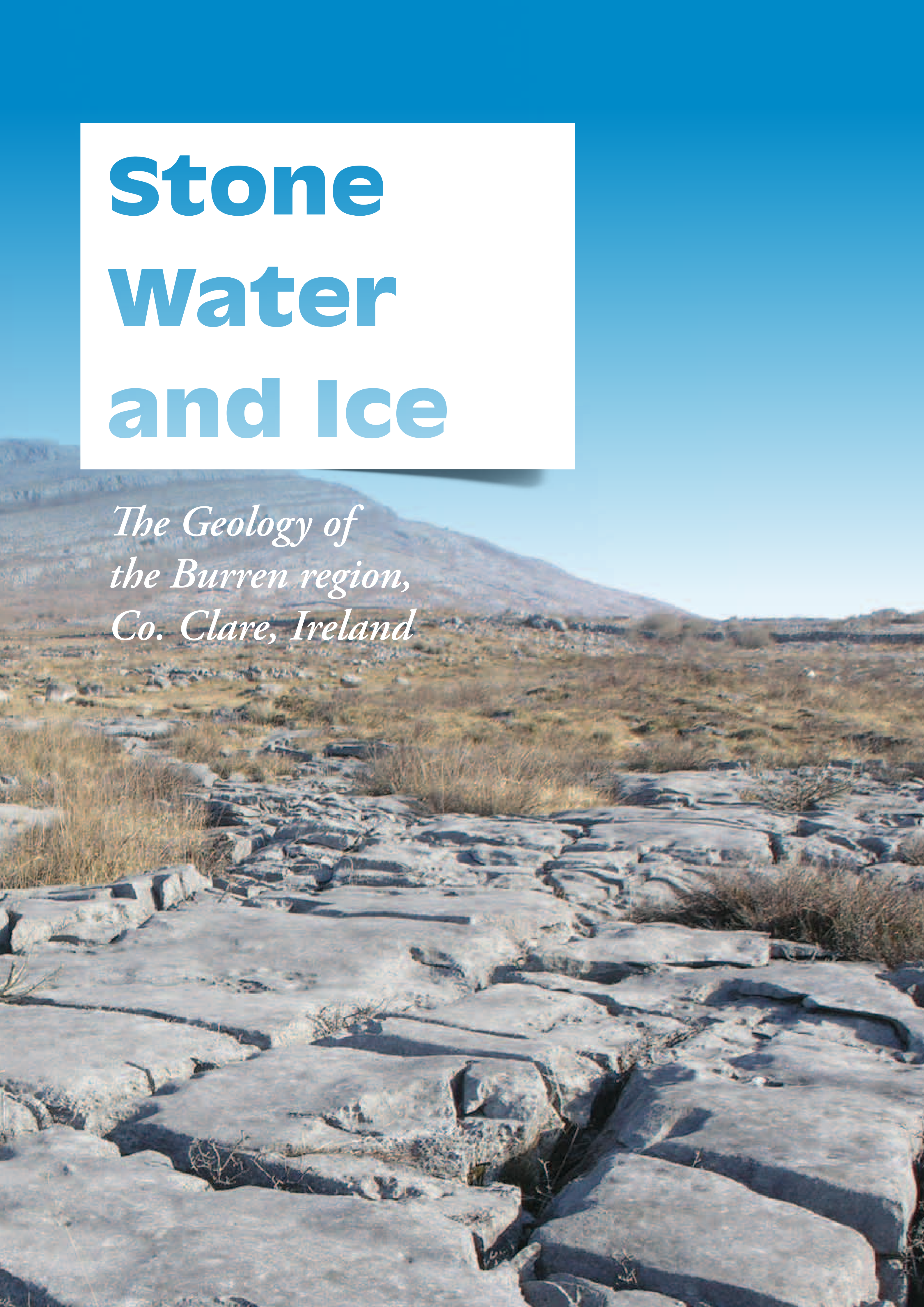
# Stone Water and Ice

*The Geology of the Burren region, Co. Clare, Ireland*



# The Geology of the Burren region, Co. Clare, Ireland

*by*

Dr. Maria E. McNamara

*&*

Dr. Ronán W. Hennessy

**First Edition**

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This publication was compiled by
Dr. Maria McNamara and
Dr. Ronán Hennessy.

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Photographs by
Maria McNamara and Ronán Hennessy

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This book was compiled as part of the NEED (Northern Environmental Education Development) project. NEED is a transnational European initiative that focuses on the development of geo-education resources in four regions on Europe's northern Atlantic periphery. NEED supports the development of geological learning resources, the promotion of an awareness of the landscape, and the establishment of sustainable contacts between education providers, visitor centres and the wider tourism community.

The Burren represents Ireland as one of the four European regions within NEED. The other countries are Norway, Finland and Iceland. NEED is coordinated in Ireland by the Burren Connect Project (www.burrenconnect.ie). For further information please visit www.geoneed.org.

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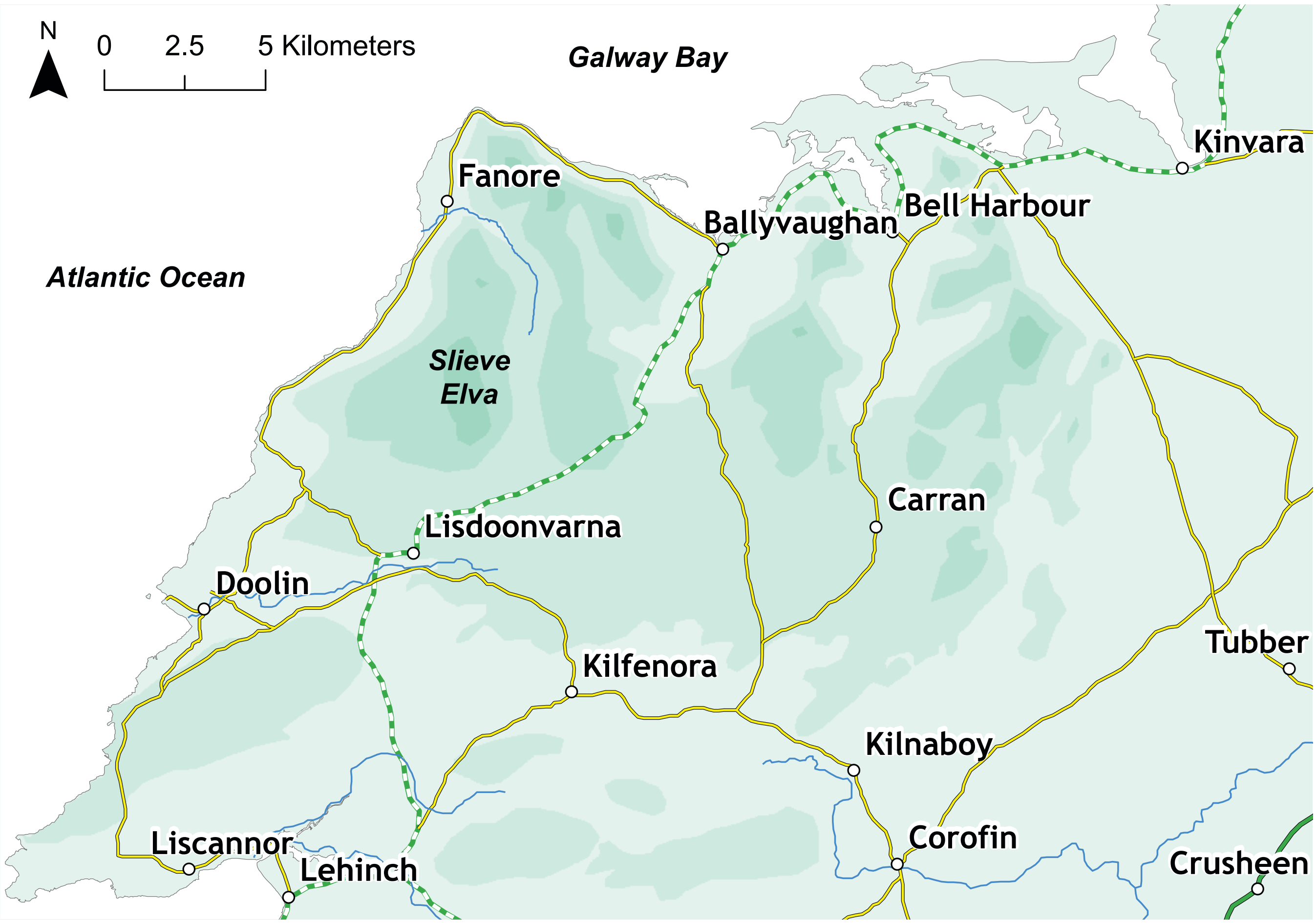


