Telling The Drifting Apart Story

Garrison Sill, Marble Arch Caves Global Geopark

DRIFTINGAPART

Northern Periphery and Arctic Programme 2014-2020

EUROPEAN UNION
Investing in your future
European Regional Development Fund

Drifting Apart is funded though the Northern Periphery and Arctic Programme under the European Regional Development Fund

CONTENTS

1 Drifting Apart

2 Our Dynamic Planet

3 Plate Tectonic Theory

3.1 Continental drift
3.2 Sea-floor Spreading
3.3 Wilson Cycles

4 Drifting Apart Storyline

4.1 Ancient Foundations
4.2 A New Ocean is Born
4.3 A Growing Ocean
4.4 Mountain Building
4.5 Movers and Shakers
4.6 Tropical Seas and Coal Swamps
4.7 One World
4.8 The Birth of the Atlantic Ocean
4.9 Crystal Clear Seas
4.10 Drifting Apart
4.11 A New Island

5 Storyline Summary

1 Drifting Apart

The Drifting Apart project has worked to improve understanding, appreciation and enjoyment of the fascinating and interconnected geological heritage of the Northern Periphery and Arctic region, and its many links to natural, built and cultural heritage. The project supported the development of new and aspiring UNESCO Global Geoparks, the promotion of innovative products and services for social and economic prosperity and created a strong network of geological heritage destinations in the Northern Periphery and Arctic Region.

The project brought together a series of partners from Northern Ireland, Ireland, Scotland, Norway, Iceland, Canada and Russia (Figure 1). The total value of the project was € 1.6 million with € 1.03 million provided through the Northern Periphery and Arctic Area Programme under the European Regional Development Fund. The program's vision was to generate vibrant, competitive and sustainable communities, by harnessing innovation, expanding the capacity for entrepreneurship and seizing the unique growth initiatives and opportunities of the Northern and Arctic regions in a resource efficient way.

This document has been developed by Marble Arch Caves UNESCO Global Geopark and Geological Survey of Northern Ireland.

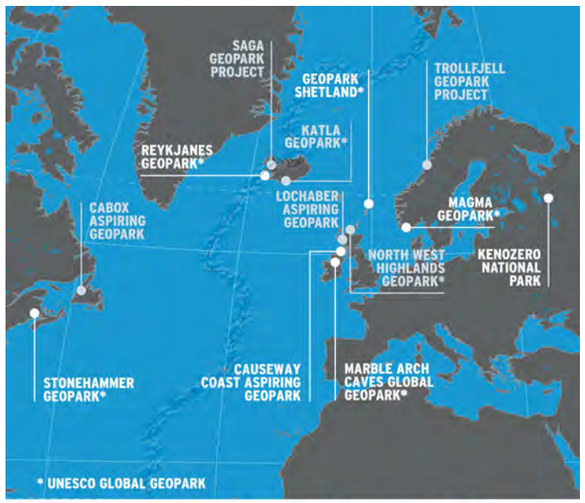


Figure 1 Drifting Apart partner location map

2 Our Dynamic Planet

The Earth is a dynamic planet, most of us witness this every day in the form of changing weather, but it's perhaps not so obvious in relation to the ground we walk on and the rocks found beneath. Processes above and below the Earth's surface, atmosphere, oceans, continents, lithosphere, crust, mantle and core, not to mention the moon and the sun are interacting across the globe to continually modify the geography of the Earth's surface.

Geological processes are not random, but follow a well-established pattern that is repeated in cycles such as the tectonic cycle and the rock cycle. The Earth was formed around 4,500 million years ago and since then nothing has been added to it apart from minor incursions of meteorite material and yet the world is very different now because of these cycles. Ultimately, the engine of change in the cycles is the heat derived from the Earth's interior, driven by the decay of natural radioactive mineral isotopes.

Cuilcagh Mountain, Marble Arch Caves Global Geopark

3 Plate Tectonic Theory

If you look at where earthquakes occur around the world, it is immediately obvious that most of the activity is concentrated in a number of distinct belts. These earthquake belts provide an important clue to the development of the Theory of Plate Tectonics.

The outer shell of the Earth, or lithosphere, is made up of a number of rigid segments called tectonic plates (Figure 2). These plates continually move at rates of a few centimetres per year, driven by forces deep within the Earth. It is this movement that accounts for earthquakes, volcanic eruptions, and the construction and destruction of continents and oceans.

The Theory of Plate Tectonics was largely developed in the 1960s by a number of geologists working independently in different countries. The theory was controversial at the time but is now accepted, with a huge body of data collected in support of it. It is now the unifying theory of geology, explaining how the Earth works. Two important forerunners of the theory, which are incorporated into it, are the theories of Continental Drift and Sea-floor Spreading both of which are fundamental to the Drifting Apart project, not least because it is where the project name comes from. An important outcome of plate tectonics is the Wilson Cycle, or the cycle of opening and closing of ocean basins, something that is an integral element of the Drifting Apart story.

