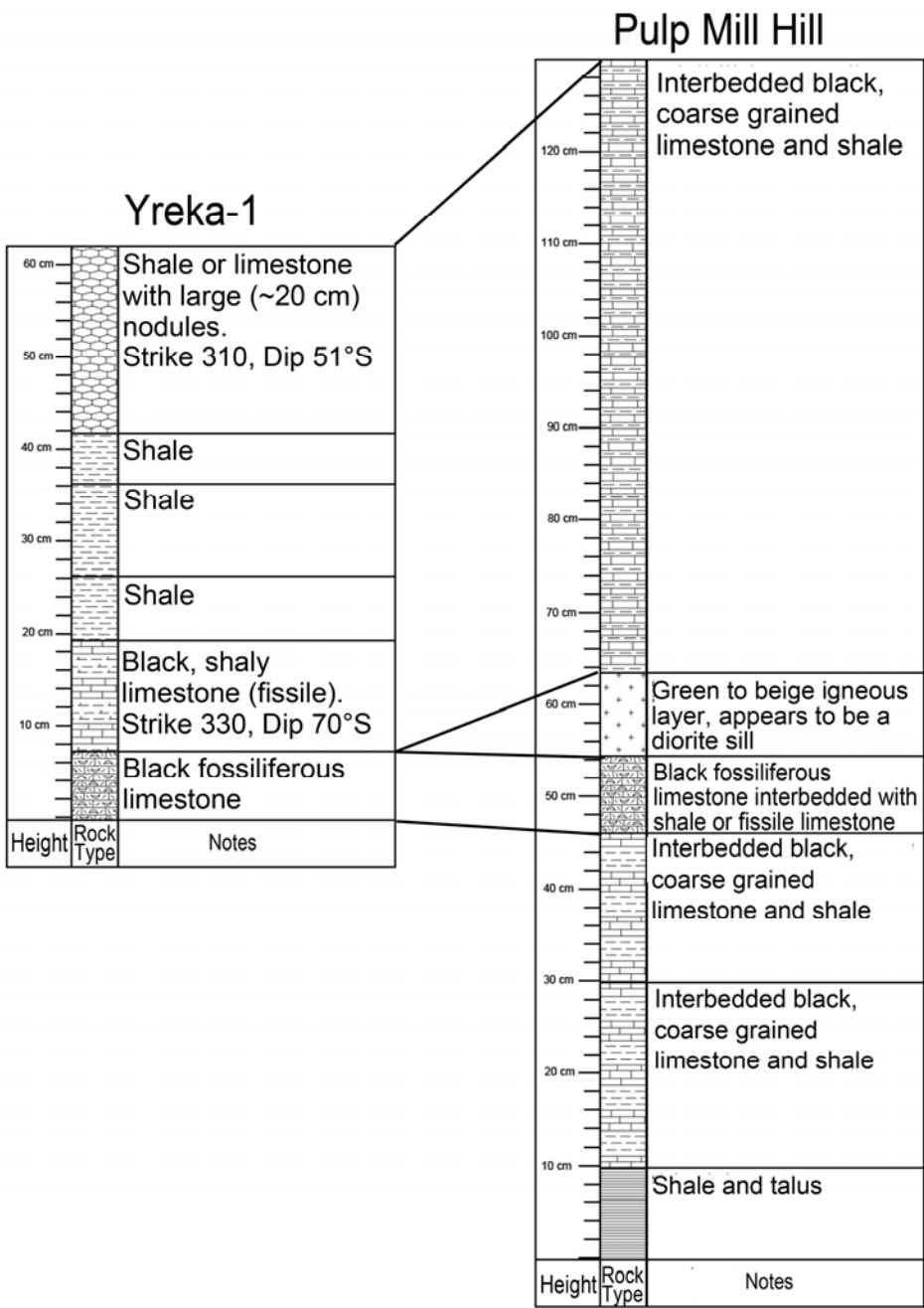
Figure 7: Correlated stratigraphic columns from Yreka-1 and Pulp Mill Hill localities

(2)   Lab methods

The primary purpose of laboratory methods was making suitable casts and identification

of the abundant bivalves and scleractinian corals, since large portion of the bivalves, from both

the Pulp Mill Hill and Yreka-1 localities, are external molds. Fossils were curated and

accessioned into the University of Montana Paleontology Center research museum and entered

on the UMPC database. Casts were made using Smooth-On Oomoo silicone rubber with added

india ink (to create black color) to replicate the original fossil. Silicified corals were removed

from limestone matrix using a weak hydrochloric acid. In order to help with identification and

lithological analysis fossils were also directly compared to specimens in the University of

Montana Paleontology Center collections from Tahsis, BC. I then photographed the significant

specimens with a Cannon EOS D30 digital SLR. I used Adobe Photoshop CS5 to edit out

unnecessary matrix, enhance contrast, and create photographic plates.

(3)   Statistical Methods

Species diversity was calculated using the Shannon's H diversity index (Equation 1). I

used Microsoft Excel to calculate relative species abundance (p_i), as number of specimens of

each species within the formation divided by the total number of specimens within the formation.

Species diversity was calculated for the Parson Bay Formation (Yreka-2, Yreka-3, and Colonial

Creek localities) and for the Volcaniclastic-Sedimentary Unit (possibly Upper Parson Bay).

Species diversity was expressed as $e^{H'}$ for ease of comparison between the units.

$$H' = -\sum p_i \ln(p_i)$$

Equation 1: Shannon's H diversity index, where p_i is the relative species abundance (number of specimens/total)

Yreka-3

Height	Rock Type	Notes
260 cm		Bioclastic limestone with large branching coral heads
240 cm		Bioclastic limestone, finely broken bioclasts
		"Stick-like" Retiophyllia, light weathering medium to dark limestone in a fine grained matrix
220 cm		
		Individual corals in fine grained matrix, dark limestone
200 cm		Dark limestone with laminar corals
180 cm		
160 cm		Dike or Sill
140 cm		
120 cm		
100 cm		Dark, massive limestone, medium to coarse grained with silicified coral colonies
80 cm		Broken coral heads
		Dike
60 cm		Continuation of broken coral head section, large laminar corals, large coral head, upside down coral head, and brachiopod. Medium grained quartzy bioclastic dark massive limestone with areas of light weathering.
40 cm		
20 cm		

Figure 8: Stratigraphic column of measured section at Yreka-3 (stratigraphically below sections at Yreka-1 and Pulp Mill Hill)

4)   Locality descriptions

Table 2: Locality descriptions near Port Alice, BC on Vancouver Island

Locality	Lat. / Long. UTM	Elev.	Strike/Dip	Map	Lithology	Age
Yreka-1	50°26'51.7"N 127°33'30.9"W 09U 0602337 5589397	2183 ft	Strike 320 Dip 20°SSW	NTS 092L/ 05	Black, extremely fissile shale which produces red and black soil with cm to dm scale bedding; Further described in measured section (Fig. 7)	Likely Rhaetian based on Re-Os whole-rock isochron date of 202.4±1.7 mya and Triassic fossils
Yreka-2	50°26'47.9"N 127°33'26.1"W 09U 0602435 5589208	2129 ft	Strike 300 Dip 42°S	NTS 092L/ 05	Limestone interbedded with black shale, very fossiliferous; mostly fragments.	Likely Rhaetian
Yreka-3	50°26'25.1"N 127°32'58.9"W 09U 0602985 5588591	1604 ft	Lower Section: Strike 317 Dip 41° WSW Upper Section: Strike 315 Dip 24° WSW	NTS 092L/ 05	Bioclastic limestone; Further described in measured section (Fig. 8)	Norian - Rhaetian, based on zircon date 206-212±2
Pulp Mill Hill	50°21'56.5"N 127°25'02.6"W 09U 0612557 5580489	1327 ft	Strike 225 Dip 24°S Strike 220 Dip 10°S	NTS 092L/ 06	Black shale, similar to Yreka-1; Further described in measured section (Fig. 7Figure 7)	Likely Rhaetian based on correlation to Yreka-1
Colonial Creek	50°18'14.7"N 127°27'48.7"W 09U 609416 5573569	~2000 ft (est. from map)	Not recorded	NTS 092L/ 06	Dark, recrystallized limestone, with *Chondrocoenia sp.; Retiophyllia sp.;* spongiomorphs and *Wallowaconcha sp.*)	Likely Rhaetian

Chapter 3: Results

(1)   Faunal Assemblage

Table 3: Fossils found in field area

Taxa	Plates	Localities and MI number		UMIP Number (or CGS Number)
Cnidaria				
Scleractinia	1			
Chondrocoenia sp.	1.1	Yreka-2	MI 9997	Outcrop only
(Roniewicz, 1989)	1.6	Yreka-3	MI 9996	Outcrop only
Retiophyllia alfurica	1.8, 1.9	Yreka-3	MI 9997	13493C
(Wilckens, 1937)				
Retiophyllia sp. (Cuif, 1967)	1.2-1.5, 1.7	Yreka-3	MI 9997	13493A,B
		Colonial Creek	MI 10000	Outcrop only
Mollusca				
Bivalvia	2-4			
Eoplicatula sp. (Carter, 1990)	2.1-2.2	Yreka-1	MI 9998	Outcrop only
	2.4, 2.6	Pulp Mill Hill	MI 9999	Outcrop only
Myophorigonia cf. *paucicostata*	3.1-3.2, 3.6	Yreka-1	MI 9996	13497
(Jaworski, 1922)	3.3-3.5, 3.7	Pulp Mill Hill	MI 9999	13498, C532668
Megalodon sp. (Agassiz, 1843)		Yreka-2	MI 9997	Outcrop only
	2.7-2.9	Yreka-3	MI 9996	13494, 13495
Wallowconcha raylenea	4.1-4.2	Yreka-2	MI 9997	13479
(Yancey and Stanley, 1999; Stanley et al., 2013)	4.3	Colonial Creek	MI 10000	13481

(2)   Lithology

(a)   Parson Bay Formation

At the Colonial Creek, Yreka-2, and Yreka-3 localities, fine to medium grained, dark

gray limestone (Table 3, Fig. 8). Much of this limestone is recrystallized, and based on fossil

positions was likely reworked at some point before it was finally lithified. The branching

'heads' of Retiophyllia sp. (Plate 1, Figs. 2 and 4) occur upside down at times and appear to have

edges that separate them from the massive limestone. In addition to *Retiophyllia* sp., bivalves

including an unidentified megalodontid bivalves (Plate 2, Figs. 7-9) and giant alatoform bivalves

Wallowaconcha raylenea (Plate 4, Figs. 1-3) were recovered from Yreka-2 and Colonial Creek

(Stanley et al., 2013). Fossils found in this limestone are occasionally silicified (Plate 1, Figs. 3, 5-9), though not consistently. This allowed for removal from the matrix of a few fossils (Plate 1, Figs. 7-9), but they were generally heavily recrystallized, precluding precise identification. Reefs or bioherms do not appear to be present in these sections. Towards the top of the Yreka-3 section, there is limestone termed the "Sutton Limestone equivalent" by Graham Nixon (Nixon et al., 2011d) because of its similarity to the Sutton Member of the Parson Bay Formation (Dawson, 1887; Clapp and Shimer, 1911) limestone found by Lake Cowichan, southern Vancouver Island (Fig. 4). Species diversity based on Shannon's H' for the Parson Bay Formation at these localities is calculated to be 4.78 (expressed as $e^{H'}$).

(b)   Volcaniclastic-Sedimentary Unit (possibly the upper Parson Bay Formation)

Above the light weathering limestone lies black fissile limestone and shale that occurs at Pulp Mill Hill, Yreka-1, and Yreka-2 localities (Figs. 6 and 7). The black limestone contains *Retiophyllia* sp. and various bivalve species (Plate 2). Many of these fossils are recrystallized and white, making them easily distinguishable from the black, fine grained limestone matrix (Plate 2, Figs. 1-2, 6). Some of the fossils found in the more fissile portions above the lithified black limestone consist of casts and molds (Plate 2, Figs. 3-5).

The shale section at Yreka-1 and Pulp Mill Hill lie above the black limestone (Fig. 7), and contains abundant trigonid bivalve fossils (Plate 3). All of the trigonid fossils are external molds, and appear to be all of the same species, *Myophorigonia paucicostata* (Jaworski, 1922). The shale ranges from black to medium brown. One external mold of a branching coral (UMIP 13499, likely *Retiophyllia*) was collected, but it was impractical to make casts and identify the fossil because the specimen is so fissile. This specimen is filled with holes from dissolved

Retiophyllia, and no remnants of the coral itself, like the bivalve fossils, was only preserved as an external mold. The overall species diversity of the Volcaniclastic-Sedimentary Unit at these localities is 1.98 (expressed as $e^{H'}$).

Chapter 4: Discussion

The Late Triassic coral and bivalve fauna on northern Vancouver Island represent a relatively low diversity, high abundance assemblage dominated by bivalves and a few poorly preserved corals. The Parson Bay Formation at localities Yreka-2, Yreka-3, and Colonial Creek is much higher diversity than the diversity in the Volcaniclastic-Sedimentary Unit, perhaps indicating that this upper unit represents a decline relating to the end-Triassic mass extinction. The limestone at Colonial Creek and Yreka-3 seems to have been reworked and does not form a bioherm or reef, indicating that the corals and bivalves may have been moved in a mass wasting event. This reworked limestone may represent a slump deposit on a carbonate ramp. The association of the "Sutton Equivalent" limestone with the Sutton Member at Lake Cowichan does seem appropriate, though the Lake Cowichan site represents bioherm and biostrome buildup, unlike the limestone found near Port Alice (Stanley, 1989). The discovery of *Wallowaconcha raylenea* (Yancey and Stanley, 1999) at these localities is of interest because this extends the geologic range of this species into the Rhaetian (Stanley et al., 2013). The Yreka-3 section has been dated as Rhaetian, 202.4+-1.7 Ma based on whole rock isochron dating, and 206-212 Ma based on U-Pb zircon dating (Nixon et al., 2011d).

Interestingly, the black limestone found at Yreka-1 and Pulp Mill Hill is quite similar in appearance to the limestones found at Black Marble Quarry in the Wallowa terrane (Stanley, 1979; Stanley et al., 2008), perhaps indicating these limestones have a similar post-depositional

history. Petrographic and chemical analysis may reveal similarities, if there are any, in carbon content. The only faunal similarity found in this study between the northern Vancouver Island sediments and Black Marble Quarry is *Wallowaconcha raylenea* (Yancey and Stanley, 1999), though the Port Alice example was found in float near the lighter colored limestone, not the the black limestone (Stanley et al., 2013). Further research into the foraminifera of the black limestone near Port Alice may tell us more about whether these formations are similar lithologicaly, but as they are different ages (Black Marble Quarry is Carnian-Norian while the limestone at Port Alice is likely Rhaetian), foraminiferal similarities seem unlikely (Rigaud et al., 2008). Early studies have connected the Wallowa terrane to Wrangellia (Hillhouse, 1977; Jones et al., 1977; Stanley and Whalen, 1989), although more recent studies of fossil evidence have shown they were likely separate terranes (Sarewitz, 1983; Newton et al., 1987; White et al., 1992; Aberhan, 1998; Yarnell, 2000).

Based on the similarity of the upper shale layers of the Port Alice deposits to the shale sediments found at Tahsis, also on Vancouver Island (Fig. 4), these units can likely be correlated stratigraphically. Both the sedimentary rocks and fossils are very similar, indicating a close association between Tahsis and Port Alice rocks (Caruthers, 2005; Caruthers and Stanley, 2008a, 2008b). The Yreka-1 and Pulp Mill Hill shale is like the material found at Lutes Creek near Tahsis, BC, in that it is very fissile and has only external molds. The corals and bivalves at both locations are dissolved out of the rocks. Among the rocks found near Port Alice, these are the only ones with evidence of dissolution. Dissolution could be caused by ocean acidification, but could also be post depositional, e.g. caused by sub-aerial (above sea level) exposure (Kershaw et al., 2012). The shale layers, lying above the Rhaetian limestone, are at the earliest Rhaetian (Late Triassic) or may be Hettangian (Early Jurassic).

Chapter 5: Conclusions

The lithological associations of the strata near Port Alice with other Vancouver Island strata (Tahsis and Lake Cowichan) and with Wallowa terrane (Black Marble Quarry) are interesting because they help us better understand the environmental conditions at deposition and post depositional conditions. It is unlikely that the Wallowa terrane was a separate terrane from greater Wrangellia, but rather that post depositional conditions were similar enough to make them analogous. The two terranes were also likely close enough that *Wallowaconcha raylenea* (Yancey and Stanley, 1999) was able to disperse to both.

Sedimentary rocks found on northern Vancouver Island in the Port Alice represent an interesting snapshot of corals and bivalves living nearing the end of the Triassic. The taxa found at the study sites near Port Alice on Vancouver Island are also fauna that may have survived the end-Triassic mass extinction. Many phaceloid corals like the branching ones found on northern Vancouver Island, at the Yreka-2 and Colonial Creek sites, including a few species of *Retiophyllia*, survive into the Hettangian (early Jurassic). In particular, *Retiophyllia clathrata* (Emmrich, 1853) is found in the Late Triassic on northern Vancouver Island (Stanley, 1989; Caruthers and Stanley, 2008b) and in the Early Jurassic in northern Chile (Prinz, 1991). However, *Retiophyllia alfurica* (Wilckens, 1937), the species of *Retiophyllia* found as part of this work, have not been reported from the Early Jurassic.

According to data collected for database research (found in the second half of this thesis), apart from *Wallowaconcha raylenea* (Yancey and Stanley, 1999; Stanley et al., 2013), the bivalve genera found at the Yreka-1, Yreka-2, Yreka-3 and Pulp Mill Hill sites also survived the T-J extinction. These include *Megalodon* sp., *Eoplicatula* sp., and *Myophorigonia* sp. Trigonid

bivalves such as *Myophorigonia* are an excellent example of end-Triassic extinction suvivors, as they not only survived, but quickly diversified in the Early Jurassic. It is quite intriguing that these fauna that also exist in the Early Jurassic comprise the bulk of the fossils found at this Late Triassic site. Future research at for these Port Alice fossil sites could include more detailed lithological studies and geochemical analysis (such as organic carbon content of the black limestone), search for microfossils in the Port Alice sediments to those at Tahsis and Lake Cowichan, and more detailed stratigraphic analysis.

The sedimentary units found near Port Alice do not reveal a well-defined Triassic-Jurassic boundary because the earliest Jurassic layers are all volcanic. Therefore I could not address the hypothesis of the end-Triassic ocean acidification as the mechanism for mass extinction. Ocean acidification in the end-Triassic is gaining acceptance based on new findings from other Cordilleran locations and from the Tethys (Hautmann et al., 2008a; Greene et al., 2012; Hönisch et al., 2012). I did find some evidence of dissolution in the upper parts of Yreka-1 and Pulp Mill Hill in the form of extensive fossil dissolution. This evidence is not enough to show that there was ocean acidification, however, since it also can be caused by diagenesis or sub-aerial exposure. One more method for examining ocean acidification events is the changes in diversity of marine calcifying organisms before and after the event (Greene et al., 2012; Kershaw et al., 2012; Martindale et al., 2012). Besides field studies at Triassic-Jurassic boundaries, another way to test changes in diversity of marine calcifiers is by using a database to record and compare the global diversity changes, which is the research found in the Part 2 of this thesis.