*Figure 1. The Burren Region*

# 1 Introduction

The publication was produced as part of the educational resources developed for the Northern Environmental Education Development (NEED) project. The objective is to provide a detailed review of the geology of the Burren region.

The NEED project is a transnational European initiative that focuses on the development of geo-education resources for schools and environmental education businesses in four regions on Europe's northern Atlantic periphery. The objective of NEED is to develop geological and environmental learning resources; to promote awareness of the local landscape among local inhabitants; and to establish sustainable business opportunities in environmental education for education providers, visitor centres and the wider tourism community. The Burren represents Ireland as one of the four European regions within the NEED project (the other countries include Norway, Finland and Iceland). The project is coordinated in Ireland by the Burren Connect Project (www.burrenconnect.ie). All education resources and learning activities developed for NEED are available on a dedicated website (www.geoneed.org). The NEED project is funded under the Interreg Northern Periphery Program.

There are several regional partners involved in the NEED (Burren) project. These include the Burren Centre Kilfenora, Burren National Park (NPWS), the Burrenbeo Trust, the Cliffs of Moher Visitor Experience, the Clare Farm Heritage Tours Co-operative, and the Burren Outdoor Education Centre. The NEED project national partners are the Geological Survey of Ireland, Clare County Council and Shannon Development.

## 1.1 The Burren region

The Burren region (Fig. 1) encompasses the landscapes of the Burren, the Cliffs of Moher, and the western part of the Gort-Kinvarra lowlands. The Burren and the Cliffs of Moher are major tourist attractions that are celebrated primarily for their spectacular scenery, but also for other aspects of their natural and cultural heritage, e.g. the internationally important seabird colonies at the Cliffs of Moher, and the diverse flora and archaeological monuments of the Burren. In contrast, the Gort-Kinvarra lowlands to the east comprise a relatively subdued, and less well-known landscape. Nonetheless, the geomorphology of these lowlands contrasts sharply with that of the rest of the target area.

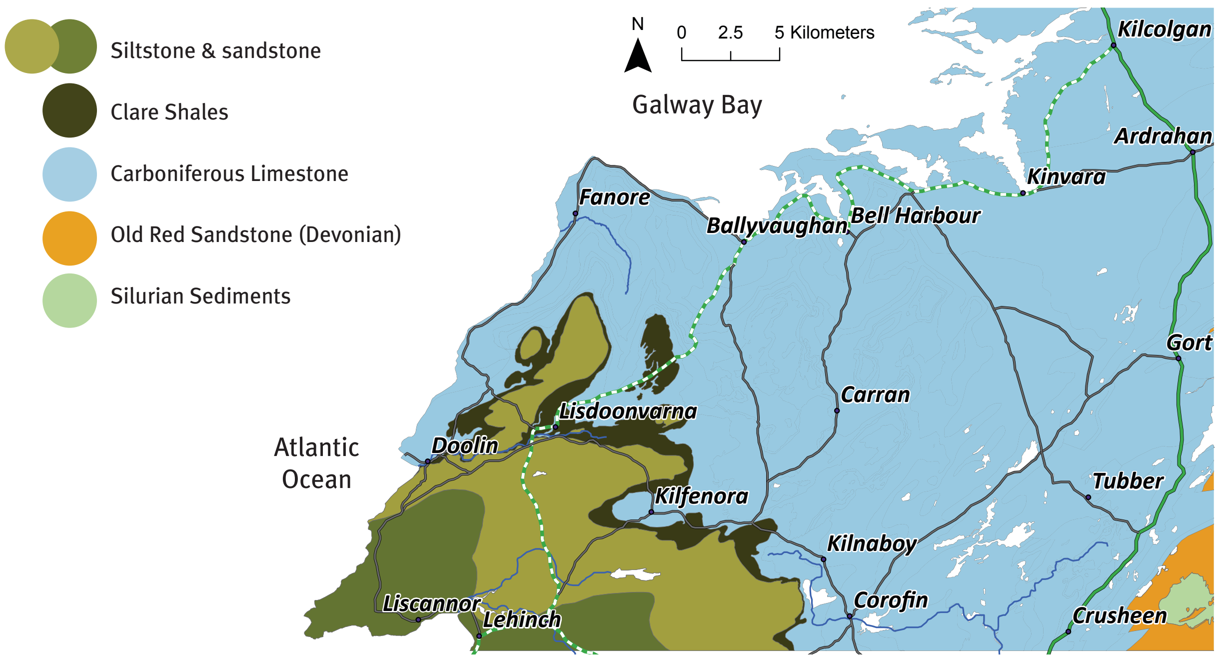


*Figure 2. Simplified geological map of the Burren region and surrounding area, showing limestone (pale blue), younger siliciclastic rocks (green/pale brown), and older siliciclastic and older Devonian Old Red Sandstone rocks (orange) in the Slieve Aughty Mountains*

