Atoll and Island Formation in the Maldives

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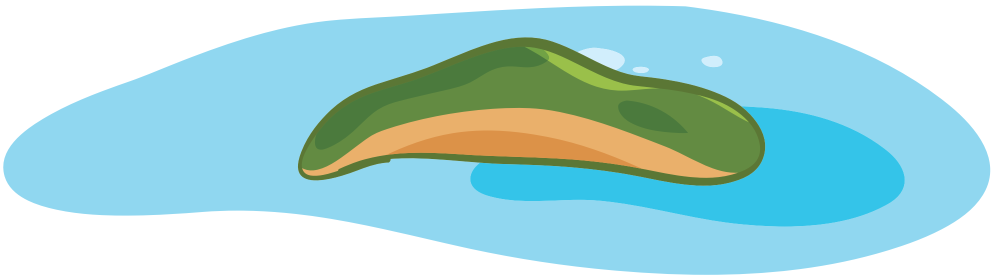

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The initial idea of the book was born and implemented during the four months-long tenure of André Droxler at The Maldives National University as a Fulbright Senior Scholar in 2023.

The authors acknowledge and appreciate the support and contribution of Dr Claire Lee (Oxford Brookes University) in checking the language of this book.

The authors are profoundly grateful to the Atmosphere Foundation for their generous donation to print 500 copies of this book. This support has been invaluable in bringing this work to a wider audience.

The materials in this book are connected to the following SDGs.

TABLE OF CONTENTS

INTRODUCTION TO THE BOOK

The Maldives' islands, formed almost entirely from coral debris and sand, are extraordinarily low-lying, making them particularly vulnerable to changes in sea level. The interconnectedness of geological, biological, and environmental forces is evident throughout the Maldivian archipelago, where islands continue to evolve in response to rising seas, climate change, and ocean currents.

The purpose of this book is to provide supplementary materials to introduce students to contemporary data on the formation of the coral reef atolls and coral islands in the Maldives Archipelago. This book explores the complex processes that formed the atolls in the Maldives.

This book explores not only the geological mechanics of atoll formation but also the role of coral reefs in the formation of atolls and islands. These coral reefs are not just land-builders but also serve as ecosystems, home to a diverse range of marine life. In the Maldives, the reefs have been crucial in forming the islands' fragile but resilient ecosystems, supporting a unique range of flora and fauna.

Through the activities in this book, students will explore the extraordinary journey of the Maldives from submerged coral reefs to tropical islands. Islands are often viewed as remote, isolated land areas, yet they are dynamic environments shaped by complex geological, biological, and environmental processes, from volcanic eruptions that birth new landmasses to the slow rise and fall of sea levels that reveal or submerge islands.

HOW TO USE THIS BOOK

This book on atoll and island formation in the Maldives is structured to provide a contemporary understanding of the geological, ecological, and environmental processes that shape the islands and atolls in the Maldives. This supplementary book is designed for teachers and students.

This book is developed to align with the National Curriculum Framework. The Shared Values from the National Curriculum Framework (NCF) that relate to the activities in this book are 'Relating to Local and Global Community'. The Key competencies that are addressed in this book are:

1. Thinking critically and creatively
2. Related people
3. Making meaning
4. Using technology and the media

This book is targeted for Key Stages 1, 2, 3, and 4 of the NCF. The focussed subjects are Social Studies, Science and Marine science. The relevant strands from these subject areas are identified in the activities. These activities are designed to assist teachers in implementing the identified Learning Outcomes from the curriculum.

How are the activities structured?

We have utilized various learning methods in the different key stages, including visual approaches and kinaesthetic activities such as drawing and map reading for Key Stages 1 and 2, and auditory techniques such as listening to podcasts, and reading comprehension exercises for Key Stages 3 and 4. These activities are structured so that teachers can implement them with minimal effort, and students can easily engage with them. The pack includes student worksheets and teacher readings that will assist in facilitating the activities. The Teacher Notes section at the end of this booklet includes maps, diagrams, web links, podcasts, videos, and readings.

The overall themes for the activities outlined in this key stage are:

- Landscapes of atolls and islands in the Maldives
- Coral Reef construction, formation of atolls, and islands in the Maldives

Prior to implementing these activities, it is advised that the teachers read the 'Teacher Notes' Section in this book for background information.

MESSAGE TO THE TEACHERS FROM THE AUTHORS

Dear Teachers,
It is our pleasure to introduce this supplementary guide on the formation of atolls and coral reef islands in the Maldives, developed to help you deliver engaging and scientifically accurate lessons on this crucial topic. This guide aligns closely with the Maldives **National Curriculum Framework** (NCF) and aims to support the development of key competencies and values outlined within it.

Our nation's unique geography provides a rich context for learning, and the study of atoll and island formation is an ideal platform for teaching essential skills such as critical thinking, inquiry-based learning, and problem-solving—all central to developing the key competencies of the NCF. By using up-to-date research data and evidence, this guide ensures that students gain a clear understanding of the natural processes shaping the development of the atolls and islands in the Maldives.

Incorporating the latest research into your lessons will empower students to become well-informed, scientifically literate citizens, with an understanding of the pressing environmental issues facing the Maldives. By equipping students with contemporary knowledge, the teachers can help the students make informed decisions and develop the values of responsibility, sustainability, and active citizenship that are core values in our curriculum.

The guide also offers short classroom activities that are practical that not only align with the NCF aims, but also provide opportunities for students to explore, discuss and research - providing a holistic learning experience. These activities foster collaboration, creativity, and a deeper connection to the local environment, helping students appreciate both the natural and cultural significance of the country we call home.
Thank you for your dedication to shaping the next generation of scientifically informed and responsible Maldivian citizens. We trust that this resource will be a valuable tool in your classroom.


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MESSAGE FROM THE NATIONAL INSTITUTE OF EDUCATION

Atoll and Island Formation in the Maldives is a valuable resource for educators and students alike, offering a comprehensive exploration of the fascinating geological, ecological, and environmental processes that have shaped the Maldives. This book is more than just a supplementary book; it is an invitation to discover the wonders of our islands and to develop a deep appreciation for our natural heritage.

By aligning with the National Curriculum Framework, this book seamlessly integrates into the classroom, fostering critical thinking, creativity, and a sense of global citizenship. The engaging activities and projects encourage students to explore, investigate, and understand the complex interplay between land, sea, and life.

As we face the challenges of climate change and environmental degradation, it is imperative that we educate the next generation about the importance of sustainability and conservation. *Atoll and Island Formation in the Maldives* plays a crucial role in this endeavour, empowering young minds to become informed and responsible stewards of our planet.

I commend the authors for creating such an insightful and inspiring resource. I am confident that this book will ignite curiosity, spark imagination, and inspire a lifelong passion for learning about our islands.

Fathmath Nishan, PhD
National Institute of Education

KEY STAGE 1

The following activities can be incorporated into Key Stage 1 lessons of Science and/or Social Studies lessons.

These activities are based on the following themes

- Landscapes of atolls and islands in the Maldives
- Coral Reef construction and formation of atolls and islands in the Maldives

Teachers can refer to the 'Teacher Notes' Section for background information in implementing these activities

In Key Stage 1, the following Learning Outcomes from the National Curriculum are relevant to the topic.

Science – Earth and Beyond: Physical Features of the Earth (Grades 1-3)		
Grade 1	**Grade 2**	**Grade 3**
Learning Outcome		
EB101 Observe the patterns that occur in the sky and land	EB201 Observe the changes that occur in the locality over time	EB301 Explore the changes that occur due to rotation of the Earth on its axis
Associated Indicators		
a) Observing familiar patterns of events that occur on the Earth and in the sky such as appearance of moon, day and night, monsoons b) Observing to identify the changes in nearby environment such as, cut down of trees, new building, parks c) Recognising the indigenous knowledge of daily and seasonal changes in weather patterns and how they are used in daily life d) Discussing the effect of destroying the natural environment	a) Exploring the environment to observe the changes that occur to the locality overtime b) Observing to identify that some changes in the locality are fast while others are slow such as changing of landscape, day and night c) Discussing the human activities which affect the environment such as beach erosion	a) Recognising the significance of cyclic nature of changes on Earth such as day and night to work and rest, praying five time at specific times of day and night b) Making sundials to observe shadows and relate it to the movement of Earth on its axis c) Modelling the relative size and movement of the Earth, sun and moon

Social Studies – People, places, and Environment: The Word in Spatial Terms (Grades 1-3)		
Grade 1	**Grade 2**	**Grade 3**
Learning Outcome		
PPT108: Observe maps of familiar settings (home, school) and use simple directional words.	PPT208: Demonstrate an understanding of the atoll and the island that they belong to	PPT312: Use map skills (map keys and directions) to locate and identify important places of one's island/city
Associated Indicators		
a) Identifies that real things can be shown on maps and plans of different settings (home, school). b) Identifies and talks about the pictorial symbols on a map which represents real objects. c) Locates objectives in the classroom using relative location and direction (e.g., near/far, right/ left, up/ down, behind/ front etc.). d) Identifies different places from a given map of school (e.g., restrooms, library, staffroom, computer lab, etc.).	a) Marks the location of the atoll and the island one belongs to on a given map of the Maldives.	a) Uses the map keys given on a map of one's island/city to identify and locate places of Importance b) Uses directions and map keys to create a simple journey from one significant point to the another in their island or city. (e.g., route from hospital to island council office or police station, etc.) c) Identifies and locates on a map of their island/city, the routes to some of the places that one visits every day
Learning Outcome		
PPT109: Use map keys to illustrate journeys from one point of the school to another	PPT209: Use map skills, (significant map keys, follows directions) to locate and identify important places of their island	PPT313: Explore the significant physical (natural geographical) features of the atoll one belongs to.
Associated Indicators		
a) Draws a map of the school using given pre-cut objects to place on their map. b) Draws a simple map to give the direction (journeys) from a significant point to the other (e.g.; route from library to, playground, etc.) of their school using symbols and directions.	a) Identifies and locates the important places of their island (e.g., Location of school, mosque, play areas, hospital, play areas, parks, island office, police station, etc.) b) Identifies on a map of their island, the easiest and fastest route to travel to different places that they are familiar using map keys and directions. c) Creates a simple journey from a significant point of the island to the other (e.g., route from hospital to school, etc.) of their island using map keys and directions	a) Demonstrates an understanding of the formation of an atoll with the help of a diagram b) Identifies and gains understanding of the natural features of the atoll that one belongs to (coastal and other features such as mangroves, wetlands, etc.) c) Observes the map of the Maldives and discusses the natural features such as the shape and size of the islands of the atoll that one belongs to

Activity 1 - Landscapes of atolls and islands in the Maldives

Duration

35 minutes (or can be given as an extended activity)

Target Grade

Grade 1

Objectives of the activity

a. Locate the Maldives and its atolls on the Earth map.
b. Compare the landscape of different atolls and islands in the Maldives
c. Discuss how the atolls and islands look different and similar

Teacher Instruction

1. Refer to the map of the Maldives (in the Appendix). You can also use the administrative map of the Maldives along with any online map. The maps in the Appendix can be printed for student use, together with the associated student worksheet.
2. Use the zoom feature on the online map, explore the Satellite version of the map.
3. The teachers can do this in the class and ask the students to answer the associated questions in their worksheet. (Specifically, teachers can show an atoll, and zoom in to show an island and demonstrate the differences between an atoll and an island)
4. With the students, identify two different atolls and two different islands within those atolls, and ask the students to answer the questions in their worksheet.
5. Instruct the students to choose one large atoll and another atoll that is smaller, for example, North Male' Atoll and Goidhoo Atoll.

Student Worksheet

Let's Explore the landscapes of atolls and islands in the Maldives

In this activity you will learn a bit more about the wonderful atolls and islands in the Maldives.

Instructions

1. Your teacher will share with you some maps of the Maldives
2. With the teachers' instructions and using the map, answer the following questions.

Do you know?

The Maldives Archipelago is situated southwest of Sri Lanka and India, approximately 700 kilometres (435 miles) from the Asian mainland. Its strategic location along ancient trade routes made it a historical hub for maritime trade.

Student Worksheet

Questions

How are atolls different from islands?

	Name of one atoll studied Atoll 1:	Name of one atoll studied Atoll 2:
What is the shape of the atoll? Make a rough drawing		
What makes the atoll ring?		
Where are the islands located in this atoll? (is it at the edge or in the middle?)		
Zoom in and count how many islands are there		
Draw the shape of an island from each of these two atolls. Where in the atoll is the island located? (Is it in the atoll lagoon, or in the rim)		

Activity 2 - How Coral reefs are constructed, and how atolls and islands are formed in the Maldives

Duration

35 minutes (or can be given as an extended activity)

Target Grade

Grade 3

Objectives of the activity

a. Explain what coral reefs are
b. Discuss how atolls are formed
c. Identify the atoll coral ring and its lagoon.
d. Discuss how islands are formed.

Teacher Instruction

1. Show students the video – called "**Darwin's theory of atolls formation is incorrect!**". This video was developed by André W. Droxler (Rice University, USA) and Stéphan J. Jorry (IFREMER, France). This video can be accessed at https://www.youtube.com/watch?v=J950wu7tsmw
2. Distribute copies of the student worksheet.
3. Instruct the students to answer the questions on the worksheet while watching the video
4. Below are the answers

About 2.5 million years ago, Earth's climate changed a lot when big ice ages started in the northern part of the world. Ice caps grew bigger and smaller over time, causing sea levels to rise and fall a lot—sometimes by as much as 135 meters! During a long time, around 2 million years, some underwater coral reefs were mostly above water. These coral reefs consisted of marine fauna and flora. Once exposed to the air, these coral reefs would die. Once exposed and when it rained, the rain was a bit acidic, which slowly wore away the coral rocks, making the tops of these reefs look different.

Student Worksheet

Let's Explore how Coral Reefs are constructed, and how atolls and islands are formed in the Maldives!

In this activity we will explore the coral reefs, the atolls, and islands to see if we can get an idea of how old they are.

Instructions

1. You will watch a video called 'Darwin's theory of atolls formation is incorrect!'. This video is developed by André W. Droxler (Rice University, USA) and Séphan J. Jorry (IFREMER, France).
2. This video can be accessed at https://www.youtube.com/watch?v=J950wu7tsmw
3. Watch it carefully and answer the following questions based on the video.

Questions

1. Fill in the blanks

About .... (2.5 million/ 300) years ago, Earth's climate changed a lot when big ice ages started in the .... (northern/southern) part of the world. Ice caps grew bigger and smaller over time, causing .... (Sea levels/ moon phases) to rise and fall a lot—sometimes by as much as 135 meters! During a long time, around 2 million years, some underwater .... (coral reefs/ trees) were mostly above water and died coral reefs consisting of marine fauna and flora. Once the coral reefs were exposed and when it rained, the rain was a bit...................... (sweet/ acidic), which slowly wore away the coral rocks, making the tops of these reefs look different.

2. Draw how the Maldives might have looked like when sea level was 135 m below current sea level.
3. How do you feel learning about this information about the Maldives

Do you know?

The One and Half Degree Channel (Huvadhoo Kandu) is the largest Channel in the Maldives, located between Laamu Atoll and Gaafu Alif Atoll. This channel is named for its proximity to the 1.5° latitude line.

Latitude lines are like invisible hoops around the Earth parallel to the Equator. They help us know how far north or south a place is from the Equator.

Activity 3 - Comparison of coral reefs and atolls of the Maldives

Duration

35 minutes (or can be given as an extended activity)

Target Grade

Grade 2 or 3

Objectives of the activity

a. Compare the shapes of some atoll coral reefs and islands of the Maldives.
b. Identify similarities and differences in the shapes of some atoll coral reefs and of some islands in the Maldives.

Teacher Instruction

1. Below are the images from the Book 'Maps of Maldives – The complete guide to the atolls and islands of the Maldives', page 11 (included here with permission). This book is developed by Water Solutions Private Limited, Maldives.

2. Print copies of these maps for the students (either as printouts or shared as PowerPoint)
3. Provide copies of the student worksheet and guide students to answer the question on the worksheet.

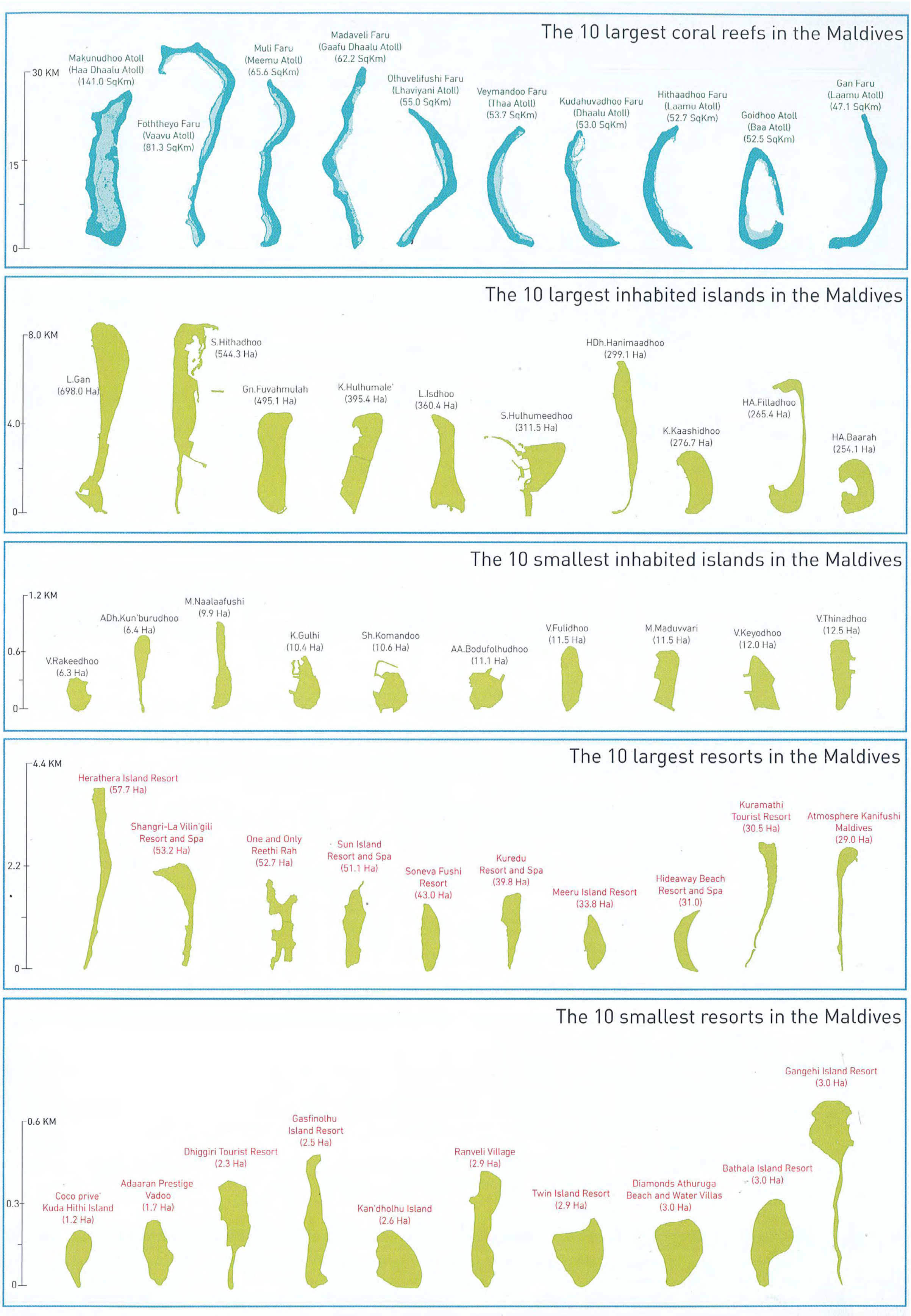


Photo courtesy Water Solutions Private Limited, Maldives

Student Worksheet

Reefs, Atolls, and Islands – How Big are they?

Instructions

1. You will be provided with images of the following.
   - The 10 largest coral reef atolls in the Maldives,
   - 10 largest islands in the Maldives and
   - 10 smallest islands in the Maldives.
2. Observe them carefully and answer the following questions.

Questions

1. What shapes do you notice in the coral reef atolls? Why do you think they are in these shapes?
2. Imagine you could visit one of the largest islands in the Maldives.
   a) If you had the opportunity to name the island, what would you call this island?
   b) What is the size of this island?
   c) Why did you choose this island?
   d) What activities would you want to do there, and why?
   e) Draw a map of this island.
3. Observe the 10 smallest islands and pick one island that looks the most interesting to you.
   a) Why did you choose this island?
   b) What is the area of this island?
   c) How many people do you think can live on this island?
   d) If you could live on this island, where in the island would you build your home?
4. Observe the 10 smallest islands and pick one island that looks the most interesting to you.
   a) What is the name of the biggest island in the Maldives?
   b) What is the name of the smallest island in the Maldives?
   c) If you could own an island draw a map of the different things or activities, you will do in this island. Draw a map of these.

Do you know?

The Maldives is home to a rich and diverse marine ecosystem, including coral reefs, high diversity of coral species, algae, sponges, manta rays, whale sharks, and various species of colourful fish, making it a top destination for diving and snorkelling enthusiasts.