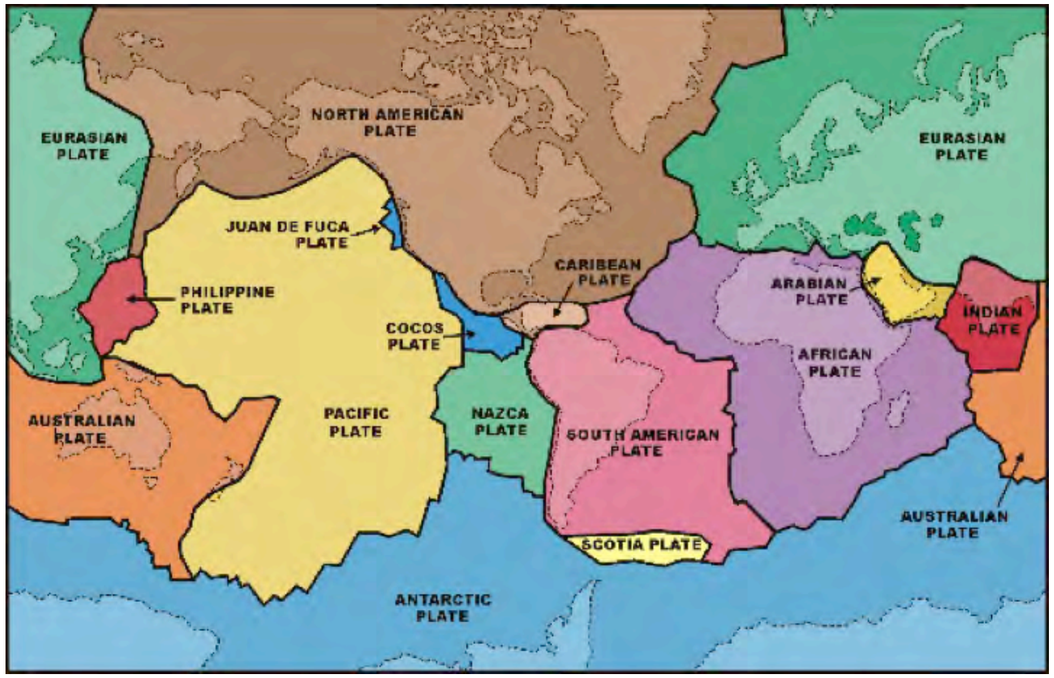


Figure 2 Pesent day tectonic plates

3.1 Continental Drift

Although continental drift was first pondered as early as the 15th century, it wasn't until 1912, that a German meteorologist and geologist called Alfred Wegener first proposed the theory. His theory was based on the observation that the west coast of Africa and the east coast of South America would fit together if they were moved across the map. This was also true for other continents so he assumed that they had all drifted apart from a single continent. Wegener went on to call his theory Continental Drift but his observations and theory were largely ignored at the time, and many other geologists, himself included, could not find a satisfactory mechanism for the movement of the continents.

3.2 Sea-floor Spreading

In 1959, Harry Hess of Princeton University who had been studying the ocean ridges and troughs first presented his theory of seafloor spreading. He proposed that rock (oceanic crust) was created at mid-ocean ridges from magma welling up from the mantle. The new rock gradually spread out either side of the ridge and was pushed towards the ocean trenches at the other side of the ocean where it disappeared downwards and was consumed (known as a subduction zone).

This theory provided an explanation of continental drift proposed by Alfred Wegener. It also explained why sediments on the ocean floor were very young. The oldest sedimentary rocks are 3 billion years old, but the oldest sediments on the ocean floor are no more than 200 million years old. In addition, the age of the ocean sediments increases the further they are from the mid-ocean ridge.

3.3 Wilson Cycles

A direct result of plate tectonics is the cycle of the opening and closing of ocean basins, something that is seen several times within the Drifting Apart story. This cycle is referred to as a Wilson Cycle and is named after John Tuzo Wilson, a Canadian from the University of Toronto who also studied at the Universities of Cambridge (UK) and Princeton (USA). Tuzo Wilson achieved worldwide acclaim for his contribution to the theory of plate tectonics including the idea of 'hotspots' and plate tectonic boundaries known as transform faults. The Wilson Cycle is part of the process involved in the Supercontinent Cycle where most or all of the continents come together to form a single landmass.

4 Drifting Apart Storyline

The storyline for Drifting Apart is based around the notion of plate tectonics. Each of the partners involved have been physically connected in their geological past, but due to plate tectonic activity this is often no longer the case. But what has happened and how did this come about?

The Drifting Apart storyline is intended for the non-specialist so for the most part, geological terminology hasn't been used, and where it has, it has been explained in such a way to make it easy to understand. Each main event in the storyline has been grouped and described and examples given from the Drifting Apart partner areas. Whilst these main events are roughly comparable with geological time periods, they sometimes extend across more than one so for that reason the names of the geological time periods have been omitted to avoid confusion.