Part 2:   Comparing Corals and Bivalves before and after the end-Triassic Mass Extinction
           Using a Taxonomic Database

Chapter 1: Introduction

(1)   <u>The Big 5 Mass Extinctions</u>

One of the most important tenants in geology is that the present is the key to the past, but it can also be said that the past is the key to the present. Over the course of geologic history, there have been five events which are considered major mass extinctions, Late Ordovician (440 Ma), Late Devonian (370–350 Ma), end-Permian (250 Ma), end-Triassic (201 Ma) and end-Cretaceous (65 Ma) (Raup and Sepkoski, 1982, 1984). Although it is likely that these events have different causes, such as bolide impacts, increase or decrease in global sea level, and massive volcanism, it is also likely that they have common themes in the pattern of recovery (Erwin, 2001). Therefore in an effort to understand mass extinctions on the grand scale, we can study one mass extinction event and compare our findings to those of another mass extinction. We can also apply this to the world today, as we may be facing global extinctions with the predicted global climate change (Alroy, 2008; Veron, 2008; Barnosky et al., 2011). Understanding the details and dynamics of past mass extinctions and the recoveries which follow may help us better understand and perhaps prevent the impending present-day global extinction. Although more than 20 mass extinctions are recorded in the geologic past, the five great extinction events contain some of the key events that can help us to understand how changes in climate and sea chemistry can cause great changes in the ecology of our planet.

There is a growing scientific consensus that Central Atlantic Magmatic Province (CAMP) volcanism is the cause of the end-Triassic mass extinction (Schoene et al., 2010; Whiteside et al., 2010; Greene et al., 2012). During the Triassic period, the supercontinent

Pangea was rifting apart, opening up the Atlantic Ocean (Fig. 9). This rifting resulted in an

enormous amount of volcanism, known as the Central Atlantic Magmatic Province (CAMP).

This volcanism spewed CO_2 and SO_2, causing massive atmosheric, climactic, and sea-chemistry

changes, in addition to sea-level changes caused by the change in continental arrangement. The

long-term change to the climate and ocean chemistry caused by elevated CO_2 is eerily similar to

the global climate warming and ocean acidification that are happening today (Caldeira et al.,

2006; Hönisch et al., 2012). The end-Triassic oceans probably had reduced pH, which would

also explain the biocalcification crisis that caused the extinction of many calcifying organisms

such as corals and bivalves (van de Schootbrugge et al., 2007; Ries et al., 2009; Ridgwell and

Schmidt, 2010; Greene et al., 2012; Hönisch et al., 2012). For more information on the

circumstances affecting the end-Triassic, see Part 1 of this thesis, "Nearing the End: Reef

Building Corals and Bivalves in the Late Triassic," earlier in this volume. Since various

calcifying organisms are affected by acidification differently (Orr et al., 2005; Ries et al., 2009),

it would make sense that if the end-Triassic mass extinction was an ocean acidification event the

organisms involved would respond in three ways. Based on modern ocean acidification studies,

some organisms may have reduced calcification but recover after oceans return to normal

conditions (e.g. "naked coral hypothesis" of Stanley, 2003), some actually went extinct because

from calcification losses, and others have actually benefited and diversified in reduced pH

oceans (Fine and Tchernov, 2007; Ries et al., 2009; Rodolfo-Metalpa et al., 2011).

There are two purposes of this study: 1) to test how closely the diversity of bivalves and

corals correlate from the Middle Triassic to Early Jurassic (through the extinction boundary) and

2) to test whether integration types within corals affected their extinction survival. My

hypothesis is that corals and bivalves responded to the end-Triassic mass extinction differently,

with corals losing more diversity, and that highly integrated corals had greater diversity losses than solitary and low integration corals. My hypothesis regarding the bivalves is that they will have similar losses in diversity to the corals across the Triassic-Jurassic boundary. These tests will help us better understand how different organisms respond to a probable ocean acidification event.
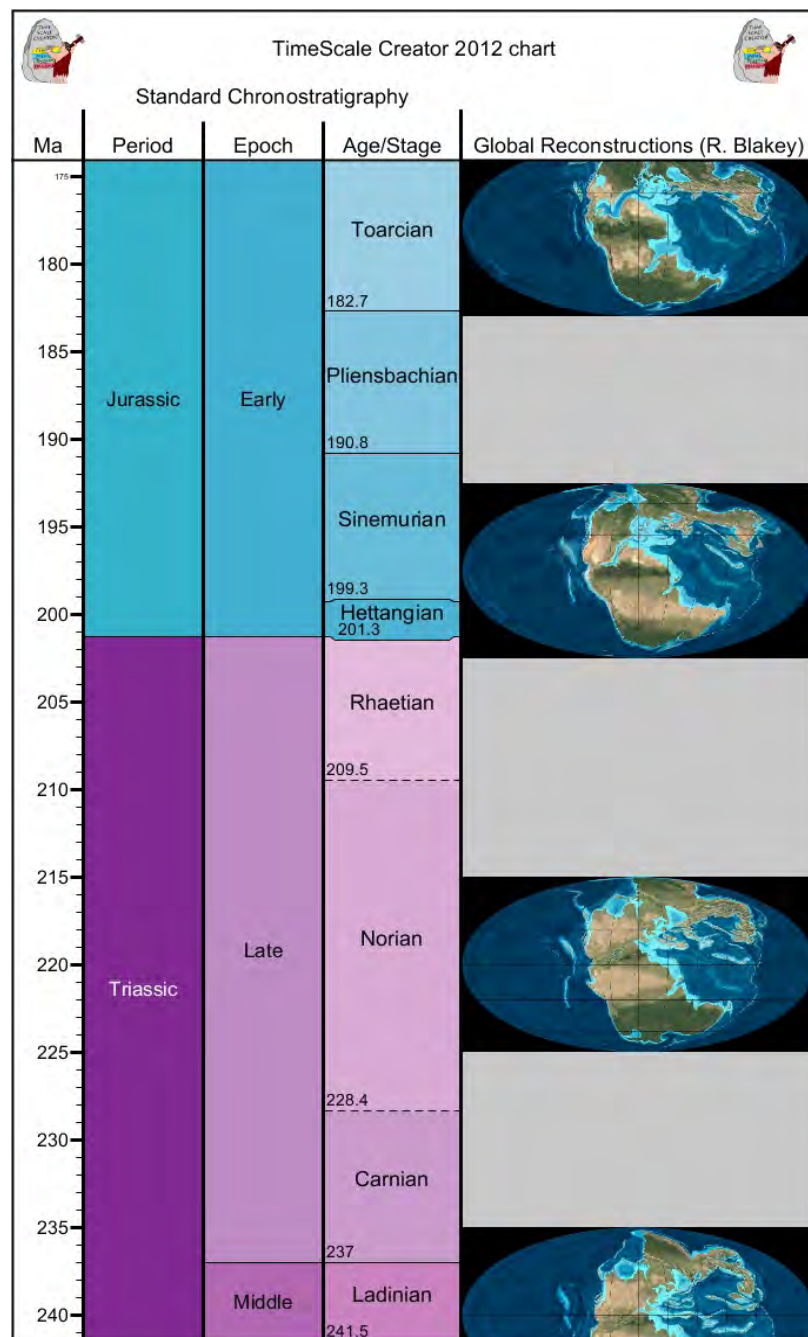
Figure 9: Time scale of the middle Triassic (Ladinian) through the early Jurassic (Toarcian) based on Gradstein (2012) with paleogeographic reconstructions of continental positions from Blakey (2011). Created using TimeScale Creator 6.1.2 (Ogg and Lugowski, 2013).

(2) Value of Database Applications in Paleontology

Database research has been a growing source of insight in the field of paleontology in the last thirty years. Thanks to paleobiological data compiled into integrated datasets including taxonomic information (Kingdom, Phylum, class, order, family, genus, and species), geographic range, geologic range, preservation, morphology, and life mode, paleontologists are able to assess what characteristics lead to extinction risk and how they relate to changing environmental factors such as climate changes and ocean chemistry (Kiessling and Aberhan, 2007; Alroy, 2008; Finnegan et al., 2008; Veron, 2008; Janevski and Baumiller, 2009; Harnik, 2011). Based on database research, paleontologists have also analyzed patterns of diversity through time, which lead to a better understanding of extinction and recovery patterns of various animal groups (Sepkoski, 1982; Conway Morris, 1998; Budd et al., 2001; Sepkoski et al., 2002; Alroy, 2003, 2010; Bonuso and Bottjer, 2008; Foote et al., 2008; Sahney and Benton, 2008; Sahney et al., 2010; Foote and Miller, 2013). Databases have also given paleontologists insight into not only how organisms evolve over time, but how communities such as reefs evolve in relation to climate and ocean chemistry (Kiessling et al., 1999; Kiessling and Flügel, 2002).

A major problem in paleontology which has been better studied through database research is the question of how representative the fossil record is of the actual diversity of organisms through time (Miller, 2000; Alroy et al., 2001; Alroy, 2003; Ros and De Renzi, 2005; Mander and Twitchett, 2008).   Critics have claimed that since the fossil record is imperfect, databases therefore will not reveal true trends in paleontological diversity (Raup, 1972; Mander and Twitchett, 2008) or at least that diversity in the most recent periods will be exaggerated by the greater area of recent rock formations (Miller, 2000; Alroy, 2003). Small scale trends in diversity certainly seem to be greatly affected by the amount of available sedimentary rock, but

large scale trends may not be so biased by the rock record (Foote and Sepkoski, 1999; Peters and Foote, 2001). The known rock record may also be used to compare to the fossil record to test paleontological hypotheses using databases (Wignall and Benton, 1999; Peters and Foote, 2001). Another method for testing the quality of the fossil record is subsampling (Alroy et al., 2001; Alroy, 2003), which can reduce some of the sampling bias. Three of the 'big five' mass extinctions are also too large to be affected by bias from the rock record (end-Ordovician, end-Permian, and end-Cretaceous), though this does not necessarily discount the end-Triassic as a true mass extinction, only that it wasn't big enough to not be biased by the fossil record (Bambach et al., 2004; Bambach, 2006)

Mass extinctions have been studied using taxonomic databases since Sepkoski (1982) who first created a computer-generated list of families for all fossil marine animals and animal-like protista (Table 4), later expanded this into a list of the fossil marine animal genera (Sepkoski, Jablonski, & Foote, 2002). Sepkoski used published research on fossil occurrences to record the first and last occurrence of each marine animal family and genus throughout geologic history. This data enabled Sepkoski and others (Raup and Sepkoski, 1982, 1984, 1986; Miller and Sepkoski, 1988; Foote and Sepkoski, 1999) to investigate important and relevant topics of originations, extinctions, and biodiversity. Raup and Sepkoski (1982, 1984, 1986) used their database to hypothesize that mass extinctions happen at regular intervals, leading to the idea that the 5 big mass extinctions may have common causes, perhaps through astronomical cycles such as the movement of the solar system through the arms of the Milky Way increasing bolide imapcts. Recently the Sepkoski (2002) database was formatted for online search by Shanan Peters at The University of Wisconsin-Madison (Peters, n.d.).

In order to understand the mechanisms and patterns of mass extinction including the end-Triassic mass extinction, researchers must either be able to study a complete extinction boundary section, or use global patterns to compare time periods. Since there are very few sections across the Triassic-Jurassic boundary that contain sedimentary rocks and fossils on both sides of the boundary, it is useful to study the global patterns using a taxonomic database. Taxonomic databases enable us to research the changes in diversity of taxa, which can be compared across extinction boundaries. We can also use these databases to compare changes in geographic distribution of taxa. Although no database can ever be 100% complete, citing all papers ever published on a particular organism, can provide a reasonable dataset of information about the organisms, which can then be used to analyze patterns of fossil occurrences. Understanding the geographic distribution of fossils can tell paleontologist where organisms were surviving during times of crisis (such as extinctions) and give us clues as to what environmental conditions permitted survival through extinctions.

A good paleontological taxonomic database is more than just a list of species or genera, it contains information on many aspects of fossils, including number of occurrences of a taxon (species, genus, etc), age, locality, authors, publications, and morphology. How many fossils of a particular taxon have been reported or described in journal articles is recorded in the occurrence data. Occurrence data is based on the number of fossils reported in papers, and is recorded with age and locality information. Fossil age needs to be formatted such that it can be understood as both stages within a period, and as a numerical value (i.e. mya). How that date was obtained also comes into play. Was it based on associated fossils (e.g. conodont zones), radiometric dates of that bed or those above/below it, or was it purely based on relative dating of the bed? In addition to the age of the fossil, it is important to know fairly precise locality

information for biogeographical research. The latitude and longitude where the fossil was

collected is sometimes provided in the journal articles describing the fossil, but often it must be

extrapolated using descriptions of the geography provided in the text. It's also important to

record the original author who described a given taxon, and the name changes (synonomies) that

have occurred in that taxon's history. Finally, in order for other researchers to double check the

reliability of data, the source of this information (i.e. publication) should always be cited.

The Paleobiology Database (PBDB, www.pbdb.org) is a public domain database of

paleobiological information contributed by a wide range of experts throughout the world (Table

4). The database was started by the Phanerozoic Marine Paleofaunal Database initiative 1998 by

a grant from the National Center for Ecological Analysis and Synthesis (NCEAS) and from 2000

to 2008 was funded by the National Science Foundation and is funded by the Australian

Research Council (Alroy, 2012). It is currently the world's most complete and accessible general

database of paleontology. The PBDB allows researchers to download data as lists of species or

genera, with the time period, stage, age in mya, geographic locality today and paleogeographic

locality, and publishing authors. This information can then be analyzed to compare the diversity

and abundance of species within and across time periods.

Since the end-Triassic mass extinction is a likely ocean acidification event (Hautmann et

al., 2008a; Greene et al., 2012; Hönisch et al., 2012; Martindale et al., 2012), diversity and

abundance of calcifying organisms are the best way to assess the extinction and the recovery.

Expansive coral reefs of the Late Triassic were dominantly built by corals, with sponges and

microbes as important secondary reef builders (Kiessling, 2010). Reefs in the Hettangian

(earliest Jurassic) are, for the most part, missing or poorly developed, with the notable exception

of one coral reef found in France (Kiessling et al., 2009) and another another ?Hettangian-

Sinemurian reef in Tajikistan (Melnikova and Roniewicz, 2012). From the Sinemurian to the Toarcian, reefs were dominantly built by bivalves (Kiessling et al., 1999; Fraser et al., 2004), although there are a few coral-dominated reefs from the Sinemurian, such as found in the Telkwa Range in British Columbia (Stanley and Beauvais, 1994). Since both corals and bivalves are negatively affected by CO_2 induced ocean acidification (Fine and Tchernov, 2007; Hall-Spencer et al., 2008; Ries et al., 2009), we can be enlightened by understanding which organisms survived the end-Triassic mass extinction. This understanding may even help us understand how to best manage marine reefs today, given the current ocean acidification crisis.

Table 4: Comparison of select databases relevent to the study of Triassic and Jurassic corals and bivalves.

Database	Author or Contributors, Years	Format	Organisms included	Taxonomic level	Availability
A compendium of fossil marine animal families	Sepkoski, 1982	Print	Animals and "animal-like protista"	Family	Must buy paper publication
A compendium of fossil marine animal genera	Sepkoski, Jablonski, & Foote, 2002	Print	Animals and "animal-like protista"	Genus	Yes, online at strata.geology.wisc.edu/jack
Paleobiology Database	~144 Paleobiological Researchers from around the globe, 1998 - Present	Online	Plants and Animals	Species (when identification to species level possible)	Yes, online at pbdb.org
Corals of the Triassic Tethys	Reidel, 1991	Doctoral Thesis	Triassic Corals	Species	Out of print and only available in German
Scleractinia of North American Cordillera	Schlichtholz, UG thesis UM, 1997	Undergraduate Thesis and PaleoTax Software	North American Triassic Corals	Species	Not available, unpublished bachelors thesis
Corallosphere	26 Coral Paleontology researchers from around the globe, 2010 - Present	Online	Mesozoic to recent Corals	Genus	Yes, online at www.corallosphere.org
Global diversity of Triassic to Middle Jurassic corals	Lathuilière and Marchal, 2009	Journal paper	Triassic and Jurassic Corals	Genus	No
PaleoReefs (PARED)	Kiessling, 1999, 2002	Journal papers	Phanerozoic coral reefs	Occurences of reefs (not taxonomic info)	No, Some Data is available in Phanerozoic Reef Patterns, SEPM Special Publication 72; Maps are available in Kiessling et al 1999
Dynamics of paleodiversity of Lower Triassic to Lower Jurassic Bivalves	Ros, 2009	Doctoral Thesis	Lower Triassic to Lower Jurassic Bivalves	Genus	Yes, in spanish, online at http://www.tdx.cat/handle/10803/9952

(3)   Databases Developed for Scleractinian Corals

  (a)   Background on coral morphology

    (i) Definition of Scleractinia and explanation of their morphology

The ultimate goal of most taxonomic databases is to better understand the evolution of organisms through time. Scleractinian corals are no exception. Scleractinia, or 'stony corals' first appear in the Middle Triassic and survive to the present (Stanley and Fautin, 2001). Scleractinian corals are an order of the class Anthozoa, which are in the phylum Cnidaria, along with organisms such as anemones and jellies (or Jellyfish). Like other Cnidaria, scleractinia do not have organs, and have radial symmetry and cnidoblasts (stinging cells) (Oliver and Coates, 1987). Cnidaria also have a life cycle that involves both sexual and asexual reproduction. Asexual reproductiom can produce colonies of clones (Coates and Oliver, 1973; Oliver and Coates, 1987). Scleractinia are differentiated from other Anthozoa by their six sided radial symmetry and their aragonitic skeletons.

The following definitions are used throughout this paper to refer to aspects of scleractinian coral morphology (Fig. 10) (Budd and Johnson, 1998; Cairns et al., 2012):

- Calice: "cup-like structure seen at the distal end of solitary corals and on the outermost surface of colonial corals (Johnson in Cairns et al., 2012)." Each calice represents one individual clone within a colonial coral, sometimes separated by walls or dissepiments (see definitions [below] and coral integration [next section]).
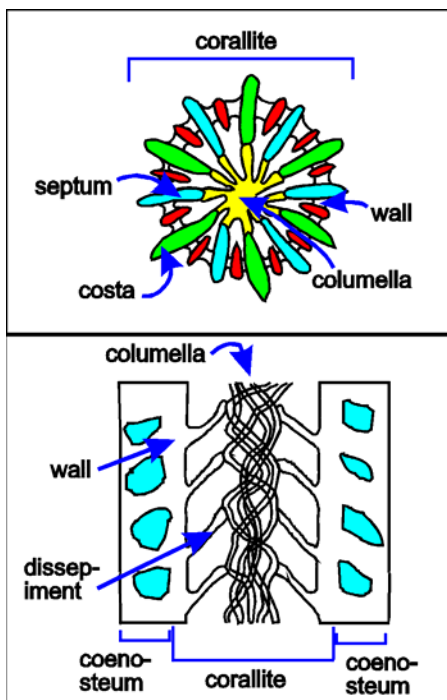
Figure 10: General diagram of coral morphologic features (from Budd and Johnson, 1998)

- Corallite: "skeleton of a solitary individual or an individual within a colony (Budd and Johnson, 1998)." Contains features such as septa, dissepiments, and walls, but not all features are present in every corallite (Cairns et al., 2012)

- Coenosteum: skeletal elements between each corallite within a colony

- Septa: "radially-arranged vertical partitions within a corallite (Budd and Johnson, 1998)." In scleractinian corals, septa generally grow in groups of 6 (i.e. 6 than 12, and so on).