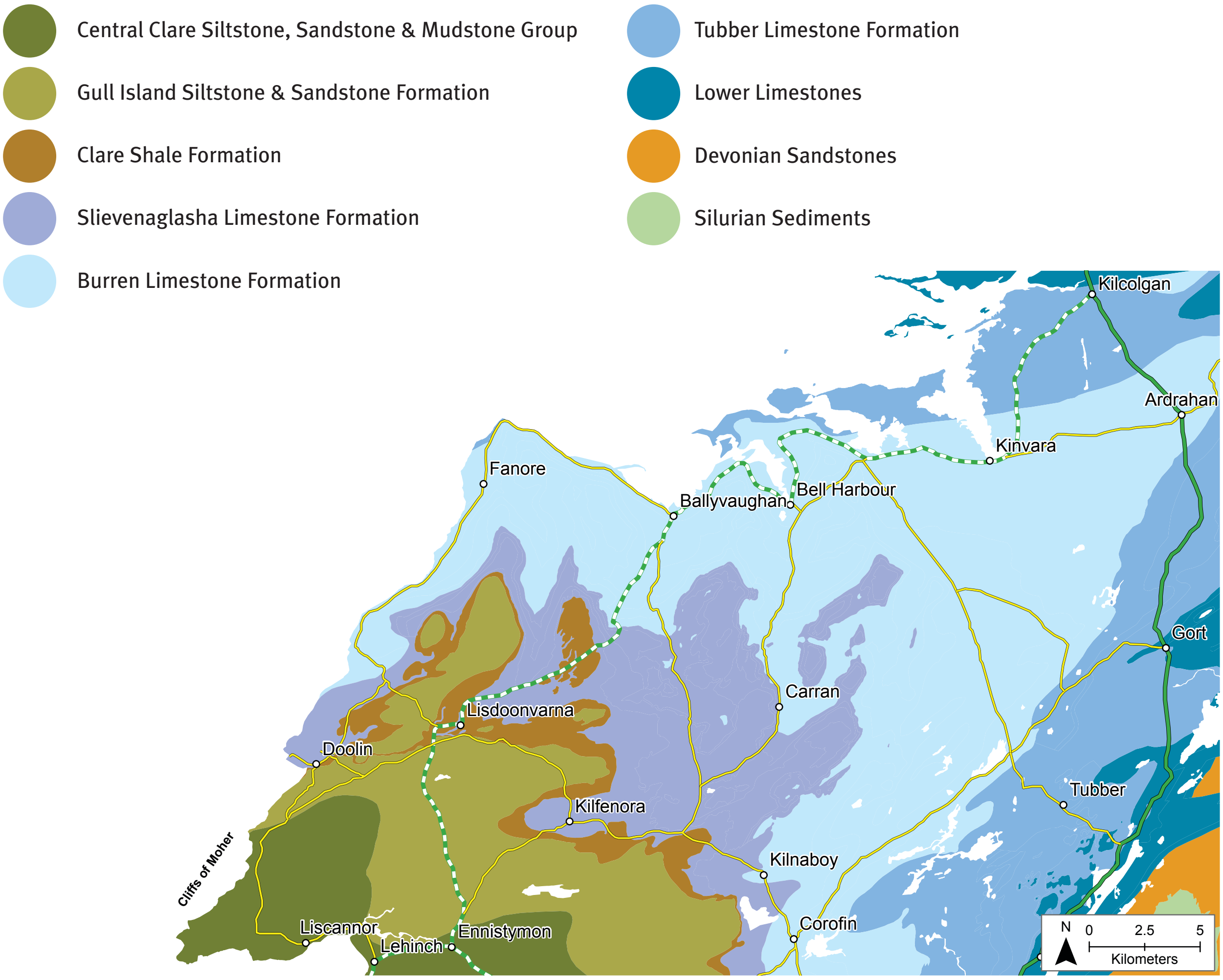


*Figure 3. Geological map of the Burren region (and south County Galway) showing the main lithological units*

The landscape of the Burren region is underlain by several different rock types: limestones in the north and east (i.e. the Gort-Kinvarra lowlands and most of the Burren), and sandstones, siltstones and shales (siliciclastic rocks) in the south and west (i.e. high ground in the west and centre of the Burren e.g. Slieve Elva, and the Cliffs of Moher). Siliciclastic rocks also occur outside, and to the southeast of, the target area in the Slieve Aughty Mountains east of Gort; these are older than the rocks in the Burren region (Figure 3).

Variations in the landscape across the region reflect not only rock type, however, but also the more recent geological history, such as the effects of glaciation and the duration of exposure. This report summarises the primary geological and geomorphological characteristics of the Burren region.

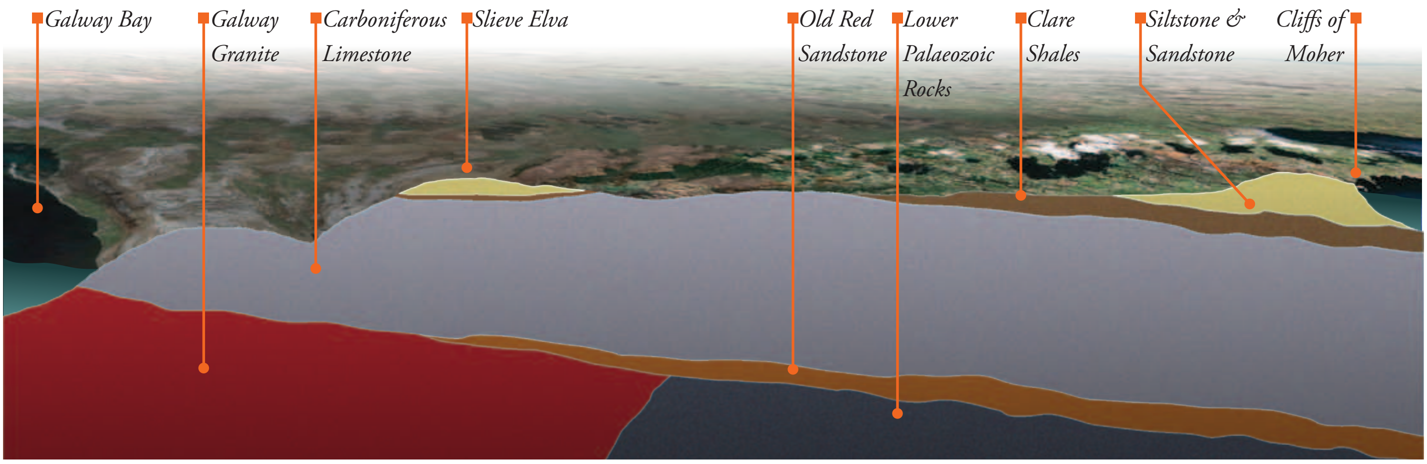


*Figure 4. Simplified geological cross section through the Burren region, showing the main rock types underlying the landscape*

# 2 Location of the Burren Region In Ireland

The Burren region has geographic coordinates corresponding to approximately 53° 05' N and 09° 15' W. It is bounded to the west by the Atlantic Ocean and to the north by Galway Bay (Fig. 2); the eastern boundary runs approximately from Kinvara in the north, through Gort, to the region south of the village of Tubber. The southern boundary runs south of the towns and villages of Corofin, Kilnaboy, Kilfenora, Lisdoonvarna and to the Cliffs of Moher. The location and extent of the three component landscape regions in the Burren region (the Burren, the Cliffs of Moher, and the western part of the Gort-Kinvarra Lowlands) are described below.

The eastern boundary of the Burren limestone uplands is the foot of the scarp at approximately 60 m OD (ordnance datum; above sea level) that extends from Corranroo Bay in the north to Kilnaboy in the southeast. The southern limit of the Burren limestone uplands can be defined as an irregular line that extends from Corofin through the towns and villages of Kilinaboy, Kilfenora, Lisdoonvarna, to Doolin at the coast.