This symbol indicates where in the Drifting Apart project area you can see evidence of this part of the storyline

4.1 Ancient Foundations

Our story begins with the oldest rocks of the Drifting Apart area, around 3 billion years ago. Little is known about the geography of the Earth but the rocks do tell us about the creation of continental crust. The rocks that we find are called gneiss (pronounced 'nice') and are a type of metamorphic rock, meaning that they have changed form due to intense heat and / or pressure. Most of these gneisses are thought to have started out as igneous rocks, or rocks that were once molten, and tell of a growing continental crust. The original igneous rocks formed as repeated injections of molten rock (or magma) and this is most likely to have occurred above a subduction zone.

Lewisian gneiss in the **North West Highlands Geopark** and in **Geopark Shetland**

Continental crust can also grow through the addition of magma due to rifting (when the crust is pulled apart). This leads to a very different rock chemistry and often comes in batches intruded along cracks, known as dykes. These features are found as part of the Ancient Foundations and formed between 2.4 and 2 billion years ago.

Scourie Dykes in the **North West Highlands Geopark**

Tectonic activity led to extensive plate movement causing the igneous rocks and any sedimentary rocks to be buried to great depths (between 35 and 50km) and metamorphosing them to form gneiss. It is thought that an ancient supercontinent called Columbia existed between 2.1 and 1.6 billion years ago, made up of all of the existing continents joined together. The formation of this supercontinent and the resulting plate tectonic activity would have produced vast amounts of molten rock both above and below the surface, and it is likely that this was the origin of some of the gneisses found in other Drifting Apart partner areas.

Banded gneisses in **Magma Geopark**, Lewisian gneiss at Rhum in **Lochaber**, Archaean rocks in **Kenozero National Park**

The tectonic cycles mean that the ancient supercontinent of Columbia eventually broke up in to several smaller continents, before reforming again as single supercontinent known as Rodinia just over 1 billion years ago. The heat and pressure that this plate tectonic movement produced led to a huge amount of deformation and metamorphism as well as the generation of magma beneath the surface that ultimately cooled and solidified to form granite (a type of igneous rock).

Deformation and metamorphism in **Magma Geopark**. Granites in **Magma Geopark**.

It wasn't all violent earth movements though as rocks that originally formed as sediments on the ocean floor off the coast of Rodinia are found. About 1200 million years ago the first evidence of life appeared in the Drifting Apart area as the shallow seas and temporary lakes would have contained cyanobacteria (or blue-green algae). These are now preserved as fossil stromatolites and are found in both the North West Highlands Geopark and Stonehammer Geopark. The release of oxygen by these micro-organisms actually aided the development of more complex life on Earth and some of the most amazing and unusual fossils found throughout the entire Drifting Apart area. At the same time, another unusual event took place in the Drifting Apart area when a meteorite strike took place, now preserved as a layer of 1200 million year old impact ejecta after an asteroid hit the area now known as the North West Highlands Geopark!

Stromatolitic limestone in **Stonehammer Geopark (shallow sea)** and in **North West Highlands Geopark (temporary lakes)**, Stac Fada Member meteorite ejecta in **North West Highlands Geopark.**

Around 1000 million years ago, many parts of the Drifting Apart area would have been covered by river systems with vast thicknesses of river sediments bring deposited on land. The source of the sediment came from the north west so this shows a real link between the Drifting Apart areas with sediments from Canada and Greenland being deposited in Scotland!

Vast thicknesses of river sediments deposited as Torridonian sandstone in **North West Highlands Geopark**.

Around 800 million years ago, Rodinia began to break up and as it ripped apart it caused the crust to stretch and thin. This crustal thinning caused a basin (or large depression) to form that started out as a shallow sea. Sediments built up in the shallow sea and are now preserved as a suite of metamorphosed rocks found across many parts of the Drifting Apart area. The stretching and thinning also produced magma that squeezed its way up through the inevitable cracks in the surface, where it solidified to form dykes.

Egersund dyke swarm in **Magma Geopark**, dykes and flood basalts in **Cabox Aspiring Geopark**