- Costae: "extension of a septum beyond the wall (Budd and Johnson, 1998)."

- Columella: "central axial structure (vertical rod) within a corallite (Budd and Johnson, 1998)."

- Dissepiment: "horizontal partition (flat or curved) within or outside of a corallite (Budd and Johnson, 1998)."

- Wall or Theca: "vertical structure enclosing a corallite (Budd and Johnson, 1998)."

(ii) Coral colony integration

In order to understand the evolution of scleractinian corals through time, we must also include data about their coloniality. All coral groups from the Paleozoic to the modern exhibit some aspects of coloniality, because they can reproduce asexually through budding. This means that forming colonies is an important aspect of growing and building coral reefs (Coates and

Oliver, 1973). According to these authors a colony is defined by as "a group of individuals, structurally bound together in varying degrees of skeletal and physiological integration, all genetically linked by descent from a single founding individual." This "degree of integration" between colonies is the extent to which the individual colonies are intergrown and how closely they cooperate in their life activities (Figure 11, Table 5). Solitary corals by their very nature are those without integration, phaceloid corals are those that branch, but the corallites are separated from each other, plocoid (coenosteoid) corals branch and corallites are adjacent but separated by skeletal tissue (coenosteum), cerioid have corallites that are juxtaposed with walls between the corallites, astreoid corallites are adjacent with no wall between them, thamnasterioid corallites have contiguous septa, and meandroid corals have chains of fully connected corallites that look like valleys, with ridges between each chain (Oliver and Coates, 1987; Budd and Johnson, 1998; Stanley, 2003; Cairns et al., 2012). Aphroid coral integration, which was not found in the descriptions for the corals included in this database, has corallites which are adjacent with septa limited to the calice area (not continuous as they are in thamnasterioid), connected by dissepiments, and may or may not be separated by an inner wall (Oliver and Coates, 1987).
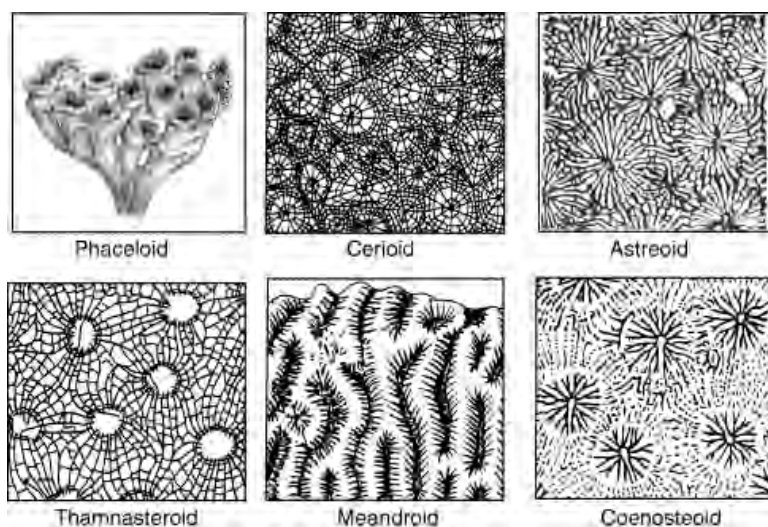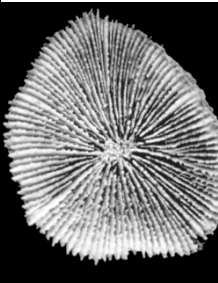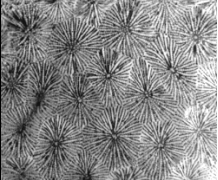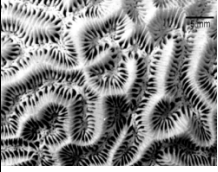
Figure 11: Illustrations of coral colony integration types (Stanley, 2003)

Table 5: Coral integration types, with definitions and examples (Modified from Budd, 1998)

Integration type	Definition	Illustration
Solitary	Corallum formed by only one individual	
Phaceloid	Coralites separated by void space	
Plocoid	Corallites separated by coenosteum	
Cerioid	Corallites juxtaposed	
Meandroid	Corallites arranged in multiple series	

(iii)   Photosymbiosis in Scleractinia

Modern scleractinian corals (as well as a variety of other shallow-water, tropical groups of invertebrates) have a mutualistic relationship with algae, which perform photosynthesis and provide extra nutrients and energy for the coral while the coral hosts provide the algal symbionts with protection, CO_2 and nitrogen (Cowen, 1988; Stanley and Lipps, 2011).   These symbionts in corals are usually a dinoflagellate known as zooxanthellae, which unfortunately are not fossilized.

Evidence of this photosymbiotic relationship may be found in the fossil record, however. Modern zooxanthellate (photosymbionts-bearing) corals are far more likely to be colonial, highly integrated, and have small corallites (Coates and Oliver, 1973; Coates and Jackson, 1987). Zooxanthellate corals are also able to calcify more quickly and thus may be better adapted at building reefs (Goreau, 1959; Stanley, 1981, 2006). This is why in modern corals, hermatypic ('reef building') is nearly synonymous with zooxanthellate. Whether this association of zooxanthellae with reef building is always true throughout the fossil record is difficult to test, but does not always seem to hold (Coates and Jackson, 1987). Another test for zooxanthellae in the fossil record is stable isotope analysis (Stanley and Swart, 1995). Stable isotope analysis compares the carbon and oxygen isotope composition of modern zooxanthellate and azooxanthellate coral to ancient corals. Unfortunately, in order to perform these tests it is necessary for the corals to be unaltered aragonite, which is relatively uncommon in the fossil record. Zooxanthellate corals of today also show evidence of alternating high-density and low-density growth bands, which are not found on azooxanthellate corals. This is another source of evidence for photosymbiosis that can be applied to fossil colonial corals (Stanley and Helmle, 2010). Photosymbiosis may have evolved or spread during the Triassic as a response to low nutrient availability, declining CO_2, or climactic cooling (Cowen, 1988; Kiessling, 2010). Wood (1993) suggested that photosymbiosis evolved in the mid-Mesozoic and early Tertiary. without exception, photosymbiosis correlates with high levels of integration in modern corals (Coates and Oliver, 1973; Coates and Jackson, 1987), so it is possible to infer that highly integrated corals were photosymbiotic (Kiessling, 2010; Stanley and Lipps, 2011).

(b)   History of scleractinian databases

Riedel (1991) published a printed database of scleractinian corals of the Triassic as part of a doctoral thesis at the University of Erlangen, Germany (Table 4). It is useful in that it incorporated some of the basic categories of coral colony integration type. Riedel simplified more than 20 types of colonial integration into only three categories: solitary, dendroid, and cerioid (Cairns et al., 2012). Simplifying the many growth forms common to scleractinian coral is useful for entering data, but using only three categories also means we lose a lot of information, especially about more highly integrated growth forms of coral (such as meandroid, coenosteoid etc.). Although Riedel's database contains useful information regarding Triassic coral diversity and growth forms, it has not been updated since 1991 and is only available in print (in German). For the purposes of comparing the Triassic to the Jurassic corals, it is not sufficient, because the database does not include Jurassic corals.

Sarah Schlichtholz, an undergraduate student at the University of Montana developed for a senior thesis, a database for Triassic Scleractinia of North America (Table 4, Schlichtholz, 1997). Schlichtholz used the PaleoTax software (Loser, 1993, 2004), which is a database management system similar to Microsoft Access, but specifically geared towards paleontological applications. The PaleoTax software is useful because it allows paleontologists to enter all the information necessary for taxonomic records, and it has tools for data analysis. However, the software is also challenging to master. Schlichtholz' database is not available online and has not been revised since 1996, especially for new occurrences of corals and taxonomic changes. Also, like Reidel's database, the Schlichtholz database is only for Triassic corals, so it is not sufficient for comparing with corals of the Jurassic.

Another database of Mesozoic to Modern coral information available online, is Corallosphere (Table 4, Cairns et al., 2012). This extensive internet based database contains more information on old names, identification, and morphology of corals, but only has data for each genus of coral, rather than data on each species. One piece of information I obtained from Corallosphere to integrate into my database is the coral integration types (Fig. 3, Table 5).

Lathuilière and Marchal (2009) published database information on Triassic to Middle Jurassic coral taxa developed from bibliographical information (Table 4). This database is genus-level, but does also incorporate coral integration and geographical information. This allowed the researchers to analyze some ideas and postulates about the extinction and the recovery, such as which integration types survived the extinction and/or were the first to recover. Lathuilière and Marchal also were able to analyze the geographical patterns of the recovery. While the analyses of this database have been published, the database itself is not publically available.

The PaleoReefs database, PARED (Kiessling et al., 1999; Kiessling and Flügel, 2002; Kiessling and Aberhan, 2008a) , is an electronic database that contains information on reef type, distribution, and biota (higher level taxa) of critical time slices throughout the history of life (Table 4). The PaleoReefs database has been used by Kiessling and others to produce maps of reefs from different Phanerozoic time periods. Kiessling has been able to use this database to compare the effects of climate and ocean chemistry on coral reefs (Kiessling et al., 2008; Kiessling, 2010). Like Lathuilière and Marchal (2009), PARED is not publically available.

The Paleobiology Database (PBDB) is the most up to date and readily available database on coral species (Table 4). In order to ensure the completeness of the PBDB, paleontologists enter occurrences of species from publications. Previous databases (Riedel, 1991; Schlichtholz,

1997; Kiessling et al., 1999; Kiessling and Aberhan, 2008b; Lathuilière and Marchal, 2009; Cairns et al., 2012) are some of the easiest publications for updating the PBDB and checking it for accuracy and completeness, since the information is already compiled. PBDB is publicly available and anyone can download information, but the information it contains is limited mostly to geographic and temporal information. As a contributor to the PBDB, I enter species data into the database anytime I find species or other information from publications not already included. Because some contributors do enter information about morphology, I am working to expand the coral morphology information by including integration type with the coral species I personally enter.

       (c)   Development of a new database for scleractinian corals

No coral Triassic to Jurassic coral databases have incorporated species level diversity data with coral integration types. In addition, the databases by Riedel (1991) and Lathuilière and Marchal (2009) grouped integration types into only three categories, limiting the range of analysis of extinction effects on coral integration type. Therefore in an effort to better analyze the effect of the end-Triassic mass extinction on reef organisms, I endeavored to create a new database compiling this information. The database thus developed, is an integration of species information from PBDB, Schlichtholz (1997), and Riedel (1991). This new database contains geographic information, based on occurrences of coral species, temporal information, based on the age of the geologic units in which the fossil corals occur, and growth form information, based on the integration types of the corals. Riedel (1991) also used only three categories of integration, thus limiting the usefulness. I have expanded this to include seven categories: solitary, phaceloid, plocoid, cerioid, astreoid, thamnasterioid, and meandroid integration forms.

By numbering these categories with integers, I was able to statistically analyze the trends of integration through the Late Triassic and Early Jurassic. I was also able to use the means of these integers to incorporate intermediate forms (e.g. cerio-thamnasteroid) and coral species that have multiple possible morphologies.

(4) Databases of bivalves

Researchers have created bivalve databases to study extinction and recovery patterns in specific geographic areas (McRoberts and Newton, 1995; McRoberts et al., 1995; Yin and McRoberts, 2006; Hautmann et al., 2008b) and globally (Fraiser and Bottjer, 2007; Ros, 2009; Ros and Echevarría, 2011; Ros et al., 2011). Most notable is the extensive database created by Ros (2009) as part of her doctoral dissertation to study recovery patterns after the Permian and end-Triassic mass extinctions (Table 1). Ros compiled information from the literature on bivalve genera from early Triassic to early Jurassic, including stratigraphic range, paleogeographic distribution, life mode, and shell mineralogy, using this data to draw conclusions about changes in bivalve diversity and life modes through time. The database created by Ros is included in her thesis, available in print and online (in Spanish). More commonly, paleontologists (Kiessling and Aberhan, 2007; Kiessling et al., 2007, 2008; Mander and Twitchett, 2008; Harnik, 2011; Hautmann, 2012) use the Paleobiology Database (PBDB, www.pbdb.org) to study extinction and recover patterns of bivalves. Bivalve databases can also be used for other types of analysis. Aberhan (1999) created a database of pectinoid bivalves in North America in order to analyze the latitudinal displacement of the Wrangellia and Stikinia terranes. Several researchers have also used bivalve databases as test cases for analyzing the quality of the fossil record (Ros and

De Renzi, 2005; Mander and Twitchett, 2008), concluding that both mode of life and mineralogy can affect fossil preservation.

Chapter 2: Methods

(1)   Database methods

The purpose of developing the database of Late Triassic and Early Jurassic corals and bivalves is to examine and compare global trends with what was found on Vancouver Island, and to make comparisons of changes in diversity and morphology across the Triassic-Jurassic boundary. I began by converting the North American Triassic coral database developed by Sarah Schlichtholz (1997) from the PaleoTax software into an Excel spreadsheet that could be more easily amended. I then scanned the Tethyan Triassic coral database developed by Riedel (1991), and converted it into Microsoft Excel format. Finally I downloaded species data from all Carnian (Late Triassic) to Pliensbachian (Early Jurassic) corals from the Paleobiology Database (www.pbdb.org Alroy, 2012). Before adding information from publications the may not have included in any of these databases, I combined the three, and checked through each species to make sure there were no duplicates (including synonymies, species with more than one name). I also checked each species for accurate information on author, date, temporal range, and geographic range and added relevant information on morphology (integration type) for each genera that did not already have this information, based on information from Corallosphere (Cairns et al., 2012). Based on more recent and overlooked publications, I also added species to both my database and the PBDB from publications that had not previously been part of Paleobiology Database.

Because bivalve mollusks are an important component of Upper Triassic to Jurassic invertebrates and often co-occur with corals, I included them in my project. To improve the utility of the research on bivalve data, I downloaded species data from Carnian to Pliensbachian bivalves from the Paleobiology Database (www.pbdb.org Alroy, 2012). As a contributor to the Paleobiology database, I added species of bivalves from publications which were absent from the PBDB database.

(2)   Statistical methods

In order to test the correlation through time between bivalve and coral diversity, I used Excel to find the counts of coral species and bivalve species for each stage (Late Triassic: Carnian, Norian, and Rhaetian; Jurassic: Hettangian, Sinemurian, and Pliensbachian). I also used Excel to plot and graph the bivalves and corals through time (Figure 12). The results of these counts were then analyzed using the R program (http://www.r-project.org/). Since this is a time series, I used a Pearson's product moment correlation coefficient (Equation 1) to test the correlation between bivalves and corals through time.

$$r_{BC} = \frac{\sum_{i=1}^{n}(B_i - \overline{B})(C_i - \overline{C})/(n-1)}{s_B s_C}$$

Equation 2: Equation for Pearson's product moment correlation coefficient, where B is the number of bivalve species per stage, and C is the number of coral species per stage, s_B and s_C are the sample standard deviations.

To test the correlation between survival (from Triassic to the Jurassic) of coral species relative to integration levels I began by assigning each integration type a number (0=solitary, 1=phaceloid, 2=plocoid, 3=cerioid, 4=astreoid, 5=thamnasterioid, 6=meandroid). I used these numbers to assign each coral species a number (intermediate integration forms and species with multiple possible forms were given an average, e.g. ploco-cerioid=2.5). I then used Microsoft

Excel to find a count of the integration types from each stage and graphed the number of species of each integration type through time (Figs. 5, 6). I also assigned each species a number based on whether they survived the end-Triassic mass extinction (i.e. existing both in Triassic and Jurassic periods), to form a binomial data set (0=did not survive, 1=survived). I then analyzed this data in the R program (http://www.r-project.org/) using a two sample T-test, and created a boxplot comparing the non-surviving species to those that did not (Fig. 7).
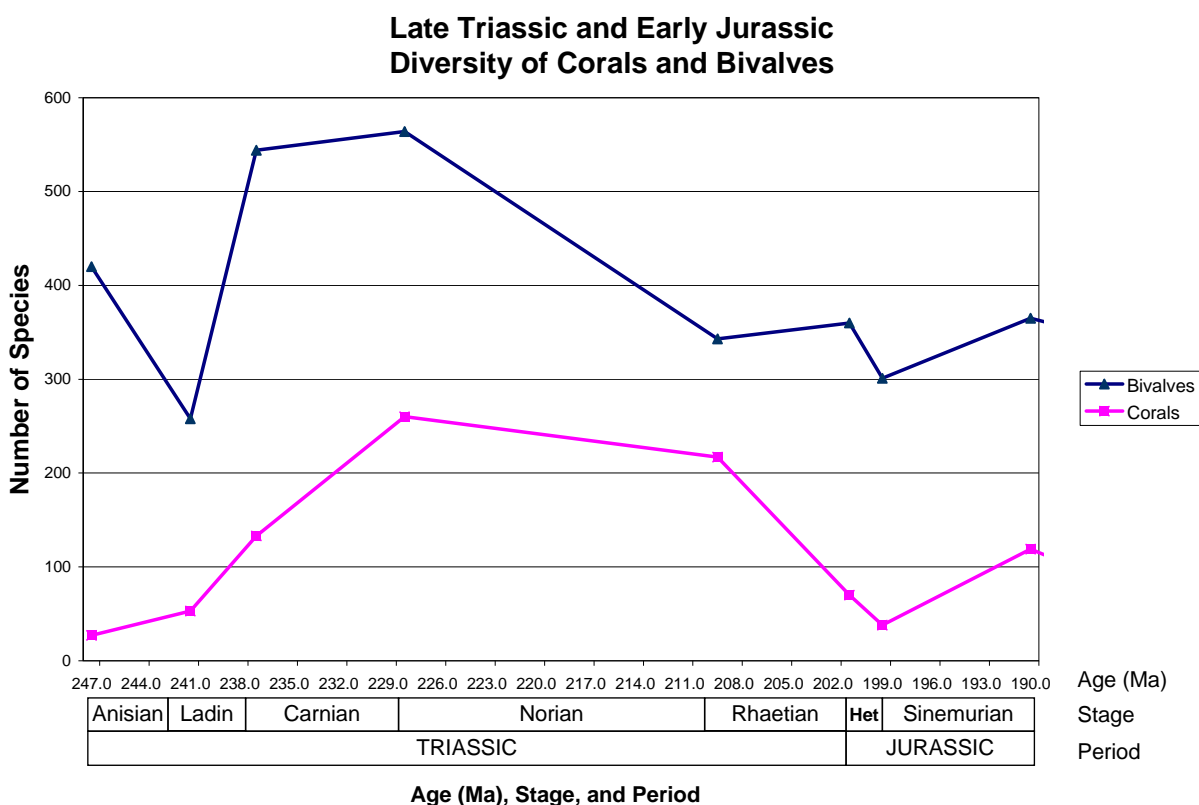
Figure 12: Diversity of corals and bivalves from Ladinian (Middle Triassic) to Toarcian (Early-Middle Jurassic) based on database of coral and bivalve species created for this paper. Species data for each stage are averaged, since for many species exact age of occurrences are unknown. Although Late Triassic to Early Jurassic data is the most relevant to this paper, surrounding stages were included in order to show longer term trends.