Burren limestone uplands extend over ~360km$^2$ and form a gently inclined plateau that decreases from ~ 300 m OD in the north to ~ 75 m in the south. The highest point in the Burren is Slieve Elva, at 344 m OD. The only significant areas of lowland (below 50 m OD) are a narrow strip along the western coast (this strip averages 0.25-0.75 km wide except close to Doolin, where it widens in the lower part of the Aille River valley) and two valleys extending south inland for ~ 5 km each from Ballyvaughan and Bell Harbour. The Burren is characterised by a paucity of surface drainage, extensive areas of bare rock and rocky pasture, and cliffed and terraced hills.

The Gort-Kinvarra lowlands are characterised by an almost complete lack of surface drainage, abundant seasonal lakes (turloughs), and extensive underground drainage systems.

The Cliffs of Moher stretch for almost 8 km along the Atlantic coast from Doolin to Hag's Head and rise to a maximum of 214 m.

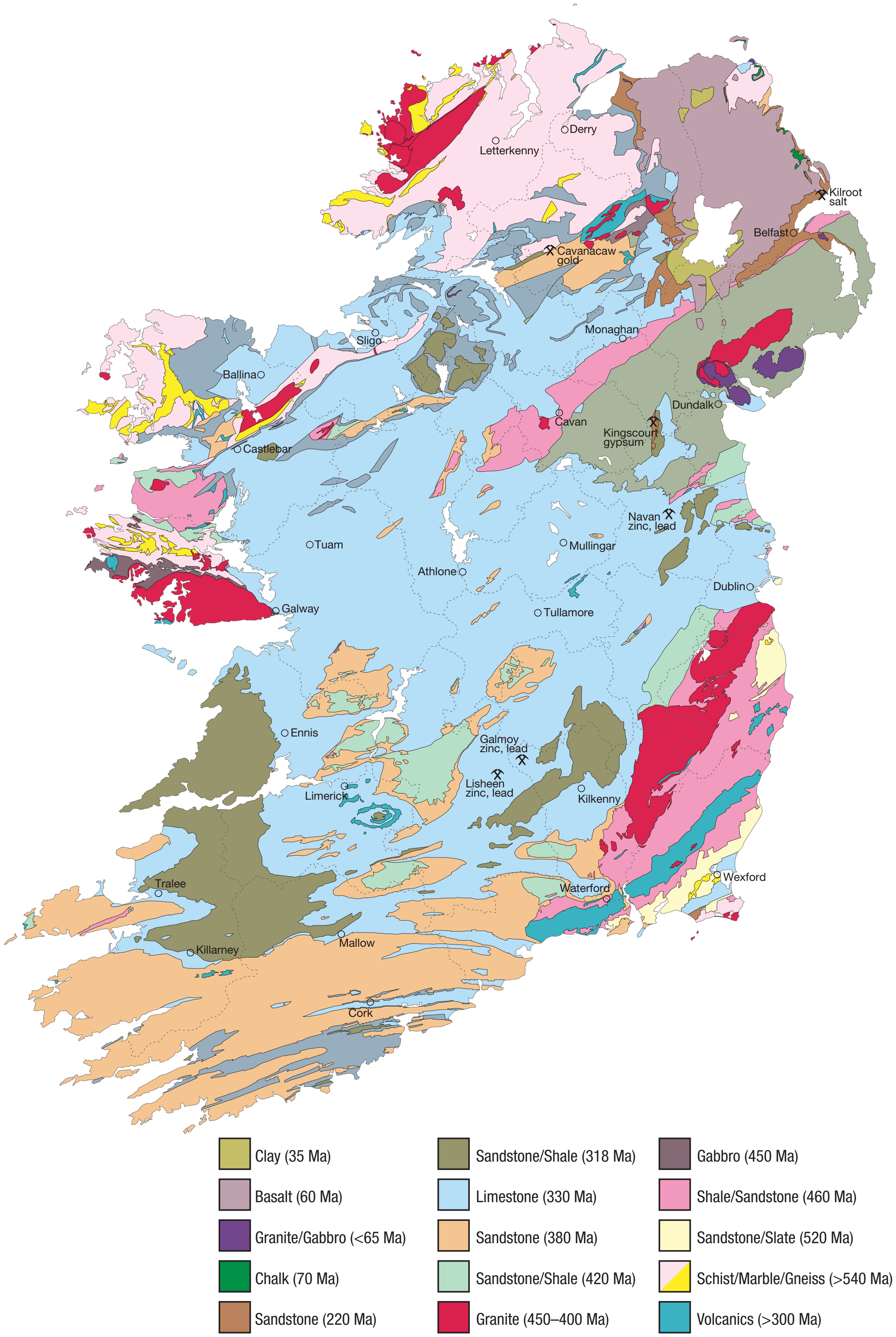


*Figure 5. Bedrock Geology Map of Ireland (Geological Survey of Ireland 1:1,000,000 Scale Map). From "Understanding Earth processes, rocks and the geological history of Ireland" published by the Geological Survey of Ireland. General key: blue and grey = limestone; greenish browns and beige = siliciclastic rocks; pinks = metamorphosed siliciclastic rocks; purples and reds = igneous rocks; yellow = quartzite*

# 3 Geology

## 3.1 The Burren region in the wider context of the geology of Ireland

Ireland's complex geological history has been evolving for over two billion years. It spans several major orogenies (mountain-building episodes), erosion of great mountain chains, the birth of oceans, and multiple ice ages. For much of Ireland's history, the north and south halves of the country (defined by a line between approximately Limerick in the southwest and Dundalk in the north) were located on separate continents up to ~5000 km apart.

Today, Ireland is a mosaic of sedimentary, igneous and metamorphic rocks (Fig. 5), most of which are Precambrian and Palaeozoic in age (i.e. older than 250 Ma (megaannum: million of years)). Much of the bedrock of Ireland is today blanketed by glacial drift, i.e. unconsolidated sediments that were deposited during the most recent glaciation.

The oldest rocks in Ireland are dated at around 1.7 billion years and crop out on the island of Inistrahull, off Malin Head, Co. Donegal. These, and similar rocks elsewhere in Ireland, are fragments of ancient continents and form much of the country's geological basement. Many of Ireland's younger rocks were associated with, or deformed by, the Caledonian (~400 Ma) and, later, the Variscan (~290 Ma) orogenies. The first of these resulted in significant deformation of rocks in Connemara and south Leinster, intrusion of granite batholiths, and extensive volcanic activity.

This orogeny also produced a major chain of mountains (the Caledonides), the vestiges of which stretch from the Appalachians of North America to the Arctic Circle in Norway. The Caledonian orogeny also generated the northeast-southwest grain of the landscape and rocks in central and northern Ireland. The Variscan orogeny did not affect Ireland as intensely as the Caledonian (as the zone of continental collision was located far to the south of the country), but nonetheless resulted in strong folding of rocks in the southern half of the country, producing the east-west grain that characterises the landscape in Counties Cork and Kerry.

The rocks of the Burren region record a relatively quiescent period in Ireland's geological history between these two major orogenies. Erosion of the Caledonian mountain chain, and deposition of significant volumes of sediment (the "Old Red Sandstones" that crop out in the anticlines of the Slieve Aughty Mountains and elsewhere in Munster) by large braided rivers was followed by a rise in sea level and deposition of limestones on a shallow-water, gently sloping, ramp in a submarine basin. This basin was later filled by sediment deposited by a complex of deltaic systems.