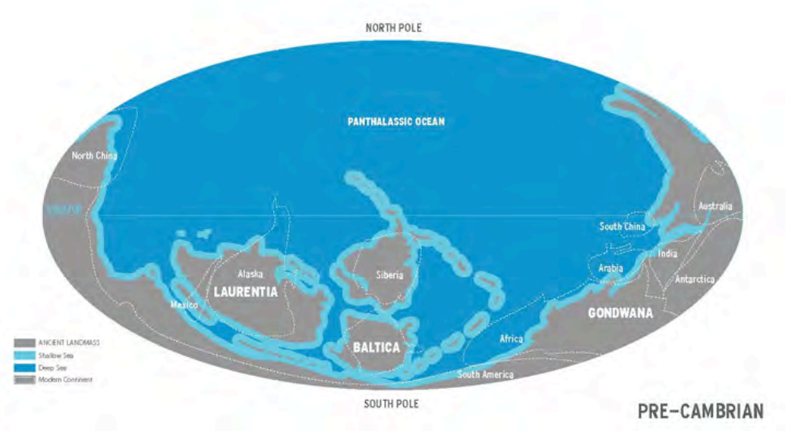


Figure 3 Plate reconstruction after the break up of Rodinia

4.2 A New Ocean is Born

As Rodinia continued to break up, our present day areas of Scotland, the north of Ireland, Greenland and North America formed part of a continent known as Laurentia. The shallow sea that was created continued to grow as a result of rifting and eventually formed a major new ocean as it extended outwards from the mid ocean ridge. This new ocean became known as the Iapetus, and formed between Laurentia and another large continent known as Gondwana. Two other smaller continents existed between Laurentia and Gondwana, known as Siberia and Baltica, the latter of which now forms Scandinavia.

Humber Zone in **Cabox Aspiring Geopark**, komatiite at Catpund in **Geopark Shetland.**

The Iapetus Ocean continued to open between Laurentia and Gondwana, pushing Laurentia, Baltica and Siberia further away from Gondwana. Between 600 and 500 million years ago, Gondwana began to fracture, with pieces tearing off to form microcontinents or terranes, two of these known as Avalonia and Ganderia would later form parts of eastern Canada.

Sediments deposited on the continental margins of Iapetus are now seen as metamorphosed sedimentary rocks in parts of Canada, Scotland and the north of Ireland as very shallow seas and beach sediments led to the formation of quartzites and limestone. This time also saw the first fossils of animals with hard parts such as trilobites as well as the preservation of more stromatolites.

Saint John Group rocks and Green Head Group limestone / marble at Reversing Falls, in **Stonehammer Geopark.** Moine rocks in **Lochaber** and **Marble Arch Caves Global Geopark**, Dalradian rocks in **Causeway Coast and Glens**, Moine & Dalradian rocks in **Geopark Shetland**, Cambrian metasediments in **North West Highlands Geopark.**

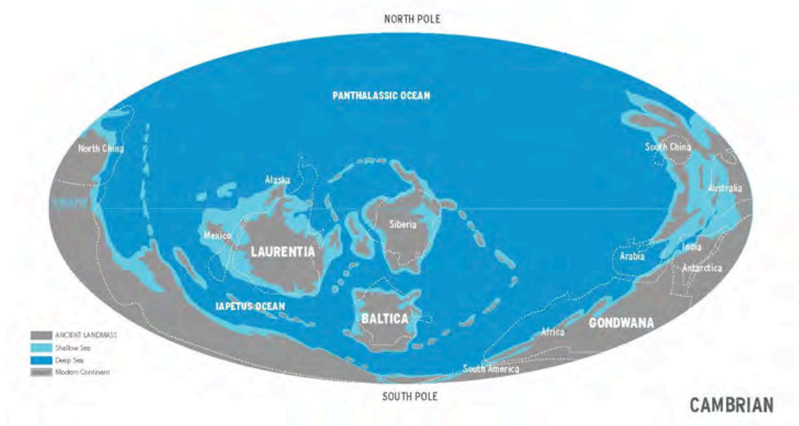


Figure 4 Plate reconstruction for the Cambrian

4.3 A Growing Ocean

By around 500 million years ago, the Iapetus Ocean had reached its maximum width of up to 5000km, similar in scale to today's Atlantic, before it began to close. In some places sediment that formed on the Iapetus Ocean floor can now be seen.

Bruse Hill mudstones in **Marble Arch Caves Global Geopark**, sediments deposited on Iapetus floor in **Trollfjell.**

The process of ocean closure is not a straightforward one and over a period of 200 million years, the Iapetus Ocean slowly closed as Baltica and Avalonia (and the associated Ganderia terrane) moved northwards and collided with Laurentia, leading to the formation of the Rheic Ocean behind them. Ocean closure was enabled by subduction of the ocean floor. As this happened volcanic rocks were erupted into the older crustal rocks, building up volcanic arcs along the margins and within this ocean. As subduction continued, the volcanic arc around the northern margin of the Iapetus collided with Laurentia, causing intense deformation and metamorphism. In some cases as the ocean closure continued, ophiolites formed when oceanic crust was thrust on top of continental crust.

Steinstind, Leka, Trofjell Geopark Project

Shetland ophiolite in **Geopark Shetland**, Leka ophiolite in **Trollfjell,** Bay of Islands Ophiolite Complex in **Cabox Aspiring Geopark,** Kingston Terrane volcanics in **Stonehammer Geopark.**

Figure 5 Plate reconstruction for the middle Ordovician

4.4 Mountain Building

The various collisions and deformations that resulted from the closure of the Iapetus Ocean are known as the Caledonian-Appalachian Orogeny, and just as the recent and continuing collision of India with Eurasia has formed the Himalayas, so the combined effects of the Caledonian-Appalachian Orogeny raised a composite mountain chain over a period of 200 million years. Remnants of this ancient Caledonian-Appalachian mountain belt are found from the Appalachians of North America, through the north of Ireland to Scotland, and to the Arctic Circle in Norway.