A. Coral Species Integration Types by Stage
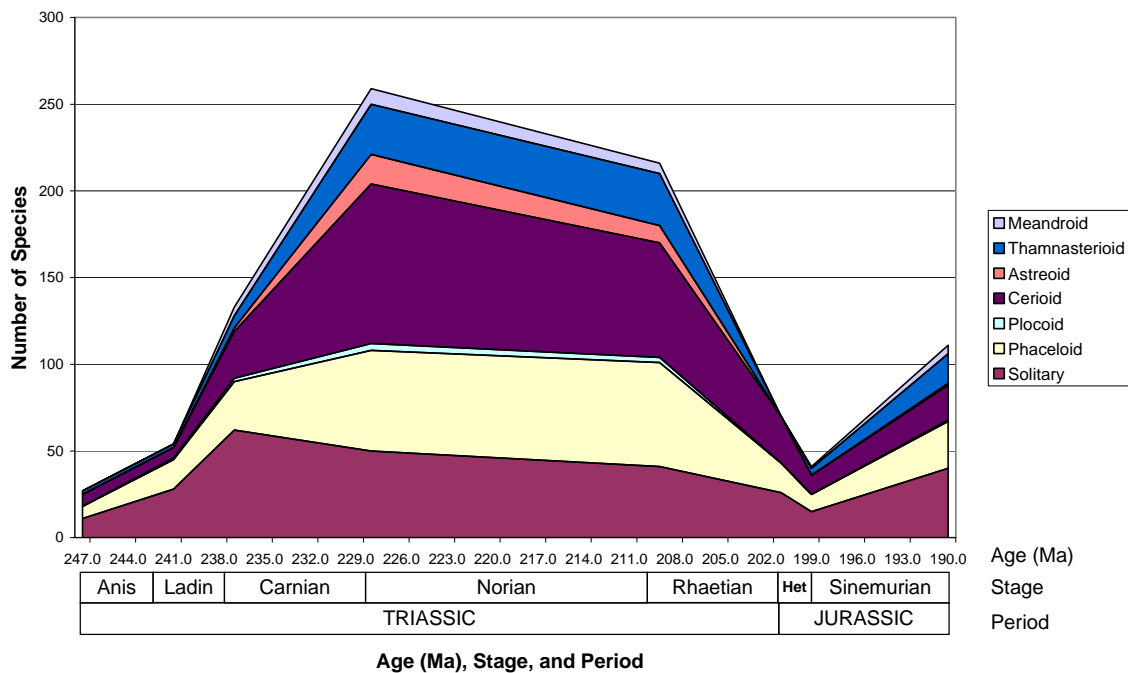
B. Proportional comparison of Integration types by Stage
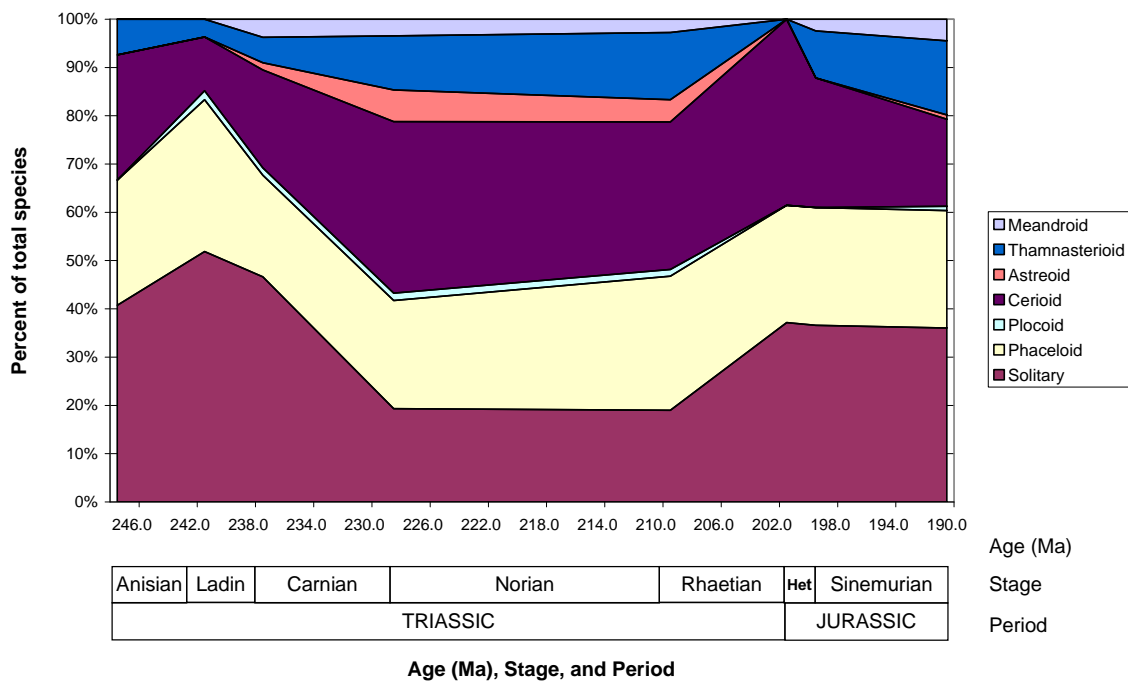
Figure 13: Number of coral species by integration type from Anisian (Middle Triassic) to Pliensbachian (Early Jurassic) based on database of coral and bivalve species created for this paper. A. Absolute numbers of species by integration types. B. Proportional comparison of integration types by percent of total species.

Chapter 3: Results

(1)   Corals and Bivalves:

There is a low level of correlation between the diversity curve for bivalves from the Ladinian to the Toarcian and the diversity curve for scleractinia through the same stages (R^2 of 0.3447 and 2 sided p-value of 0.07367). If these data are correct it suggests that although both bivalves and Scleractinian corals were experiencing the same environmental pressures, their responses did not affect diversity in the same ways. An interesting note, as shown in Table 3 and Figure 4, is that there is no decrease in diversity of bivalves from the end of the Triassic to the beginning of the Jurassic. In fact, there is a reduction in bivalve diversity in the Late Triassic (Rhaetian) prior to the extinction. Some diversity loss in the Early Jurassic would be expected if bivalves are negatively affected by the extinction.

Table 6: Diversity of bivalves and coral from the Ladinian (Middle Triassic) through the Toarcian (Early-Mid Jurassic)

		Total Species	
Stage	Base Age (Ma)	Bivalves	Corals
Toarcian	183.0	322	61
Pliensbachian	189.6	361	119
Sinemurian	196.5	284	38
Hettangian	199.6	342	70
Rhaetian	203.6	335	217
Norian	216.5	548	260
Carnian	228.7	538	133
Ladinian	237.0	246	53

(2)   Coral Morphology

There is no correlation between survival from the Triassic to the Jurassic and level of integration (2-sided p-value = 0.9345). Only twelve species from this database are found in both the Triassic and Jurassic, so the data set for the t-test was relatively small. Corals with higher levels of integration survived the Triassic-Jurassic extinction about as well as those with lower levels of integration (Fig. 7). This result is counterintuitive, because it is thought that corals with

more complex morphology had a closer reliance on stable environmental conditions. Modern highly integrated corals are found mostly at low latitudes and shallow water and require stable temperatures (Oliver and Coates, 1987).   Also and perhaps equally important, high levels of integration in corals are correlated with a photosymbiotic relationship with zooxanthellae because living zooxanthellate corals are highly integrated (Coates and Oliver, 1973; Wood, 1999; Stanley, 2003).

Photosymbiosis is a rather fragile relationship, so corals would be likely to lose their symbionts because of poor environmental conditions in the end-Triassic time. However, it is also possible that the photosymbiotic relationship was not lost for many corals in the end-Triassic, and the ability to rapidly calcify allowed photosymbiotic corals to thrive again after oceanic chemistry returned to normal. Zooxanthellate corals can lose their symbionts if conditions are inhospitable to them, since photosymbionts require sunlight and are sensitive to chemistry changes (Anthony et al., 2008; Finney et al., 2010). Since zooxanthellae help corals build carbonate quickly (Goreau, 1959; Stanley, 1979, 2006), most tropical to subtropical reefs of today, and probably in the past, are made up of zooxanthellate corals (Kiessling, 2010; Stanley and Lipps, 2011). Loss of photosymbiosis would also explain the relatively small number of reefs in the Early Jurassic (Kiessling et al., 2009; Melnikova and Roniewicz, 2012), and the highly integrated coral that did survive the extinction likely survived in or near one of these Early Jurassic reefs.
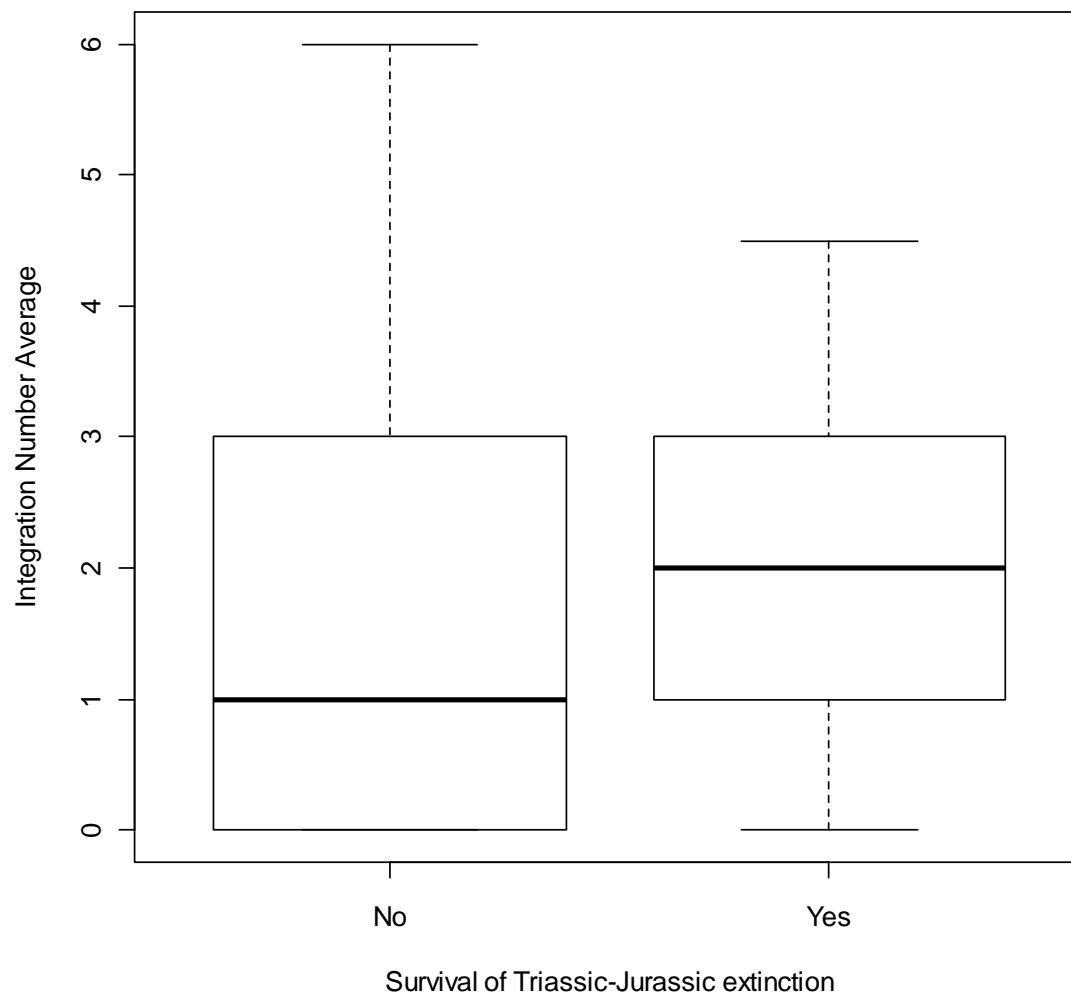
Figure 14: Boxplots of coral integration numbers for corals that survived the extinction (right) vs. those that did not (left); (0=solitary, 1=phaceloid, 2=plocoid, 3=cerioid, 4=astreoid, 5=thamnasterioid, 6=meandroid). Dashed lines on boxplots represent the full range of values.

Table 7: Diversity of Corals by Integration type

Integration		Triassic					Jurassic		
Integration type	Number	Anis	Ladin	Carn	Nor	Rhaet	Het	Sin	Plien
Solitary	0	11	28	62	50	41	26	13	29
Phaceloid	1	7	17	28	59	61	17	9	25
Plocoid	2	0	1	2	4	3	0	0	1
Cerioid	3	7	5	27	92	66	27	11	17
Astreoid	4	0	0	2	17	10	0	0	1
Thamnasterioid	5	2	2	7	29	30	0	4	16
Meandroid	6	0	0	5	9	6	0	1	2

Chapter 4: Discussion

As mentioned at the beginning of this study, today our oceans are threatened by the rise in anthropogenic CO_2, which is causing ocean acidification, making it more difficult for calcifying organisms such as corals and bivalves to survive and build reefs (Orr et al., 2005; Kleypas et al., 2006). Two hundred million years ago, at the end of the Triassic period, similar conditions are postulated to have arisen primarily from volcanism caused by the rifting of Pangea (CAMP). Findings here indicate that the conditions in the end-Triassic and early Jurassic affected bivalves and corals differently. Based on the findings here, bivalve diversity was not negatively affected by the mass extinction (Fig. 12), but bivalves were already losing diversity in the Rhaetian stage. The reason for the pre-extinction bivalve diversity loss was not investigated by this study. Coral diversity, on the other hand, was greatly reduced after the extinction (Fig. 12). In addition corals with high integration had similar diversity losses than those with low integration (Figs. 13 and 14). Modern studies indicate that different calcifying organisms do in fact have different responses to reduced pH (Kleypas et al., 2006; Ries et al., 2009).

Even among bivalves, different life modes, such as infaunal and epifaunal, have different responses to changing conditions (McRoberts and Newton, 1995; Hautmann, 2006; Ros and Echevarría, 2011; Ros et al., 2011; McRoberts et al., 2012). Ros and Echevarría (2011) found that it was the specialists (i.e. epifaunal-sedentary and shallow burrowing) bivalve species that were most severely affected by the end-Triassic extinction, and that generalists were able to preferentially survive. According to McRoberts and Newton (1995) epifaunal bivalve species survived the end-Triassic mass extinction with greater diversity than the infaunal species. Among the epifaunal species, shell morphology and mineralogy seems to make the greatest difference to survival (Hautmann, 2006), in that thick-shelled aragonitic bivalves either adapted

by secreting calcite rather than aragonite to survive the changes in sea chemistry, or suffered extinction losses, whereas thin-shelled varieties survived without adapting.

The lack of correlation between coral integration level and extinction survival is surprising, because highly integrated corals were also probably photosymbiotic (Coates and Oliver, 1973; Coates and Jackson, 1987). In modern oceans, coral bleaching or loss of zooxanthellae caused by elevated temperature is rampant (Wilkinson, 2008), and likely to be closely tied to ocean acidification from rising CO_2 (Anthony et al., 2008). Early Jurassic coral fauna may or may not have been photosymbiotic, since zooxanthellae themselves do not fossilize it is difficult to tell, stable isotope analysis on well preserved specimens may help (Stanley and Swart, 1995). Other studies have found that the corals present in the early Jurassic tend to differ morphologically from the Late Triassic corals, such as the low diversity, phaceloid corals found in a rare reef in the lower Hettangian in France (Kiessling et al., 2009). Melnikova and Roniewicz (2012) found that in Hettangian?-Sinemurian and Sinemurian corals of the Pamir Mountains in Tajikistan, coral fauna were morphologically and microstructurally simpler than those found in the late Triassic. While this study concludes that integration level did not affect coral extinction survival, there are so few coral species that survived in both the Triassic and Jurassic that the data may not be reflecting the whole story.

The findings here further support the idea that ocean acidification is not just a simple reduction in pH which causes extinctions among all calcifying organisms. Extinction losses also seem to greatly depend on an organism's ecology, morphology, and ability to adapt to new conditions, with rapid changes affecting more organisms. However, coral integration seems to be an exception, with all levels of integration being equally affected by the extinction.

Chapter 5: Conclusions from Database Analyses

The findings based on the new database of scleractinian corals and PBDB bivalve data show that corals had major diversity losses in the Early Jurassic, and that bivalves had diversity losses in the Late Triassic. These results support the hypothesis that if ocean acidification was indeed a major cause of the end-Triassic mass extinction, calcifying organisms would have a major loss in diversity in the Early Jurassic. However, there are more complex issues in regard to the effect of reduced pH on corals and bivalves:

1. Bivalve diversity was not reduced in the Early Jurassic, but rather was already depleted by the latest Triassic (Rhaetian), whereas coral diversity had its greatest loss across the Triassic-Jurassic boundary (Fig. 4).

2. Highly integrated corals suffered the same diversity losses in the end-Triassic as solitary and phaceloid forms (Fig. 13 and 14).

The findings here are interesting, because rising CO_2 happening today is causing ocean acidification. If today's ocean acidification is similar to the conditions that caused the end-Triassic mass extinction, we can probably expect high diversity losses among corals, but not as high diversity losses among bivalve species. We can also expect that corals with different levels of integration will all be greatly affected by the ocean acidification, not just coral with high levels of integration. Understanding the different affects of this acidification may help us to better understand what to expect with reef organisms today and how to better conserve them.