KEY STAGE 2

2

The following activities can be incorporated into Key Stage 2 Social Studies lessons. These activities are based on the following themes:

- Landscapes of atolls and islands in the Maldives
- Coral Reef construction, formation of atolls, and islands in the Maldives

Teachers can refer to the 'Teacher Notes' Section for background information in implementing these activities

In Key Stage 2, the following Learning Outcomes from the National Curriculum have been identified as being relevant for the topic.

Social Studies – People, places,and Environment: Society and Environment - Grade 4	
Outcome PPE411: Demonstrate understanding of atoll formation in the Maldives and describe the natural features associated with the formation of atolls	**Indicator:** a. Explains the process of atoll formation in the Maldives b. Describes the natural features found in Maldivian atolls (such as coral reefs, lagoons, and islets, such as faru, futtaru, giri, heylhi, vilu, kandu, etc)

Social Studies – People, places, and Environment: Society and Environment - Grade 5	
Outcome PP2.1 Compares natural and built features of the Maldives.	**Indicators:** This is evident when the student: a. Uses a range of geographical terms to describe locations and features of places in Maldives (e.g. atolls, islands, faru, thila, vilu, etc.)

Activity 1 - Landscapes of atolls and islands in the Maldives

Duration
35 minutes (or can be given as an extended activity)

Target Grade
Can be used for any grade in Key Stage 2

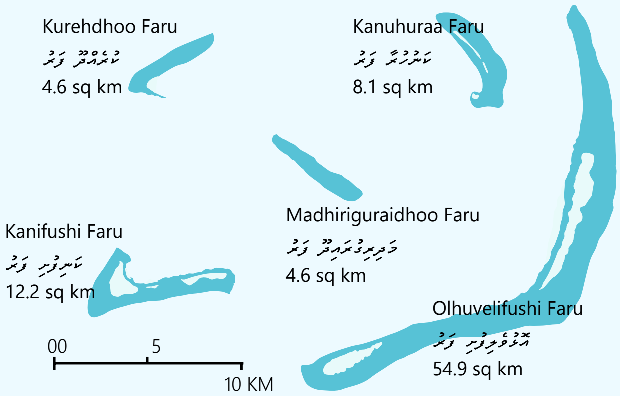
Objectives of the activity
a. Discuss how the atolls and islands look different and similar
b. Locate the islands in the given atoll
c. Compare overall the landscape of the islands in the given atoll

Teacher Instruction

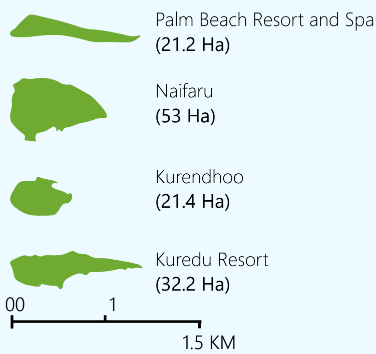
1. Below are the images from the Book 'Maps of Maldives – The complete guide to the atolls and islands of Maldives', page 11 (included here with permission). This book is developed by Water Solutions Private Limited, Maldives. The image shows Lhaviyani atoll.
2. Print copies of the maps on the next page for the students (either as printouts or shared as PowerPoint)
3. Provide copies of the student worksheet and guide them to answer the question.

Lhaviyani Atoll

5 Biggest reefs



How big are the islands?



Student Worksheet

Landscapes of atolls and islands in the Maldives

Instructions

1. You will be provided with a map of Lhaviyani atoll.
2. Observe them carefully and answer the following questions, selecting one specific atoll.

Questions

a. How many inhabited islands are in this atoll?

b. What are their names and size of these islands?

c. Name 4 resort islands in this atoll.

d. What is the name of an industrial island in this atoll? What is the work undertaken in the factories in this island?

e. Which island houses the airport in this atoll?

f. Write a letter to a person who is living in this atoll (Ask about their day-to-day activities and any other aspect that is of interest to you.

Do you know?

The Maldives experiences a tropical monsoon climate, characterized by two primary seasons: the dry season (northeast monsoon – *Iruvai Moosum)* from November to April, and the wet season (southwest monsoon – *Hulhangu Moosum*) from May to October. The dry season is generally sunnier, while the wet season brings more rainfall and occasional storms.

Activity 2 - How coral reefs are constructed, and how atolls and islands are formed in the Maldives

Duration

2 periods of 35 minutes (or can be given as an extended activity)

Target Grade

Can be used for any grade in Key Stage 2

Objectives of the activity

a. Explain what coral reefs are
b. Discuss how atolls are formed
c. Discuss how islands are formed

Teacher Instruction

1. Show students the video – called 'Darwin's theory of atolls formation is incorrect!'. This video is developed by André W. Droxler (Rice University, USA) and Stéphan J. Jorry (IFREMER, France). This video can be accessed at https://www.youtube.com/watch?v=J950wu7tsmw
2. Distribute copies of the student worksheet.
3. Instruct the students to answer the questions on the worksheet while watching the video.
4. Below are the answers:

1) According to the video, what is the estimated age of modern atolls?

It is less 500,000 years, the last phase of atoll growth is about 10,000 years, while the modern islands are not older than 3000-4000 years.

2) According to the video, what is the estimated number of sea-level cycles which have caused the current structure of the atolls?

Numerous (about four to five 100,000 years-long cycles.

3) Complete the blanks in the paragraph below

Earth's climate drastically deteriorated at the onset of major glaciations in the northern hemisphere 2.5 million years ago, and ice caps systematically and cyclically expanded, inducing high amplitude sea level variations and drops down to 135 m below the present-day level. The coral flat-topped banks which were about 3.5-million-years-old remained largely exposed during a 2-million-year-long interval of stepwise increase in ice volume. During this exposure, relatively acidic rain partially dissolved the coral limestone and created karstified bank-top morphologies, characterized by a central depression surrounded by raised margins.

4) What is a question you want to ask the scientists who did the research that led to the development of this video?

Any answer is acceptable

Student Worksheet

Exploring How Coral Reefs are constructed, and how atolls and islands are formed in the Maldives!

Questions

1. According to the video, what is the estimated age(s) of modern atolls?

2. According to the video, what is the estimated number of sea-level cycles which have caused the current formation of the atolls?

3. Complete the blanks in the paragraph below

Earth's climate drastically deteriorated at the onset of major .... in the northern hemisphere .... million years ago, and ice caps systematically and cyclically ...., inducing high amplitude sea level variations and drops down to .... below the present-day level. The coral flat-topped banks, which were 3.5 million years old, remained largely exposed during a 2 million yearslong interval of stepwise .... in ice volume. During this exposure, relatively .... partially dissolved the coral limestone and created karstified bank-top morphologies, characterized with a central depression surrounded by raised margins.

4. What is a question you want to ask the scientist who did the research that led to the development of this video?

Do you know?

Summer Island's 3D-printed coral reef was recognized by the Guiness World Records in 2021 as the largest of its kind in the world. Summer Island Maldives is located on Ziyaaraiyfushi in the North Malé Atoll.

KEY STAGE 3

The following activities can be incorporated into the Key Stage 3 lessons of science and/or social studies.

These activities are based on the following themes

- Landscapes of atolls and islands in the Maldives
- Coral Reef construction, and formation of atolls and islands in the Maldives

Teachers can refer to the 'Teacher Notes' Section for background information in implementing these activities

Key Stage 3 – Social Studies – People, places, and Environment: Geography, a sense of the world & The Physical World	
Grade 7	**Grade 8**
Learning Outcomes and indicators	
PPE1.2: Recognize the geographical features in the different regions of the Maldives. Indicators: a) Identifies and describes the process of the formation of atolls b) Explores and describes the unique flora and fauna of some of the regions of the Maldives	PPE1.2: Collect geographical statistics about some of the islands, atolls of Maldives and creates profiles of islands and atolls Indicators: a) Investigates, gathers information and creates island and atoll profiles of some regions of Maldives

Key Stage 3 – Social Studies – People, places, and Environment: Geography, a sense of the world & The Physical World	
PPE1.3: Discuss about the internal structure of the Earth, process and formation of lithosphere and rocks Indicators: a) Describes the internal structure of the Earth b) Draws and annotates a diagram showing the internal structure of the Earth c) Examines the physical formation and process of lithosphere d) Discusses the characteristics and formation of the three major rock types and its importance.	PPE1.3: Recognize and demonstrate awareness about the water bodies of the Earth and the process and the development of water bodies Indicators: a) Describes water bodies of the Earth b) Describes different landforms and the physical processes that cause water development in water bodies c) Demonstrates an understanding of the work of a river in eroding, transporting and depositing d) Recognizes forms of river valleys
PPE1.4: Explore and gain knowledge about the processes and patterns in the physical environment Indicators: a) Describes the physical processes that affect the natural environments of regions	PPE1.3: Demonstrate comprehensive knowledge about, climates, climatic patterns, the interrelated processes and its impact on environments Indicators: a) Explains Distribution of climate regions and the climatic belt b) Explains the influence of climate on the distribution of biomes in different regions c) Investigates about the changing climatic patterns in the local community and the world d) Obtains and gathers information on the reasons, effect and change in the climate around the world due to the changing climatic patterns
PPE1.5: Demonstrate awareness about natural hazards, the nature and interactions of the environment that causes natural hazards. Indicators: a) Explores the reasons and causes that cause natural hazards that affect people's lives b) Investigates the impact of the natural hazards that have happened in the local community	PPE1.4: Recognize the different impacts and loss that occurs due to some of the natural hazards Indicators: a) Investigates the impact of some of the natural hazards (environmental, personal and social)

Activity 1 - Landscapes of atolls and islands in the Maldives

Duration

35 minutes (or can be given as an extended activity)

Target Grade

Can be used for any grade in Key Stage 3

Objectives of the activity

a. Locate the Maldives and its atolls on the Earth map.

b. Compare overall the landscape of the atolls and islands in the Maldives.

Teacher Instruction

1. Refer to the map of Maldives (in the Appendix) You could also use the administrative map of the Maldives along with the online map. The maps in the Appendix can be printed for student use, together with the associated student worksheet.
2. Use the zoom feature on the online map to explore the Satellite version of the map.
3. The teachers can do this in the class and ask the students to answer the associated questions in their worksheet.
4. With the students, identify two different atolls and two different islands and ask the students to answer the questions in their worksheet.
5. Instruct the students to choose one large atoll and another that is smaller, for example, North Male' Atoll and Goidhoo Atoll.

Student Worksheet

Landscapes of atolls and islands in the Maldives

Instructions

1. Your teacher will share with you a map of the Maldives
2. In groups of 3-4 students, identify two different atolls and answer the following questions. Choose one large atoll and another that is smaller.
3. Answer the following questions based in these two atolls.

Do you know?

The equator passes through the southern part of the Maldives, specifically Gaafu Dhaalu Atoll and Fuvahmulah. Addu Atoll is the southern most atoll of the Maldives, and it lies just below the equator. This makes the Maldives one of the few countries in the world that has territory both north and south of the equator.

Questions

Questions	Name of one atoll studied Atoll 1:	Name of one atoll studied Atoll 2:................................
What is the shape of the atoll? Make a drawing		
Where are the islands located in this atoll?		
Estimate how many of these islands are inhabited.		
From each atoll, choose one inhabited island and describe its overall landscape (what is the percentage estimate of the green coverage vs buildings)		
How many openings/ channels occur in the outer reef rim in the atoll. (These openings are called *Kandu Olhi*).		
What is the significance of these '*Kandu Olhi*'		

Activity 2: How coral reefs are constructed, and how atolls and islands are formed in the Maldives

Duration

35 minutes (or can be given as an extended activity)

Target Grade

Can be used for any grade in Key Stage 3

Objectives of the activity

a. Explain what coral reefs are
b. Discuss how atolls are formed
c. Discuss how islands are formed

Teacher Instruction

1. Get the students to listen to the podcast: https://saruna.mnu.edu.mv/items/23016bab-0750-4ff6-8fbb-c0e66200a45e (The transcript of the podcast is in the Appendix – this even be read out loud in the classroom).
2. Distribute the Student Worksheet, and guide the students to answer the questions on it, while listening to the podcast.
3. Below are the answer.
    1) Understanding that over millions of years, sea levels haven't stayed the same but have fluctuated widely.
    2) A global ocean rising and falling dramatically, driven by huge ice sheets waxing and waning.
    3) It is the development of the volcanic plateau as foundation for the growth of the kilometre-thick coral reefal platform
    4) 55 million years
    5) A foam mattress adjusting to your weight
    6) Formation of the flat-topped banks
    7) Warmer and more stable climate
    8) The warm climate melted the ice causing the oceans to overflow and they filled the top of the volcanoes with sediment and water – sunken volcanoes capped with massive plateaus and filled with water. Note at the time of the volcanic plateau formation and the initial growth of the carbonate platform, in the Eocene (The Earth was essentially ice sheet free for 55 to 34 million years).
    9) The volcanic plateau would have subsided mostly because of the cooling of the volcanic plateau.)
    10) Time of upheaval

Activity 2: How Coral Reef are constructed, atoll and islands are formed in the Maldives (Cont..)

Teacher Instruction

11) As Earth started to get colder, ice caps formed, and the ocean water levels receded exposing the flat-topped banks to air. When it rains this carbonate base are dissolved in a process called karstification, consisting of central depressions surrounded by raised margins

12) Plateaus get flooded, exposed, sculpted, and these three steps happen multiple times over hundreds of thousands of years.

13) The ice gives away.

14) Answers

i. With each cycle, the coral grows fastest around the raised edges /margins of the karstified plateau, where along the raised margins there's more wave action, more nutrients, more of everything coral loves. So, the outer rim growing faster than the inner part, which eventually becomes a lagoon. It's like building an outer wall brick by brick, but here those bricks are layers of coral growing on top of each other.

15) The cyclic multiple floodings and exposures associated with ice sheet waxing and waning and related global high amplitude sea level fluctuations

16) Evidence of those ancient flooding and exposure events. The drill samples show these distinct layers of coral growth, each one from a time when that atoll was underwater and gaps in those karstified formations when the reefs are exposed.

Student Worksheet

Coral Reefs atoll and islands in the Maldives

Instructions

1. You will listen to the podcast on atolls and island formation
2. Listen to it carefully and answer the following questions.

Questions

1. What was some knowledge Darwin did not have about atoll formation when he published his model of atoll formation in 1842?
2. What does the presenter refer to as a 'yoyoing ocean'?
3. What is Phase1 of the atoll formation called?
4. How old was the oldest fossil researchers found in the Maldivian carbonate reefal platform/plateau?
5. What is the analogy the presenters use to describe how the Earth's crust adjusts to the weight of the sinking massive volcanoes?
6. What is Phase 2 of the atoll formation called?
7. What was the Earth's climate like in the mid-Pliocene?
8. What were some changes that happened to the oceans during Phase 2?
9. What is Phase 3 of the atoll formation called?
10. What happened in this phase when the Earth started to get colder?
11. Over time in a cyclic nature there are three major processes happening to the carbonate plateau. What are they?
12. What is Phase 2 called?
13. Complete the blanks in the below paragraph

With each cycle, the coral grows fastest around the .... (edges/middle) of the plateau, where there's more wave action, more................ (oxygen/nutrients), more of everything coral loves. So, the .... (inner/outer) rim grows faster than the inner part, which eventually becomes a .... (island/lagoon). It's like building a .... (wall/bridge) brick by brick, but here those bricks are layers of .... (coral/mountains) growing on top of each other.

14. What key processes did Darwin miss in his theory?
15. What do the evidence from the drilling samples show about the formation of the atolls and islands?

Do you know?

The Largest natural atoll in the Maldives includes the administrative atolls of North Thiladhunmathi, South Thiladhunmathi, North Miladhunmadulu and South Miladhunmadulu, while excluding Ihavandhippolhu and Maamakunudhoo. This vast atoll does not have a distinct name.

Activity 3 - Comparison of Maldives Islands with others

Duration
35 minutes (or can be given as an extended activity)

Target Grade
Can be used for any grade in Key Stage 3

Objectives of the activity
a. Compare the Maldives island nation with other island nations in the world
b. Identify similarities and differences in the geography between the Maldives and other island nations

Teacher Instruction
1. As preparation for the activity, ask students to find out information about Faro Island (Denmark) or Islands of Scotland and their geographies and bring to class.
2. Provide the students with a map of either Faro Island (Denmark) or Islands of Scotland.
3. Provide a map of any atoll of the Maldives.
4. Alternatively, the teacher can guide the answering and provide these photos on a PowerPoint to the students where you can use the Google Map Zoom features to do this.
5. Ask the students to compare these islands with islands on some atolls in the Maldives and answer the questions in their worksheet. Answers can also be made as discussions.

Student Worksheet

Comparison of Maldives Islands in Other Countries

Instructions

1. You will be provided with 2 maps, one from either Faro Island or Islands of Scotland and one from the Maldives.
2. In groups discuss the similarities and differences among these two islands.
3. Answer the following questions.

Questions

1. In groups of 3-4, use the zoom feature to explore the Satellite version of the map and zoom into a country such as Faroe Island (Denmark), Islands of Scotland.
2. Answer the following questions by comparing the features of the Maldives and that of the country you have chosen.
3. How are the island formations different and similar? (Look for reefs, vegetations, mountains and built-up areas, climate, latitudes and longitudes)
4. What do you think are some unique features of the Maldive Islands?

Do you know?

The Maldives and Mauritius are both island nations in the Indian Ocean, known for their beaches and reliance on tourism. While the Maldives consists of flat, low-lying coral islands, Mauritius is a volcanic island with mountains and higher elevations. Both nations face climate-related risks like rising sea levels, but their landscapes and geographies are quite different.

KEY STAGE 4

4

In Key Stage 4, the following Learning Outcomes from the National Curriculum have been identified as being relevant for the topic.

These outcomes are in the subject Marine Science in the topic Marine Ecology, and sub-topic, Tropical Coral Reef. They syllabus outcome is:

Candidates should be able to describe the Darwin Subsidence Theory of atoll formation.

Activity 1 - How coral reefs are constructed, and how atolls and islands are formed in the Maldives

Duration

This can be given as an extended activity or for 35 minutes.

Target Grade

Can be used for any grade in Key Stage 4

Objectives of the activity

a. Express a major timeline of events on Earth due to sea-level changes
b. Explain how coral reefs are formed and their origins
c. Explain how atolls and islands in the Maldives are formed

Teacher Instruction

1. Provide the students copies of the reading in the worksheet ask students to answer them.
2. The answers can be done in groups and as a long-term project.

Student Worksheet

Student Reading and questions for Key Stage 4 Activity

Instructions

1. Read the article carefully and answer the following questions.

Reading

ATOLL & ISLAND FORMATION IN THE MALDIVES

A. Introduction

The Maldives Archipelago consists of over 1,780 islands, with only 188 inhabited, and stretches across an 800 km-long north-south-oriented string of numerous small atolls (**Figure 1B**), located in the Central Equatorial Indian Ocean (**Figure 1A)**. Those small atolls, often referred to as faroes, are organized into 26 larger atolls, tens of km in diameter, which are only a tiny fraction of the submerged long lived 2-3 km-thick, huge Maldives carbonate reefal ridge, in extent and volume, also referred to platform. These large atolls form part of a submerged 2-3 kilometres thick carbonate platform,in brown in **Figure 1C**), sitting on a volcanic plateau (in yellow Color in **Figure 1C**), which has been drilled and studied extensively in wells like NMA-1, ARI-1, and ODP Hole715 (**Figures 1C and 3**). The bathymetry, of the Equatorial Central Indian Ocean which, when shown in 3D (see **Figure 2**), reveals the imposing structure of the Maldives' carbonate platform.