Moine Thrust Zone in **Lochaber** & **North West Highlands Geopark**, Great Glen Fault in **Lochaber**, westernmost part of Norwegian Caledonides in **Trollfjel**l, Appalachians in **Cabox Aspiring Geopark** and **Stonehammer Geopark**

Figure 6 The Caledonian-Appalachian Orogeny

The final stages of the closure of the Iapetus Ocean were by continent-to-continent collision around 400 million years ago. This was accompanied by the generation of large volumes of magma within the crust. Most of this was associated with major faults and as a result, many of the granites were deformed as they cooled and crystallised. There are also some more unusual igneous rocks such as syenite, that is typically fomed in subduction zones, and carbonatite, an igneous rock that is rich in carbonate minerals.

Crossdoney Granite in **Marble Arch Caves Global Geopark**, granite magmatism in **Lochaber**, Vega Granite and Andalshatten batholith in **Trollfjell**, the Walls Boundary Fault at Ollaberry in **Geopark Shetland**, syenite and carbonatite rocks in **North West Highlands Geopark.**

4.5 Movers and Shakers

Whilst the Iapetus Ocean may have closed, the Rheic Ocean was also closing as Gondwana continued to move northwards and was subducted beneath Laurentia. At this time, all of the Drifting Apart areas were part of the same landmass and were about 35°S of the equator with a semi-arid climate and seasonal rainfall. Rapid erosion of the Caledonian-Appalachian Mountains led to the deposition of massive amounts of sand and cobbles that were supplied via large rivers to extensive desert plains.

Cushendun and Cushendall in **Causeway Coast and Glens**, sandstone and conglomerates in **Geopark Shetland,** Devonian sediments in **Kenozero National Park.**

Eshaness Coast Geopark Shetland.
Copyright Billy Fox Photography

Middle Arm Point sedimentary layers of limestone and sandstone closing of Iapetus, Cabox Aspiring Geopark

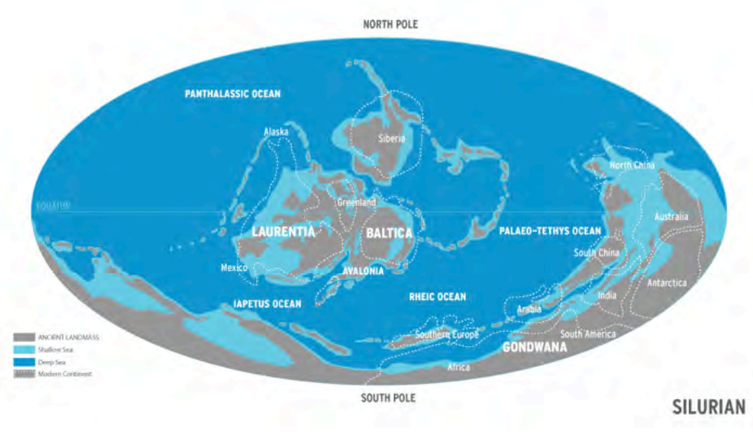
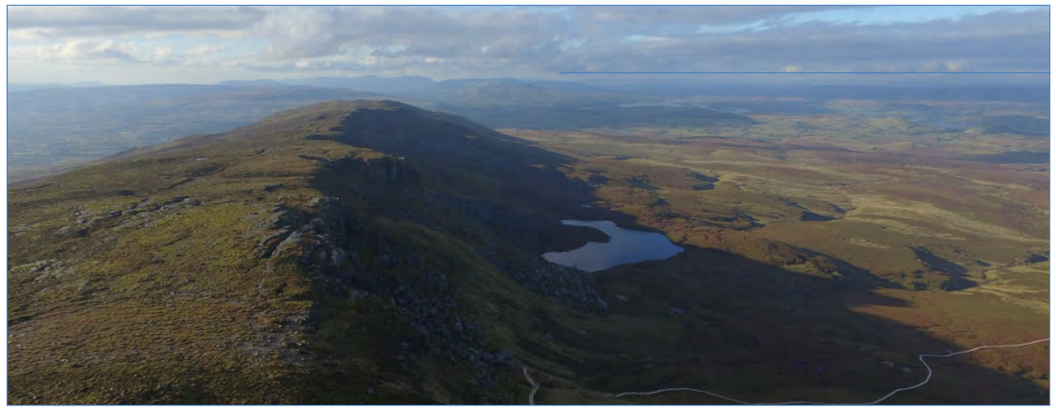


Figure 7 Plate reconstruction for the Silurian

4.6 Tropical Seas and Delta Swamps

By around 350 million years ago, the Rheic Ocean had all but disappeared and the Drifting Apart areas had moved slowly northwards, and were now located on or very near to the equator. Some areas, such as those located on the edge of a landmass were covered by a shallow tropical sea. This resulted in the deposition of fossil-rich limestone. However, over the next 20 million years the sea level would fall and delta and swamp conditions prevailed as sediment continued to be transported from the eroding Caledonian-Appalachian Mountains, and sandstone and coals formed.