Acknowledgements

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Plate 1: Corals

1. Outcrop photo of *Chondrocoenia* sp. at Yreka-3, scale 4 cm

2. Outcrop photo of *Retiophyllia* sp. at Yreka-3, scale 2 cm

3. *Retiophyllia* sp. in matrix, prior to treatment with acid, source of specimens in 7-9 scale 5 mm, UMIP 13493A

4. Outcrop photo of *Retiophyllia* sp. at Yreka-3, scale 2 cm

5. Outcrop photo of *Retiophyllia* sp. at Yreka-3, scale 15 cm

6. Outcrop photo of *Chondrocoenia* sp. at Yreka-3, scale 2 mm

7. Calice view of specimen in 8, note the recrystallized septa, scale 1 mm, UMIP 13493B

8. *Retiophyllia* sp. after removal from matrix with acid, scale 1 mm, UMIP 13493B

9. *Retiophyllia* cf. *alfurica* after removal from matrix with acid, scale 3 mm, UMIP 13493C

Plate 1   74
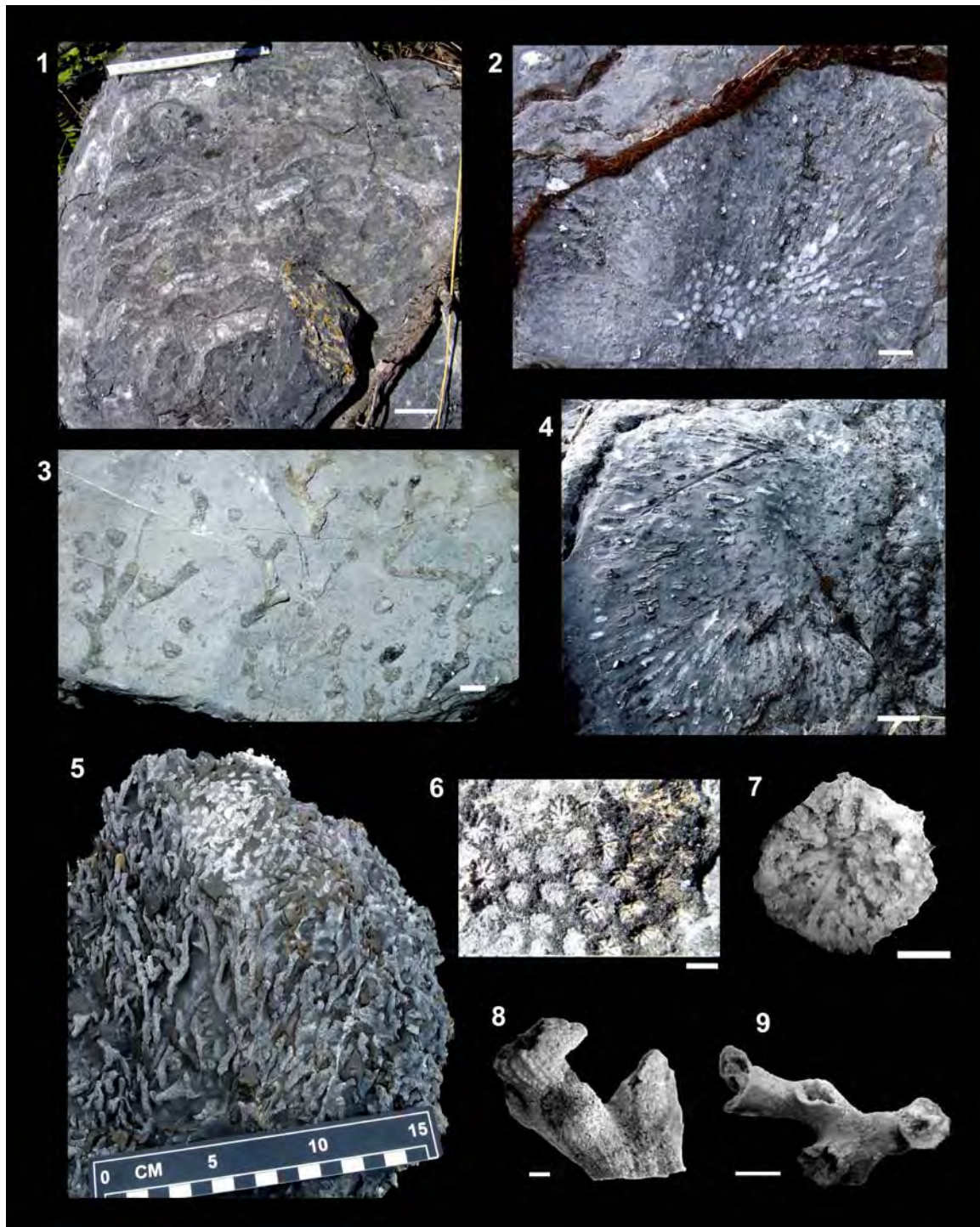
Plate 2: Bivalves

1. Outcrop photo of *Eoplicatula* sp. at Yreka-1, scale 3 mm

2. Outcrop photo of *Eoplicatula* sp. at Yreka-1

3. Outcrop photo of unidentified bivalve cast at Pulp Mill Hill, scale 5 mm

4. Outcrop photo of unidentified bivalve cast at Pulp Mill Hill, scale 5 mm

5. Outcrop photo of unidentified bivalve cast at Pulp Mill Hill, scale 5 mm

6. Outcrop photo of *Eoplicatula* sp. at Pulp Mill Hill, scale 5 mm

7. Outcrop photo of *Megalodon* sp. at Yreka-3, scale 10 mm

8. Rough cut of *Megalodon* sp. at Yreka-3, scale 10 mm, UMIP 13494

9. Counterpart of specimen in 8, Rough cut of *Megalodon* sp. at Yreka-3, scale 10 mm, UMIP 13495

Plate 2   76
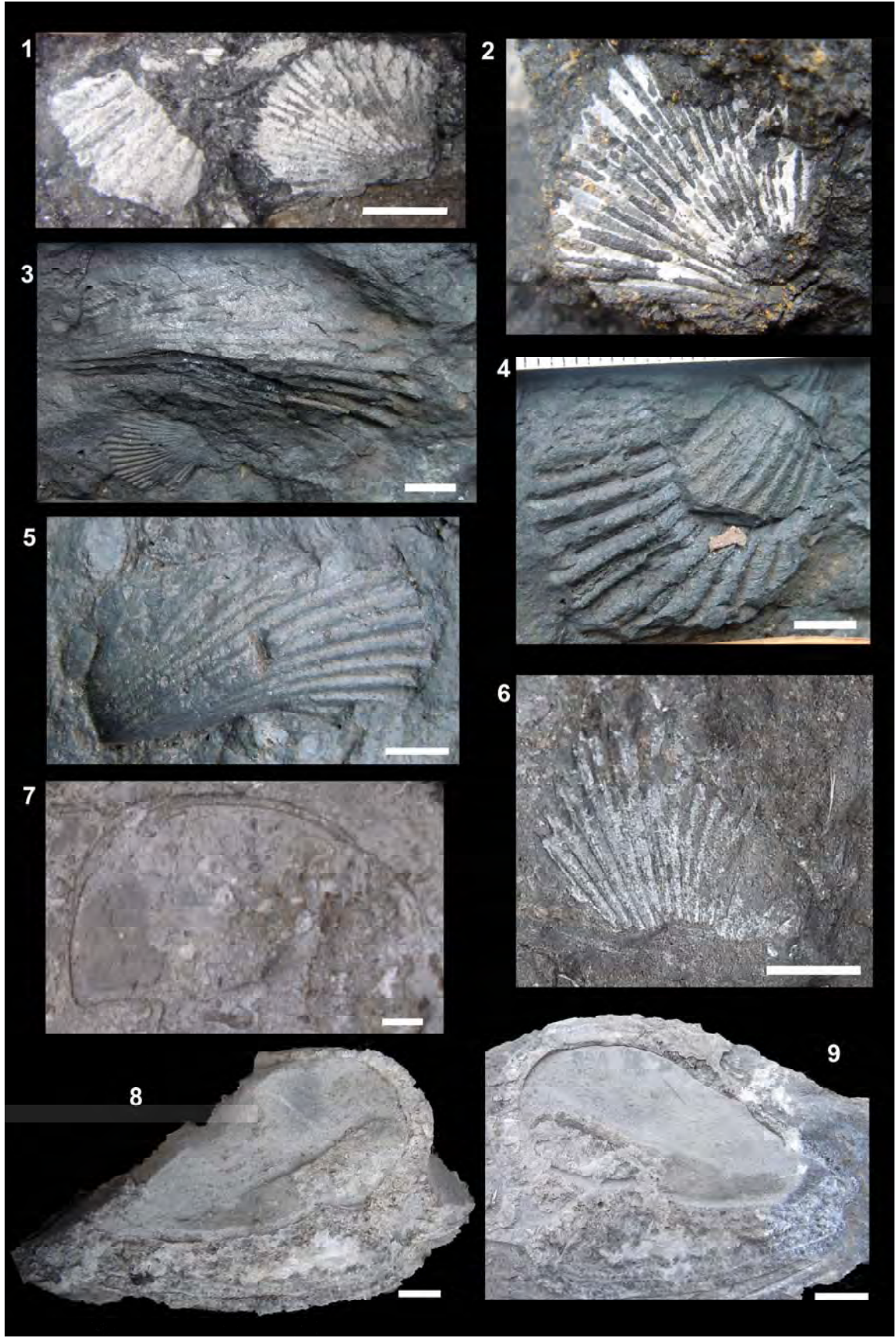
Plate 3: *Myophorigonia* cf. *paucicostata*

1. Left valve of *Myophorigonia* cf. *paucicostata* from Pulp Mill Hill, scale 10 mm, UMIP 13496

   a. Natural external mold of left valve

   b. Silicon cast from mold pictured in 1a

2. Left valve of *Myophorigonia* cf. *paucicostata* from Yreka-1, scale 5 mm, UMIP 13497

3. Left valve of *Myophorigonia* cf. *paucicostata* from Tahsis, scale 5 mm, UMIP 12194A

4. Left valve of *Myophorigonia* cf. *paucicostata* from Pulp Mill Hill, scale 10 mm, UMIP 13498

5. Right valve of *Myophorigonia* cf. *paucicostata* from Pulp Mill Hill, scale 5 mm, CGS C532668
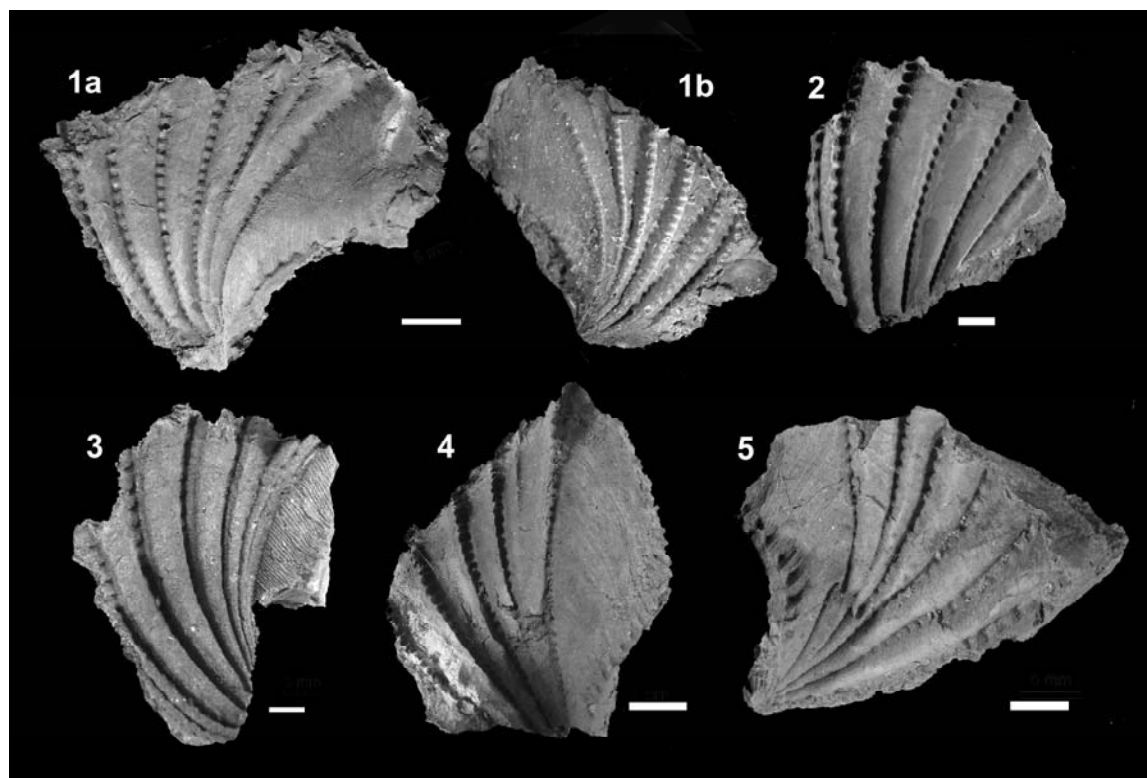
Plate 4: Wallowaconcha raylenea

1. Naturally broken surface showing chambers from *Wallowaconcha raylenea*, from Yreka-2, also pictured in (Stanley et al., 2013), scale 10 mm, UMIP 13479

2. Polished surface of UMIP 13479, scale 10 mm

3. Polished surface of *Wallowaconcha raylenea* from Colonial Creek, scale 10 mm, UMIP 13481
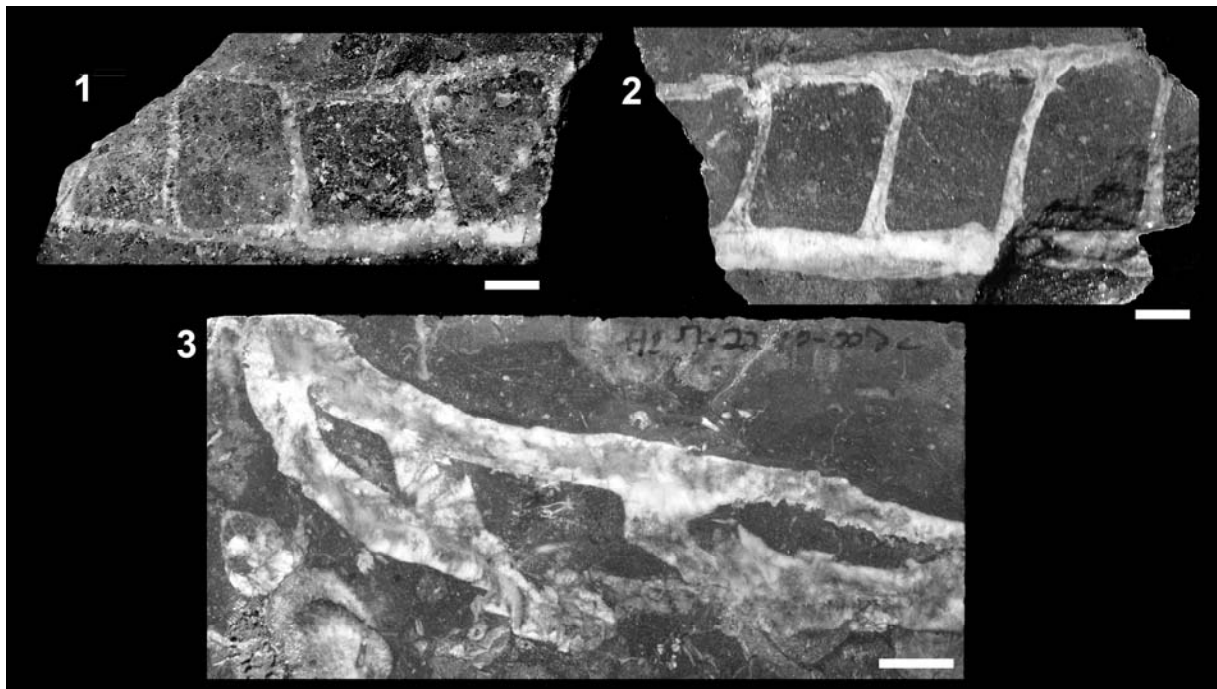
ID	Oldest Stage	Youngest Stage	Integration	Integration Number	Integration2	Integration3	IntNumAvg	Source of Integration Type
"Latomeandra" alaskana	Nor	Rh	phaceloid	1	NA	NA	1	Corallosphere
"Latomeandra" eucystis	Nor	Nor	phaceloid	1	NA	NA	1	Corallosphere
Acrosmilia praecursor	Nor	Nor	solitary	0	NA	NA	0	Corallosphere
Actinastrea gibbosa	Het	Plien	cerioid	3	NA	NA	3	Corallosphere
Actinastrea minima	Sin	Plien	cerioid	3	NA	NA	3	Corallosphere
Actinastrea parasitica	Het	Het	cerioid	3	NA	NA	3	Corallosphere
Actinastrea pedunculata	Het	Het	cerioid	3	NA	NA	3	Corallosphere
Actinastrea plana	Het	Toar	cerioid	3	NA	NA	3	Corallosphere
Actinastrea shastensis	Nor	Nor	cerioid	3	NA	NA	3	Corallosphere
Actinastrea sp.	Nor	Nor	cerioid	3	NA	NA	3	Corallosphere
Alakiria spheroidea	Nor	Het	cerioid	3	NA	NA	3	Corallosphere
Allocoeniopsis dendroidea	Het	Toar	cerioid	3	thamnasteroid	NA	3	Corallosphere
Allocoeniopsis expansa	Aal	Bath	cerioid	3	thamnasteroid	NA	3	Corallosphere
Allocoeniopsis favoidea	Het	Het	cerioid	3	thamnasteroid	NA	3	Corallosphere
Allocoeniopsis globosa	Sin	Sin	cerioid	3	thamnasteroid	NA	3	Corallosphere
Allocoeniopsis insignis	Het	Het	cerioid	3	thamnasteroid	NA	3	Corallosphere
Alloiteausmilia boudaharensis	Plien	Plien	solitary	0	NA	NA	0	Corallosphere
Alpinophyllia flexuosa	Nor	Rh	cerioid	3	meandroid	6	4.5	Corallosphere
Alpinoseris dendroidea	Rh	Rh	thamnasterioid	5	NA	NA	5	Corallosphere
Ampakabastraea nodosa	Nor	Nor	cerioid	3	NA	NA	3	Corallosphere
Andrazella labyrinthica	Carn	Carn	meandroid	6	NA	NA	6	Corallosphere
Andrazella sp.	Nor	Nor	meandroid	6	NA	NA	6	Corallosphere
Anthostylis acanthophora	Nor	Het	cerioid	3	NA	NA	3	Corallosphere
Anthostylis sp.	Rh	Rh	cerioid	3	NA	NA	3	Corallosphere
Araiophyllum liasicum	Plien	Plien	phaceloid	1	NA	NA	1	Corallosphere
Araiophyllum triassicum	Carn	Carn	phaceloid	1	NA	NA	1	Corallosphere
Archaeosmilia beata	Het	Plien	solitary	0	NA	NA	0	Corallosphere
Archaeosmilia duncani	Het	Sin	solitary	0	NA	NA	0	Corallosphere
Archaeosmilia menchikoffi	Plien	Plien	solitary	0	NA	NA	0	Corallosphere
Archaeosmilia subrecta	Sin	Sin	solitary	0	NA	NA	0	Corallosphere
Archaeosmilia sp.	Plien	Plien	solitary	0	NA	NA	0	Corallosphere
Archaeosmiliopsis densus	Het	Plien	phaceloid	1	NA	NA	1	Corallosphere
Astraeomorpha confusa	Carn	Rh	thamnasterioid	5	NA	NA	5	Corallosphere
Astraeomorpha crassisepta	Carn	Rh	thamnasterioid	5	NA	NA	5	Corallosphere
Astraeomorpha cuneata	Rh	Rh	thamnasterioid	5	NA	NA	5	Corallosphere
Astraeomorpha minor	Rh	Rh	thamnasterioid	5	NA	NA	5	Corallosphere
Astraeomorpha multisepta	Nor	Rh	thamnasterioid	5	NA	NA	5	Corallosphere
Astraeomorpha pratzi	Carn	Rh	thamnasterioid	5	NA	NA	5	Corallosphere
Astraeomorpha reimani	Nor	Rh	thamnasterioid	5	NA	NA	5	Corallosphere
Astraeomorpha robusta	Ladin	Carn	thamnasterioid	5	NA	NA	5	Corallosphere
Astraeomorpha sp.	Nor	Rh	thamnasterioid	5	NA	NA	5	Corallosphere
Astrocoenia hexactis	Nor	Rh	cerioid	3	NA	NA	3	Corallosphere
Astrocoenia idahoensis	Nor	Rh	cerioid	3	NA	NA	3	Corallosphere
Astrocoenia martini	Nor	Nor	cerioid	3	NA	NA	3	Corallosphere
Astrocoenia shastensis	Nor	Nor	cerioid	3	NA	NA	3	Corallosphere
Astrocoenia sinemuriensis	Het	Het	cerioid	3	NA	NA	3	Corallosphere
Astrocoenia sp.	Lad	Pliocene?	cerioid	3	NA	NA	3	Corallosphere
Bavarosmilia bavarica	Carn	Rh	cerioid	3	NA	NA	3	Corallosphere
Beneckastraea benecki	Carn	Carn	cerioid	3	NA	NA	3	Corallosphere
Beneckastraea kenkerensis	Carn	Nor	cerioid	3	NA	NA	3	Corallosphere
Brachyseris walfordi	Plien	Plien	meandroid	6	NA	NA	6	Beauvais and Stump, 1976
Calamophylliopsis stockesi	Plien	Valanginian	phaceloid	1	NA	NA	1	Corallosphere