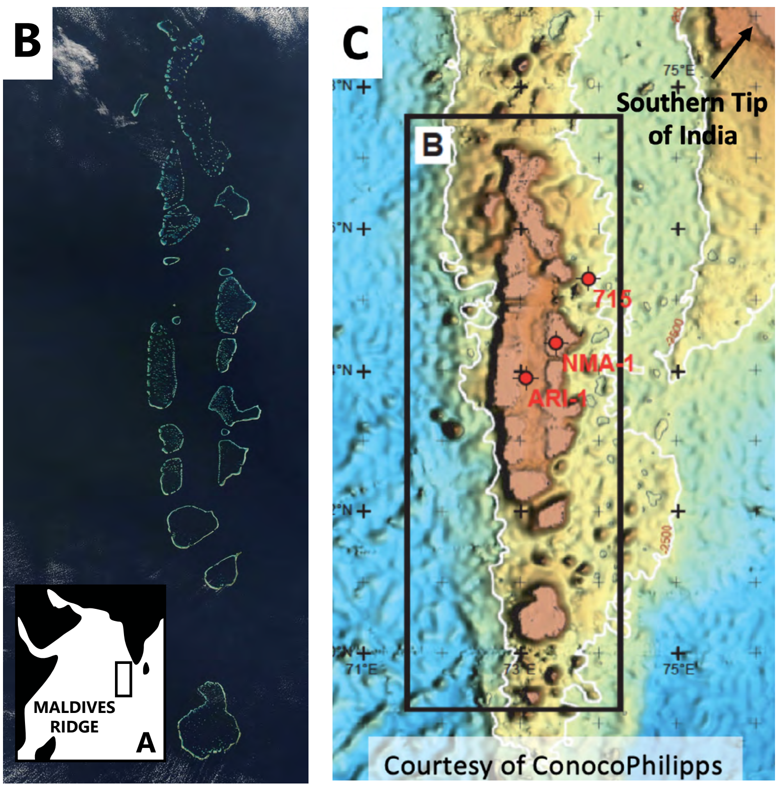


Figure 1 :
A. Location of the Maldives Archipelago, shown in B, in the Western Indian Ocean.
B. Satellite view of the Maldives Archipelago, consisting of 26 larges atolls.
C. Locations of the three wells (shown in red) that penetrated the 2-3km thick carbonate platform (shown in brown), established on the top of a volcanic plateau (shown in yellow), 57-55 million years ago

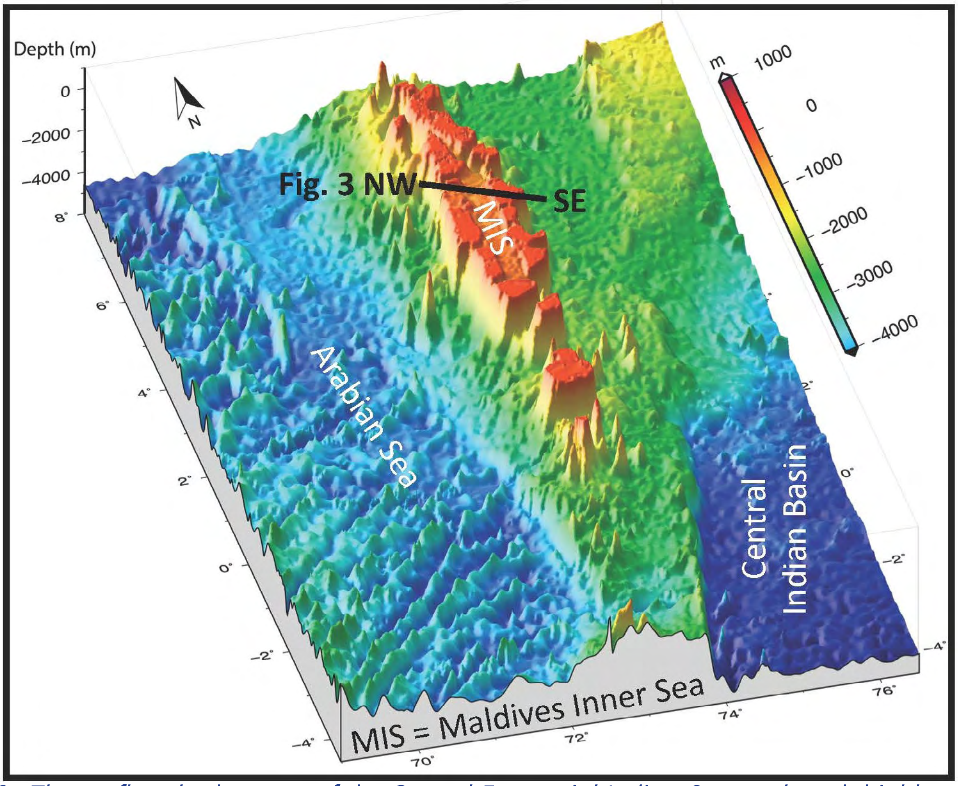


Figure 2 : The seafloor bathymetry of the Central Equatorial Indian Ocean, though highly vertically exaggerated, illustrates the imposing structure of the Maldives carbonate platform (modified from Kunnummal and Anand, 2019*). Note the location of the NW to SE cross section shown in Figure 3*

B. Long-Term Evolution of the Maldives Carbonate Platform

Research since the 1970s has focused on the northern Maldives and the Maldives Inner Sea, which sits between the two chains of atolls (see **Figure 2**). Hydrocarbon exploration via seismic surveys and drilling, and academic research have revealed a thick carbonate sedimentary succession dating back 55 million years, with significant drilling providing key insights into the region's geological past.

1. Historical Drilling and Research:
   - Wells like NMA-1, drilled by Elf Aquitaine, and ARI-1 by Shell, have penetrated 2-3 kilometres-thick carbonate successions and reached the underlying volcanic plateau. See **Figures 1C and 3** for the location of these wells.
   - In 1987, Ocean Drilling Program (ODP), an academic international collaboration, drilled sites 715 and 716 providing more data on the carbonate sedimentary and volcanic sequences. See **Figures 1C and 3** for the location of ODP Site 715 and **Figure 3** for Site 716. These studies have outlined the Maldivian carbonate platform's evolution from the Eocene to the present (or the last 57-55 million years), with volcanic activity playing an initial key role in its original formation (**Figure 3**). However, the volcanic substratum lost its influence in the Neogene and Quaternary or the last 23 million years, when global sea level fluctuations and regional environmental factors played the major roles in the evolution of the Maldives carbonate platform (**Figure 3**). The modern atolls, currently characteristic of the

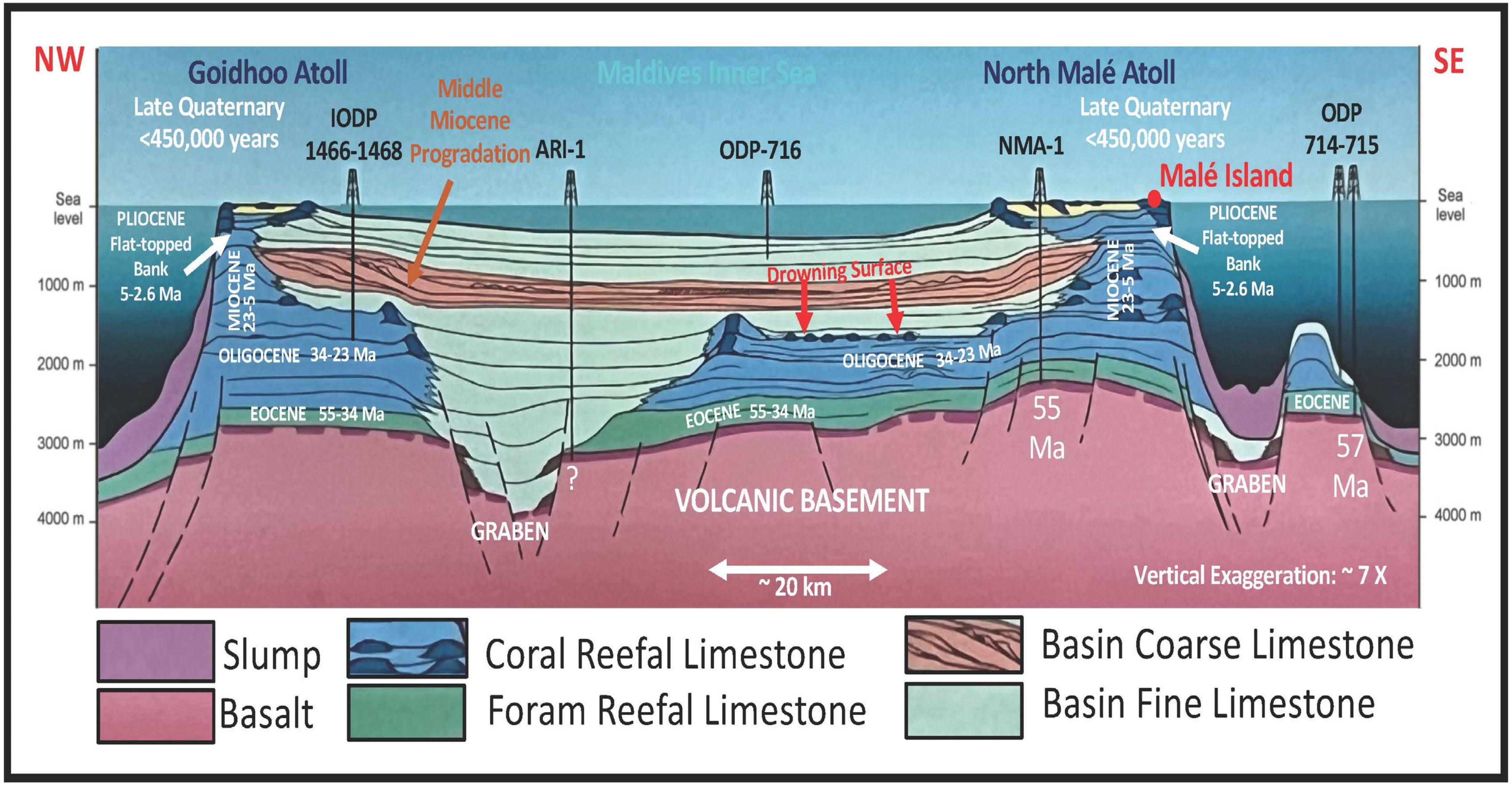


Figure 3 : Figure 3 : Northwest to southeast Cross-section through the Maldives archipelago (Note it is vertically exaggerated about 7X) illustrates well the 2-3 km thick Maldives carbonate (limestone) platform, established on a volcanic plateau that is 57 – 55 million years old. The modern atolls, eequivalent to the ultimate or about the last 450,000-year old phase of the long-term evolution of the Maldives carbonate platform, are clearly not connected to the volcanic basement (See the location of the NW/SE cross-section in Figure 2). Figure modified from Belopolsky and Droxler (2004)

Key Stage 4

4

archipelago, correspond to the ultimate phase, or about 450,000 years, of the 55 million years long evolution of the Maldives carbonate platform (**Figure 3**).

2. Major Geological Events:
    - The volcanic plateau formed as part of the Indian Plate, drifting over the Réunion hot spot about 55-57 million years ago.
    - The evolution of the carbonate platform saw periods of vertical growth during the Eocene and Oligocene, followed by drowning events, or also referred to as partial demise, especially at the Oligocene-Miocene transition (~23-20 million years ago). This partial drowning led to a significant decrease of the platform surface area, the formation of the Inner Sea, and the segmentation of the overall platform.
    - Recent Studies and Discoveries:

    Multibeam mapping, seismic data, and recent drilling by the International Ocean Discovery Program (IODP) expedition (e.g., Sites 1466-1468; see **Figure 3** for their locations) provided further insights into the carbonate platform's evolution during the last 23 million years (Neogene and Quaternary), confirming long-standing theories and revealing more about the complex interplay of climatic changes (in particular global sea level fluctuations) and environmental factors, superseding the initial influences of volcanic and tectonic factors during the Paleogene (55-23 million years) on the initial growth of the carbonate platform (**Figure 3**). The modern atolls, such as Goidhoo and Malé Atolls as shown in the cross-section in **Figure 3**, formed only as about the last 450,000 year phase of the 55 million years long evolution of the Maldives carbonate platform and, therefore, their origins have had clearly no direct connection with the volcanic Plateau itself (**Figure 3**).

C. Outdated Darwin's Subsidence Theory and Emergence of the Improved Antecedent Karst Theory to Explain the Modern Atoll Formation in the Maldives

1. Darwin's Subsidence Theory (1842):

Darwin proposed that atolls evolved from fringing and barrier reefs attached to subsiding volcanic edifices or islands, based on detailed British nautical charts from his voyage on the HMS Beagle (**Figure 4**). His **Subsidence Theory**, illustrated in his 1842 publication, was widely accepted through the years and has remained a staple in Earth Science education, even until recently.

2. Improved Antecedent Karst Theory Superseding Darwin's Subsidence Theory for the Maldives Atoll Formation:

Starting in the 1930s, the Antecedent Karst Theory emerged, suggesting a more complex process for the formation of atolls, mostly influenced by sea-level fluctuations during glacial/interglacial periods. This theory was developed by various researchers over decades (Hoffmeister, 1930; Kuenen, 1933; MacNeil 1954; Purdy, 1974) and was recently revisited and improved by a set of new scientific data (Droxler and Jorry, 2021), detailing three phases of atoll formation involving as shown in **Figure 4** right side: (A) flat-topped, not atoll, platform when sea level fluctuations were minimum, (B) cyclic subaerial emergence when sea level had fallen, resulting in bank top karstification during exposure, with the development of typical karstic morphologies with central depressions surrounded by raised margins, then (C) preferential coral growth along the bank raised margins during successive sea level submergence, forming the modern atolls as we know them today. **Figure 4** below shows the comparison between the **Subsidence** and **Antecedent Karst Theories.**

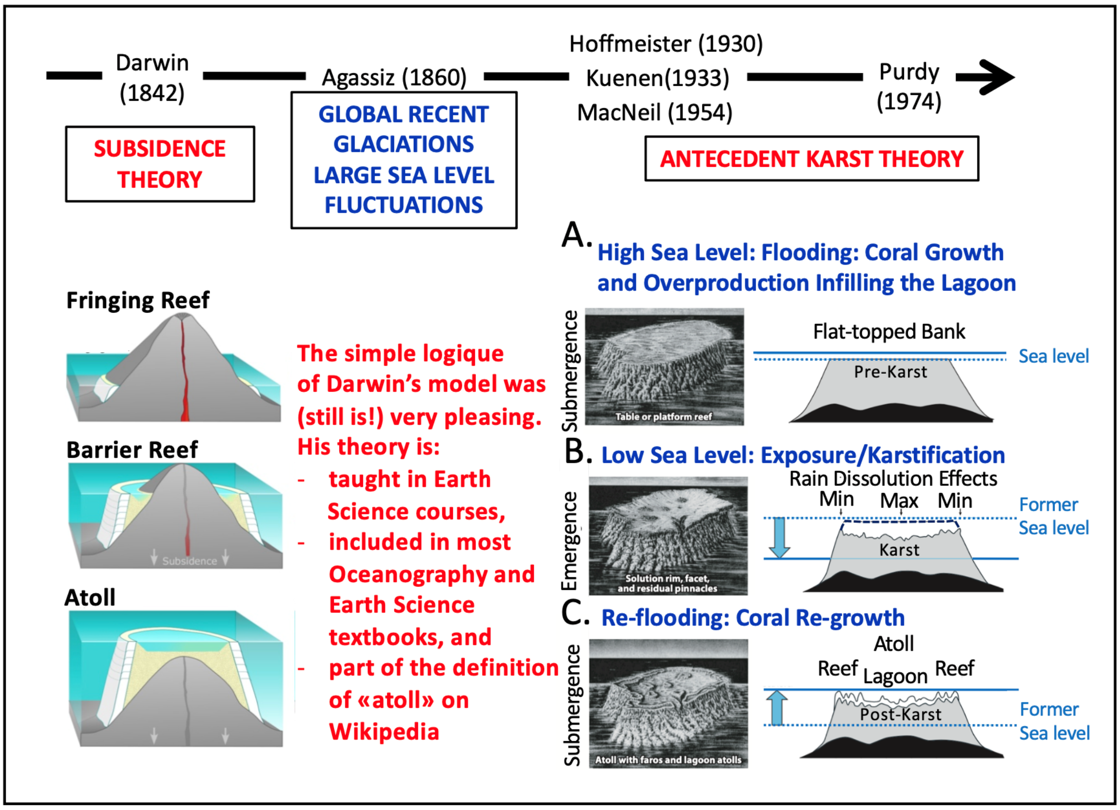


Figure 4 : Comparison of key theories on atoll formation, from the Subsidence Theory proposed by Darwin (1842) to the Antecedent Karst Theory initially propoposed by Hoffmeister (1930) and Kuenen (1933)

D. Sea Level Fluctuations in the Last 3.6 million years

Over the last 3.6 million years, the Earth's sea levels have fallen and risen multiple times in unison with the waxing and waning of large ice sheets, in particular in the Northern Hemisphere. During the warmer Pliocene era, prior to the growth of major ice sheets in the Northern Hemisphere, sea levels were higher than today, more stable, and fluctuated only by around 10-20 meters (**Figure 5**). About 2.6 million years ago, ice sheets began forming in the Northern Hemisphere, which marked the start of the Quaternary. This increased ice volume on Earth, in particular in the high latitudes of the Northern Hemisphere, caused sea levels to drop. Numerous major ice ages through the Quaternary caused sea levels to drop significantly and systematically (**Figure 5**), such as during the Last Glacial Maximum, 20,000 years ago, when levels of the global oceans were around 125-135 meters lower than today. **Figure 5** shows the overall global sea level fluctuation pattern in the last 3.6 million year.

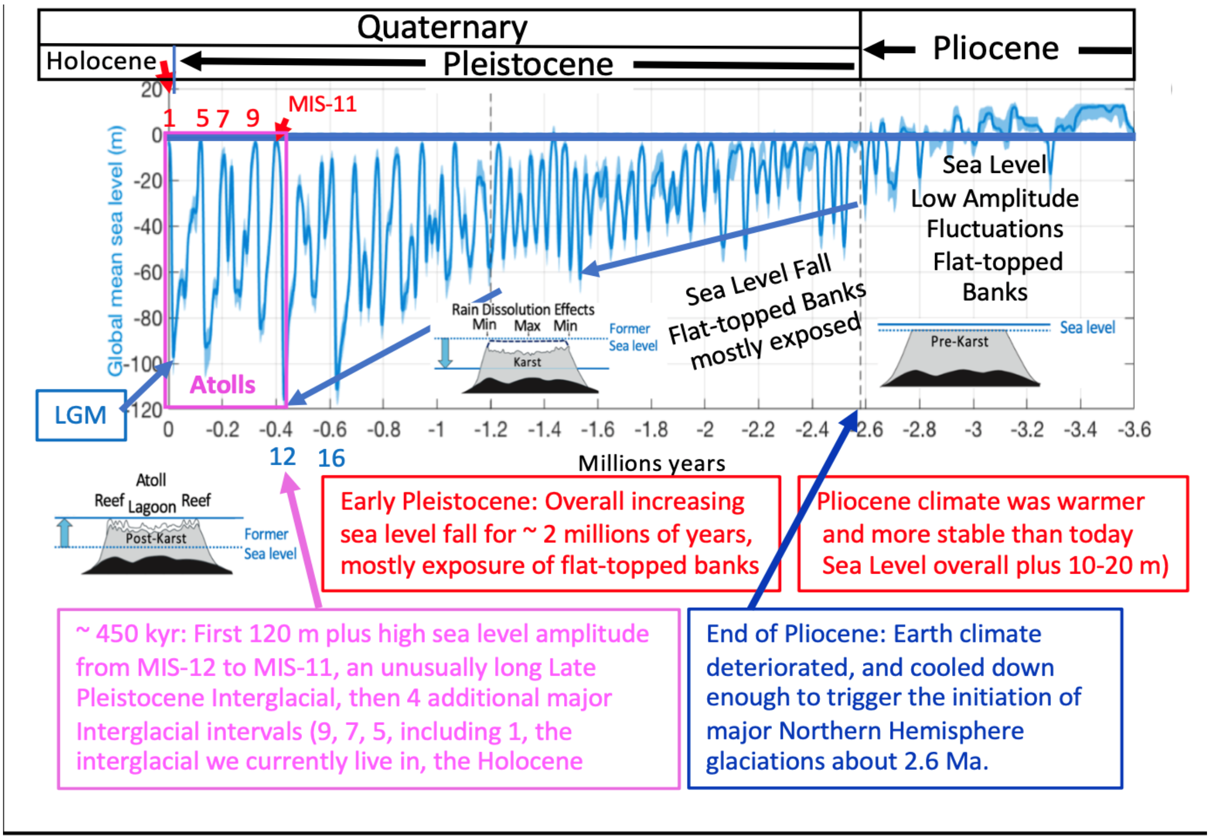


Figure 5 : Sea level fluctuations over the last 3.6 million years, framework to explain the modern atoll origin only in the past 450,000 years by the newly published Improved Antecedent Karst Theory (Droxler and Jorry, 2021)

E. Atoll Formation in the Maldives Explained by the Newly Published Improved Antecedent Karst Theory

As illustrated in **Figure 5**, based upon our knowledge of sea level fluctuations since the late Pliocene or the past 3.6 million years, atolls were initiated on late Pliocene flat-topped banks that formed during, a warm and climatically stable 80-kyr time interval during which sea level did not fluctuate. The exposure of these bank tops occurred during a ~2 million years long interval of ice-volume stepwise increase (from 2.6 million years to ~ 450,000 years). During this time interval, sea level continued to fall systematically, creating karstified bank-top morphologies with central depressions surrounded by raised margins (**Figure 5**).

The modern atolls originated only in the last 450,000 years, using, as substratum, the antecedent karst morphologies that formed during the previous 2 million years long interval (**Figure 5**). High-amplitude 125–135-m sea-level cycles flooded the karstified bank tops approximately five times, for about 20% of a full sea level cycle, when coral reefs re-established themselves, preferentially along the raised bank margins. The duration of each late Quaternary sea-level highstand, on the order of 11,000–29,000 years, was not long enough for atoll lagoons to be filled up with carbonates produced within the lagoon or imported detritus from carbonate produced on the atoll coral reef rim (Gischler et al., 2008; Klostermann & Gischler, 2015; Purdy & Gischler, 2005). During the late Quaternary (or the last 450,000 years), following a succession of relatively long exposure intervals that stimulated preferential chemical erosion through karst dissolution in the central part of the exposed bank top, the successive short-term bank-top reflooding, triggered coral growth preferentially along the raised bank margins and, therefore, enhanced the relief between reef margins and lagoon seafloors and created the templates for the modern atolls as we know them. This newly understanding on how modern atolls formed is referred to the Improved Antecedent Karst Theory, proposed by Droxler and Jorry, 2021). A recent article by Liu et al. (2022) using computer based numerical simulations confirm the Improved Antecedent Karst Theory.