Cuilcagh Mountain in **Marble Arch Caves Global Geopark**, Ballycastle in **Causeway Coast and Glens**, Carboniferous rocks in **Stonehammer Geopark, Carboniferous limestones in Kenozero National Park**.



Cuilcagh Mountain, Marble Arch Caves Global Geopark

By around 300 million years ago, the Rheic Ocean finally closed and the resulting orogeny is often referred to as the Alleghenian Orogeny or the Variscan Orogeny. The resulting deformation and metamorphism is seen in many parts of Europe and in North America. This final closure led to the formation of a single supercontinent, known as Pangaea that once again was home to all of the Drifiting Apart partners.

Alleghenian folding in **Cabox Aspiring Geopark**.

4.7 One World

Not long after Pangaea formed, it began to rift apart again. The first attempt at this was just under 300 million years ago when a rift began to form down the middle of what we now know as the North Sea, between Scotland and Norway. This rift failed and it only managed to form a depression or a basin before rifting ceased. Around 250 million years ago, more rifting began, this time along the eastern side of North America. At this time, the majority of the Drifting Apart areas were in semi-arid latitiudes again, but this time north of the equator. In some areas, when the desert landscapes were flooded, they dried out and left thick salt deposits behind, whilst in others desert sandstones were formed.

Triassic rifting in **Stonehammer Geopark**, salt mines in **Causeway Coast and Glens.**

Figure 8 Plate reconstruction for the Devonian

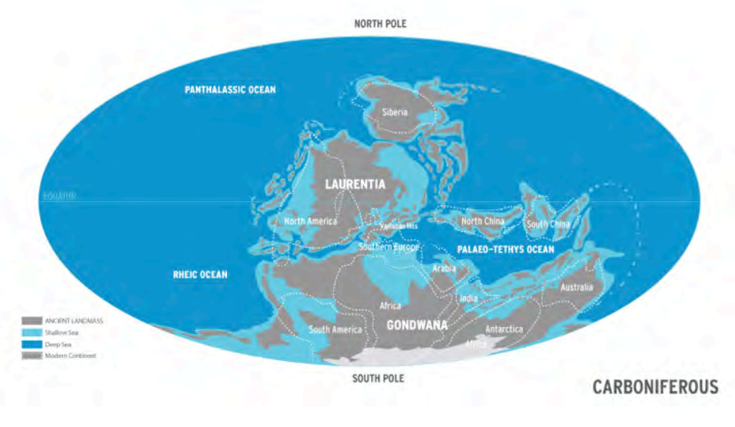


Figure 9 Plate reconstruction for the early Carboniferous

4.8 The Birth of the Atlantic Ocean

By 200 million years ago, as Pangaea continued to break up, the developing rift between North America and northwest Africa was marking the opening of the future Atlantic. As the crust stretched and thinned, cracks began to appear, up through which magma rose to form dykes. The Drifting Apart area was now 40ºN of the equator with a climate that resembled that of present day humid countries with monsoon-type summers.

Warm shallow seas repeatedly covered the edge of the landmasses and mudstones and limestone were deposited, with considerable thickness of sediments in the failed rift that existed in the North Sea. These would eventually form the rocks of the North Sea oil and gas fields.

Jurassic dykes located just outside **Stonehammer Geopark**, North Sea oil and gas field in **Geopark Shetland**, Waterloo Bay and Tircrevan Burn in **Causeway Coast and Glens.**