Despite this relative quiescence, the limestones and deltaic sedimentary rocks of the Burren region show evidence for periods of volcanic activity, oscillations in sea level, and sea floor subsidence, and were deformed to varying extents by the Variscan orogeny. These rocks were later uplifted and, as overlying rocks were eroded, brought to the Earth's surface.

As with the rest of Ireland, the landscape of the Burren region has been modified significantly by the effects of the most recent series of glaciations. Unlike elsewhere in Ireland, however, much of the Burren region is characterised by the rarity, or absence, of glacial drift.

The following sections describe the geology of the Burren region, including an introduction to the general geographic- and tectonic setting, the succession of rock units (stratigraphy), the characteristics of the ancient environments in which the rocks were deposited (palaeoenvironmental setting), and evidence for Earth movements (tectonic deformation). The geological evolution of the Burren region is summarised in Fig. 6.

| Age | Period / Epoch | Events |
|---|---|---|
| 0 | Holocene | Extensive Karsification |
| 0.01 – 1.8 | Pleistocene | Glaciation. weathering of rock at the surface during interglacial periods and erosion of this weathered rock during glacial periods. Increasing exposure and karstification of limestone in the Burren |
| 23 | Neogene | Exposure of the Burren region above sea level. Intense weathering and erosion of the shales, siltstones and sandstones. Extensive karistification in the Gort-Kinvara Lowlands. Formation of Ballyvaughan and Tulough Valleys and the Carran Depression. |
| 65 | Palaeogene | |
| 145 | Creatceous | Prolonged periods of exposure above sea level. Desert conditions on land for much of this time. Minimal or no deposition of sediment. Several phases of uplift and erosion. |
| 199 | Jurassic | |
| 251 | Triassic | |
| 299 | Permian | |
| 359 | Carboniferous | Flooding of land and formation of shallow sea. Deposition of shallow marine limestones followed by deep marine mudstones, slope deposits and deltaic sandstones and siltstones. Burial of these marine sediments. Gentle deformation during Variscan orogeny. |
| 416 | Devonian | Caledonian orogeny (mountain-building episode). Intrusion of Galway granite. Intense erosion of Caledonian mountain chain and deposition of Old Red Sandstones. |
| 443 | Silurian | No rocks or evidence of events during these periods in the Burren region. |
| 488 | Ordovician | |
| 542 | Cambrian | |
| 2500 | Proterozoic | |
| 4560 | Archaean | |

*Figure 6. Geological timescale showing the major events occurring in, and affecting the rocks of, the Burren region*

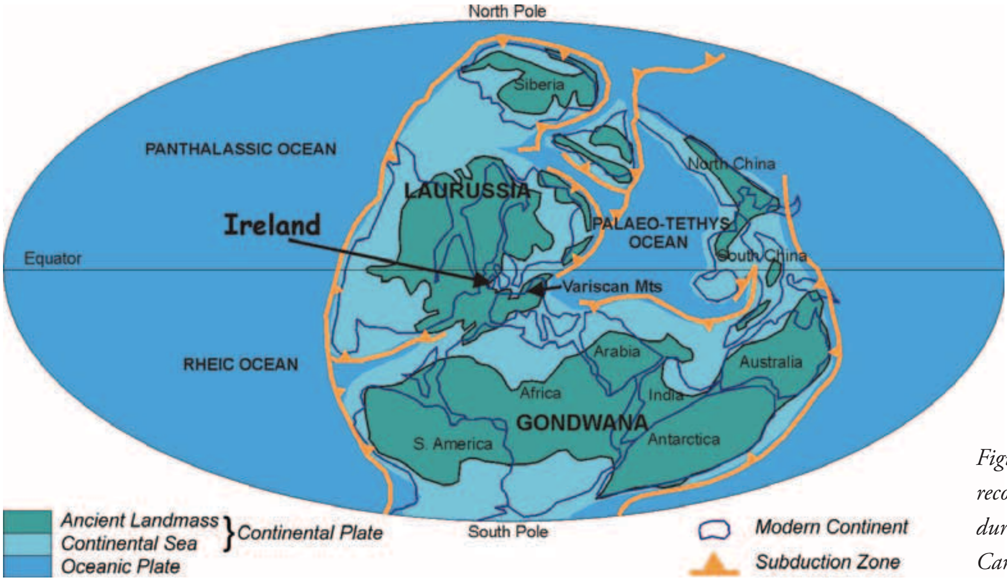


*Figure 7. Plate reconstruction during the Early Carboniferous period*

## 3.2 Palaeogeographic and tectono-stratigraphic setting

The rocks of the Burren region were deposited during the Carboniferous period in Earth history, which spans 359-299 Ma. In the Early Carboniferous, the palaeocontinents of Gondwana and Laurussia were separated by the palaeo-Tethys Ocean; Ireland was located approximately 10°S of the equator (Fig. 7). Closure of the palaeo-Tethys Ocean was associated with strike-slip faulting and widespread crustal extension that generated several intracratonic sedimentary basins (in Laurussia) along the flanks of the Caledonides. These basins possessed few connections to the major oceans at the time and facilitated the accumulation of thick volumes of sediment.

Subsidence in the Burren region during the Viséan stage (328-345 Ma) of the Early Carboniferous allowed the deposition of a thick (~800 m) succession of limestones on a shallow-water platform. This platform passed southwards into a basin (the Shannon Trough), in which the deep-water calciturbidites of West Clare and North Kerry were deposited at the same time as the limestones in the Burren region. The limestones are succeeded abruptly by siliciclastic rocks deposited during the Namurian stage (328-316 Ma) of the Carboniferous. This transition reflects a dramatic deepening of the basin (now termed the Clare Basin) possibly due to rapid subsidence and / or glacio-eustatic changes in sea levels, and access to new sediment source areas. The basin was tectonically relatively quiescent during its evolution. The palaeogeography of Ireland during the Viséan and Namurian is summarised in Fig. 8.

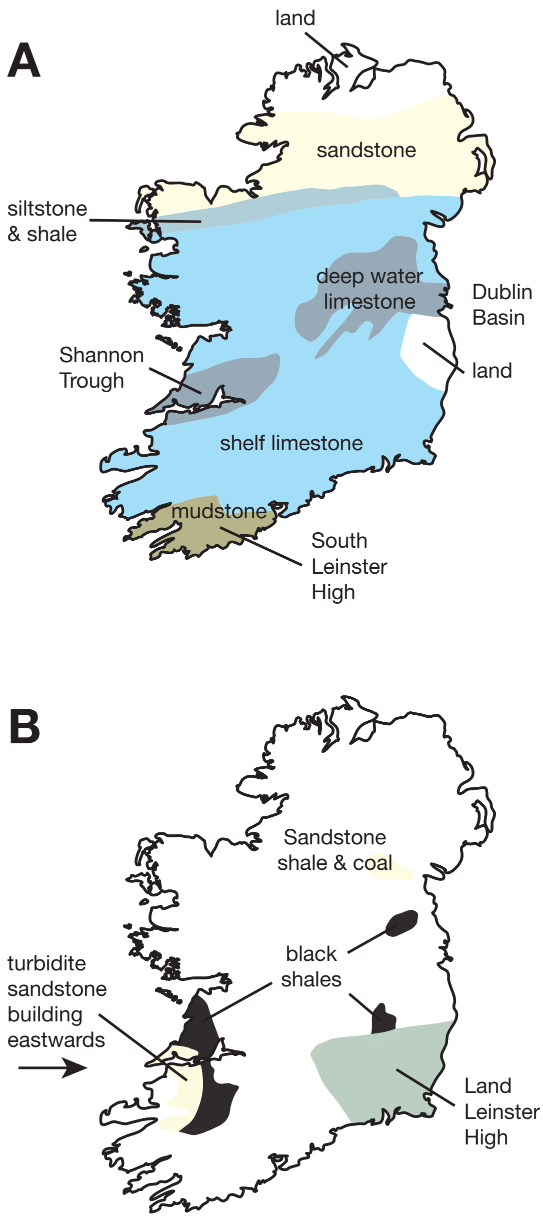


*Figure 8. Palaeogeographical maps of the landmass of Ireland at around 330 Ma (A) and 318 Ma (B)*