F. Very Recent Formation of Modern Low Relief Coral Islands in the Maldives

The modern islands in the Maldives are very young in the geological context of the formation of atolls, with most of them being formed within the last 5000-2000 years. In his initial article, Kench et al. (2005) developed a model of reef-island evolution, based on detailed morpho-stratigraphic analysis, multiple cored boreholes, ground penetrating radar (or GPR) subsurface imaging, and radiometric dating of the recovered carbonates in three islands within South Maalhosmadulu Atoll (**Figure 6**). Once the different observed sedimentary units are placed in a chronological framework, it becomes clear that the islands did not start forming before ~5,000 years ago. Prior to it, until ~6,000 years ago, the faroes reefs (Agassiz, 1902) were growing vertically,

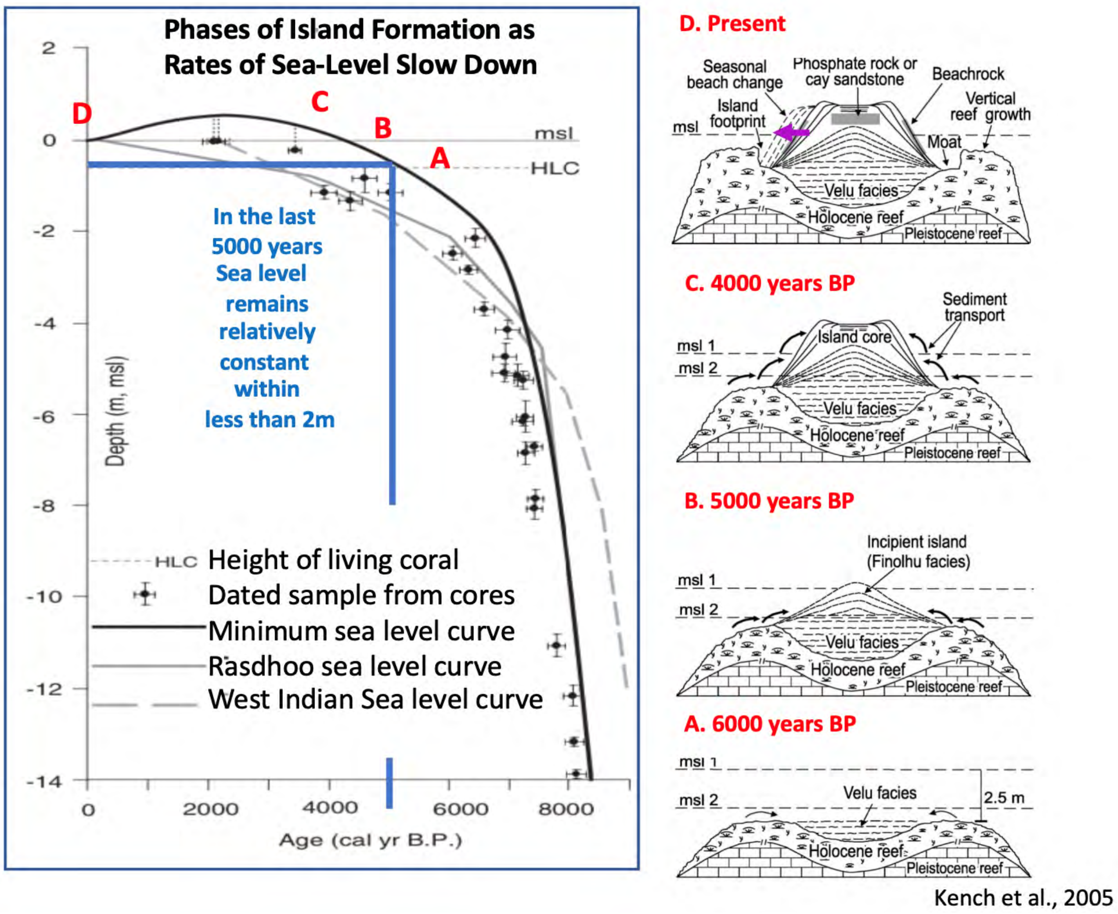


Figure 6 : Very recent formation (< 5000 years) of low relief coral islands, forming the Maldives Archipelago (Figure right side), in the context of the decreasing rates of sea level rise in the last 6000 years (Figure left side)

trying to keep up with rates of sea level rise as fast as 13 mm/year, barely infilling their small lagoons (see Velu Facies in **Figure 6A**). As shown in **Figures 6B, 6C, and 6D**, modern reef islands started forming only when the rates of sea level rise dramatically decreased from 5,000 years, when the rates of sea level rises systematically decreased to as low as 1.3 mm/year; sea level even stopped rising between 4,000 and 2,000 years, and, in the last 2,000 years, sea level even fell by 60 cm according to observations by Kench et al. (2005) (see **Figure 6** left part). The coral reefs in the past 4,000 years kept growing laterally instead of vertically, not having to keep up with sea level rise at high rates as prior to 5,000 years, and their overproduction of sediments created wide sand aprons (also called pavements) behind them, on top of which local emergent accumulations of reefal cobbles, pebbles, and sands formed the Maldives islands as we know them today (see **Figures 6B, 6C and 6D**).

Summary

The atolls in the Maldives Archipelago, as we see them today, correspond to the very ultimate, 450,000 years old, phase of the 55 million years-long evolution of a 2-3 kilometres thick carbonate platform. The volcanic basement and tectonic activity, while influential on the initial evolution of the Maldives carbonate platform, ceased their influence about 23 million years ago as sea level fluctuations, during the Neogene and Quaternary, took over as key drivers of the platform growth. In conclusion, the volcanic basement played no role in the modern atoll formation in the Maldives and, therefore, the Darwin **Subsidence Theory** has been superseded by the newly published **Improved Antecedent Karst Theory.**

Modern low relief coral Islands are very recent, less than 5,000 years old. They only formed during the very end of the last deglaciation when the rates of sea level rise decreased dramatically. The sea level stopped rising 4,000 years ago, or even fell in the last 2,000 years. These islands are formed by the emergent accumulations of reefal cobbles, pebbles, and sands, originating from the overproduction of the adjacent living coral reefs when those did not have to grow vertically to keep up with the high rates of sea level rise, as it was the case prior to 6,000 years ago.

Questions

1. Describe geological processes that contributed to the formation of the submerged 2-3 kilometres-thick 55 million years old carbonate platform in the Maldives. Use a timeline of events to support your answer.
2. Explain why the volcanic activity around 57-55 million years ago did not contribute to the formation of the Maldives' atolls.
3. What role did sea-level fluctuations over the past 450,000 years play in shaping the Maldives' atolls and, in the past 5,000 years, the low relief coral islands of the Maldives Archipelago?
4. Using examples that we have observe yourself, explain how the modern islands of the Maldives Archipelago adapted to rising sea levels over the last 50 years.

TEACHER NOTES

Background Reading

Recent Origin of the Maldives Atolls and its Archipelago Islands, Ultimate Growth Phases of the Maldives Carbonate Platform in the Equatorial Indian Ocean

André W. Droxler (PhD)

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in Marine Geology Oceanography
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Take Home Message:

1. The Maldives Archipelago is only the veneer of coral atolls, including numerous barely emergent small islands that dot the equatorial Indian Ocean, and consists only of the thin cover of a 55 million years old, 2-3 km-thick, large carbonate platform.

2. This thick and large carbonate platform was established on a slowly subsiding volcanic plateau formed when the part of the Indian plate, on which the Maldives Archipelago is rooted, translated on top of the hot spot of the Island of Réunion 55-57 million years ago.

3. The modern atolls in the Maldives were formed only in about the last 450,000 years, the most recent phase of the long term evolution of the Maldives carbonate platform. The origin of the atolls was fully disconnected from the volcanic plateau, but rather was influenced by the Quaternary large amplitude of sea level fluctuations related to the intensification of major cyclic glaciations, in particular in the Northern Hemisphere.

4. The islands of the Maldives Archipelago only formed in the last 5,000-4,000 years, as the results of the local emergent accumulations of reefal cobbles, pebbles, and sands behind the active coral reefs, when the rates of sea level rise slowed down dramatically and even came into a standstill at the very end of the last deglaciation, following the Last Glacial Maximum, 20,000 years ago, when sea level had dropped down to 125-135 m below modern sea level.

A. INTRODUCTION

The Maldives Archipelago, located in the Equatorial Indian Ocean southwest of the southern tip of India (**Figure 1A**), consists of a series of more than 1780 Islands, among them only 188 are inhabited, and is established on 800-km long north-south oriented strings of numerous small atolls (**Figure 1B**). Those small atolls, often referred to as faroes, are organized into 26 larger atolls, tens of km in diameter, and are only a tiny fraction of the submerged long lived 2-3 km-thick, huge Maldives carbonate reefal ridge, in extent and volume, also referred to platform (**Figures 1C and 1D**). The volcanic plateau, (in light greenish orange), on top of which the carbonate platform was established and grew (in brown), has been sampled successfully in three deep wells (shown in red), two industrial wells NMA-1 and ARI-1, and Ocean Drilling Program (ODP) Hole 715 (**Figure 1C**). Once the bathymetry of the ridge is shown in 3D, when the water has been removed (**Figure 1D**), the 2.5 km-high carbonate reefal platform of the Maldives (in red-orange-yellow), sitting on a volcanic plateau in water depth range averaging 2500 m (in green), is rather imposing!

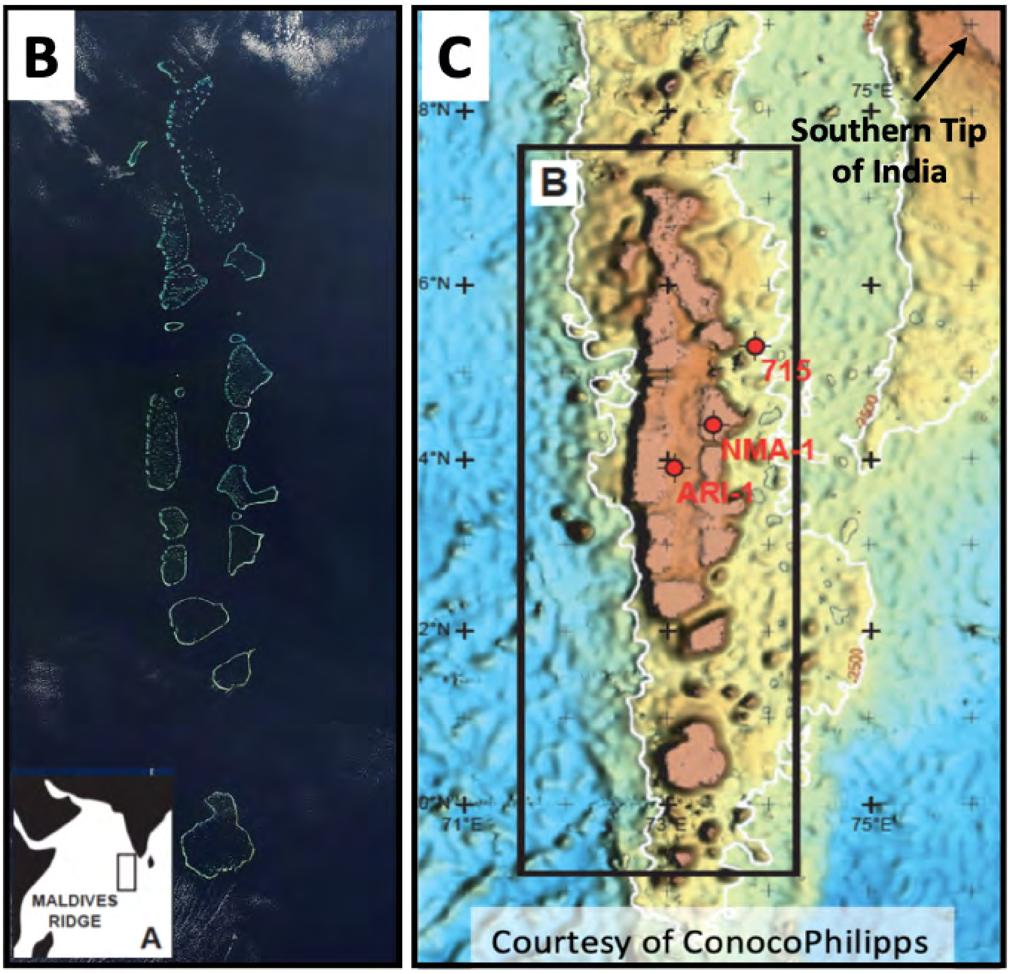

Figure 1 : A. The Maldives Archipelago in the equatorial Indian Ocean.

B. Satellite Image showing the numerous large atolls in the Maldives, stretching on eight degrees of latitude.

C. Bathymetry map showing the carbonate platform extent in brown and the underlying volcanic plateau in light greenish orange. The three drill sites in which the top of the volcanic plateau was recovered are shown in red.

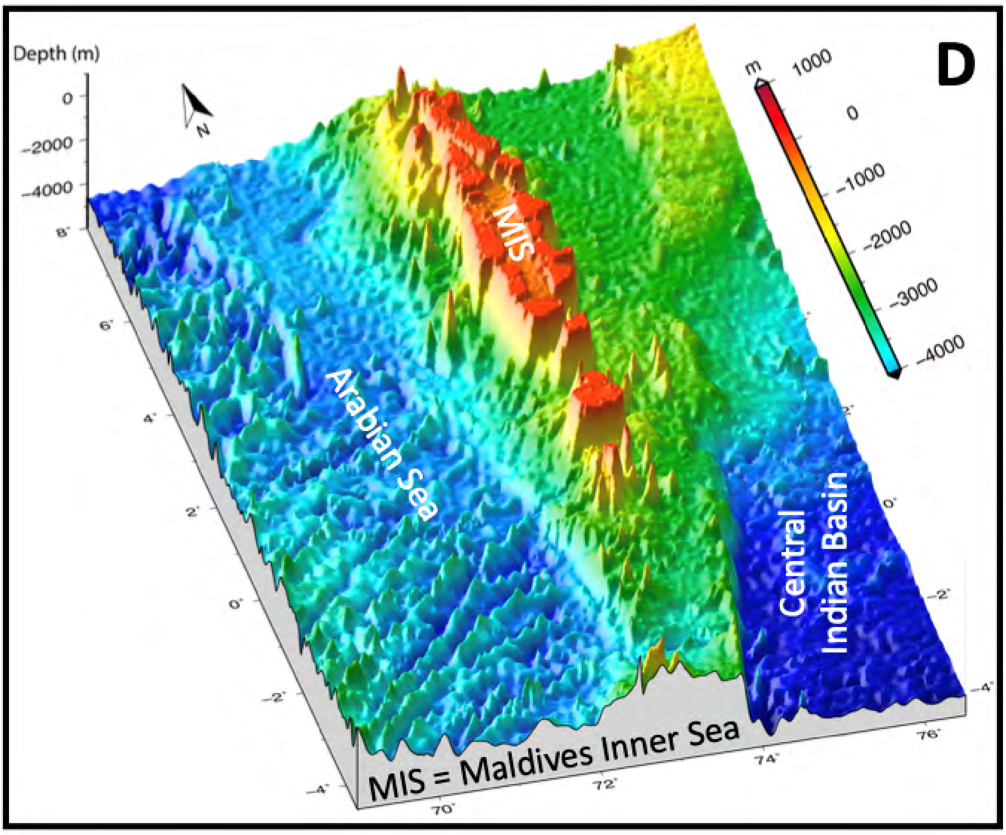

Figure 1D. 3D model of the carbonate platform (in red, orange, and yellow) and the underlying volcanic plateau in green. (Kunnummal and Anand, 2019)

B. LONG TERM EVOLUTION OF THE MALDIVES CARBONATE PLATFORM

Fortunately, extensive research has been done since the early 1970s in the northern part of the Maldives Archipelago, either on the atolls themselves or within the Inner Sea, located in between the double chains of atolls (**Figures 1D, 2A, 2B and 2C**). In the central part of the archipelago, the large atolls form two parallel, relatively continuous north–south chains, surrounding an internal basin, the Inner Sea, with water depths of up to 600 m (**Figures 1D, 2A, 2B, and 2C**). However when one looks carefully, the western chain of atolls is interrupted on the northwest margin of the Inner Sea, between Ari/Rasdhoo atolls in the south and Goidhoo atoll in the north, by three large submerged flat-topped banks under ~235-250 m in water depths (shown in light blue in **Figure 2A**). To illustrate the long-lived and thick Maldives carbonate platform, a NW to SE schematic cross section (located in **Figure 2A**), along which existing wells and drill sites are projected, is shown in **Figure 2C**.

Hydrocarbon exploration in the Maldives, initiated by Elf Aquitaine in the early 1970s, has provided some excellent data sets that were made available for academic research. Several two-dimensional seismic surveys were acquired both in the Inner Sea and in the atoll lagoons. In 1976, Elf Aquitaine drilled an exploration well, NMA-1, in the southwest part of the North Malé Atoll lagoon, northwest of the island of Malé (**Figures 1C, 2A, and 2C**). The well penetrated a 2,106-m-thick carbonate sedimentary succession, laid down from the Eocene (55 million years) to recent times, before drilling into 116 m of weathered Paleocene basalts, corresponding to the top of the volcanic basement, dated at 57-55 million years old by the argon–argon method (Duncan & Hargraves 1990) (**Figure 2C**). The interpretation of these early data sets by Aubert & Droxler (1992, 1996) and Purdy & Bertram (1993) provided the first framework for the overall evolution of the Maldivian carbonate platform. Moreover, in the late 1980s, Royal Dutch Shell acquired a relatively dense (1–2-km spacing), 6,000-km regular seismic grid spanning the entire Inner Sea and covering an area of 275 km by 50 km. Shell drilled the ARI-1 well at a water depth of 300 m in the Inner Sea, southeast of Ari Atoll (**Figures 1C, 2A, and 2C**). This well reached the volcanic plateau top at approximately 3.3 km (Aubert & Droxler 1996; Belopolsky & Droxler 2003, 2004). Because the basalts in ARI-1 were highly altered, radiometric age dating of the basalt was not successful.

In 1987, Ocean Drilling Program (ODP) drilled three sites in the Maldives, located in **Figures 1C, 2A, and 2C**. ODP Site 716 was drilled at a water depth of 500 m in the northern part of the Inner Sea; this site recovered 262 m of oozes (carbonate mud) and chalks from the Pleistocene to the late Miocene (Backman & Duncan 1988a) and is a good complement to the ARI-1 well drilled farther south in the Inner Sea, in which the top 250 m of the sedimentary sequence was not recovered. Site 716 fully recovered a

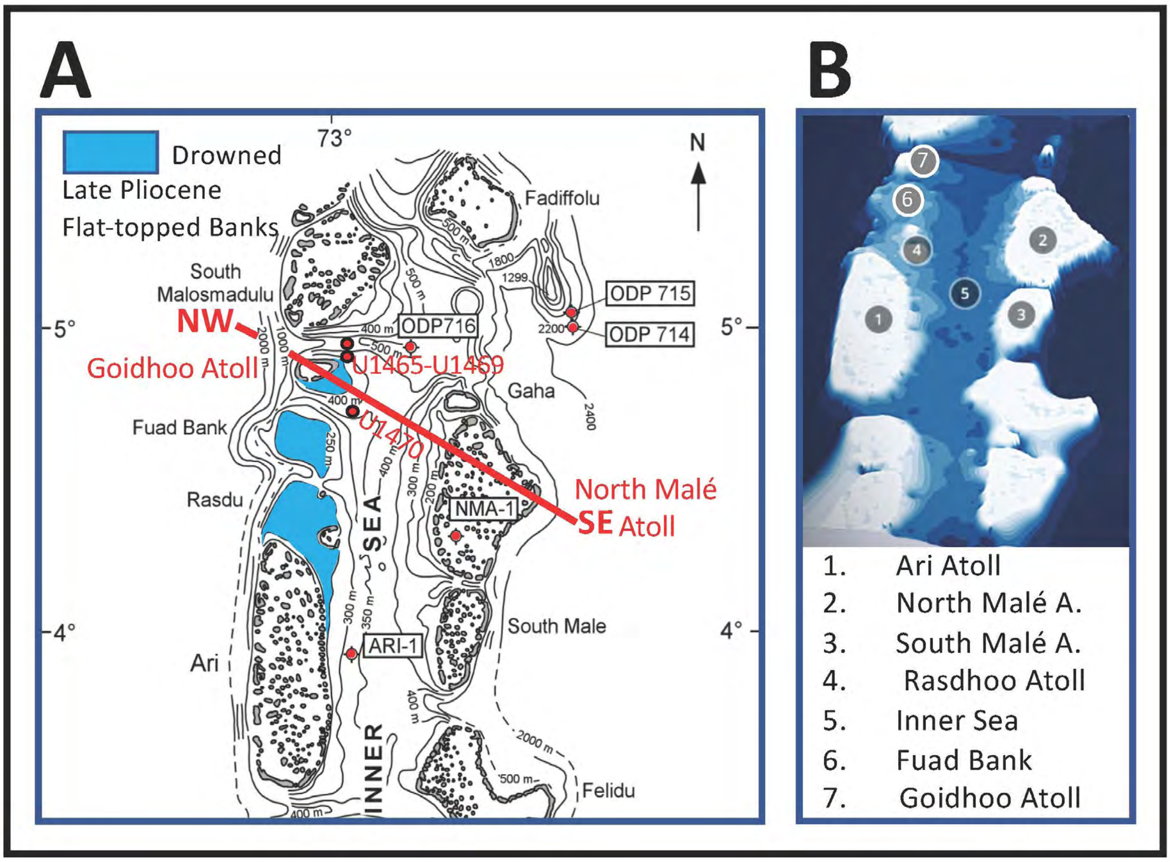

Figure 2 :

A. Bathymetric map showing the double chains of atolls surrounding the Inner Sea in the central part of the Maldives Archipelago. Red line shows the location of the NW/SE cross section in C.