ID	Oldest Stage	Youngest Stage	Integration	Integration Number	Integration2	Integration3	IntNumAvg	Source of Integration Type
Campesteria prolixia	Nor	Rh	meandroid	6	NA	NA	6	Corallosphere
Caryophyllia sp.	Plien	Plien	solitary	0	NA	NA	0	Corallosphere
Cerioheterastraea cerioidea	Carn	Nor	cerioid	3	NA	NA	3	Corallosphere
Ceriostella variabilis	Ladin	Ladin	cerioid	3	NA	NA	3	Corallosphere
Ceratocoenia sp.	Plien	Plien	solitary	0	NA	NA	0	Corallosphere
Chevalieria grandis	Nor	Nor	thamnasterioid	5	NA	NA	5	Corallosphere
Chomatoseris sp.	Het	Call	solitary	0	NA	NA	0	Corallosphere
Chomatoseris orbulites	Plien	Pleistocene	solitary	0	NA	NA	0	Corallosphere
Chondrocoenia ohmanni	Nor	Rh	cerioid	3	NA	NA	3	Corallosphere
Chondrocoenia paradoxa	Ladin	Rh	plocoid	2 cerioid	3	NA	2.5	Corallosphere
Chondrocoenia reptans	Het	Het	cerioid	3	NA	NA	3	Corallosphere
Chondrocoenia schafhaeutli	Nor	Plien	cerioid	3	NA	NA	3	Corallosphere
Chondrocoenia sp.	Nor	Rh	plocoid	2 cerioid	3	NA	2.5	Corallosphere
Chondrocoenia waltheri	Nor	Rh	cerioid	3	NA	NA	3	Corallosphere
Cladophyllia dresnayi	Plien	Plien	phaceloid	1	NA	NA	1	Corallosphere
Coccophyllum liasicum	Plien	Plien	cerioid	3	NA	NA	3	Corallosphere
Coccophyllum sp.	Anis	Rh	cerioid	3	NA	NA	3	Corallosphere
Coccophyllum sturi	Nor	Rh	cerioid	3	NA	NA	3	Corallosphere
Coenastraea maccoyi	Plien	Baj	cerioid	3	NA	NA	3	Stanley and Beauvais, 1990
Coenastraea sp.	Plien	Plien	cerioid	3	NA	NA	3	Stanley and Beauvais, 1990
Collignonastraea sp.	Plien	Plien	meandroid	6	NA	NA	6	Corallosphere
Comophyllia thamnastroides	Plien	Plien	meandroid	6	NA	NA	6	Corallosphere
Comoseris sp.	Plien	Oxf	meandroid	6	NA	NA	6	Corallosphere
Confusastrea borealis	Nor	Nor	astreoid	4 plocoid	2 subcerioid	NA	3	Corallosphere
Confusastrea descussata	Nor	Rh	solitary	0	NA	NA	0	Corallosphere
Confusastrea dictyophora			cerioid	3	NA	NA	3	Corallosphere
Confusastrea grandissima	Nor	Nor	solitary	0	NA	NA	0	Corallosphere
Confusastrea incrassata	Nor	Nor	astreoid	4 plocoid	2 subcerioid	NA	3	Corallosphere
Conophyllia boletiformis	Ladin	Carn	solitary	0	NA	NA	0	Corallosphere
Conophyllia clepsydrae	III	III	solitary	0	NA	NA	0	Corallosphere
Conophyllia granulosa	Carn	Carn	solitary	0	NA	NA	0	Corallosphere
Conophyllia hellenica	Carn	Nor	solitary	0	NA	NA	0	Corallosphere
Conophyllia omphale	III	III	solitary	0	NA	NA	0	Corallosphere
Conophyllia radiciformis	Ladin	Carn	solitary	0	NA	NA	0	Corallosphere
Coryphyllia elliptica	Carn	Rh	solitary	0	NA	NA	0	Corallosphere
Coryphyllia frechi	Nor	Rh	solitary	0	NA	NA	0	Corallosphere
Coryphyllia gigantella	Nor	Rh	solitary	0	NA	NA	0	Corallosphere
Coryphyllia marmorea	Nor	Nor	solitary	0	NA	NA	0	Corallosphere
Coryphyllia moiseevi	Ladin	Carn	solitary	0	NA	NA	0	Corallosphere
Coryphyllia regularis	Ladin	Nor	solitary	0	NA	NA	0	Corallosphere
Coryphyllia subregularis	Plien	Plien	solitary	0	NA	NA	0	Corallosphere
Coryphyllia tenuiseptata	Ladin	Rh	solitary	0	NA	NA	0	Corallosphere
Coryphyllia xraanensis	Anis	Ladin	solitary	0	NA	NA	0	Corallosphere
Coryphyllina rhaetica	Rh	Rh	solitary	0	NA	NA	0	Corallosphere
Craspedophyllia alpina	Ladin	Nor	solitary	0 phaceloid	1	NA	0.5	Corallosphere
Craspedophyllia cristata	Ladin	Carn	solitary	0	NA	NA	0	Corallosphere
Craspedophyllia gracilis	Carn	Carn	solitary	0	NA	NA	0	Corallosphere
Craspedophyllia ramosa	Carn	Carn	solitary	0	NA	NA	0	Corallosphere
Crassistella juvavica	Nor	Rh	cerioid	3	NA	NA	3	Corallosphere
Crassistella parvula	Nor	Rh	cerioid	3	NA	NA	3	Corallosphere
Crassistella vesiculosa	Nor	Rh	cerioid	3	NA	NA	3	Corallosphere
Cuifastraea arthaberi	Nor	Rh	thamnasterioid	5	NA	NA	5	Corallosphere

ID	Oldest Stage	Youngest Stage	Integration	Integration Number	Integration2	Integration3	IntNumAvg	Source of Integration Type
Cuifastraea granulata	Nor	Rh	thamnasterioid	5	NA	NA	5	Corallosphere
Cuifastraea incurva	Rh	Rh	thamnasterioid	5	NA	NA	5	Corallosphere
Cuifastraea lopatensis	Plien	Plien	thamnasterioid	5	NA	NA	5	Corallosphere
Cuifastraea tenuiseptata	Nor	Rh	thamnasterioid	5	NA	NA	5	Corallosphere
Cuifia columnaris	Carn	Rh	solitary	0	NA	NA	0	Corallosphere
Cuifia gigantella	Nor	Rh	solitary	0	NA	NA	0	Corallosphere
Cuifia marmorea	Nor	Rh	solitary	0	NA	NA	0	Corallosphere
Curtoseries kuschlini	Rh	Rh	cerioid	3 meandroid	6	NA	4.5	Corallosphere
Curtoseries parva	Nor	Nor	cerioid	3	NA	NA	3	Corallosphere
Cyathocoenia alpina	Nor	Rh	cerioid	3	NA	NA	3	Corallosphere
Cyathocoenia carinata	Nor	Nor	cerioid	3	NA	NA	3	Corallosphere
Cyathocoenia dendroidea	Het	Het	cerioid	3	NA	NA	3	Corallosphere
Cyathocoenia gerthi	Nor	Nor	cerioid	3	NA	NA	3	Corallosphere
Cyathocoenia idahoensis	Rh	Rh	cerioid	3	NA	NA	3	Corallosphere
Cyathocoenia minor	Nor	Nor	plocoid	2 cerioid	3	NA	2.5	Corallosphere
Cyathocoenia parva	Nor	Nor	cerioid	3	NA	NA	3	Corallosphere
Cyathocoenia shastensis	Nor	Rh	cerioid	3	NA	NA	3	Corallosphere
Cyathocoenia sp.	Anis	Rh	cerioid	3	NA	NA	3	Corallosphere
Cyathocoenia squiresi	Nor	Rh	cerioid	3	NA	NA	3	Corallosphere
Cycliphyllia cyclica	Nor	Rh	phaceloid	1	NA	NA	1	Corallosphere
Cycliphyllia major	Rh	Rh	phaceloid	1	NA	NA	1	Corallosphere
Cyclophyllopsis cornutiformis	Plien	Plien	solitary	0	NA	NA	0	Beauvais, 1986
Dendrastrea sp.	Het	Het	cerioid	3	NA	NA	3	Corallosphere
Dichopsammia gozdensis	Plien	Plien	phaceloid	1	NA	NA	1	Corallosphere
Dimorphastrea menchikoffi	Plien	Plien	thamnasterioid	5	NA	NA	5	Corallosphere
Dimorphastraea? triadica	Nor	Rh	thamnasterioid	5	NA	NA	5	Corallosphere
Discocoenia ruperti	Het	Het	solitary	0	NA	NA	0	Vaughn and Wells
Discocoeniopsis nummiformis	Sin	Plien	phaceloid	1	NA	NA	1	Beauvais, 1978
Distichoflabellum zapfei	Rh	Rh	meandroid	6 phaceloid	1 flabelloid	NA	3.5	Corallosphere
Distichomeandra austriaca	Nor	Rh	cerioid	3 meandroid	6	NA	4.5	Corallosphere
Distichomeandra austriaca	Carn	Plien	cerioid	3	NA	NA	3	Corallosphere
Distichomeandra dieneri	Rh	Rh	cerioid	3 meandroid	6	NA	4.5	Corallosphere
Distichomeandra minor	Nor	Rh	cerioid	3 meandroid	6	NA	4.5	Corallosphere
Distichomeandra primorica	Nor	Nor	cerioid	3 meandroid	6	NA	4.5	Corallosphere
Distichomeandra spinosa	Nor	Nor	cerioid	3 meandroid	6	NA	4.5	Corallosphere
Distichomeandra tenuiseptata	Nor	Nor	cerioid	3 meandroid	6	NA	4.5	Corallosphere
Distichophyllia decora	Anis	Anis	solitary	0	NA	NA	0	Corallosphere
Distichophyllia fritschi	Rh	Rh	solitary	0	NA	NA	0	Corallosphere
Distichophyllia gosaviensis	Nor	Rh	solitary	0	NA	NA	0	Corallosphere
Distichophyllia maior	Rh	Rh	solitary	0	NA	NA	0	Corallosphere
Distichophyllia martini	Rh	Het	solitary	0	NA	NA	0	Corallosphere
Distichophyllia melnikovae	Nor	Nor	solitary	0	NA	NA	0	Corallosphere
Distichophyllia norica	Carn	Rh	solitary	0	NA	NA	0	Corallosphere
Distichophyllia sp.	Anis	Rh	solitary	0	NA	NA	0	Corallosphere
Distichophyllia tabulata	Nor	Rh	solitary	0	NA	NA	0	Corallosphere
Distichophyllia gosaviensis	Nor	Rh	solitary	0	NA	NA	0	Corallosphere
Duncanosmilia moorei	Het	Het	solitary	0	NA	NA	0	Corallosphere
Elasmophyllia andreaei	Carn	Rh	cerioid	3	NA	NA	3	Corallosphere
Elasmophyllia milchi	Ladin	Ladin	cerioid	3	NA	NA	3	Corallosphere
Elysastraea austriaca	Nor	Nor	cerioid	3	NA	NA	3	Corallosphere
Elysastraea cystis	Nor	Rh	cerioid	3	NA	NA	3	Corallosphere
Elysastraea fischeri	Lad	Carn	cerioid	3 meandroid	6	NA	4.5	Corallosphere

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Elysastraea haueri	Ladin	Ladin	cerioid	3	NA	NA	3	Corallosphere
Elysastraea hebridensis	Plien	Plien	cerioid	3	NA	NA	3	Corallosphere
Elysastraea juliana	Carn	Nor	cerioid	3	NA	NA	3	Corallosphere
Elysastraea parva	Nor	Nor	cerioid	3	NA	NA	3	Corallosphere
Elysastraea profunda	Nor	Rh	cerioid	3	NA	NA	3	Corallosphere
Elysastraea vancouverensis	Nor	Rh	cerioid	3	NA	NA	3	Corallosphere
Eocomoseris gurumdyensis	Sin	Sin	thamnasterioid	5	cerioid	3	NA	4	Corallosphere
Eocomoseris lamellata	Sin	Sin	thamnasterioid	5	cerioid	3	NA	4	Corallosphere
Eocomoseris ramosa	Nor	Rh	thamnasterioid	5	cerioid	3	NA	4	Corallosphere
Epismilia mauretaniensis	Plien	Plien	solitary	0	NA	NA	0	Corallosphere
Epismiliopsis liasica	Plien	Plien	solitary	0	NA	NA	0	Corallosphere
Epismiliopsis sp.	Sin	Baj	solitary	0	NA	NA	0	Corallosphere
Epistreptophyllum vetusum	Plien	Plien	solitary	0	NA	NA	0	Corallosphere
Funginella domeriensis	Plien	Plien	solitary	0	NA	NA	0	Yazdi et al, 2011
Gablonzeria ajor	Nor	Rh	cerioid	3	NA	NA	3	Corallosphere
Gablonzeria dalnegorica	Nor		cerioid	3	NA	NA	3	Corallosphere
Gablonzeria eandriformis	Nor	Nor	cerioid	3	NA	NA	3	Corallosphere
Gablonzeria grandiosa	Nor	Nor	cerioid	3	NA	NA	3	Corallosphere
Gablonzeria kiparisovae	Nor	Nor	cerioid	3	NA	NA	3	Corallosphere
Gablonzeria major	Carn	Rh	cerioid	3	NA	NA	3	Corallosphere
Gablonzeria profunda	Carn	Rh	cerioid	3	NA	NA	3	Corallosphere
Gablonzeria reussi	Nor	Nor	cerioid	3	NA	NA	3	Corallosphere
Gablonzeria singularis	Nor	Nor	cerioid	3	NA	NA	3	Corallosphere
Gigantostylis epigonus	Rh	Rh	solitary	0	NA	NA	0	Corallosphere
Gillastraea delicata	Nor	Rh	phaceloid	1	NA	NA	1	Corallosphere
Goldfussastrea toarciensis	Plien	Toar	astreoid	4	cerioid	3	meandroid	6	4.333333333	Corallosphere
Goniocora concinna	Plien	Barremian	phaceloid	1	NA	NA	1	Vaughan and Wells, 2013
Guembelastraea guembeli	Carn	Nor	cerioid	3	NA	NA	3	Corallosphere
Guembelastraea martini	Nor	Nor	cerioid	3	NA	NA	3	Corallosphere
Guembelastraea pamphyliensis	Carn	Nor	cerioid	3	NA	NA	3	Corallosphere
Guembelastraea whiteavesi	Nor	Rh	cerioid	3	NA	NA	3	Corallosphere
Haimeicyclus haimei	Het	Sin	solitary	0	NA	NA	0	Stolarski and Russo 2002
Haplaraea sp.	Plien	Valanginian	solitary	0	NA	NA	0	Corallosphere
Heterastraea angelae	Plien	Plien	cerioid	3	NA	NA	3	Corallosphere
Heterastraea endotheca	Sin	Sin	cerioid	3	NA	NA	3	Corallosphere
Heterastraea eveshami	Sin	Plien	cerioid	3	NA	NA	3	Corallosphere
Heterastraea excavata	Het	Het	cerioid	3	NA	NA	3	Corallosphere
Heterastraea fischeri	Het	Het	cerioid	3	NA	NA	3	Corallosphere
Heterastraea gracilis	Rh	Rh	cerioid	3	NA	NA	3	Corallosphere
Heterastraea insignis	Sin	Sin	cerioid	3	NA	NA	3	Corallosphere
Heterastraea latimeandroides	Het	Het	cerioid	3	NA	NA	3	Corallosphere
Heterastraea murchisoni	Het	Het	cerioid	3	NA	NA	3	Corallosphere
Heterastraea sp.	Nor	Het	cerioid	3	NA	NA	3	Corallosphere
Heterastraea stricklandi	Het	Sin	cerioid	3	NA	NA	3	Corallosphere
Heterastraea tomesii	Het	Plien	cerioid	3	NA	NA	3	Corallosphere
Hispaniastraea murciana	Plien	Plien	cerioid	3	NA	NA	3	Corallosphere
Hispaniastraea ramosa	Sin	Plien	cerioid	3	NA	NA	3	Corallosphere
Intersmilia djartyrabatica	Sin	Sin	phaceloid	1	NA	NA	1	Corallosphere
Intersmilia trnovensis	Plien	Plien	phaceloid	1	NA	NA	1	Corallosphere
Isastrea alfurica	Nor	Rh	cerioid	3	NA	NA	3	Corallosphere
Isastrea ampezzana	Carn	Carn	cerioid	3	NA	NA	3	Corallosphere
Isastrea boehmi	Nor	Nor	cerioid	3	NA	NA	3	Corallosphere

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Isastrea confracta	Rh	Rh	cerioid	3	NA	NA	3	Corallosphere
Isastrea esrnensrs	Ladin	Ladin	cerioid	3	NA	NA	3	Corallosphere
Isastrea explanulata	Plien	Callovian	cerioid	3	NA	NA	3	Corallosphere
Isastrea eucystis	Nor	Rh	cerioid	3	NA	NA	3	Corallosphere
Isastrea foliosa	Carn	Carn	cerioid	3	NA	NA	3	Corallosphere
Isastrea globosa	Het	Het	cerioid	3	NA	NA	3	Corallosphere
Isastrea haueri	Carn	Nor	cerioid	3	NA	NA	3	Corallosphere
Isastrea marcoui	Plien	bajocian	cerioid	3	NA	NA	3	Corallosphere
Isastrea murchisoni	Het	Het	cerioid	3	NA	NA	3	Corallosphere
Isastrea orbignyi	Het	Het	cerioid	3	NA	NA	3	Corallosphere
Isastrea parva	Nor	Nor	cerioid	3	NA	NA	3	Corallosphere
Isastrea plana	Carn	Nor	cerioid	3	NA	NA	3	Corallosphere
Isastrea richardsoni	Plien	Aptian	cerioid	3	NA	NA	3	Corallosphere
Isastrea salinaria	Nor	Nor	cerioid	3	NA	NA	3	Corallosphere
Isastrea seranica	Nor	Rh	cerioid	3	NA	NA	3	Corallosphere
Isastrea serpentina	Anis	Anis	cerioid	3	NA	NA	3	Corallosphere
Isastrea sinemuriensis	Het	Het	cerioid	3	NA	NA	3	Corallosphere
Isastrea sp.	Carn	Sin	cerioid	3	NA	NA	3	Corallosphere
Isastrea telleri	Carn	Carn	cerioid	3	NA	NA	3	Corallosphere
Isastrea vetbeeki	Nor	Nor	cerioid	3	NA	NA	3	Corallosphere
Karatchastraea karatchensis	Carn	Nor	astreoid	4	NA	NA	4	Corallosphere
Koilocoenia major	Carn	Carn	plocoid	2	cerioid 3	NA	2.5	Corallosphere
Koilocoetiie decipiens	Ill	Rh	plocoid	2	cerioid 3	NA	2.5	Corallosphere
Kompsasteria oligocystis	Nor	Rh	cerioid	3	NA	NA	3	Corallosphere
Kuhnastraea borealis	Nor	Nor	astreoid	4	kuhnastreoid NA	NA	4	Corallosphere
Kuhnastraea cowichanensis	Nor	Hettangium	astreoid	4	kuhnastreoid NA	NA	4	Corallosphere
Kuhnastraea decussata	Nor	Rh	astreoid	4	kuhnastreoid NA	NA	4	Corallosphere
Kuhnastraea descussata	Nor	Nor	astreoid	4	NA	NA	4	Corallosphere
Kuhnastraea incrassata	Nor	Rh	astreoid	4	kuhnastreoid NA	NA	4	Corallosphere
Latomeandra steini	Nor	Nor	phaceloid	1	NA	NA	1	Corallosphere
Latomeandra? cassiana	Carn	Carn	phaceloid	1	NA	NA	1	Corallosphere
Lepiconus bassii	Rhat	Rh	solitary	0	NA	NA	0	Corallosphere
Lepiconus gastaldii	Rh	Rh	cerioid	3	NA	NA	3	Corallosphere
Lophosmilia praecursor	Rhat	Rh	solitary	0	NA	NA	0	Corallosphere
Margarastraea eucystis	Nor	Nor	meandroid	6	NA	NA	6	Corallosphere
Margarastraea jenski	Sin	Sin	meandroid	6	NA	NA	6	Corallosphere
Margarastraea klipsteini	Carn	Carn	meandroid	6	NA	NA	6	Corallosphere
Margarastraea pulchra	Nor	Nor	meandroid	6	NA	NA	6	Corallosphere
Margarophyllia capitata	Ladin	Nor	solitary	0	NA	NA	0	Corallosphere
Margarophyllia crenata	Ladin	Carn	solitary	0	NA	NA	0	Corallosphere
Margarophyllia decora	Carn	Nor	solitary	0	NA	NA	0	Corallosphere
Margarophyllia inculta	Anis	Nor	solitary	0	NA	NA	0	Corallosphere
Margarophyllia michaelis	Ladin	Carn	solitary	0	NA	NA	0	Corallosphere
Margarophyllia multisepta	Ladin	Carn	solitary	0	NA	NA	0	Corallosphere
Margarophyllia radiciformis	Ladin	Carn	solitary	0	NA	NA	0	Corallosphere
Margarophyllia richthofeni	Carn	Carn	solitary	0	NA	NA	0	Corallosphere
Margarophyllia stylophylloides	Carn	Nor	solitary	0	NA	NA	0	Corallosphere
Margarophyllia vortica	Anis	Anis	solitary	0	NA	NA	0	Corallosphere
Margarophyllia zhengfengensis	Ladin	Ladin	solitary	0	NA	NA	0	Corallosphere
Margarosmilia carpatica	Ladin	Ladin	phaceloid	1	NA	NA	1	Corallosphere
Margarosmilia charlyana	Nor	Rh	phaceloid	1	NA	NA	1	Corallosphere
Margarosmilia confluens	Anis	Nor	phaceloid	1	NA	NA	1	Corallosphere