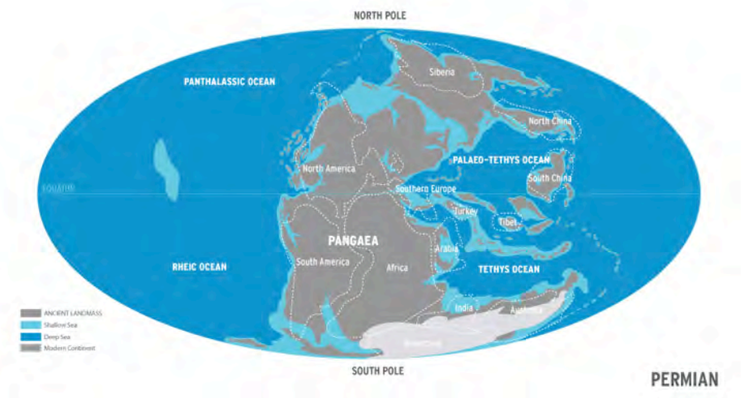


Figure 10 Plate reconstruction for the late Permian

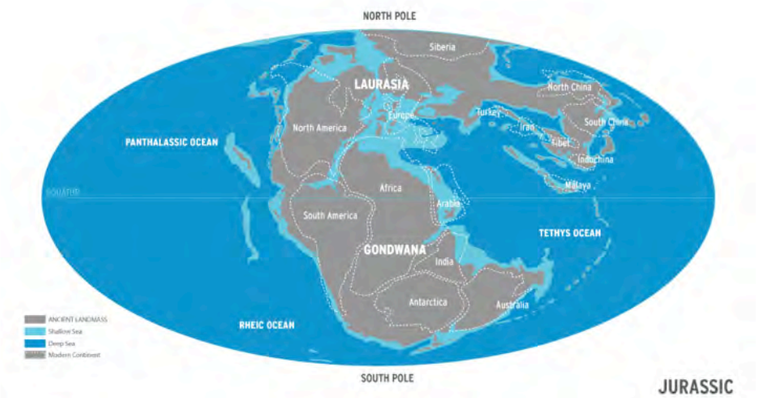


Figure 11 Plate reconstruction for the early Jurassic

4.9 Crystal clear seas

Between 145 and 65 million years ago, rifting continued as Europe moved away from North America. High sea levels time and a relatively warm climate resulted in very productive oceans. The remains of millions of micro-organisms that lived there formed thick deposits of white limestone (or chalk) in some areas.

Garron Point and Tircrevan Burn in **Causeway Coast and Glens**, North Sea oil and gas fields in **Geopark Shetland**.

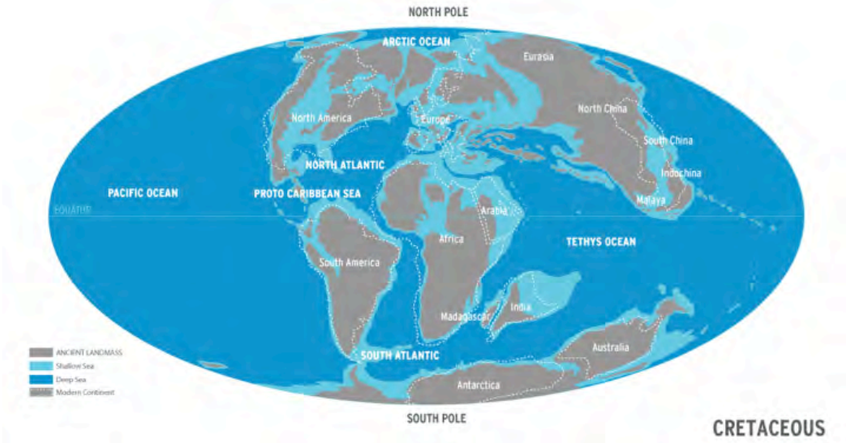


Figure 12 Plate reconstruction for the late Cretaceous

4.10 Drifting Apart

Around 65 million years ago, the continued effects of crustal stretching as a result of North Atlantic rifting as well as a localised ‘hot spot’ within the Earth’s mantle led to the creation of great volumes of magma that intruded and erupted to form the North Atlantic Igneous Province. This extensive area of igneous activity can now be found in the Inner Hebrides, the North Sea, the Faroe Islands, Iceland and eastern Greenland as well as in the north of Ireland.

Sheer lava cliffs at Hafnarberg, Reykjanes Geopark

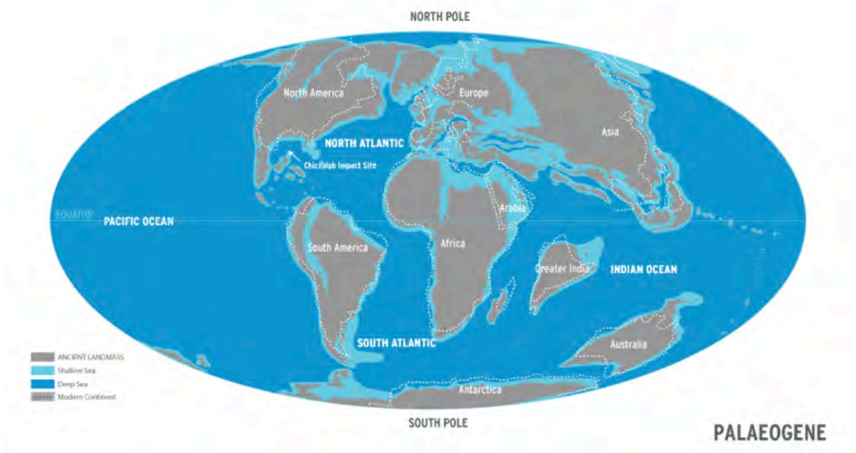


Figure 13 Plate reconstruction for the early Palaeogene

The main period of volcanic activity extended from around 60 to 55 million years ago and began with explosive eruptions that resulted in thick deposits of ash. This was then followed by the intrusion of a swarm or a group of related dykes along northwest to southeast fractures. In addition to the dykes, extensive lava flows issued from the northwest-southeast cracks creating great lava fields across northeastern Ireland, and the Inner Hebrides, and extending northwards to the Faroe Islands.