B. 3D model of the northern part of the Maldives Archipelago, by Dr. Andreas Paul available to be visualize on Sketchfab: https://sketchfab.com/3d-models/bathymetric-model-of-the-maldives-5d6e55c2cc4d482c86f8d1c92a88a2e8

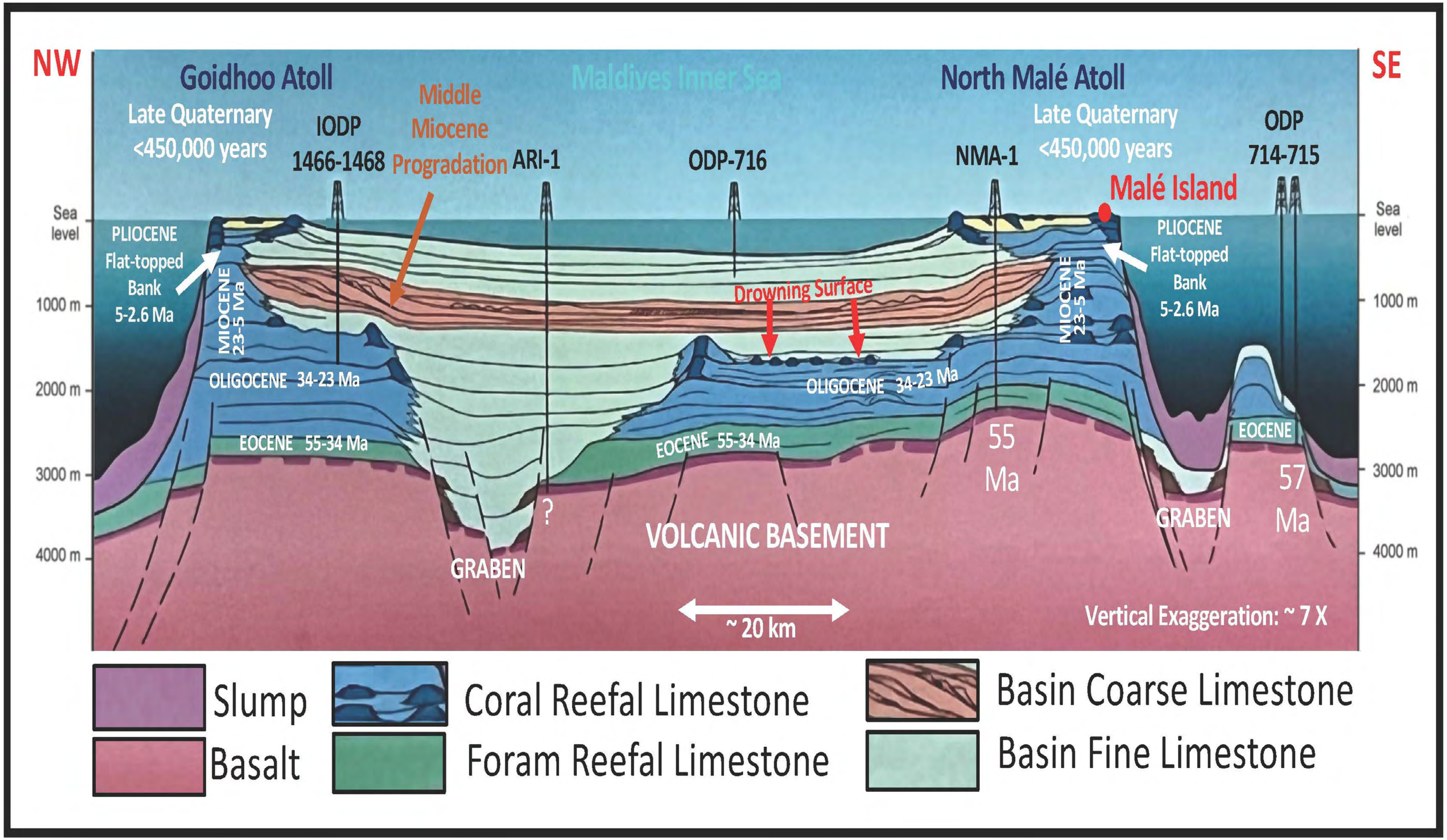

Figure 2C. Modified figure from Belopolsky and Droxler (2004). Cross section (its location shown in A) showing the 2-3 km thick, 55 million year old and younger, Maldives carbonate platform, initially established on a volcanic plateau that is 57 – 55 million years old. The modern atolls, as Goidhoo and Malé atolls in C, corresponding to the ultimate or the last 450,000-year-phase of the long-term 55 million year evolution of the Maldives carbonate platform, are clearly disconnected to the volcanic basement.

continuous sedimentary section that covers the last 7 million years (Backman & Duncan 1988b) and helps tying the well stratigraphy to the main reflectors identified in the Elf and Shell seismic data sets (Aubert & Droxler 1996; Belopolsky & Droxler 2003, 2004). ODP Site 715 was drilled at the toe of the Maldivian carbonate platform escarpment in 2,262 m of water depth, approximately 40 km southwest of Fadhippolhu Atoll (**Figures 1C, 2A, and 2C**). The basalt–shallow-water limestone transition was recovered at Site 715, 210 m below the seafloor, or 2,472 m below sea level. The basalt was dated by the argon–argon method at 57 million years and was recognized to have been altered while exposed on land (Duncan & Hargraves 1990). The oldest carbonate overlying the basalt was dated by biostratigraphy as late early Eocene in age or 55 million years old (Nicora & Premoli Silva 1990). The 57-55 million years old volcanic plateau underlying the thick Maldives carbonate platform, growing since the Eocene, formed as part of the Indian Plate, on which the Maldives is located, while drifting on top of the volcanic hot spot of the Island of Réunion.

Aubert & Droxler (1992, 1996), Purdy & Bertram (1993), and Belopolsky & Droxler (2003, 2004) documented the long-term evolution of the Maldivian carbonate platform over the past 55–57 million years (**Figure 2C**). **Figure 3** illustrates the time-structure map of the volcanic basement top (uppermost Paleocene, about 57-55 million years in age, Belopolsky & Droxler, 2003-2004). The morphology of the volcanic basement top, imaged below the Maldives Inner Sea and viewed from above, clearly shows a relatively flat basement top, dissected by two well-developed relatively north-northeast and south-southwest steeply sided and deep valleys, referred to as grabens. "Cold" colors

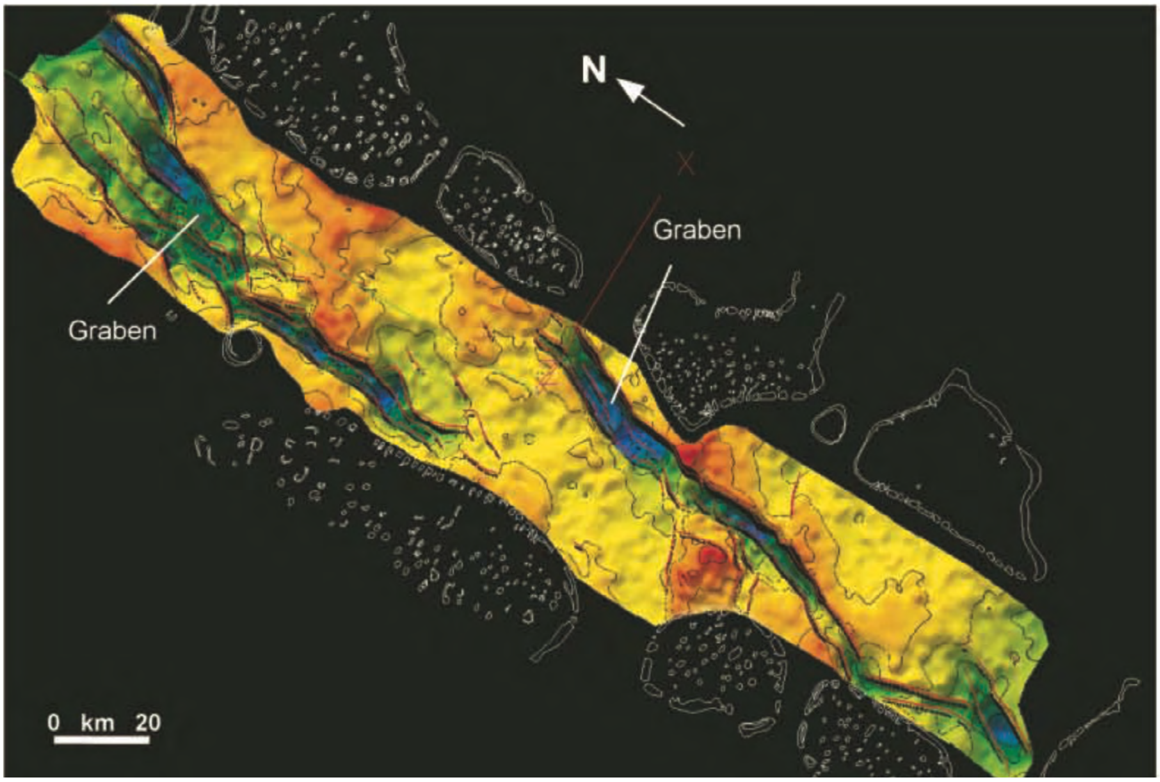

Figure 3 : Morphology of the volcanic basement top, imaged below the Maldives Inner Sea and viewed from above (see text for detailed information)

(blue and green) represent topographically low areas or deep grabens; "hot" colors (red and yellow) represent topographically high relatively flat areas.
The Eocene carbonate banks established themselves on topographically relative flat high areas of the faulted volcanic plateau, when it subsided below sea level (**Figures 2C and 3**). Tectonic movements along the graben faults continued until the late Oligocene or about 23 million years (**Figure 2C**). The 55-million years evolution of the 2 to 3-km thick carbonate platform is quite complex, with a long interval of vertical growth during the Eocene and Oligocene, followed by an interval of massive drowning at the end of the Oligocene and the beginning of the early Miocene, resulting in the partial demise of the Eocene/Oligocene platform (**Figure 2C**). Recent data sets (multibeam maps, multichannel high-resolution seismic data using a wide range of high-frequency energy sources, and coring) were acquired during the 2007 R/V Meteor research cruise (Betzler et al., 2009; Fürstenau et al., 2010; Lüdmann et al., 2013, 2018). International Ocean Discovery Program (IODP) Expedition 359 recovered in 2015 two transects of drill sites directly north and south of Goidhoo Atoll (Betzler et al., 2016a, 2017). As already observed in NMA-1 well where a very early Miocene interval is characterized by laminated black calcareous shales (Aubert & Droxler, 1996), IODP Expedition 359 drilled twice, at Sites 1466-1468, (see their location in Figure 2C), a 100-m-thick sequence of interbedded organic-rich sediment and pelagic carbonates that were deposited in the late Oligocene and early Miocene when the proto–Inner Sea basin became anoxic devoid of oxygen (Swart et al. 2019), which would explain the massive drowning of the Oligocene mega platform at the Oligocene/Miocene transition around 23-20 million years ago (**Figure 2C**).

In summary, in the first 25 million years of the Maldives platform, the volcanic basement morphology and tectonic faulting remained the two main factors controlling the distribution of shallow carbonate banks through the very first part of the early Miocene, after which their influence became muted. Variations of the volcanic subsidence influenced the growth of the Eocene Platform with minimum impact of sea level fluctuations, at a time of greenhouse conditions when no major ice sheets occurred on Earth. With the onset of glaciations in Antarctica at the beginning of the Oligocene (34 million years ago), sea level fluctuations also influenced the growth phases of the Oligocene Maldives carbonate platform and increased their impact during the Neogene, and even more during the Quaternary, since the onset of major glaciations in the northern hemisphere, 2.6 million years ago (Miller et al. 2005, 2020).

Following the major partial drowning of the Oligocene mega-platform top, the platform evolved into a giant atoll-like structure in which both ocean-facing margins continued to grow vertically, enclosing a deep basin, currently the Inner Sea, and evolved into the double chains of atolls characteristic of the Maldives Archipelago as we know it today (**Figure 2C**). During the early Miocene, the shallow carbonate system, which is much more restricted in surface areas relative to the underlying Oligocene platform, continued to grow in a vertically restricted way to both ocean margins of the Maldivian carbonate platform and then became partially exposed during the late middle Miocene at approximately 13 Ma (Betzler et al. 2016a, 2017). Three sites from Expedition 359—U1465, U1469, and U1470 reached the top or drilled the Miocene flat-topped platform (**Figure 2C**). As interpreted in earlier studies by Aubert & Droxler (1992, 1996) and Belopolsky & Droxler (2003, 2004), the IODP drilling results confirmed that Ghoidoo Atoll is the remnant, through segmentation and back stepping, of a much larger flat-topped platform that partially drowned in the middle Miocene (approximately 13 Ma) at depths of 575 m and 650 m below modern sea level (Betzler et al., 2016a, Lüdmann et al., 2018).

Strong currents, related to the abrupt onset of the monsoonal regime about 13 million years ago (Betzler et al. 2016b), still highly influencing the Maldives Archipelago today (Betzler et al., 2009); Owen et al., 2011), triggered the initial segmentation of the late middle Miocene flat-topped platform. In the late middle Miocene and late Miocene, the carbonate system grew laterally only through bidirectional progradations that partially filled the Inner Sea, illustrated by the orange/brown unit, referred to "Basin Coarse Limestone" in **Figure 2C** (Aubert & Droxler 1996; Belopolsky & Droxler 2003, 2004b; Lüdmann et al., 2013, 2018), which since IODP Expedition 359 have been interpreted as thick carbonate delta drifts (Betzler et al., 2016a; Lüdmann et al., 2013, 2018).

Full reflooding of the external margins of the carbonate platform, which became segmented in the middle Miocene, occurred in the late Miocene and Pliocene (**Figure 2C**). The segmented platforms that remained along both the western and eastern margins of the Maldivian carbonate system evolved into systematic and characteristic segmented flat-topped banks (**Figure 2C**), such as the late Pliocene partially drowned banks in the northern part of Ari Atoll and southeastern part of Goidhoo Atoll (in light blue in **Figure 2A**), in addition to contemporaneous flat-topped banks imaged under North and South Malé Atolls in seismic lines (Aubert & Droxler 1996, Droxler & Jorry, 2021). Fuad Bank (in light blue in **Figure 2A**) corresponds to a fully drowned late Pliocene carbonate flat-topped platform (**Figures 2A and 2C**) on top of which an atoll could not develop, probably for some inimical environmental reasons. In conclusions, the modern atolls in the Maldives have grown on those late Pliocene flat-topped banks. Consequently, modern atoll occurrence and development are clearly unrelated to the volcanic basement and correspond only to the final phase of the late Neogene and Quaternary evolution of the Maldivian carbonate platform (**Figures 2C)**. In summary and illustrated in **Figures 2C**, Goidhoo and North Malé Atolls correspond only to the most recent phase (less than 450,000 years) of the 55-Myr evolution of the Maldivian carbonate mega-platform.

C. CHALLENGING THE DARWIN SUBSIDENCE THEORY TO EXPLAIN THE ORIGIN OF THE MALDIVES ATOLLS

In 1842, Darwin explained atolls as the ultimate evolution phase of the initial fringing and subsequent barrier reefs attached to subsiding volcanic islands. During his five-year voyage around the world on the HMS Beagle (1831–1836), Darwin had access to multiple British nautical charts on which coral reefs —significant navigation hazards—

had been mapped in great details and with surprisingly high accuracy. Based on these charts, Darwin compiled the first world map of coral reef distribution, which was included in his 1842 publication and was similarly astonishing in its accuracy. On this map, he identified three types of reefs: fringing reefs, which are directly attached to volcanic islands; barrier reefs, which are separated from volcanic islands by lagoons; and ring reefs, which enclose only a lagoon, defined as atolls. The term atoll comes from the word atholhu in the Dhivehi language spoken in the Maldives, meaning the palm of the hand; its first recorded use in English was as "atollon," in 1625 (Wikipedia 2020). Despite the limited data at hand, Darwin linked those three types of reefs together in an evolutionary model that elegantly explained their interrelated origin through the slow and steady subsidence of the volcanic edifices (left side of **Figure 4A**). He initially presented his atoll observations and his model of how they formed in a well-received lecture given at the Geological Society of London on May 31, 1837, and in his subsequent 1842 publication, illustrated with multiple exquisite sketches. The simple

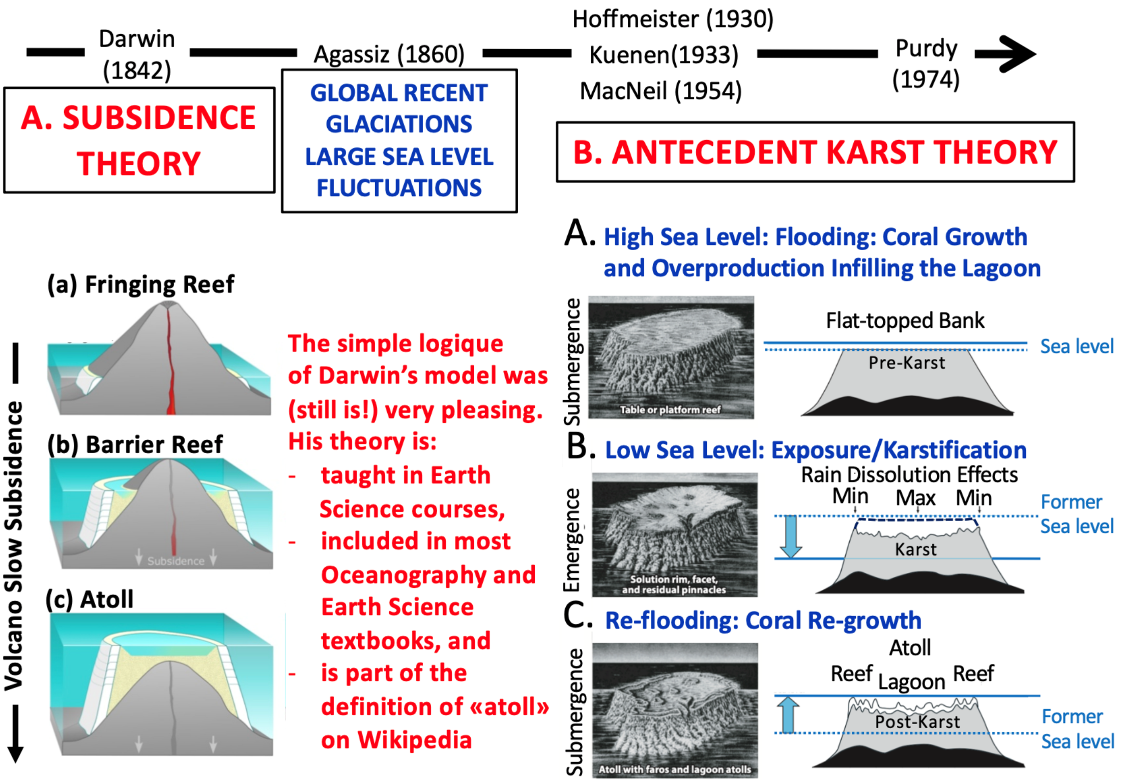

Figure 4 : Left side of Figure- Darwin's 1842 Subsidence Theory for the atoll formation includes initially (a) a fringing reef attached to a volcanic edifice, then (b) the fringing reef becomes a barrier reef, and (c) ultimately an atoll through the slow subsidence of the volcanic edifice. (see text for detailed explanations). Right side of Figure - The alternative Antecedent Karst Theory, initially proposed in the early nineteen thirties, explains that flat-topped carbonate banks formed when sea level remain constant for a long period of time (A). Then, when sea level falls, dissolution of those flat-topped banks occurs preferentially in their interior when they are exposed, creating a central depression surrounded by raised margins (B). Ultimately, when these margins are re-flooded during a sea level rise, coral growth preferentially occurs on these elevated margins and produce an atoll (C) (see text for detailed explanations)

logic of his model was (and still is!) very pleasing and, therefore, has been generally accepted since its initial publication. Darwin's Subsidence Theory is still commonly taught in Earth Science courses and included in most Oceanography and Earth Science textbooks (left side of **Figure 4A**).

As an alternative to Darwin's Subsidence Theory and once the concept of the recent occurrence of glaciations suggested by Agassiz (1860) became commonly accepted, several authors, starting in the 1930s, proposed the Antecedent Karst Theory. Based on our initial understanding of late Quaternary sea-level fluctuations, this more realistic model was first developed by Hoffmeister (1930) and Kuenen (1933, 1954), improved by Hoffmeister & Ladd (1945, 1944), clearly and comprehensively explained (and nicely illustrated) by MacNeil (1954) (right side of **Figure 4**), and later improved once more by Purdy (1974) (right side of **Figure 4**), Purdy & Winterer (2001, 2006), Purdy & Gischler (2005), and Schlager & Purkis (2013).