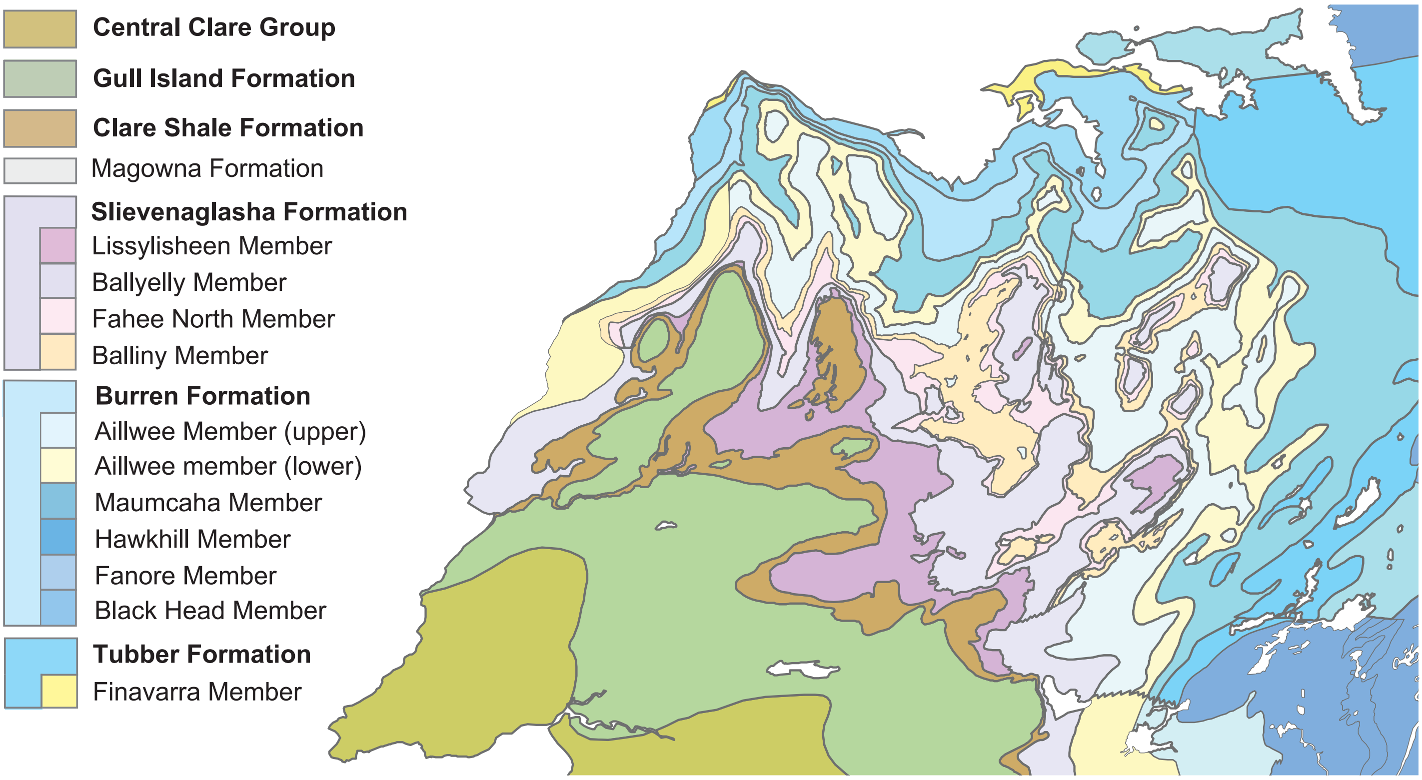


*Figure 9. Detailed geological map of the Burren region with key to formations and members. Map is modified from GSI online database*

## 3.3 Stratigraphy (succession of rocks)

Different rock units are represented on a geological map as a hierarchical series of groups, formations, and members that are named usually on the basis of the location where they were first described, or are best seen. The most fundamental division on a map is the formation, which is a distinctive sequence of related or interlayered rock types that differ significantly from adjacent rock sequences. Formations can be divided into members on the basis of more subtle differences in rock type, or can be combined into larger divisions called groups.

The total thickness of the sedimentary succession exposed in the Burren region is approximately 672 m (507 m of limestone and 165 m of siliciclastic rocks); the region is underlain by an additional ~300 m of limestone. The succession of rocks is divided into several formations, the primary features of which are summarised in Fig. 9 and described below in detail from oldest to youngest.

### 3.3.1 *Tubber Formation*

The Tubber Formation is 300 m thick and was deposited during the Arundian (341-339 Ma) to Holkerian (339-337.5 Ma) stages. It comprises relatively pure (i.e. with a low clay content) medium-grey crinoidal limestones (calcarenites) with chert bands, rare thin beds of shale, and, in the upper parts of the formation, common dolomitic layers. The macrofauna is dominated usually by crinoid ossicles, with minor brachiopods, solitary and colonial corals (fasciculate lithostrotionids), and bryozoans.

The Tubber Formation is exposed in only the extreme southeast and north of the target area, north of Lough Muckanagh and on Black Head and Finavarra Point, respectively. In the southeast of the target area, the formation is undifferentiated; in the north, it is represented by the Finavarra Member. This member is at least 26 m thick (its base is not exposed) and comprises grey, thickly bedded (1-3 m thick), strongly bioturbated and partially dolomitised limestones (Fig. 10). The macrofauna includes fasciculate solitary rugosan corals, tabulate corals,

*Figure 10. Dolomitised limestone of the Finavarra Member of the Tubber Formation, at Black Head*

*Figure 11. Fasciculate colonial corals of the Finavarra Member of the Tubber Formation at New Quay. Photo approximately 15 cm wide*

*Figure 12. Cerioid colonial corals in Burren Formation limestones in Burren National Park. Each corallite is approx. 7-10 mm diameter*

brachiopods and gastropods. Several beds with abundant in situ (Fig. 11) and overturned colonial corals are exposed on the Finavarra peninsula. The top of the member (and Tubber Formation) is marked by a dolomitic horizon above which the first cerioid lithostrotionid corals appear. The Tubber Formation represents deposition on a shallow water shelf. The Finavarra Member represents deposition within the photic zone of a shallow water, open marine, subtidal environment.