Kingscourt dyke swarm, Garrison sill in **Marble Arch Caves Global Geopark**, Ardamurchan ring complex, Mull flood basalts, Isle of Rum layered intrusion in **Lochaber**, Giant’s Causeway and Causeway Coast World Heritage Site in **Causeway Coast and Glens**.

Figure 14 Giant’s Causeway and Causeway Coast World Heritage Site and Glens Heritage Trust

4.11 A New Island (Quaternary)

The Atlantic Ocean is still opening with Greenland and Europe moving away from North America as volcanic activity along the mid ocean ridge continues to produce new crust, pushing the plates further and further apart. Located directly on and formed as a result of the mid ocean ridge is Iceland, the majority of which is formed of volcanic material that spewed out from the mid ocean ridge itself. The rocks here are much younger than elsewhere in the Drifting Apart area with the oldest rocks on Iceland being only 16 million years old.

Iceland is located at the intersection of the mid ocean ridge and the Greenland-Iceland-Faries ridge, thought to be the trail of a mantle plume (or hot spot). A hot spot is thought to be due to a plume of hot molten material rising through the mantle like smoke from a chimney. Although the plate above may move, the hot spot remains in the same position, and eventually a line of extinct volcanoes develops. This plume is now situated beneath central East Iceland, within the eastern branch of the volcanic rift zone.

Volcanic activity is still common on Iceland in the axial rift zones, with a great variety of volcanic systems present. The Western Volcanic Zone has receded somewhat with the Eastern Rift Zone taking over as the main rift in Southern Iceland in the last 3 million years. Relatively young volcanic rocks can be seen on the Rekyjanes Peninsula where eruptions from the last 11,500 years have formed the peninsula. However, by far the youngest rocks in the Drifting Apart story formed in the Eyjafjallojokull eruption in 2010 and as recently as 2015, when the Bárdarbunga fissure eruption produced an extensive lava flow north of Vatnajokull glacier north of Katla Geopark. covering an extensive area in the Katla Geopark.

Mid Atlantic ridge passes through Iceland with the Reykjanes Peninsul Rift in **Reykjanes Geopark**, the West Volcanic Rift Zone in **Saga** Aspiring Geopark, and the Easter Volcanic Rift Zone in **Katla Geopark.** The highly volcanic systems in Katla Geopark are fed by the Iceland mantle plume situated underneath the eastern most part of the Geopark.

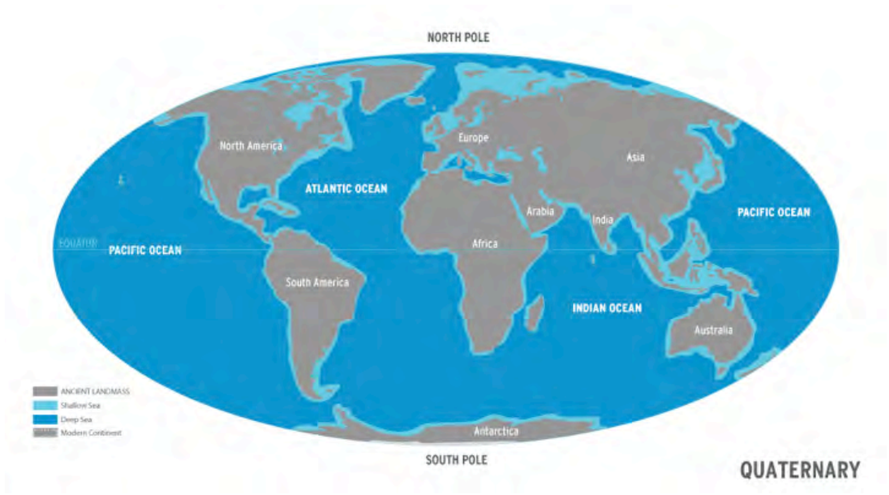


Figure 15 Plate reconstruction for the Quaternary

5 Summary

Iceland is the ideal place to end the Drifting Apart story, as it is here that many of the processes that led to the movement of tectonic plates in the 3 billion year history of the project area can be witnessed at the surface. Wilson Cycles have meant that many oceans have come and gone and the majority of the partners have been physically connected at least twice in this long history. This complex series of events means that there are many geological features that developed on the North American side of the Atlantic Ocean and are now stranded in Europe and features that developed on the European side are now found in parts of North America.

Geothermal activity at Gunnuhver,
Reykjanes Global Geopark

The Drifting Apart story is not just about geology but it is about making connections between people and place and finding out how these have been influenced by our 3 billion years of shared geological heritage.

Telling The Drifting Apart Story

DRIFTINGAPART

Northern Periphery and Arctic Programme

EUROPEAN UNION
Investing in your future
European Regional Development Fund