The antecedent karst theory includes three phases (right side of **Figure 4**). (a) The first phase is characterized by active neritic carbonate production with low amplitude sea level fluctuations, starting as a platform reef and/or an initial atoll with an infilled lagoon by the reefal overproduction. This phase is illustrated as a flat-topped bank within the photic zone (**Figure 4 subpannel A**). (b) In the second phase, the glacial lowering of sea level is larger than subsidence, resulting in the subaerial emergence of the flat-topped bank (**Figure 4 subpannel B**). This phase is illustrated as exposure and karstification of the bank/reef top with maximum dissolution in the center of the bank and minimum dissolution along its margins, creating a karstic central depression surrounded by raised solution margin (**Figure 4 subpannel B**). (c) Finally, the third phase is submergence (**Figure 4 subpannel C**). This phase is illustrated as a reflooding of the karstic topography by a deglacial rise of sea level in phase with subsidence, with preferential coral-reef growth on the karstic external raised margins, where reef growth rates are optimum relative to the interior lagoons, resulting in atolls. Reef passes across the atoll rim are inherited from glacial lowstand drainage breaches through the solution karstic margins.

D. SEA LEVEL FLUCTUATIONS SINCE THE LATE PLIOCENE OR THE LAST 3.6 MILLIONS OF YEARS

Since the 1930's and in particular in the past three decades, scientists have developed and greatly improved our knowledge, and have established, with global reproducibility, the pattern of ice-volume variations through time at different time scales and resolutions and, therefore, we have currently a much better understanding of the Plio-Quaternary sea-level fluctuations over roughly the last 3.6 Myr (i.e., Grant et al. 2019; Lisiecki & Raymo 2005; Miller et al. 2005, 2020; Spratt & Lisiecki 2016) (**Figure 5**).

The Pliocene climate was warmer and more stable than today's climate; sea level overall was fluctuating by 10-20 m above and below the modern level (Miller et al. 2020) (**Figure 5**), with very-low-amplitude cycles, from the early to late Pliocene (Draut et al.

2003 and references therein). In the late Pliocene, a 80-kyr-long (or even longer) warm interglacial interval from 3.27 and 3.19 Myr ago (Ma), often referred to as the Mid-Pliocene Warm Period (MPWP) (Draut et al. 2003), displays one of the last Pliocene very-low-amplitude cycles.

The climate deteriorated at the very end of the Pliocene and cooled enough to trigger the initiation of major Northern Hemisphere glaciations at approximately 2.6 million years ago, which marks the beginning of the Quaternary and Pleistocene, the Quaternary consisting of Pleistocene and Holocene. During the Early Pleistocene, the climate cooled with increasing intensity, the ice volume grew larger, and sea levels, therefore, fell accordingly. During this time interval, the climate was characterized by interglacial/glacial sea level cycles with amplitudes in the order of 40–50 m (**Figure 5**). At the beginning of the Brunhes (or about 800,000 years ago), the climate continued to deteriorate, driving high-amplitude interglacial/glacial cycles. Ice volume reached two initial maxima for the Plio-Quaternary, during two major glacial intervals at about 620,000 (MIS 16) and 450,000 years ago (MIS12), roughly equivalent to the observed ice volume during the Last Glacial Maximum (LGM, 20,000 years ago), when sea levels globally fell to 125–135 m below the modern level (Yokoyama et al. 2018) (**Figure 5**). An unusually warm and long interglacial, referred to as MIS-11, centered

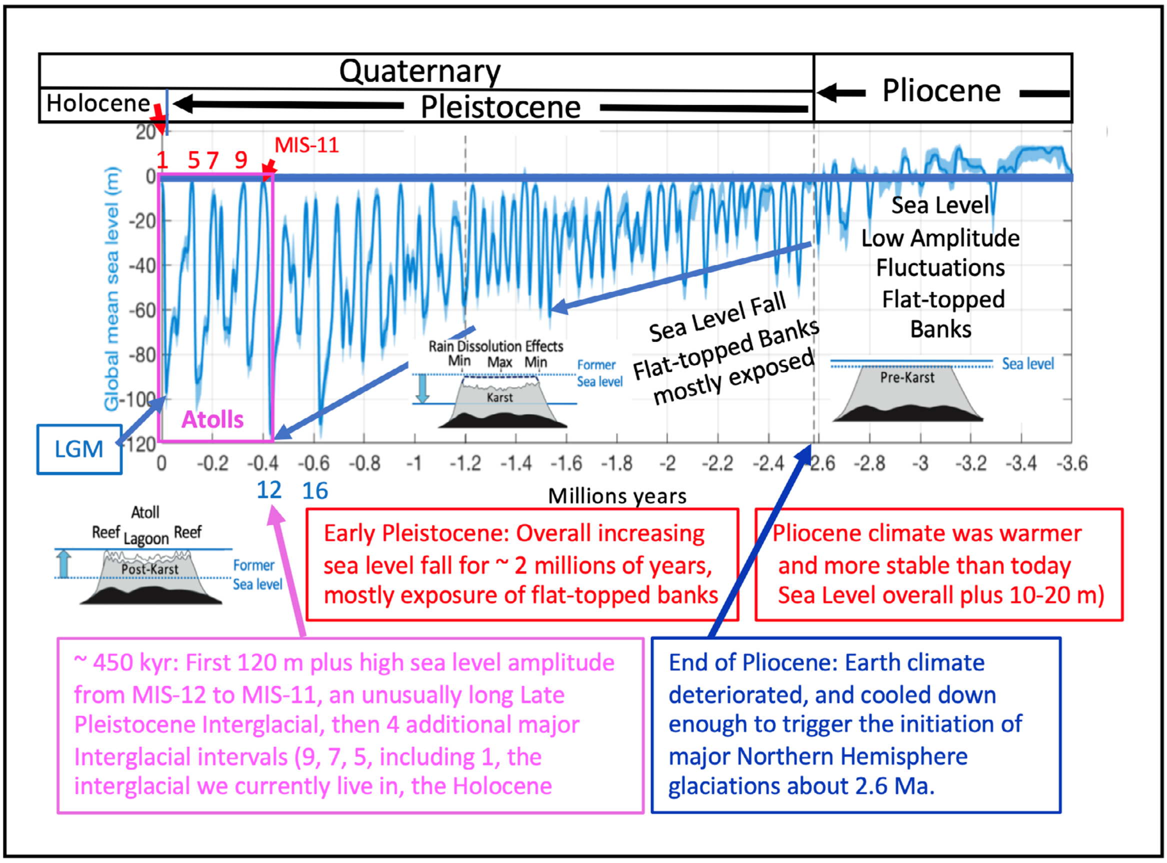

Figure 5 : The Improved Antecedent Karst Theory (Droxler and Jorry, 2011) explaining the recent formation of modern atolls (see right side of Figure 4) in the context of sea-level fluctuations over the past 3.6 million years (Miller, 2020) (see text for more detailed information in section E).

at about 400,000 years before present **(Figure 5)**, was characterized by high sea levels estimated at approximately 6–13 m above the modern level (Droxler et al. 2003, Raymo & Mitrovica, 2012). The deglaciation, the interval between the maximum glacial at MIS 12 and the minimum interglacial at MIS 11—referred to as Termination V, centered at approximately 430,000 years ago— is characterized by the highest amplitude in climate and ice-volume changes, and, therefore, sea-level amplitude change for the entire Plio-Quaternary, and even the full Cenozoic, or the last 66 millions of years (**Figure 5**). This interval of unusually high amplitude sea-level changes and the following glacial to interglacial transitions over a period of 350,000 years are, therefore, unique. Because the climate was beating at a 100-kyr eccentricity frequency and a 20-kyr precession frequency, mid-to-late Brunhes peak interglacials lasted for approximately half of the 20-kyr precession beat during intervals of high eccentricity (ranging from 16,000 to 11,000 years) and twice as long for the interglacial peaks (at MIS 11 or 27,000 years and during our current Holocene, already 12,000 years, although not complete yet) during time of low eccentricity **(Figure 5)**.

E. IMPROVED ANTECEDENT KARST THEORY EXPLAINING THE FORMATION OF MODERN ATOLLS IN THE MALDIVES IN THE CONTEXT OF THE WELL-ESTABLISHED SEA LEVEL FLUCTUATIONS IN THE LAST 3.6 MILLIONS YEARS

Based upon our knowledge of sea level fluctuations since the late Pliocene or the past 3.6 million years ago, atolls were initiated on late Pliocene flat-topped banks that formed during the MPWP, a warm and climatically stable 80-kyr time interval during which sea level fluctuated to a minimum (**Figure 5**). The exposure of these bank tops occurred during a 2-Myr long (from Early Pleistocene to ~ 600,000 years ago) interval of ice-volume stepwise increase and, therefore, sea level continued to fall systematically, creating karstified bank-top morphologies characterized by raised margins and central depressions (**Figure 5**). The modern atolls originated only in the last 450,000 years, using the antecedent karst morphologies that formed during the previous 2 Myr (**Figure 5**). High-amplitude 125–135-m sea-level cycles flooded the bank tops approximately five times, for about 20% of the full cycle, when coral reefs re-established themselves (particularly along the raised bank margins), but not for long enough to fill the atoll lagoons (**Figure 5**). The duration of each one of the late Quaternary sea-level highstands, on the order of 11,000–29,000 years, is not long enough for atoll lagoons to be filled up with carbonates produced within the lagoon or imported detritus from carbonate produced on the atoll rim (Gischler et al. 2008, Klostermann & Gischler 2015, Purdy & Gischler 2005). During the late Quaternary (or the last 450,000 years), these successive short-term bank-top refloodings, following a succession of relatively longer exposure times that stimulated preferential chemical erosion through karst dissolution in the center part of the exposed bank top, triggered coral growth preferentially along the raised bank margins and, therefore, enhanced the relief between reef rims and lagoon seafloors and created the templates for the modern atolls as we know them today.

F. MODERN ATOLL EVOLUTION AND ISLAND FORMATION IN THE MALDIVES DURING THE PAST 20,000 YEARS OR SINCE THE LAST GLACIAL MAXIMUM

Our current, though limited, knowledge of atoll re-initiation and island formation in the Maldives since the Last Glacial Maximum 20,000 years ago, when sea level globally was 125-135m below current sea level (**Figure 6A**), can illustrate the last phase of modern atoll formation in the last 10,000 years and demonstrate how young (less than 5,000 years, some even less than 2,000 years) islands of the Maldives Archipelago are (**Figure 6B/D**; Kench et al., 2005 and 2023).

A 17-m-deep borehole drilled on the western rim of Rasdhoo Atoll (**Figure 6B/D**), clearly illustrates the stacking of a 13.5-m-thick MIS 1 Holocene interglacial reef unit dated as far back as 8,200 years (radiocarbon age) (**Figure 6B/C**) on top of a former atoll karstified Late Pleistocene raised rim. The Holocene reef unit clearly rests on top of the previous interglacial highstand coral reef interval, dated at 136,900 years (uranium–thorium age) (**Figure 6B/A**). Both units are separated by a clear exposure horizon that, therefore, represents more than 100,000 years of exposure associated

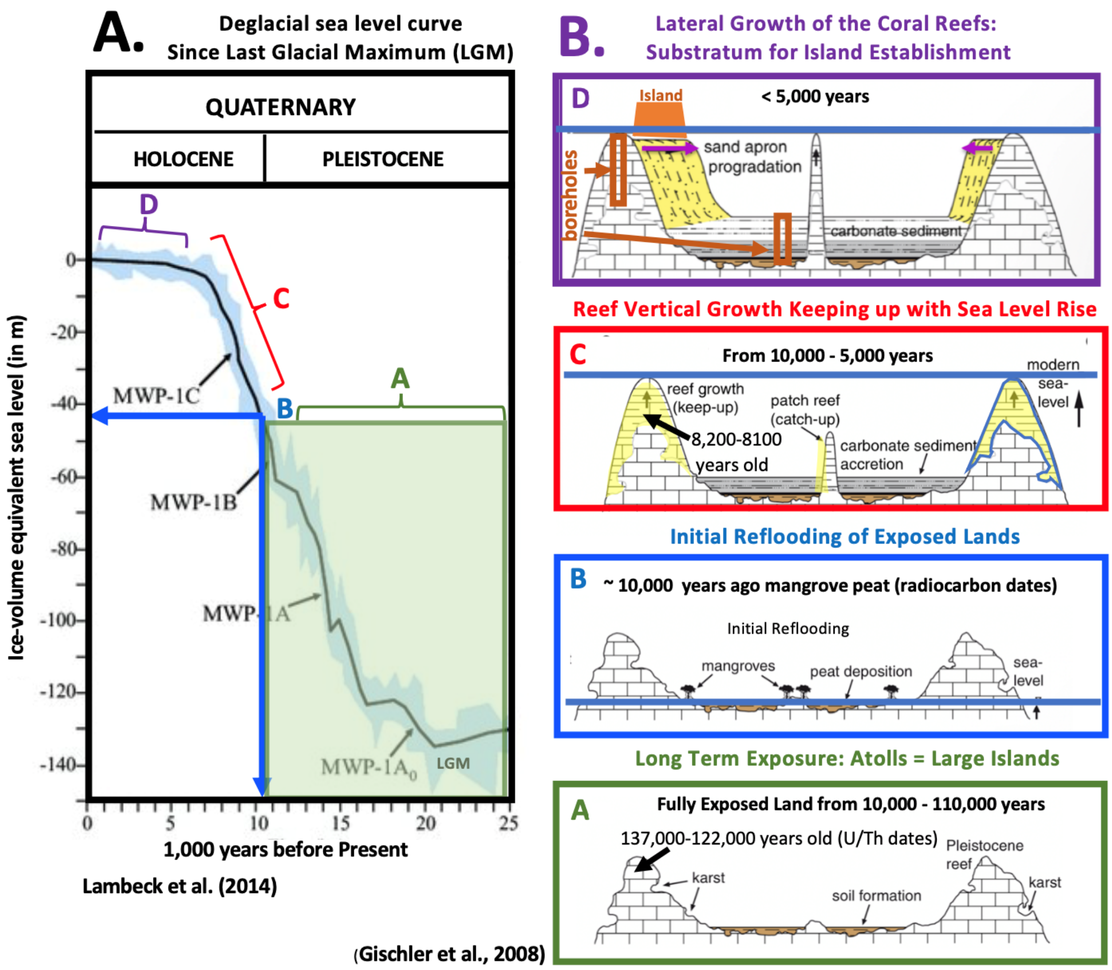

Figure 6 : A. Sea level variations over the last 25,000 years; note that sea level was globally 125-135 m below current sea level during Last Glacial Maximum (LGM). B. Four phases (A, B, C, and D) of the evolution of Rasdhoo Atoll during the last full glacial cycle or the last 130,000 years and placed on the sea level curve shown in (A). Note MWP in (A) stands for Melt Water Pulse intervals when sea level was rising an order of magnitude faster than in the last 30 years, such as MWP-1A, centered at 14,500 years ago, when sea level was rising at ~ 40-60 mm/year or 4-6 m per century.

with the end of last interglacial and the full glacial lowstand (Gischler et al. 2008) when all the large atolls in the Maldives were fully exposed lands and formed islands bounded by tenths of meter high cliffs (**Figure 6B/A**). Kench et al. (2009) reported a similar succession drilled on the Hulhudhoo reef flat on South Maalhosmadulu Atoll, where the last interglacial reef interval, dated at 122,000 years (uranium–thorium age), was recovered at 14 m below sea level. The earliest reef establishment on top of the last exposed karst surface was dated at 8,100 years, a comparable age as the one in Rasdhoo Atoll. Then in Rasdhoo Atoll, the coral reef grew steadily until 5,000 years (**Figure 6B/C**) and subsequently grew mostly laterally through its sand apron at a decreasing rate for the next 2,000, when sea level had reached or even exceeded, the current sea level, at approximately 4,500 years (**Figure 6B/D**). In both locations, the marginal reefs grew in a keep-up mode at a rate of approximately 13 m per 1,000 years or 13 mm/year from 10,000 to 6,500 years to decrease by a factor 10 for the last 6,500 years or an average rate of 1.2 mm/year (**Figure 6A**). For comparison, the average rate of global sea level rise measured based on satellite data sets since 2015 is about 3 times faster or almost 5mm/year!

The cored incomplete sediment infilling of Rasdhoo Atoll lagoon in a shallow borehole is typified by a thin (~4 m) sediment cover of carbonate cobble, sand, and silt, Middle to Late Holocene in age (**Figures 6B/C and 6B/D**), that rests on top of Early Holocene mangrove peat dated at ~10,000 years overlying some paleo-soil deposits (**Figure 6B/B**). During the ~100,000 years long exposure, between the previous MIS-5e interglacial and the current interglacial, significant limestone dissolution occurred particularly in the former atoll lagoons, enhancing the initial karstic “empty bucket” morphologies (**Figures 5 and 6B/A**), serving as templets for the rebirth of modern atolls as we know them today, when sea level reflooded those karstic morphologies (**Figure 6B/C**).

In the last twenty years, starting from 2005, Kench et al have published numerous articles on the nature, the formation, and timing of the modern reef islands in the Indo-Pacific tropical latitudes, with an emphasis on the Maldives islands. Reef islands are barely emerging parts (less than 2.5 m above sea level) of the Maldives atolls. Those islands are the results of the local emergent accumulations of reefal cobbles, pebbles, and sands behind the active coral reefs on top of which vegetation has settled and grown (**Figure 6B/D**).

In his initial article, Kench et al. (2005) developed a model of reef-island evolution, based on detailed morpho-stratigraphic analysis, multiple cored boreholes, ground penetrating radar (or GPR) subsurface imaging, and radiometric dating of the recovered carbonates in three islands within South Maalhosmadulu Atoll (**Figure 7**). Once the different observed sedimentary units are placed in a chronological framework, it becomes clear that the islands did not start forming until ~5,000 years ago (**Figure 8B/B**). Prior to it, until ~6,000 years ago, the faroe reefs (Agassiz, 1902) were growing vertically, trying to keep up with rates of sea level rise as fast as 13 mm/year, partially

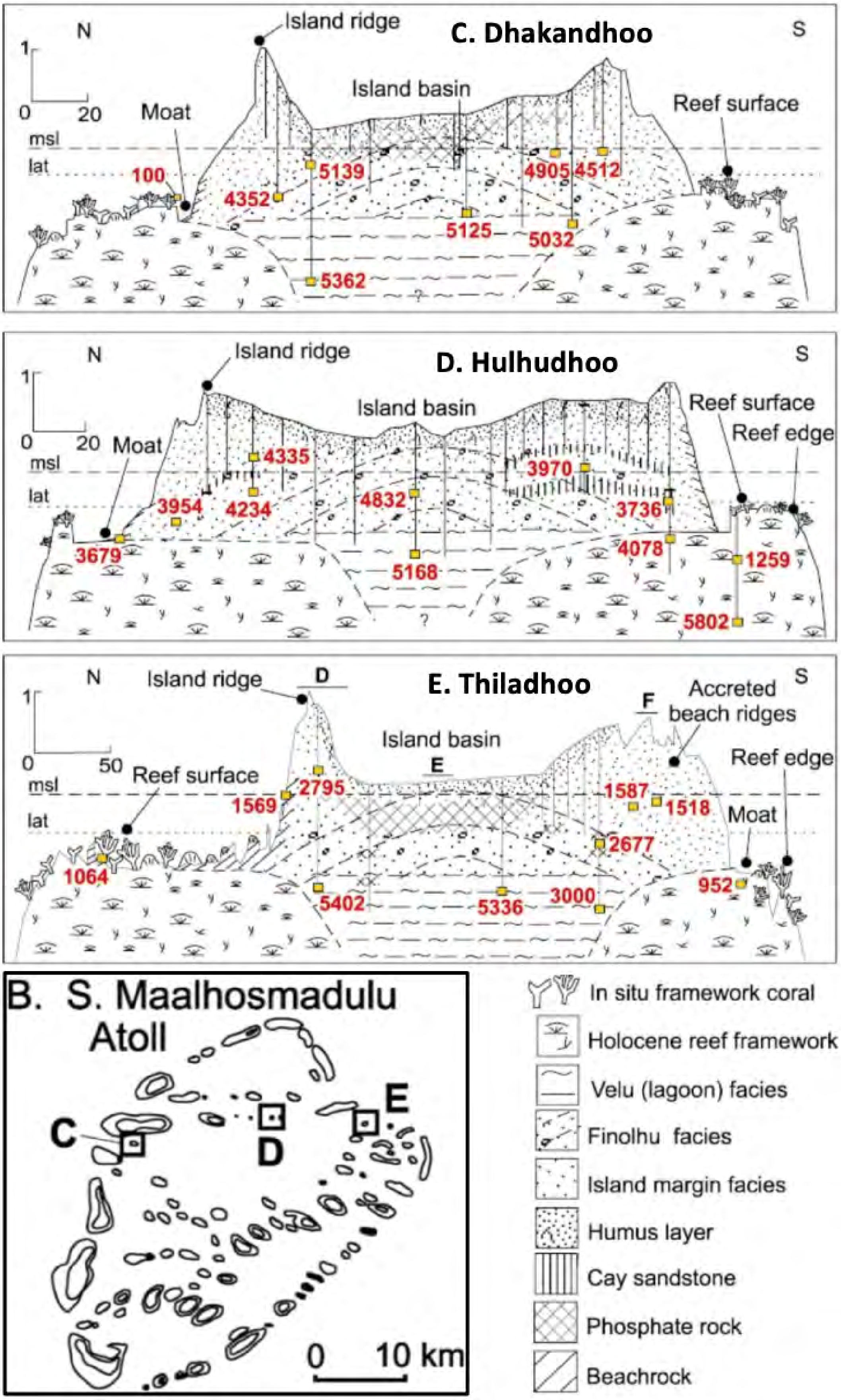

Figure 7 : Study and development model of three reef islands within South Maalhosmadulu Atoll, published by Kench et al. (2005). Red numbers are radiocarbon ages in years.

infilling their small lagoons (Gischler et al., 2008; Klostermann and Gischler, 2015) (**Figures 6B/C,** as Velu Facies in **Figure 8B/A**). Modern reef islands only formed when the rates of sea level rise dramatically decreased from 5,000 years (**Figure 8A**), when the rates of sea level rise systematically decreased to as low as 1.3 mm/year, sea level even stopped rising between 4,000 and 2,000 years, and in the last 2,000 years sea level dropped by 60 cm according to the observations by Kench et al. (2005, **Figure 8A**). The reefs, in the past 4,000 years, kept growing laterally instead of vertically not having to keep up with sea level rise at high rates, and their overproduction of sediments created wide sand aprons (also called pavements) behind them, on top of which local emergent accumulations of reefal cobbles, pebbles, and sands formed the modern islands as we know them today **(Figures 6B/D, 8B/C-D)**.