### 3.3.2 *Burren Formation*

The Burren Formation is 370-390 m thick and was deposited during the Asbian stage (337.5-333 Ma). It comprises light- to dark grey, relatively pure, massive to medium-bedded skeletal limestones. The base of the formation is marked by a dolomitic horizon above which the first cerioid lithostrotionid corals appear (Fig. 12); the top of the formation is an irregular, prominent, palaeokarst surface (i.e. a horizon that was exposed subaerially during deposition of the formation) overlain by a horizon rich in the foraminifer Saccaminopsis.

The formation crops out in the north, northwest, and extreme east of the Burren region. In the northwest of the Burren, this formation comprises five members: the Black Head, Fanore, Dangan Gate, Maumcaha, and Aillwee Members. In the east of the Burren and the Gort Lowlands, the lower three members are amalgamated into the Hawkhill Member.

The *Black Head Member* is 88 m thick and comprises homogenous, medium- to thickly bedded limestones with abundant cerioid rugosan corals, especially in its basal part. Tabulate corals, gastropods and bivalves are common, and brachiopods, rare. The microfauna includes fragments of the green alga *Koninckopora*. This member represents deposition in subtidal settings within the photic zone and above normal wave base.

The *Fanore Member* is 46 m thick and comprises medium-bedded limestones (often dolomitised) and thin interbedded shales; the top bed of the member contains chert. *In situ* fasciculate corals (e.g. *Lithostrotion* spp.) and bryozoans are common locally; *Koninckopora* is rare. This member represents deposition below normal wave base.

The *Dangan Gate Member* is 22 m thick and comprises uniform, thick-bedded limestones with rare fasciculate corals; it is capped by a dolomitic horizon. This member is recognised only in the north of the Burren and is therefore amalgamated into the Fanore Member. The microfauna includes fragments of the green alga *Koninckopora*. This member represents deposition in subtidal settings within the photic zone and above normal wave base.

The *Hawkhill Member* is the equivalent of these three members in the eastern Burren and Gort Lowlands. It is 135.5 m thick and comprises bryozoan-rich skeletal limestones and is capped by chert-rich limestones and a dolomite horizon. This member represents deposition below normal wave base.

The *Maumcaha Member* is 80 m thick and comprises pale-grey massive limestones; macrofossils are rare, but *Koninckopora* is abundant, indicating deposition below normal wave base. The member is capped by two clay bands (Figs. 13, 14) and an irregular palaeokarstic surface with rhizoliths. The clay bands ("clay wayboards"), and similar clay bands elsewhere in the formation, are considered to represent palaeosols (fossil soils) that developed on a palaeokarst surface following a fall in sea level during deposition of the formation.

*Figure 13. Contact between the Maumcaha and Aillwee Members of the Burren Formation. The prominent notch in the cliff is formed by preferential erosion of the clay bands (palaeosols) at the top of the Maumcaha Member*

The *Aillwee Member* is 152 m thick and is divided into an upper and lower part based upon the presence of the spiriferid brachiopod *Davidsonia septosa*.

The member is characterised by alternations between thick (10-12 m) intervals of limestone and thin (usually <0.2 m thick) clay bands. The lower part of each limestone interval contains few macrofossils; fragments of bryozoans occur. The upper part of the limestone section of each cycle is usually highly fossiliferous (including locally abundant brachiopods (Fig. 15) and fragments of Koninckopora), capped by a palaeokarst surface, and overlain by a clay band.

This member represents deposition during cyclical variations in sea level. The unfossiliferous limestones in the lower part of each cycle were deposited in deep, quiet, subtidal environments; the fossiliferous upper parts of each cycle represent deposition under progressively shallow-water conditions, culminating in limestone emergence and pedogenesis (soil formation). The clay bands include clay minerals that may be of volcanic origin; there was active volcanism SE of Limerick during the Early Carboniferous.

Twelve cycles are recorded in the Burren (only nine of which form prominent terraces); similar cycles occur in limestones elsewhere in Ireland, the UK, and beyond, and reflect glacio-eustatic changes in sea level.

*Figure 14. Palaeosol at the top of the Maumcaha Member of the Burren Formation. Palaeosol is approx. 200 mm thick*

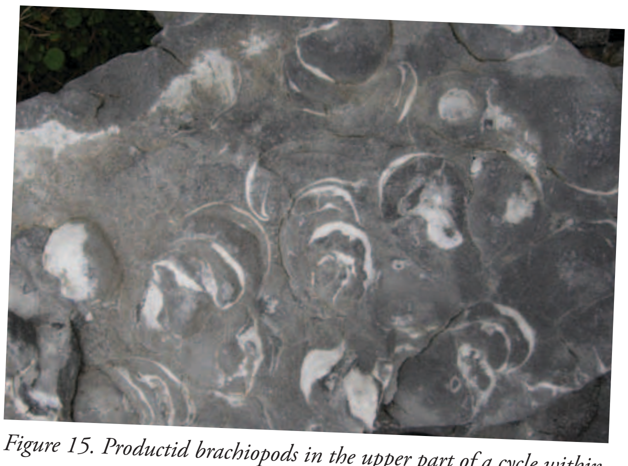

*Figure 15. Productid brachiopods in the upper part of a cycle within the Aillwee Member of the Burren Formation. Each shell fossil is approx. 35-45mm wide*

### 3.3.3 *Slievenaglasha Formation*

This formation is ~ 91 m thick and was deposited during the Brigantian stage (333-326 Ma). It comprises cherty limestones (Fig. 16) with crinoidal intervals. Its base is an irregular, prominent, palaeokarst surface overlain by a horizon rich in the foraminifer *Saccaminopsis*; its top is defined as the top of the limestone bed immediately underlying the phosphates of the Magowna Formation. The formation crops out in the central and southeast parts of the Burren region and comprises the following four members:

The *Balliny Member* is 36 m thick and comprises cherty, interbedded crinoidal packstones and grainstones, and darker, nodular wackestones; rugose corals dominate the macrofauna. This member represents cyclical deposition in deep to shallow subtidal environments.

*Figure 16. Limestones of the Balliny Member of the Slievenaglasha Formation (near Poulcraveen) with thin dark-coloured chert layers. Chert bands are approx. 50 mm thick*

The *Fahee North Member* is 25 m thick and comprises dark grey, cherty, nodular wackestones and packstones; both the base and top of the member contain abundant fossils. This member represents deposition between normal- and storm-wave base.

The *Ballyelly Member* is 30 m thick and comprises medium-bedded nodular wackestones and thickly bedded crinoidal packstones, with chert-rich horizons. This member represents deposition between normal- and storm-wave base.

The *Lissylisheen Member* is 4 m thick and comprises alternations of wackestones and crinoidal packstones and grainstones deposited between normal- and storm-wave base.

### 3.3.4 *Magowna Formation*

This formation is up to 3 m thick, exposed only intermittently, and passes laterally into the Cahermacon Member of the overlying Clare Shale Formation. It is of Brigantian – Namurian age and comprises dark micritic limestone and black calcareous shale with phosphate; the macrofauna are rugose corals, goniatites and nautiloids.

Deposition of limestones ceased with the Magowna Formation. The following formations comprise siliciclastic rocks of the Shannon- and Central Clare Groups and were deposited during the Namurian.