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Margarosmilia culta	Nor	Nor	phaceloid	1	NA	NA	1	Corallosphere
Margarosmilia cyathophylloides	Nor	Rh	phaceloid	1	NA	NA	1	Corallosphere
Margarosmilia gemminata	Plien	Plien	phaceloid	1	NA	NA	1	Corallosphere
Margarosmilia granulata	Carn	Carn	phaceloid	1	NA	NA	1	Corallosphere
Margarosmilia hintzei	Carn	Carn	phaceloid	1	NA	NA	1	Corallosphere
Margarosmilia melnikovae	Nor	Nor	phaceloid	1	NA	NA	1	Corallosphere
Margarosmilia minima	Nor	Rh	phaceloid	1	NA	NA	1	Corallosphere
Margarosmilia multigranulata	Nor	Rh	phaceloid	1	NA	NA	1	Corallosphere
Margarosmilia richthofeni	Ladin	Rh	phaceloid	1	NA	NA	1	Corallosphere
Margarosmilia septanectens	Ladin	Carn	phaceloid	1	NA	NA	1	Corallosphere
Margarosmilia sp.	Anis	Rh	phaceloid	1	NA	NA	1	Corallosphere
Margarosmilia zieteni	Carn	Nor	phaceloid	1	NA	NA	1	Corallosphere
Meandrostylis antimoniensis	Nor	Rh	cerioid	3	meandroid	6	4.5	Corallosphere
Meandrostylis frechi	Rh	Rh	cerioid	3	meandroid	6	4.5	Corallosphere
Meandrostylis grandiseptus	Nor	Nor	cerioid	3	meandroid	6	4.5	Corallosphere
Meandrostylis irregularis	Nor	Rh	cerioid	3	meandroid	6	4.5	Corallosphere
Maeandrostylis jaworskii	Plien	Plien	cerioid	3	meandroid	6	4.5	Corallosphere
Meandrostylis tener	Nor	Nor	cerioid	3	meandroid	6	4.5	Corallosphere
Meandrostylis vancouverensis	Nor	Rh	cerioid	3	meandroid	6	4.5	Corallosphere
Meandrostylophyllum vesiculare	Rh	Rh	meandroid	6	NA	NA	6	Corallosphere
Meandrovolzeia serialis	Nor	Nor	meandroid	6	NA	NA	6	Corallosphere
Meandrovolzeia sp.	Nor	Rh	meandroid	6	NA	NA	6	Corallosphere
Mesomorpha bussoni	Plien	Plien	thamnasterioid	5	NA	NA	5	Corallosphere
Mesomorpha gracilis	Plien	Plien	thamnasterioid	5	NA	NA	5	Corallosphere
Mesomorpha newpassensis	Ladin	Ladin	thamnasterioid	5	subthamnasteric	NA	NA	5	Corallosphere
Microphyllia flemingi	Plien	Plien	thamnasterioid	5	NA	NA	5	Corallosphere
Microphyllia irregularis	Plien	Aalenian	thamnasterioid	5	NA	NA	5	Corallosphere
Microphyllia pulchella	Plien	bajocian	thamnasterioid	5	NA	NA	5	Corallosphere
Microphyllia sp.	Plien	Cenomanian	thamnasterioid	5	NA	NA	5	Corallosphere
Microphyllia sp. A	Sin	Sin	thamnasterioid	5	NA	NA	5	Corallosphere
Molukkia sp.	Rh	Rh	solitary	0	NA	NA	0	Corallosphere
Molukkia triassica	Nor	Nor	solitary	0	NA	NA	0	Corallosphere
Monstroseris iranica	Rh	Rh	cerioid	3	NA	NA	3	Corallosphere
Montlivaltia cherringtonensis	Het	Plien	solitary	0	NA	NA	0	Kiessling, 2009
Montlivaltia cipitensis	Carn	Carn	solitary	0	NA	NA	0	Kiessling, 2009
Montlivaltia cuneiformis	Ladin	Ladin	solitary	0	NA	NA	0	Kiessling, 2009
Montlivaltia dewalquei	Het	Het	solitary	0	NA	NA	0	Kiessling, 2009
Montlivaltia doriai	Het	Plien	solitary	0	NA	NA	0	Kiessling, 2009
Montlivaltia foliacea	Plien	Plien	solitary	0	NA	NA	0	Kiessling, 2009
Montlivaltia gigas	Nor	Val	solitary	0	NA	NA	0	Kiessling, 2009
Montlivaltia gimnae	Rhat	Rh	solitary	0	NA	NA	0	Kiessling, 2009
Montlivaltia guettardi	Het	Sin	solitary	0	NA	NA	0	Kiessling, 2009
Montlivaltia loczyana	Carn	Carn	solitary	0	NA	NA	0	Kiessling, 2009
Montlivaltia marmolatae	Ladin	Ladin	solitary	0	NA	NA	0	Kiessling, 2009
Montlivaltia mentishierosol	Carn	Carn	solitary	0	NA	NA	0	Kiessling, 2009
Montlivaltia molukkana	Nor	Nor	solitary	0	NA	NA	0	Kiessling, 2009
Montlivaltia oblique	Ladin	Nor	solitary	0	NA	NA	0	Kiessling, 2009
Montlivaltia papillata	Het	Het	solitary	0	NA	NA	0	Kiessling, 2009
Montlivaltia parasitica	Het	Het	solitary	0	NA	NA	0	Kiessling, 2009
Montlivaltia pedunculata	Het	Het	solitary	0	NA	NA	0	Kiessling, 2009
Montlivaltia polymorpha	Het	Plien	solitary	0	NA	NA	0	Kiessling, 2009
Montlivaltia radiata	Plien	Plien	solitary	0	NA	NA	0	Kiessling, 2009

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Montlivaltia radiciformis	Carn	Carn	solitary	0	NA	NA	0	Kiessling, 2009
Montlivaltia reussi	Rh	Rh	solitary	0	NA	NA	0	Kiessling, 2009
Montlivaltia salomini	Ladin	Ladin	solitary	0	NA	NA	0	Kiessling, 2009
Montlivaltia septafindens	Carn	Carn	solitary	0	NA	NA	0	Kiessling, 2009
Montlivaltia sinemuriensis	Het	Het	solitary	0	NA	NA	0	Kiessling, 2009
Montlivaltia sp.	Anis	Plien	solitary	0	NA	NA	0	Kiessling, 2009
Montlivaltia timorica	Ladin	Nor	solitary	0	NA	NA	0	Kiessling, 2009
Montlivaltia tirolensis	Carn	Carn	solitary	0	NA	NA	0	Kiessling, 2009
Montlivaltia triasina	Anis	Anis	solitary	0	NA	NA	0	Kiessling, 2009
Montlivaltia verae	Carn	Carn	solitary	0	NA	NA	0	Kiessling, 2009
Montlivaltia? martini	Nor	Nor	solitary	0	NA	NA	0	Kiessling, 2009
Morycastraea eximia	Rh	Rh	phaceloid	1	NA	NA	1	Corallosphere
Myriophyllum badioticum	Carn	Carn	solitary	0	NA	NA	0	Corallosphere
Myriophyllum constrictum	Het	Sin	solitary	0	NA	NA	0	Corallosphere
Myriophyllum dichothomum	Carn	Carn	solitary	0	NA	NA	0	Corallosphere
Myriophyllum gracile	Carn	Carn	solitary	0	NA	NA	0	Corallosphere
Myriophyllum jekeliusi	Ladin	Carn	solitary	0	NA	NA	0	Corallosphere
Myriophyllum mojsveri	Carn	Carn	solitary	0	NA	NA	0	Corallosphere
Myriophyllum muensteri	Ladin	Carn	solitary	0	NA	NA	0	Corallosphere
Myriophyllum sp.	Het	Plien	solitary	0	NA	NA	0	Corallosphere
Myriophyllum timoricum	Nor	Nor	solitary	0	NA	NA	0	Corallosphere
Neoconophyllia guiyangensis	Anis	Anis	solitary	0	NA	NA	0	Corallosphere
Neoconophyllia leidapoensis	Anis	Anis	solitary	0	NA	NA	0	Corallosphere
Neoconophyllia xiaanensrs	Ladin	Ladin	solitary	0	NA	NA	0	Corallosphere
Oedalmia norica	Nor	Rh	thamnasterioid	5	NA	NA	5	Corallosphere
Oedalmia sp.	Rh	Rh	thamnasterioid	5	NA	NA	5	Corallosphere
Omphalophyllia bittneri	Ladin	Carn	solitary	0	NA	NA	0	Corallosphere
Omphalophyllia boletiformis	Carn	Carn	solitary	0	NA	NA	0	Corallosphere
Omphalophyllia granulosa	Carn	Carn	solitary	0	NA	NA	0	Corallosphere
Omphalophyllia laubei	Carn	Carn	solitary	0	NA	NA	0	Corallosphere
Omphalophylliopsis lobatus	Plien	Plien	solitary	0	NA	NA	0	Corallosphere
Omphalophyllia radiciformes	Carn	Carn	solitary	0	NA	NA	0	Corallosphere
Omphalophyllia recondita	Ladin	Carn	solitary	0	NA	NA	0	Corallosphere
Omphalophyllia yamanbaensis	Carn	Nor	solitary	0	NA	NA	0	Corallosphere
Omphalophyllia zitteli	Carn	Nor	solitary	0	NA	NA	0	Corallosphere
Oppelismilia brodiei	Het	Het	solitary	0	NA	NA	0	Corallosphere
Oppelismilia gemmans	Het	Het	solitary	0	NA	NA	0	Corallosphere
Oppelismilia sp.	Carn	Toar	solitary	0	NA	NA	0	Corallosphere
Pachydendron microthallus	Nor	Rh	phaceloid	1	NA	NA	1	Corallosphere
Pachysmilia prima	Sin	Sin	phaceloid	1	NA	NA	1	Corallosphere
Pachysolenia cylindrica	Carn	Nor	phaceloid	1	NA	NA	1	Corallosphere
Pachysolenia mardjanaica	Ladin	Ladin	phaceloid	1	NA	NA	1	Corallosphere
Pachysolenia prima	Carn	Carn	phaceloid	1	NA	NA	1	Corallosphere
Palaeastraea alnigmata	Nor	Rh	astreoid	4	NA	NA	4	Corallosphere
Palaeastraea caryophylloides	Rh	Rh	astreoid	4	NA	NA	4	Corallosphere
Palaeastraea cyathophylloides	Nor	Rh	astreoid	4	NA	NA	4	Corallosphere
Palaeastraea grandissima	Nor	Rh	astreoid	4	NA	NA	4	Corallosphere
Palaeastraea granulata	Nor	Rh	astreoid	4	NA	NA	4	Corallosphere
Palaeastraea iljinae	Nor	Rh	astreoid	4	NA	NA	4	Corallosphere
Palaeastraea kokeni	Nor	Rh	astreoid	4	NA	NA	4	Corallosphere
Palaeastraea mandrakiensis	Carn	Carn	astreoid	4	NA	NA	4	Corallosphere
Palaeastraea minima	Nor	Nor	astreoid	4	NA	NA	4	Corallosphere

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Palaeastraea sp.	Nor	Nor	astreoid	4	NA	NA	4	Corallosphere
Palaeastraea subincrassata	Nor	Nor	astreoid	4	NA	NA	4	Corallosphere
Pamirastraea profunda	Carn	Rh	cerioid	3	NA	NA	3	Corallosphere
Pamirophyllum iranicum	Nor	Rh	cerioid	3	NA	NA	3	Corallosphere
Pamirophyllum pamiricum	Nor	Rh	cerioid	3	NA	NA	3	Corallosphere
Pamirophyllum tatricum	Rh	Rh	cerioid	3	NA	NA	3	Corallosphere
Pamiroseris alina	Nor	Rh	thamnasterioid	5	NA	NA	5	Corallosphere
Pamiroseris borealis	Nor	Nor	thamnasterioid	5	NA	NA	5	Corallosphere
Pamiroseris delicata	Nor	Rh	thamnasterioid	5	NA	NA	5	Corallosphere
Pamiroseris meriani	Nor	Rh	thamnasterioid	5	NA	NA	5	Corallosphere
Pamiroseris multispetata	Nor	Rh	thamnasterioid	5	NA	NA	5	Corallosphere
Pamiroseris rectilamellosa	Carn	Rh	thamnasterioid	5	NA	NA	5	Corallosphere
Pamiroseris seranica	Nor	Nor	thamnasterioid	5	NA	NA	5	Corallosphere
Pamiroseris silesica	Anis	Anis	thamnasterioid	5	NA	NA	5	Corallosphere
Pamiroseris smithi	Nor	Rh	thamnasterioid	5	NA	NA	5	Corallosphere
Pamiroseris sp.	Nor	Rh	thamnasterioid	5	NA	NA	5	Corallosphere
Pamiroseris tibetana	Nor	Nor	thamnasterioid	5	NA	NA	5	Corallosphere
Pamiroseris zitetlli	Carn	Carn	thamnasterioid	5	NA	NA	5	Corallosphere
Paracuifia tortuosa	Rh	Rh	phaceloid	1	NA	NA	1	Corallosphere
Paradistichophyllum dichotomum	Rh	Rh	phaceloid	1	NA	NA	1	Melnikova, 2001
Paraphyllogyra sinuosa	Plien	Plien	meandroid	6	NA	NA	6	Corallosphere
Parapleurosmilia inflata	Plien	Plien	solitary	0	NA	NA	0	Corallosphere
Parastraeomorpha minuscula	Nor	Rh	thamnasterioid	5	NA	NA	5	Corallosphere
Parastraeomorpha similis	Nor	Rh	thamnasterioid	5	NA	NA	5	Corallosphere
Parathecosmilia langobardica	Nor	Rh	phaceloid	1	NA	NA	1	Corallosphere
Parathecosmilia mokhtensis	Plien	Plien	phaceloid	1	NA	NA	1	Corallosphere
Parathecosmilia sellae	Nor	Rh	phaceloid	1	NA	NA	1	Corallosphere
Parathecosmilia sp.	Rh	Rh	phaceloid	1	NA	NA	1	Corallosphere
Parathecosmilia wanneri	Nor	Nor	phaceloid	1	NA	NA	1	Corallosphere
Phacelepismilia simplex	Het	Het	phaceloid	1	dendroid	NA	1	Corallosphere
Phacelophyllia bacari	Plien	Plien	phaceloid	1	NA	NA	1	Corallosphere
Phacelophyllia fasciata	Het	Het	phaceloid	1	NA	NA	1	Corallosphere
Phacelophyllia moorei	Het	Het	phaceloid	1	NA	NA	1	Corallosphere
Phacelophyllia suttonensis	Nor	Het	phaceloid	1	NA	NA	1	Corallosphere
Phacelophyllia termieri	Plien	Plien	phaceloid	1	NA	NA	1	Corallosphere
Phacelostylophyllum affinis	Het	Het	phaceloid	1	NA	NA	1	Corallosphere
Phacelostylophyllum caespitosa	Nor	Rh	solitary	0	phaceloid	1	0.5	Corallosphere
Phacelostylophyllum chocolatensis	Sin	Sin	phaceloid	1	NA	NA	1	Corallosphere
Phacelostylophyllum dentatum	Het	Het	phaceloid	1	NA	NA	1	Corallosphere
Phacelostylophyllum irregularis	Het	Het	phaceloid	1	NA	NA	1	Corallosphere
Phacelostylophyllum michelini	Het	Het	phaceloid	1	NA	NA	1	Corallosphere
Phacelostylophyllum peruvianum	Plien	Plien	phaceloid	1	NA	NA	1	Corallosphere
Phacelostylophyllum planum	Plien	Plien	phaceloid	1	NA	NA	1	Corallosphere
Phacelostylophyllum pontebbana	Carn	Carn	phaceloid	1	NA	NA	1	Corallosphere
Phacelostylophyllum ramosum	Plien	Plien	phaceloid	1	NA	NA	1	Corallosphere
Phacelostylophyllum robustum	Rh	Rh	phaceloid	1	NA	NA	1	Corallosphere
Phacelostylophyllum romerloana	Ladin	Carn	phaceloid	1	NA	NA	1	Corallosphere
Phacelostylophyllum rugosum	Het	Sin	phaceloid	1	NA	NA	1	Corallosphere
Phacelostylophyllum sp.	Rh	Toar	phaceloid	1	NA	NA	1	Corallosphere
Phacelostylophyllum zitteli	Nor	Rh	phaceloid	1	NA	NA	1	Corallosphere
Pinacophyllum annulatum	Nor	Rh	phaceloid	1	cerioid	3	2	Corallosphere
Pinacophyllum gracile	Ladin	Plien	phaceloid	1	cerioid	3	2	Corallosphere