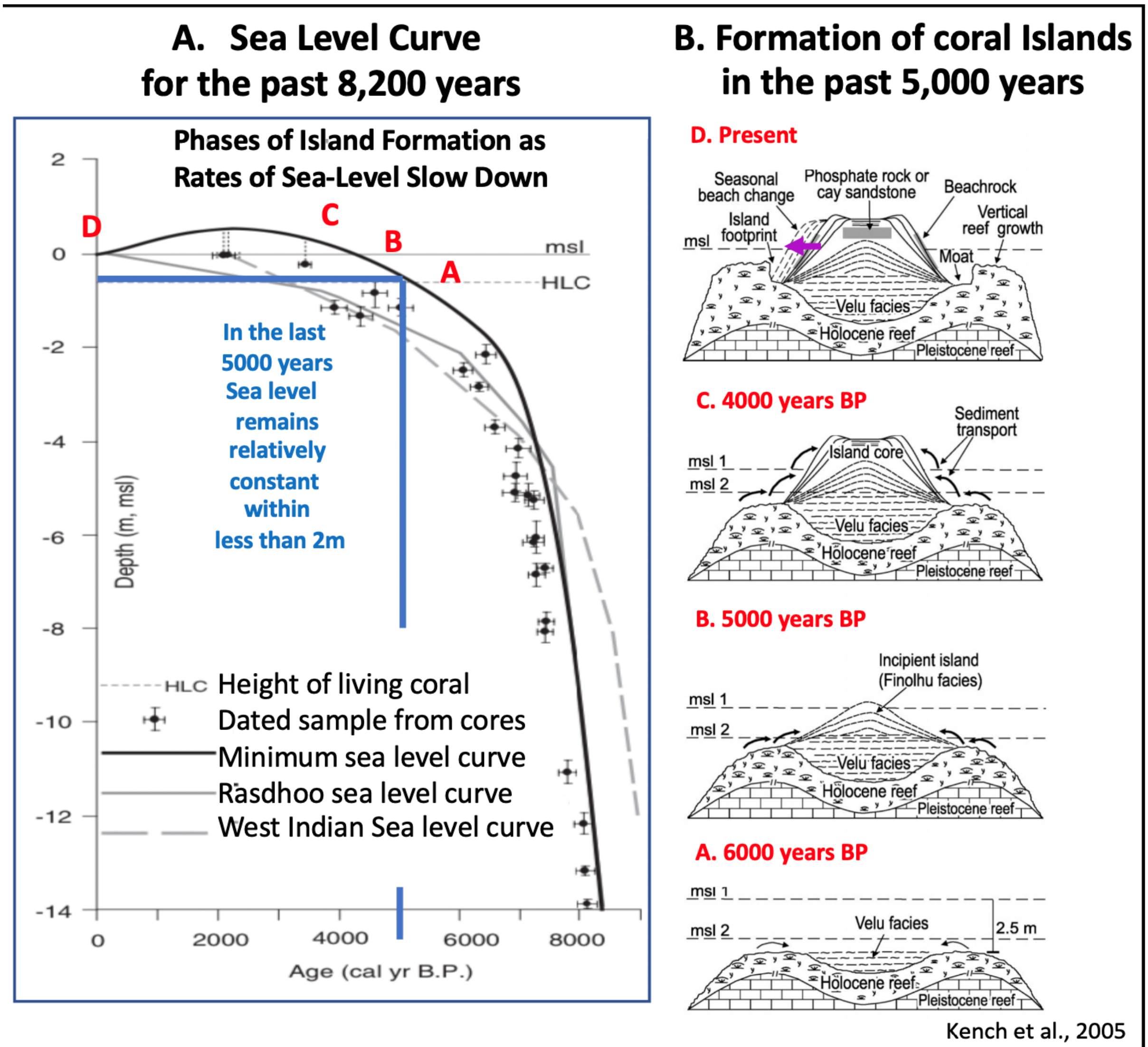

Figure 8 : A. Sea level variations in the past 8,000 years on which the four phases (as A, B, C, and D in red) of the island evolution, illustrated on (Figure 8B,) are projected (Kench et al., sea level curve, 2009). B. Schematic sequential sequence of coral island formation in South Maalhosmadulu Atoll, based on detailed field research of three reef islands within South Maalhosmadulu Atoll, Kench et al. (2005) (Figure 7). The islands only formed in the last 5,000-4,000 years. (see more explanations in the text below)

Moreover, in a recent study, Kench et al. (2023) demonstrated that the small island of Kandahalagalaa, in the southern lagoon of Huvadhoo Atoll became established less than 2,000 years ago. The authors showed also that modern reef islands in the Indian and Pacific Oceans, and in the Torres Straight and Great Barrier Reef, were formed systematically in the past 5,000 years when global sea level rise slowed down significantly, stopped rising, and even fell slightly; the majority of the islands became established, as in the Maldives, since 4,000 years, with quite a few only in the past 2,000 years.

The formation of Malé Island, studied in a recent article by Yildirim et al., 2022, is quite similar to the models of island formation initially developed by Kench et al. (2005) (**Figure 8B**). Malé island formed after 4,500 years, most likely only in the last 2,000 years (**Figure 9**). Based on a series of cored boreholes, the late Quaternary evolution of Malé Island includes two distinct sedimentary units: a lower unit made of late Pleistocene karstified coralgal limestone, shown in a brick pattern, and an upper unit, shown in a dotted pattern colored yellow, unconformably overlying the late Pleistocene limestone, consisting of unaltered and unconsolidated Holocene sediments (**Figure 9**).

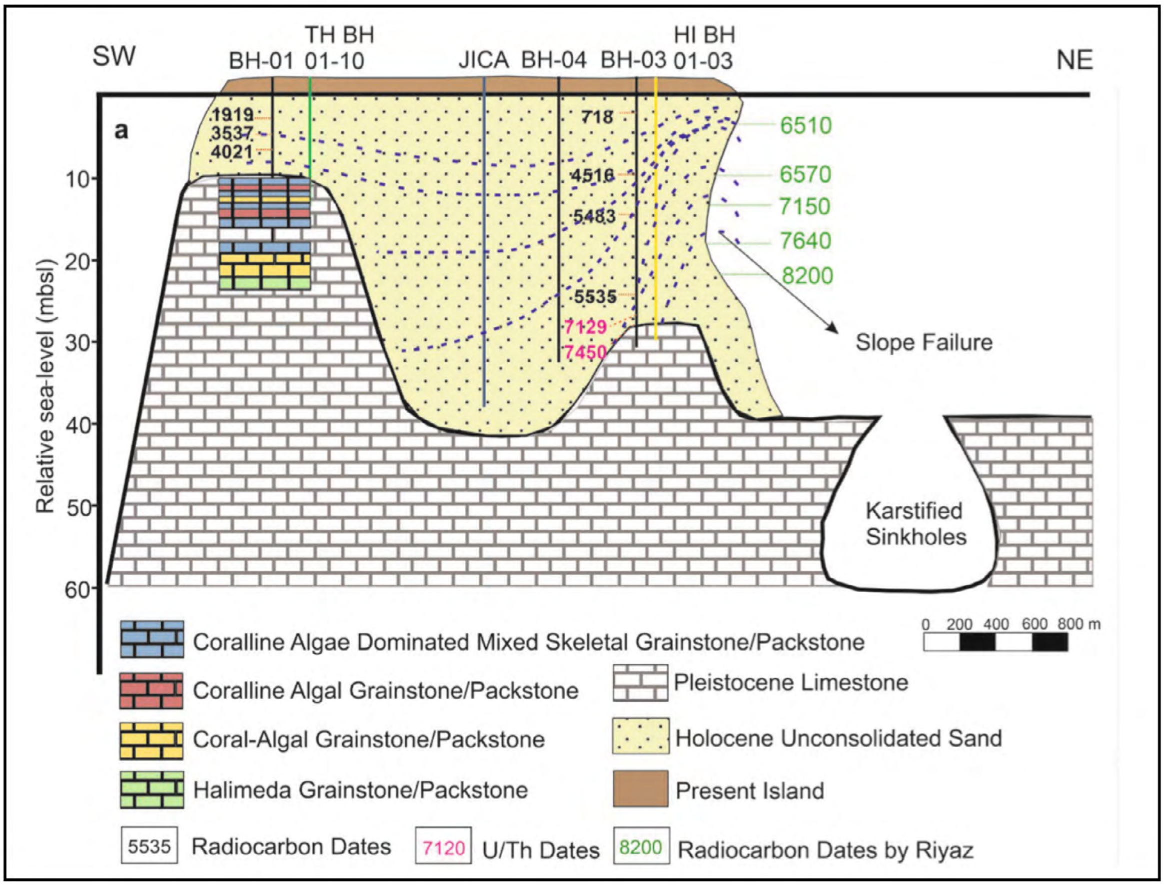

Figure 9 : Conceptual evolutionary model for the formation of Malé Island along a south-west to north-east transect across the island, based upon a series of boreholes (modified from Yildirim et al., 2022). Existing radiocarbon dates (8,200-6,510 years BP) from the area of the 2002 upper slope failure are indicated in green numbers. Coral U/Th ages at the base of borehole BH-03 (7,420 and 7,120 years BP) are indicated in red. Benthic foraminifer radiocarbon ages (ranging from 5,535 to 718 years BP) are marked in black numbers along boreholes BH-03 and BH-01, respectively. Possible Holocene sequential architecture is indicated by blue isochrones. See text for detailed explanations.

The elevation of the late Pleistocene limestone top surface, underlying Malé Island, corresponding to the MIS-5e previous interglacial warm interval, occurs at depth of ~10 mbsl (meter below sea level) along a southern and south-western ridge and at depths larger than 25 mbsl along a narrow ridge in the northern part of the island. Both ridges were enclosing a shallow lagoon, with water depths exceeding the penetration of the JICA boreholes or 35 mbls, forming a small faro (**Figure 9**).

The upper Holocene unconsolidated coralgal reef upper unit, shown in the dotted yellow pattern in **Figure 9**, overlying the karstified coralgal MIS 5e lower unit, was initiated at approximately 8,200 years BP on top of the relatively deep narrow late Pleistocene northern ridge. The reef grew vertically 25 m high until 6,510 ky BP (quite impressive in less than 2,000 years!) protected behind the karstified late Pleistocene southern reef remnant ridge. A small, 30 to 35 m-deep, newly formed lagoon fill up quickly in about 1,000 years, between 5,500 and 4,500 years BP, when sea-level rise stalled. In the southern part of Malé Island, a coralgal reef established itself, in the highest energy environment, between 5,000 and 4,000 yr BP on top of the late Pleistocene karst remnant southern high ridge and then grew relatively slowly to present sea-level (**Figure 9**). In other words, the Holocene reef on the northern side started to establish itself at about 8,200 years BP and grew until about 6,000 years BP; then until about 4,500 years ago, it shed sediments towards the center of the faro to fill its lagoon in about 1,000 years. Once the lagoon was almost completely filled with sediment and, therefore, very shallow, the Malé island formation was initiated. Based on the radiocarbon dates from the two cores, it is inferred that the island formation started well after 4,500 years BP as the Holocene reef, on its southern margin started to keep up with the sea-level rise and the sedimentation rates decrease to 1.5 to 2.0 m in 1,000 years, i.e. an order of magnitude lower than the rates of 10 to 16 m in 1,000 years before 4,500 yr. The original natural Malé Island only occupied the northern half of the current island which grew in phases by land reclamation in infilling the natural lagoon surrounding the original island.

Kench et al. (2023) have also addressed an important societal question: how reef islands have responded to the recent increasing rates in global sea level rise caused by anthropogenic global warming. After an interval in the last 4,000 years of sea level remaining about constant (**Figure 8B**), global average sea level rose in the past 140 years by about 260 mm (**Figure 10A**). Moreover, the rate of sea level rise has accelerated in recent years since 1993, based on satellite data sets, each decade of the last 30 years, from 2.27 mm/year to 3.29 mm/year, and in the last decade 4.68 mm/year (**Figure10B**) (Cazenave and Moreira (2022). Kench et al. (2023 and references herein) have concluded that natural low relief reef islands in the Maldives are dynamic landforms that have evolved, at least historically in the past 50 years or so, to vertically accrete at pace equivalent to the observed rise of sea level of about 10 cm. Their results, observed on the small island of Kandahalagalaa in the southern lagoon of Huvadhoo Atoll, show, as the authors wrote, that the magnitude of island area modification in the last 50 years in the order of +/- 40 m, a time of increasing rates of sea level rise in the order of 2 mm/year as an average, is not unprecedented compared with paleo-dynamic lines of evidence that reveals large-scale changes in island dimension, shape, beach levels, as well as location changes of +/- 200 m since the island formation about 1,500 years ago, an interval of time when sea level remained relatively constant.

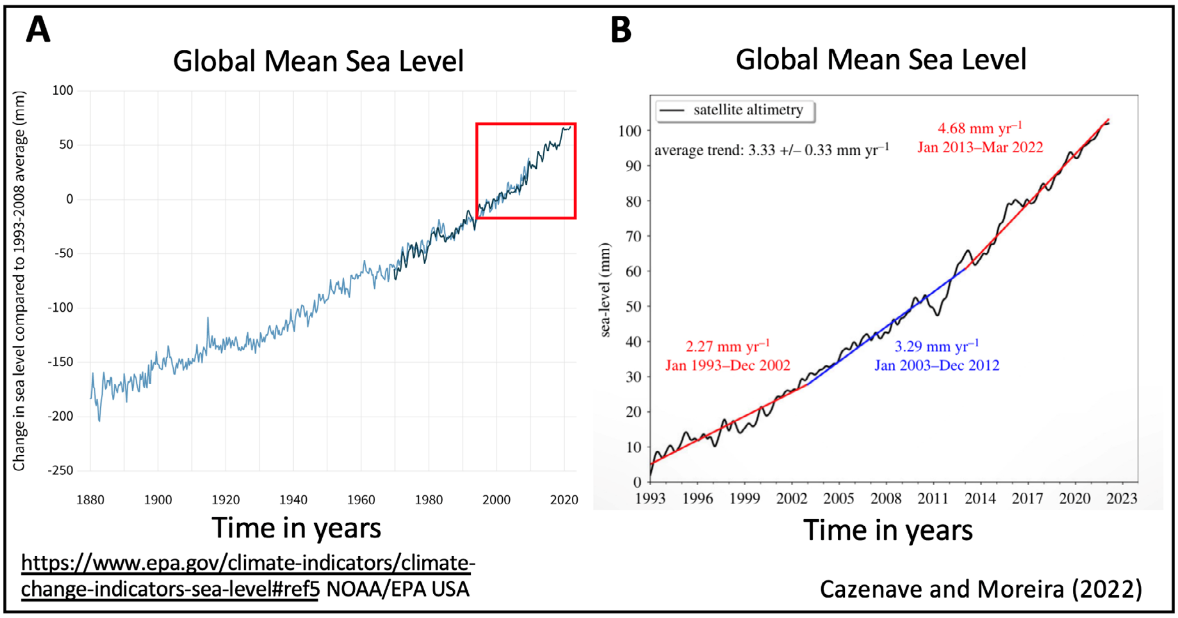

Figure 10 : A. Sea level reconstruction since 1880 published by NOAA. Red square corresponds to time intervval in B. B. Global mean sea-level time series (black curve) from multi-mission altimetry (data from AVISO, https://www.aviso. altimetry.fr) from January 1993 to March 2022. The coloured straight lines represent linear increasing sea-level decadal trends over three successive time spans. Note the systematic rates of sea level rise in the last 30 years.

One main and important question remains: how the low relief coral islands and even the atoll themselves will be able to survive future sea level rise. Because global temperatures are continuously getting warmer in the context of a steadily increasing greenhouse gas emission, sea level will continue not only to be rising in the future, but the rates of sea level rise are expected to increase in the next 75 years. (https://www.climate.gov/news-features/understanding-climate/climate-change-global-sea-level)
The difficulties are to assess the timing, amplitude, and rates of future sea level rise. Scientists, using computer models, are capable to forecast for year 2100, based upon the lowest predicted greenhouse gas emissions expected to result in a global warming of 1.5 degrees Celsius, that global sea level will rise to a minimum of 0.3 meters above the year 2000 level, illustrated in the Low scenario by the dark blue curve in **Figure11**. In the extreme scenario of non-abated rates of greenhouse gas emission, often referred to as the business as usual scenario, a global warming of 2 to 4 degree Celsius would not only trigger the partial melting of ice sheets in Greenland and Antarctica, but most likely enhance the risks of their partial collapse, generating global sea level rise of as much as 2.4 m above the year 2000 level, illustrated in the Extreme scenario by the red curve in **Figure 11**. Uncertainties remain in those forecasts because one does not know how high the values of humans-generated greenhouse gas emissions during the next 75-80 years will be. In the framework of the Intergovernmental Panel on Climate

Change (IPCC), governmental policies are aiming to decrease the global greenhouse gas emissions, i.e. the Paris Accord, and one can expect that levels of global sea level rise for year 2100 will range between 0.43 and 1.8 m, illustrated in the Intermediate to High scenarios by the two blues and two brownish-yellow curves in **Figure 11**.

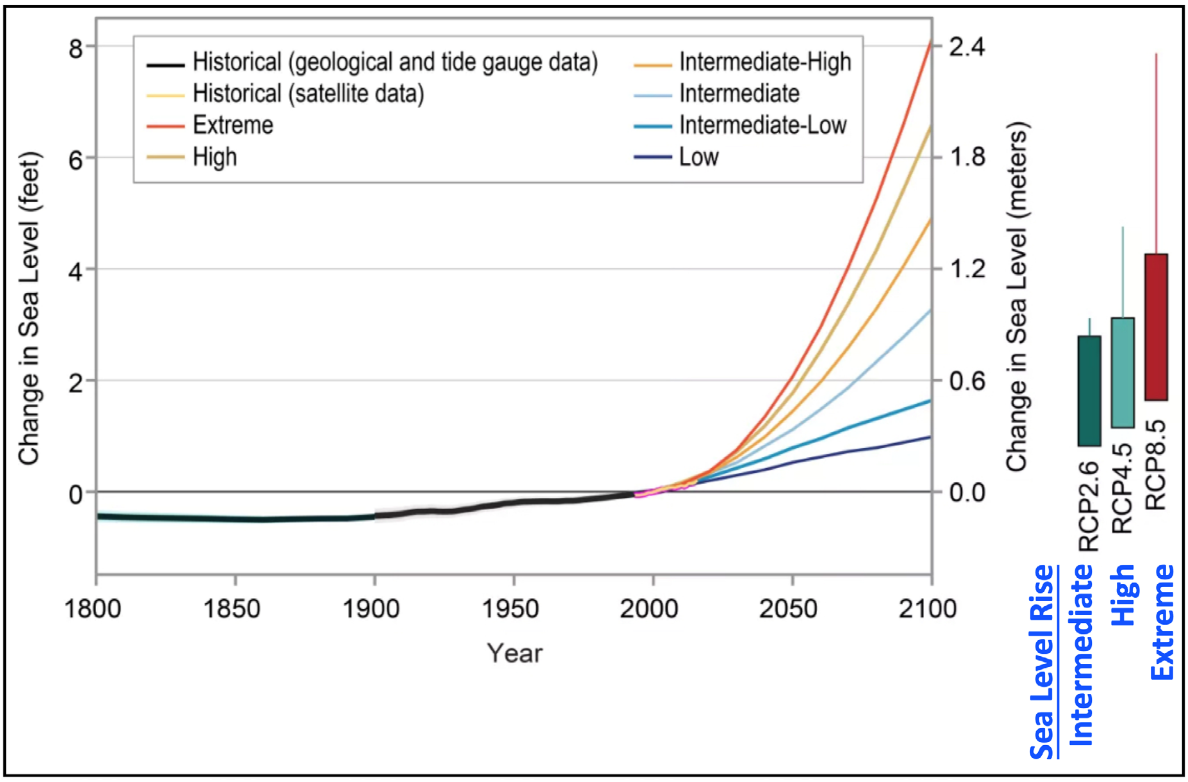

Figure 11 : Observed sea level since 1800, with future forecasted sea level amplitude rises through 2100 for six future scenarios (coloured lines). These scenarios differ based on future values of greenhouse gas emissions and related global warming and differences in the plausible rates of glacier and ice sheet loss through partial melting and collapses. NOAA Climate.gov graph, adapted from Sweet et al., 2022.

Knowing the time frame of 80-100 years (from year 2000 until year 2100) (**Figure 10**), and the different forecasted amplitudes of sea level rise related to the estimates of different humans-generated greenhouse gas emissions, resulting in a range of global temperature increases from 2 to 4 degrees Celsius (**Figure 11**), one can calculate the rates of sea level rise for the each one of the different scenarios (**Figure 12**). These calculated rates of sea level rise can then be compared with related relatively well-established responses of coral reefs and low relief coral islands during the last deglaciation since the last glacial maximum 20,000 years ago (**Figures 6B, 8 and 9**).

For an intermediate low rise of sea level of 0.43 m above the 2000-year level, corresponding to a rate of sea level rise of 5.35 mm/year, current natural islands might struggle to remain in existence and would be equivalent to the situation 5,000 years ago when island started to form (**Figures 12 and 8B/Band C**). For an intermediate high of sea level of 1.1 m above the 2,000 level, corresponding to a rate of sea level rise of 12.5 mm/year, current natural islands will be overwhelmed by the rise and most likely disappear, while the coral reefs should be capable to keep up with the sea level rise as they did between 8,000 and 6,000 years ago, although the reefs will need to grow vertically to remain within the photic zone (**Figures 12 and 6B and 8**). For extreme sea level rises of 1.8 to 2.4 m above the 2000 level, corresponding to rates of sea level rise ranging between 22.5 mm and 30 mm/year, coral reefs will struggle to keep up with those high rates and most likely will give up and cease growing, as they did during Melt Water Pulse (MWP) 1 A at 14,500 years, when sea level was rising at rates of 20-60 mm/year (**Figures 12 and 6A**).

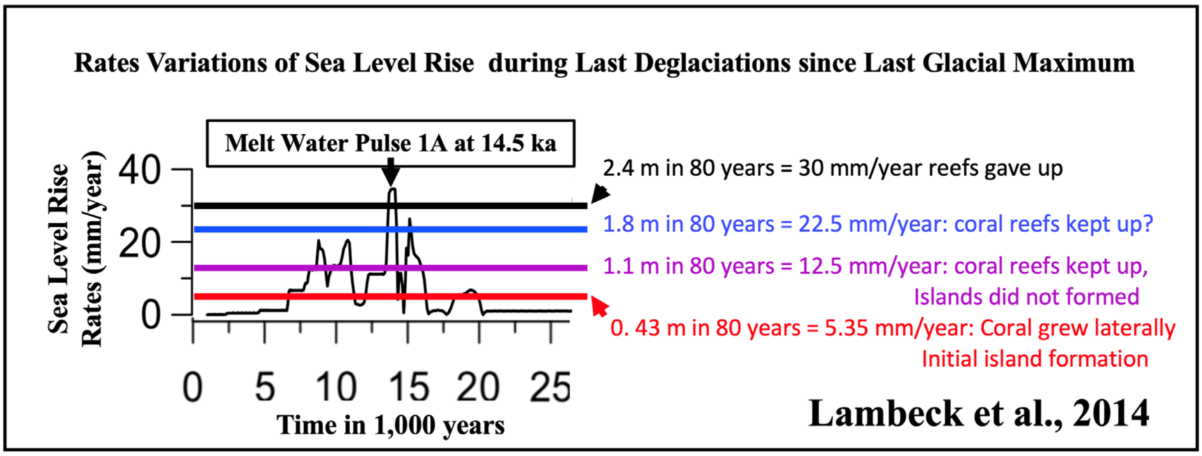

Figure 12 : Observed variable rates of sea level rise during the last deglaciation since Last Glacial Maximum, or the past 25,000 years ago). These rates of sea level rise are compared with future sea level amplitude rises, forecasted relative to year 2000, and their respective rates of rise through 2100 for the possible six future scenarios shown in Figure 11. Responses of natural low relief coral islands and atoll coral reef growth at given rates of sea level rise during the last 15,000 years are also indicated. These past responses become anchored base lines for possible future behaviour of natural relief coral islands and atoll coral reef growth in the next 80 years in the context of continuous global warming related to greenhouse gas emissions.

The future atoll reef carbonate production and growth are not only influenced by the rates of sea level rise in the context of global warming related to continuously increasing greenhouse gas emissions. Increasing global temperatures in the upper part of the oceans have triggered in the past, and will in the future, enhanced occurrences of more frequent coral reef bleaching events (van Woesik et al., 2022 and references herein; **Figure 13**, Rivera et al. 2020). In addition, the high CO2 concentrations in the atmosphere has increased the CO2 concentrations in the upper part of the oceans, decreasing its pH, referred to acidification of the oceans, and consequently lower the calcification rates of coral and other calcium carbonate secreting organisms (Pelejero et al., 2010; **Figure 13**, Rivera et al. 2020). Moreover coral reef overall health is also subjected to additional more local stressors such as (1) coral diseases, often originating from human activities, (2) sewage, brown/fresh water, high nutrient runoff from adjacent cities, towns, villages, and resorts, and (3) unregulated tourism activities, and (4) overfishing (**Figure 13**, Rivera et al. 2020).

In the next 80 years, therefore, (1) the forecasted sea level rises and expected increase of their rates, (2) more frequent coral bleaching events, (3) more acute acidification of the upper part of the oceans, all phenomena related to human related greenhouse gas emission increase, and (4) the aforementioned more local stressors related to human activities will influence negatively the overall health of the coral reef atolls and the stability of existing low relief coral islands.

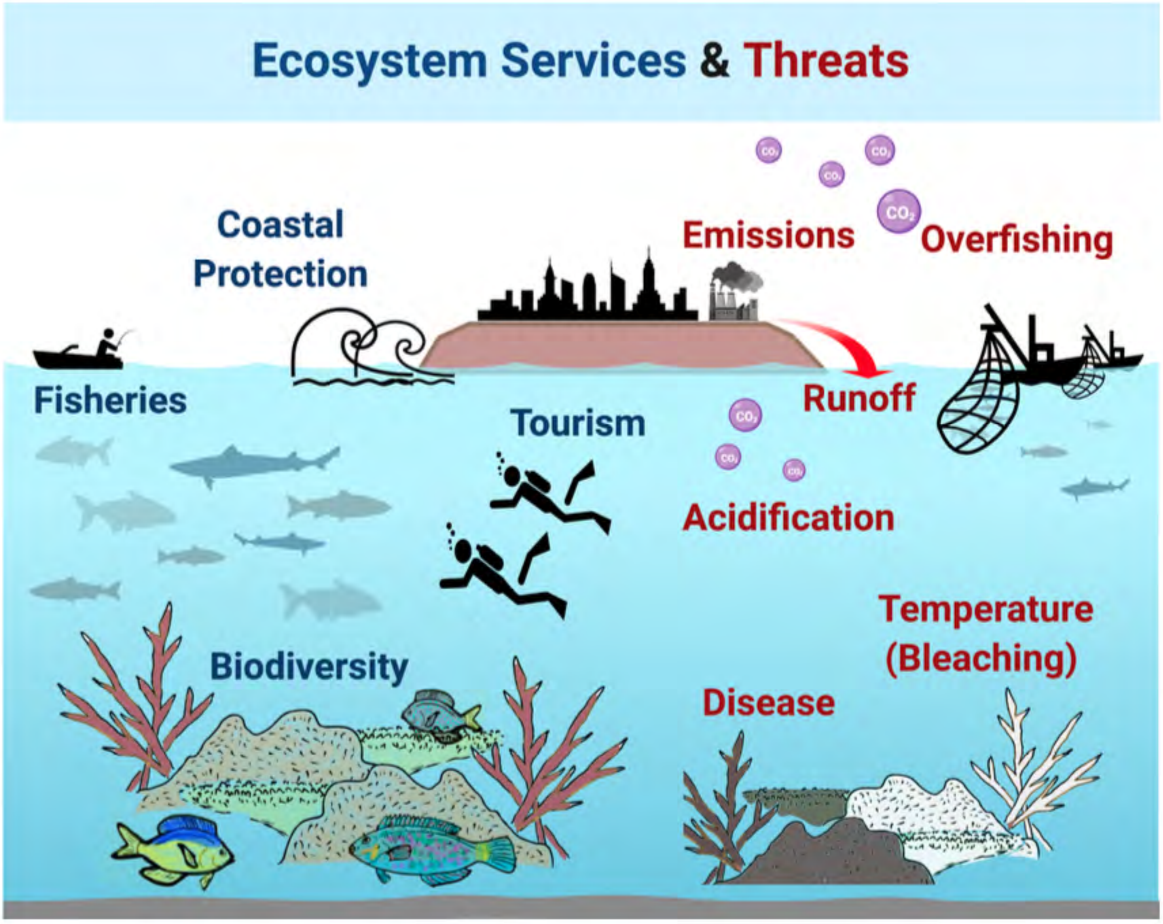

Figure 13 : Coral reef ecosystem services (blue) and threats (red). Coral reefs offer valuable services to humans., such as (1) ocean high biodiversity; often coral reefs are referred to the ocean rain forests, (2) food sources, in particular protein sources from fisheries, (3) income sources from tourism, and (4) coastal protection. Unfortunately, corals are impacted by multiple threats and stressors related to human activities, such as, on a global scale, increase atmospheric CO2 through burning fossil fuels in the past century, and related global warming, sea level rise, and upper ocean acidification, in addition to more local stressors such as coral diseases, high nutrient sewage runoff, and overfishing. Regrettably, many of these global and local stressors act to compound each other. Reproduction of the figure, initially published in **Rivera et al. (2020)** *is authorized by the MIT Science Policy Review article licensed under a Creative Commons Attribution 4.0 International License.*

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Podcast transcript on the origin of Atoll Formation

We're tackling a topic you guys requested, Atolls. We're talking about those stunning rings of coral in the ocean. You know, turquoise water, palm trees, the whole paradise image. But we're going beyond the postcards to uncover how these natural wonders form. Yeah. And it's a story that goes way deeper than what you see at first glance. We're talking about powerful ancient forces shaping the planet over millions of years, right? And you know, we've all heard the Darwin theory, right? That classic picture of a volcano slowly sinking, coral growing up to stay above the water. And while Darwin was onto something, what's wild is that what we've learned since then about Earth's climate history, well, it has a whole new layer to his theory. Absolutely. It just goes to show how science is always evolving, always uncovering new layers of understanding. Totally and ...

Today we're diving into some really cool research, the origin of modern Atolls, challenging Darwin's deeply ingrained theory. But don't worry, we'll break it down in a way that will make you see those vacation photos in a whole new light. You might be surprised by what's actually going on beneath those picture-perfect waters.

So, to get us started, picture this. The Maldives, those gorgeous chains of atolls, but here's the thing. There are so many atolls packed into that part of the Indian Ocean, it's hard to imagine they all formed from separate sunken volcanoes. Right? It's a good point. When you think about the sheer size of something like the Maldivian carbonate platform, it's huge. It dwarfs any single volcano. I mean, it's massive. And that hints at a much bigger, more complex story than we first thought. And get this, scientists now have their hands on oil exploration data from the region. It's like getting a glimpse into the distant past. And that glimpse shows us a hidden timeline stretching back 10s of millions of years. The atolls, themselves are relatively young, but that platform they sit on, that's ancient. We're talking way older than just some sunken volcanoes, way older. And the key is understanding that over those millions of years, sea level hasn't stayed the same. Picture a global ocean rising and falling dramatically, driven by huge Ice Age is coming and going. That's a detailed Darwin just didn't have, well, a yoyoing ocean. That changes everything, doesn't it? So, how do we get from these constantly changing seas to those perfect rings of coral? Well, the research breaks it down into phases, like a recipe for atolls, with each phase adding a new layer of complexity. A recipe for atolls. You've got me hooked. So what's the first ingredient in this millionaire recipe?

Phase 1: A volcanic foundation.

We're going way back to when volcanoes erupted on the ocean floor, creating those mountains of lava that eventually break the surface. In fact, the paper mentions they found 55,000,000 (55 million) year old basalt under the Maldives. That's what I called old. 55,000,000 (55 million) Wow, that's ancient. But we're not talking jagged volcanic islands here, right? How did those fiery mountains turn into those flat top platforms we talked about? That's where subsidence comes in. Imagine these huge volcanos slowly sinking overtime. But it's more than just sinking. See it's about the earth's crust adjusting to the weight of these massive volcanoes. Think of it like a like pressing down on those memory foam mattresses is it takes time to sink in, right? Same idea. Here, just on a way bigger scale. OK, that makes sense. So as these volcanoes are sinking, does that mean the coral starts growing on the slopes? To stay close to the sunlight exactly. Right as the volcano slowly goes down. But those flattops, those are a whole other chapter in the atoll recipe. That's phase two. Enter the flat-topped bank. Where things get really interesting.

Phase 2: Enter the flat-topped bank

Around 3.2 million years ago, Earth entered a period called the Mid Pliocene Warm period. Picture the planet with a much warmer, more stable climate. Now think about what that means for sea levels. Warmer climate means melting of the ice-caps. So as sea levels were higher back then, exactly much higher. Without those giant icecaps holding all that water. The oceans were overflowing. And this is where those vast shallow lagoons come in. They formed on top of the sinking volcanic platforms, and over time they filled with sediment, creating those massive underwater plateau's kind of like giant submerged mazes. OK, now I'm picturing these incredible hidden landscapes under the waves. Sunken volcanoes capped with massive plateaus. What happens next? Things get a little shaky here. This is phase 3, time of upheaval.

Phase 3: Time of upheaval.

Remember that climate yoyo we talked about earlier? The one Darwin didn't have the full picture of? Well, this is where it really comes into play. The climate start changing, ice ages intensify, and sea level goes up and down drastically exposing those flat-topped banks to the air. OK, so we've got these massive plateaus exposed to the air. After what, like millennia underwater? What happens to them when they're high and dry? Imagine the rain, right? Slowly dissolving the rock, carving out all these intricate caves and channels over millions of years. This process is called karstification. It gives the plateaus this really unique sculpted look. Giant sponge slowly being shaped by the element. Exactly. And here's where it gets really cool. When that ice melts in the sea level rises again, those carved out plateaus are flooded, creating this perfect little setup for coral to start growing. But remember that climate, yo-yo we talked about? So, this whole flooding and exposure thing, it happens again and again over millions of years. So, it's not like a onetime thing. These plateaus are getting flooded, exposed, sculpted over and over. Exactly. And with each cycle, the coral grows fastest around the edges of the plateau. You know, where there's more wave action, more nutrients, more of everything coral loves. So, the outer rim grows faster than the inner part, which eventually becomes a lagoon. You got it. It's like building a wall brick by brick, but here those bricks are layers of coral growing on top of each other over well aeons. That's phase four the ice gives way, but it's not a onetime event.

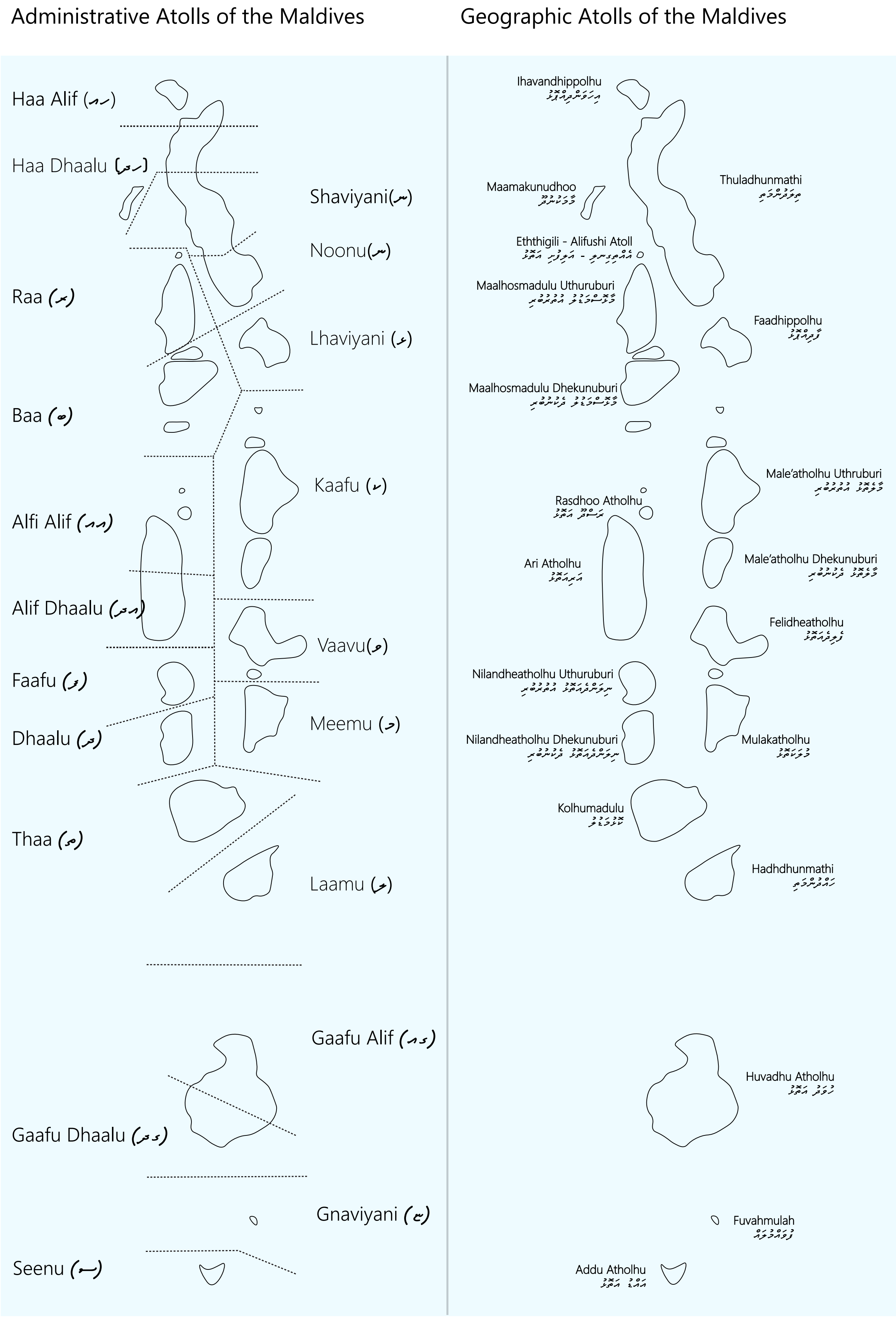
Phase 4: The ice gives way

It's that repeating cycle that really shapes the atoll. Wow. So, it's not just the sinking volcano, it's the constant flooding an exposure. Driven by the changing climate that makes that classic atoll shape, Darwin was missing a huge piece of the puzzle. Absolutely, and it really highlights how interconnected everything is on Earth. The best part? This isn't just ancient history. Scientists have drilled into modern atolls like Ari atoll and Goidhoo atoll. And guess what they found? Let me guess. Evidence of those ancient flooding and exposure events. Bingo. The drill course shows these distinct layers of coral growth, each one from a time when that atoll was underwater. Then there are gaps in those karstified formations. We talked about proof that the atoll was once high and dry. That's amazing. So, the atolls we see today, they're like living records of earth’s ancient climate. They are. It's wild, right? It's a reminder of just how much time is involved in shaping our planet. We think in terms of years, maybe decades, but these processes, they've been playing out for millions upon millions of years. It really puts things into perspective. It's like Darwin gave us the foundation, but now we're filling in all the details with what we know about how Earth climate shaped these amazing ecosystems. That's the beauty of science, right? Always learning, always revising what we think we know as we get more evidence. Totally.

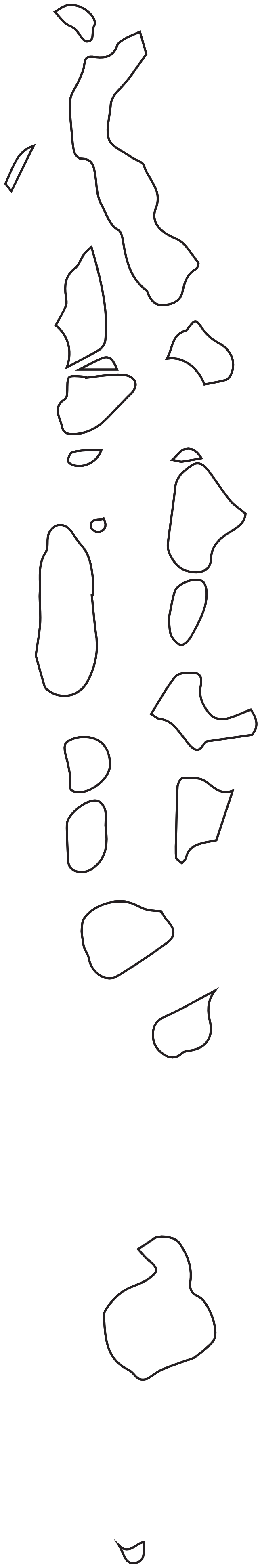
So, to wrap things up, what does all this mean for the future of atolls, especially with sea levels rising again? That's a million-dollar question, right? Something for you to think about. Will those lagoons just fill up? Or will the coral adapt and thrive even with a changing world? Only time will tell. Seems like even in paradise change is the only constant. Hope you enjoyed exploring the science behind these incredible natural wonders as much as we did. Until next time, keep those questions coming and keep diving deep.

Appendix

MAP OF THE MALDIVES



Map of the Maldives



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