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Pinacophyllum parallelum	Ladin	Plien	phaceloid	1 cerioid	3	NA	2	Corallosphere
Pinacophyllum pegesi	Nor	Nor	phaceloid	1 cerioid	3	NA	2	Corallosphere
Pinacophyllum sp.	Ladin	Plien	phaceloid	1 cerioid	3	NA	2	Corallosphere
Plesiophyllum cylindricum	Plien	Plien	solitary	0	NA	NA	0	Corallosphere
Pokljukosmilia tuvalica	Carn	Nor	phaceloid	1	NA	NA	1	Corallosphere
Primorodendron asher	Nor	Nor	phaceloid	1	NA	NA	1	Corallosphere
Primorodendron improvisum	Nor	Rh	phaceloid	1	NA	NA	1	Corallosphere
Primorodendron sp.	Rh	Rh	phaceloid	1	NA	NA	1	Corallosphere
Procyclolites septocoarte	Plien	Plien	solitary	0	NA	NA	0	Corallosphere
Procyclolites triadicus	Nor	Rh	solitary	0 thamnasteroid	NA	NA	0	Corallosphere
Procyclolites zakharovi	Rh	Rh	solitary	0 thamnasteroid	NA	NA	0	Corallosphere
Prodonacosmilia dronovi	Sin	Plien	phaceloid	1	NA	NA	1	Corallosphere
Proleptophyllia bilobata	Plien	Plien	solitary	0	NA	NA	0	Corallosphere
Proleptophyllia multiradiata	Plien	Plien	solitary	0	NA	NA	0	Corallosphere
Proleptophyllia rejuvenescens	Plien	Plien	solitary	0	NA	NA	0	Corallosphere
Proleptophyllia subcylindrica	Plien	Plien	solitary	0	NA	NA	0	Corallosphere
Protoheterastraea alakirensis	Nor	Nor	solitary	0	NA	NA	0	Corallosphere
Protoheterastraea fritschi	Carn	Carn	solitary	0	NA	NA	0	Corallosphere
Protoheterastraea hudajuznensis	Carn	Carn	solitary	0	NA	NA	0	Corallosphere
Protoheterastrea konosensis	Nor	Nor	solitary	0	NA	NA	0	Corallosphere
Protoheterastraea leonardi	Carn	Carn	solitary	0	NA	NA	0	Corallosphere
Protoheterastraea magma	Ladin	Carn	solitary	0	NA	NA	0	Corallosphere
Protoheterastraea mardjanaica	Carn	Carn	solitary	0	NA	NA	0	Corallosphere
Protoheterastraea minor	Carn	Carn	solitary	0	NA	NA	0	Corallosphere
Protoheterastraea pseudocolumella	Anis	Anis	solitary	0	NA	NA	0	Corallosphere
Protoheterastrea sp.	Carn	Rh	solitary	0	NA	NA	0	Corallosphere
Protoheterastrea trnovensis	Plien	Plien	solitary	0	NA	NA	0	Corallosphere
Protostylophyllum ulfati	Carn	Nor	solitary	0	NA	NA	0	Corallosphere
Recticostastraea wallowaensis	Nor	Rh	meandroid	6	NA	NA	6	Corallosphere
Retiophyllia alfurica	Carn	Rh	phaceloid	1	NA	NA	1	Corallosphere
Retiophyllia aksuensis	Nor	Nor	phaceloid	1	NA	NA	1	Corallosphere
Retiophyllia bavarica	Rh	Rh	phaceloid	1	NA	NA	1	Corallosphere
Retiophyllia buonamici	Nor	Rh	phaceloid	1	NA	NA	1	Corallosphere
Retiophyllia caespitosa	Carn	Rh	phaceloid	1	NA	NA	1	Corallosphere
Retiophyllia clathrata	Carn	Het	phaceloid	1	NA	NA	1	Corallosphere
Retiophyllia cyathophylloides	Nor	Rh	phaceloid	1	NA	NA	1	Corallosphere
Retiophyllia dawsoni	Nor	Rh	phaceloid	1	NA	NA	1	Corallosphere
Retiophyllia defilippi	Nor	Rh	phaceloid	1	NA	NA	1	Corallosphere
Retiophyllia delicatula	Nor	Rh	phaceloid	1	NA	NA	1	Corallosphere
Retiophyllia dendriformis	Rh	Rh	phaceloid	1	NA	NA	1	Corallosphere
Retiophyllia dichotoma	Nor	Rh	phaceloid	1	NA	NA	1	Corallosphere
Retiophyllia fenestrata	Nor	Rh	phaceloid	1	NA	NA	1	Corallosphere
Retiophyllia frechi	Nor	Rh	phaceloid	1	NA	NA	1	Corallosphere
Retiophyllia gephryophora	Rh	Rh	phaceloid	1	NA	NA	1	Corallosphere
Retiophyllia gosaviensis	Nor	Rh	phaceloid	1	NA	NA	1	Corallosphere
Retiophyllia gracilis	Rh	Rh	phaceloid	1	NA	NA	1	Corallosphere
Retiophyllia langobardica	Rh	Rh	phaceloid	1	NA	NA	1	Corallosphere
Retiophyllia mailonggangensis	Carn	Nor	phaceloid	1	NA	NA	1	Corallosphere
Retiophyllia major	Rh	Rh	phaceloid	1	NA	NA	1	Corallosphere
Retiophyllia minima	Nor	Rh	phaceloid	1	NA	NA	1	Corallosphere
Retiophyllia multigranulatum	Nor	Rh	phaceloid	1	NA	NA	1	Corallosphere
Retiophyllia multiramis	Rh	Rh	phaceloid	1	NA	NA	1	Corallosphere

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Retiophyllia norica	Nor	Rh	phaceloid	1		NA		NA	1	Corallosphere
Retiophyllia ombonii	Rh	Rh	phaceloid	1		NA		NA	1	Corallosphere
Retiophyllia oppeli	Carn	Rh	phaceloid	1		NA		NA	1	Corallosphere
Retiophyllia parviseptum	Nor	Rh	phaceloid	1		NA		NA	1	Corallosphere
Retiophyllia robusta	Nor	Rh	phaceloid	1		NA		NA	1	Corallosphere
Retiophyllia seranica	Nor	Rh	phaceloid	1		NA		NA	1	Corallosphere
Retiophyllia sp.	Anis	Plien	phaceloid	1		NA		NA	1	Corallosphere
Retiophyllia suttonensis	Nor	Rh	phaceloid	1		NA		NA	1	Corallosphere
Retiophyllia tolminensis	Carn	Nor	phaceloid	1		NA		NA	1	Corallosphere
Retiophyllia wanneri	Nor	Rh	phaceloid	1		NA		NA	1	Corallosphere
Retiophyllia weberi	Nor	Nor	phaceloid	1		NA		NA	1	Corallosphere
Retiophyllia wrangeliana	Nor	Nor	phaceloid	1		NA		NA	1	Corallosphere
Rhabdophyllia phaceloida	Plien	Plien	phaceloid	1		NA		NA	1	Corallosphere
Rhaetiastraea sp.	Nor	Rh	cerioid	3		NA		NA	3	Corallosphere
Rhaetiastraea tatrica	Rh	Het	cerioid	3		NA		NA	3	Corallosphere
Rhopalodendron juliensis	Carn	Nor	solitary	0	phaceloid	1		NA	0.5	Corallosphere
Rhopalophyllia granulata	Carn	Carn	solitary	0	phaceloid	1		NA	0.5	Corallosphere
Rodinosmilia elegantula	Plien	Plien	solitary	0		NA		NA	0	Beauvais, 1986
Semidistichophyllum guizhouensis	Anis	Ladin	phaceloid	1	plocoid	2		NA	1.5	Corallosphere
Seriastraea crassa	Rh	Rh	thamnasterioid	5		NA		NA	5	Corallosphere
Seriastraea multiphylla	Nor	Rh	thamnasterioid	5		NA		NA	5	Corallosphere
Siderosmilia perithecata	Plien	Plien	phaceloid	1		NA		NA	1	Corallosphere
Stuoresia bronni	Carn	Carn	meandroid	6		NA		NA	6	Corallosphere
Stuoresia cerioida	Carn	Nor	meandroid	6		NA		NA	6	Corallosphere
Stuoresia fluegeli	Carn	Carn	meandroid	6		NA		NA	6	Corallosphere
Stuoresia libratoseptata	Nor	Rh	meandroid	6		NA		NA	6	Corallosphere
Stuoresimorpha norica	Nor	Rh	cerioid	3		NA		NA	3	Corallosphere
Stuoresimorpha norica	Nor	Rh	cerioid	3	meandroid	6		NA	4.5	Corallosphere
Stylina norica	Nor	Rh	cerioid	3		NA		NA	3	Corallosphere
Stylophyllopsis bobrovensis	Rh	Rh	solitary	0	phaceloid	1		NA	0.5	Corallosphere
Stylophyllopsis bortepensis	Nor	Rh	solitary	0	phaceloid	1		NA	0.5	Corallosphere
Stylophyllopsis brevis	Het	Miocene	solitary	0	phaceloid	1		NA	0.5	Corallosphere
Stylophyllopsis cocchii	Rh	Rh	solitary	0	phaceloid	1		NA	0.5	Corallosphere
Stylophyllopsis cognata	Rh	Rh	solitary	0	phaceloid	1		NA	0.5	Corallosphere
Stylophyllopsis elchabirensis			solitary	0	phaceloid	1		NA	0.5	Corallosphere
Stylophyllopsis karauldyndalaensis	Nor	Nor	solitary	0	phaceloid	1		NA	0.5	Corallosphere
Stylophyllopsis lindstroemi	Carn	Rh	solitary	0		NA		NA	0	Roniewicz, 1989
Stylophyllopsis media	Nor	Rh	solitary	0	phaceloid	1		NA	0.5	Corallosphere
Stylophyllopsis mucronata	Sin	Plien	solitary	0	phaceloid	1		NA	0.5	Corallosphere
Stylophyllopsis murchisoniae	Het	Sin	solitary	0	phaceloid	1		NA	0.5	Corallosphere
Stylophyllopsis polyactis	Nor	Rh	solitary	0		NA		NA	0	Roniewicz, 1989
Stylophyllopsis patula	Sin	Sin	solitary	0	phaceloid	1		NA	0.5	Corallosphere
Stylophyllopsis praenuntians	Plien	Plien	solitary	0	phaceloid	1		NA	0.5	Corallosphere
Stylophyllopsis ramosa	Anis	Rh	phaceloid	1	solitary	0		NA	0.5	Roniewicz, 1989
Stylophyllopsis rnojsvari	Nor	Rh	solitary	0	phaceloid	1		NA	0.5	Corallosphere
Stylophyllopsis rudis	Nor	Plien	solitary	0		NA		NA	0	Roniewicz, 1989
Stylophyllopsis rugosa	Sin	Sin	solitary	0	phaceloid	1		NA	0.5	Corallosphere
Stylophyllopsis sp.	Nor	Nor	solitary	0	phaceloid	1		NA	0.5	Corallosphere
Stylophyllopsis timoricus	Nor	Nor	solitary	0	phaceloid	1		NA	0.5	Corallosphere
Stylophyllopsis veneta	Plien	Plien	solitary	0	phaceloid	1		NA	0.5	Corallosphere
Stylophyllopsis variisepta	Nor	Rh	solitary	0	phaceloid	1		NA	0.5	Corallosphere
Stylophyllopsis victoriae	Sin	Plien	solitary	0	phaceloid	1		NA	0.5	Corallosphere

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Stylophyllopsis walliae	Het	Plien	solitary	0 phaceloid	1	NA	0.5	Corallosphere
Stylophyllum bortepensis	Rh	Rh	solitary	0	NA	NA	0	Corallosphere
Stylophyllum cognata	Rh	Rh	solitary	0	NA	NA	0	Corallosphere
Stylophyllum cocchii	Rh	Rh	solitary	0	NA	NA	0	Corallosphere
Stylophyllum edwardsi	Rh	Rh	cerioid	3	NA	NA	3	Corallosphere
Stylophyllum gracilis	Rh	Rh	cerioid	3	NA	NA	3	Corallosphere
Stylophyllum lejowae	Rh	Rh	phaceloid	1 cerioid	3	NA	2	Corallosphere
Stylophyllum paradoxum	Nor	Plien	cerioid	3	NA	NA	3	Corallosphere
Stylophyllum polyacanthum	Nor	Rh	cerioid	3	NA	NA	3	Corallosphere
Stylophyllum pygmaeum	Nor	Rh	cerioid	3	NA	NA	3	Corallosphere
Stylophyllum teniuspinum	Nor	Rh	cerioid	3	NA	NA	3	Corallosphere
Stylophyllum vesiculatum	Rh	Rh	cerioid	3	NA	NA	3	Corallosphere
Stylosmilia alichurica	Sin	Sin	phaceloid	1	NA	NA	1	Melnikova and Roniewicz 2011
Stylosmilia decemseptata	Sin	Sin	phaceloid	1	NA	NA	1	Melnikova and Roniewicz 2012
Stylosmilia michelini	Plien	Berriasian	phaceloid	1	NA	NA	1	Melnikova and Roniewicz 2012
Stylosmilia sp.	Sin	Barremian	phaceloid	1	NA	NA	1	Melnikova and Roniewicz 2013
Submargarosmilia beipanjiangensi	Anis	Ladin	solitary	0	NA	NA	0	Corallosphere
Substuoresia shizongensis	Anis	Ladin	cerioid	3	NA	NA	3	Corallosphere
Substuoresia vogelsangi	Anis	Ladin	cerioid	3	NA	NA	3	Corallosphere
Synastrea sp.	Plien	Coniacian	thamnasterioid	5	NA	NA	5	Corallosphere
Synastrea walfordi	Plien	Plien	thamnasterioid	5	NA	NA	5	Corallosphere
Thamnasteria defranciana	Plien	Plien	thamnasterioid	5	NA	NA	5	Corallosphere
Thamnasteria delicata	Nor	Rh	thamnasterioid	5	NA	NA	5	Corallosphere
Thamnasteria dronovi	Plien	Plien	thamnasterioid	5	NA	NA	5	Corallosphere
Thamnasteria etheridgei	Plien	Plien	thamnasterioid	5	NA	NA	5	Corallosphere
Thamnasteria norica	Nor	Nor	thamnasterioid	5	NA	NA	5	Corallosphere
Thamnasteria rhaetica	Rh	Rh	thamnasterioid	5	NA	NA	5	Corallosphere
Thamnasteria sp.	Anis	Albian	thamnasterioid	5	NA	NA	5	Corallosphere
Thamnasteria walfordi	Plien	Plien	thamnasterioid	5	NA	NA	5	Corallosphere
Thamnasteriamoipha karapetovi	Nor	Nor	cerioid	3	NA	NA	3	Corallosphere
Thamnasteriamorpha arthaberi	Nor	Rh	cerioid	3	NA	NA	3	Corallosphere
Thamnasteriamorpha dronovi	Nor	Nor	cerioid	3	NA	NA	3	Corallosphere
Thamnasteriamorpha neumayn	Nor	Rh	cerioid	3	NA	NA	3	Corallosphere
Thamnasteriomorpha frechi	Nor	Nor	thamnasterioid	5	NA	NA	5	Corallosphere
Thamnatropis freehi	Carn	Nor	cerioid	3	NA	NA	3	Corallosphere
Thamnatropis laczkoina	Carn	Carn	cerioid	3	NA	NA	3	Corallosphere
Thamnatropis maraschinii	Anis	Anis	cerioid	3	NA	NA	3	Corallosphere
Thamnotropis bolognae	Anis	Anis	cerioid	3	NA	NA	3	Corallosphere
Thamnotropis loretzi	Carn	Carn	cerioid	3	NA	NA	3	Corallosphere
Thamnotropis rakoveci	Carn	Carn	cerioid	3	NA	NA	3	Corallosphere
Thamnotropis ramosum	Carn	Carn	cerioid	3	NA	NA	3	Corallosphere
Thamnotropis rarus	Nor	Nor	cerioid	3	NA	NA	3	Corallosphere
Thamnotropis richthofeni	Carn	Carn	cerioid	3	NA	NA	3	Corallosphere
Thamnotropis settsassi	Carn	Carn	thamnasterioid	5	NA	NA	5	Corallosphere
Thecosmilia buonemicii	Rh	Rh	phaceloid	1 dendroid	NA	NA	1	Vaughan and Wells 1943
Thecosmilia estnensts	Ladin	Ladin	phaceloid	1 dendroid	NA	NA	1	Vaughan and Wells 1943
Thecosmilia lancisii	Rh	Rh	phaceloid	1 dendroid	NA	NA	1	Vaughan and Wells 1943
Thecosmilia major	Het	Het	phaceloid	1 dendroid	NA	NA	1	Vaughan and Wells 1943
Thecosmilia mirabilis	Het	Het	phaceloid	1 dendroid	NA	NA	1	Vaughan and Wells 1943
Thecosmilia molengraaffi	Nor	Nor	phaceloid	1 dendroid	NA	NA	1	Vaughan and Wells 1943
Thecosmilia omboni	Rh	Rh	phaceloid	1 dendroid	NA	NA	1	Vaughan and Wells 1943
Thecosmilia rarisepta	Carn	Carn	phaceloid	1 dendroid	NA	NA	1	Vaughan and Wells 1943

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Thecosmilia rofanica	Het	Sin	phaceloid	1 dendroid	NA	NA	1	Vaughan and Wells 1943
Thecosmilia selamenensis	Nor	Nor	phaceloid	1 dendroid	NA	NA	1	Vaughan and Wells 1943
Thecosmilia seranrca	Nor	Nor	phaceloid	1 dendroid	NA	NA	1	Vaughan and Wells 1943
Thecosmilia sp.	Nor	Plien	phaceloid	1 dendroid	NA	NA	1	Vaughan and Wells 1943
Thecosmilia spizzetists	Ladin	Ladin	phaceloid	1 dendroid	NA	NA	1	Vaughan and Wells 1943
Thecosmilia tothpleizi	Carn	Carn	phaceloid	1 dendroid	NA	NA	1	Vaughan and Wells 1943
Toechastraea kuschlini	Nor	Rh	cerioid	3	NA	NA	3	Corallosphere
Toechastraea major	Nor	Nor	cerioid	3	NA	NA	3	Corallosphere
Toechastraea ogilviae	Carn	Carn	cerioid	3	NA	NA	3	Corallosphere
Toechastraea oppelii	Carn	Nor	cerioid	3	NA	NA	3	Corallosphere
Toechastraea pachyphyllia	Nor	Rh	cerioid	3	NA	NA	3	Corallosphere
Toechastraea plana	Nor	Nor	cerioid	3	NA	NA	3	Corallosphere
Toechastraea sp.	Rh	Rh	cerioid	3	NA	NA	3	Corallosphere
Tricycloseris anningi	Plien	Plien	thamnasterioid	5	NA	NA	5	Corallosphere
Tricycloseris sp.	Plien	Plien	thamnasterioid	5	NA	NA	5	Corallosphere
Trigerastraea minima	Plien	Plien	plocoid	2 cerioid	3 meandroid	6	3.666666667	Corallosphere
Trocharea sp.	Het	Het	solitary	0	NA	NA	0	Corallosphere
Trochocyathus sp.	Plien	Albian	solitary	0	NA	NA	0	Vaughan and Wells, 1943
Tropiastraea carinata	Nor	Nor	cerioid	3	NA	NA	3	Corallosphere
Tropidendron mlinaricensis	Carn	Carn	phaceloid	1	NA	NA	1	Corallosphere
Tropidendron rhopeiiior	Carn	Carn	phaceloid	1	NA	NA	1	Corallosphere
Tropiphyllum omatum	Nor	Nor	solitary	0	NA	NA	0	Corallosphere
Volzeia badiotica	Ladin	Plien	phaceloid	1	NA	NA	1	Corallosphere
Volzeia chagyabensis	Anis	Ladin	phaceloid	1	NA	NA	1	Corallosphere
Volzeia subdichotoma	Anis	Carn	phaceloid	1	NA	NA	1	Corallosphere
Volzeia sublaevis	Ladin	Carn	phaceloid	1	NA	NA	1	Corallosphere
Zardinophyllum carpathicum	Carn	Carn	solitary	0	NA	NA	0	Corallosphere
Zerdinopliyllutn znrdinii	Carn	Carn	solitary	0	NA	NA	0	Corallosphere