### 3.3.5 *Clare Shale Formation (Shannon Group)*

This formation is up to 12-15 m thick in the Burren region and is highly condensed (it is up to 180 m thick in the region of the Shannon Estuary). It comprises black shales with phosphate, carbonate nodules, and chert, and crops out in an irregular arc from Doolin to Slieve Elva and towards, but southwest of, Corofin. North of Kilfenora, the boundary between this formation and the underlying Visean limestones is a non-sequence, i.e. the Clare Shale Formation lies unconformably on the limestones of the Slievenaglasha Formation; south of Kilfenora, the Clare Shale Formation is underlain by the Magowna Formation, i.e. the non-sequence is not as marked. The top of the formation in the Burren region is defined by the first fine-grained sandstone of the overlying Gull Island Formation. Further south, in West Clare, however, the Clare Shale Formation and Gull Island Formation are separated by the Ross Sandstone Formation.

This formation comprises several informal members:

The *Cahermacon Member* ("cherty shales") crops out south of Kilfenora; it is 0-5 m thick and comprises chert-rich mudstones with abundant nodules of phosphate.

The *Phosphate Shale Member* is 0-4 m thick and comprises black mudstones with lenticular bodies and horizons of pyritic phosphate. The phosphate horizons are continuous over several kilometres and contain abundant fish remains and conodonts.

Figure 18. Slumped pro-deltaic slope deposits of the Fisherstreet Slide. Cliff is approx. 10m

The *Goniatite Shale Member* is 12 m thick and comprises black shales with abundant, flattened, sometimes pyritised goniatites (Fig. 17) and horizons of carbonate concretions that contain three-dimensional goniatites. Plant fragments also occur.

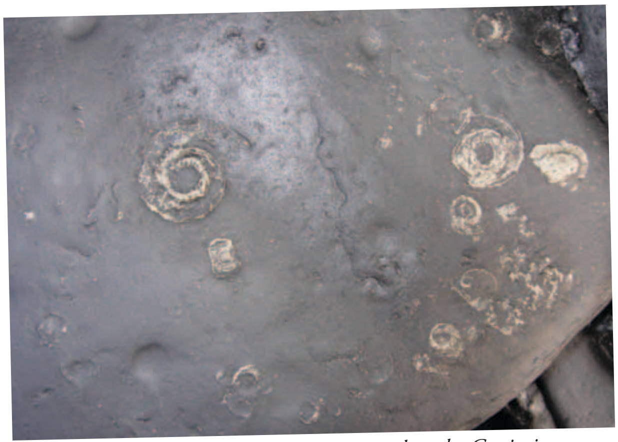

*Figure 17. Pyritised, flattened goniatites within the Goniatite Shale Member of the Clare Shale Formation at Fisherstreet. Large specimen on left is approx. 25 mm diameter*

This formation represents an abrupt transition to deep-water conditions, i.e. inundation of the shallow-water carbonate platform on which the underlying Visean limestones were deposited. The black shales and, in particular, the phosphate deposits, are characteristic of extremely slow sedimentation rates (sediment starvation) and suspension deposition of clays under deep, euxinic conditions. The fossils all represent pelagic fauna. The deep basin in which these sediments accumulated was approximately 100 x 60 km.

### 3.3.6 *Gull Island Formation (Clare Shale Group)*

This formation is 140 m thick in the Burren region but is 550 m in the region of the Shannon Estuary. It crops out in the west and southwest of the Burren region and comprises predominantly fine-grained sandstones and siltstones. The beds close to the base of the formation are characterised by spectacular synsedimentary deformation (the Fisherstreet Slide, Fig. 18) and exhibit features such as recumbent and near-isoclinal folds and low angle faults and thrusts. The slumping indicates southeast-dipping palaeoslopes.

The Fisherstreet Slide is overlain by a rippled sandstone bed that contains flute marks, tool marks, and sand volcanoes (Fig. 19) that formed during late-stage dewatering of the slumped beds. The interbedded siltstones can exhibit wrinkling (Fig. 20), lamination, or can be homogenous; the latter condition may indicate sediment thixotropy. The upper part of the formation comprises planar-bedded and channelised sandstones with interbedded siltstones. This formation represents tubiditic deposition on an unstable shelf margin, possibly a pro-deltaic slope, that prograded eastwards into the Shannon Trough from a land mass to the southwest.

*Figure 19. Sand volcano in slumped pro-deltaic sediments of the Fisherstreet Slide*

*Figure 20. "Elephant skin" texture on the base of a slumped sandstone bed in the Fisherstreet Slide*

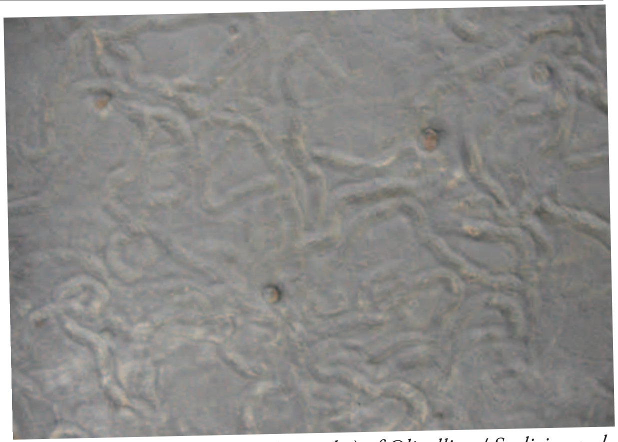

*Figure 21. Horizontal traces (squiggles) of Olivellites / Scolicia, and vertical (holes) burrows, in siltstone at the Cliffs of Moher*

### 3.3.7 *Central Clare Group*

This group is ~200m thick in the Burren region but is ~900m in the region of the Shannon Estuary, and crops out in the extreme southwest of the Burren region, at the Cliffs of Moher. The base of the group in the Burren region is approximate. The group is divided into five cyclothems (repeated cycles of sandstone, siltstone, and mudstone) separated by intervals of condensed marine mudstones. Only the lowermost two cyclothems (I (Tullig) and II (Kilkee)) crop out in the Burren region.

Each cyclothem commences with 7-18 m of laminated marine mudstones and coarsens upwards into 35-80 m of massive grey siltstones overlain by thick-bedded, laminated and cross-bedded sandstones. The mudstones typically contain brachiopods, gastropods, crinoids and rare corals. The siltstones often exhibit evidence of synsedimentary deformation, e.g. flow-folding, ball and pillow structures, sand volcanoes, and growth faults. The sandstones are typically graded and exhibit ripples and abundant trace fossils. Channel sandstones occur throughout the succession, are erosively based, and fine upwards from fine- to medium sand. Trace fossils are abundant. The most abundant trace fossil, a meandering horizontal trace with a prominent medial ridge and spreiten, has been interpreted as *Olivellites* and as *Scolicia* (Fig. 21). Other trace fossils present include *Zoophycos*, *Olivellites* and *Rhizocorallium,* with minor *Diplichnites, Helminthoides* and *Arenicolites.*

This group represents deposition in a shallow-water deltaic system prograding in a deep basin from a large Avalonian landmass to the southwest. The deltaic sediments are fine-grained, river-dominated, and comprise primarily mouth-bar deposits with moderate wave-reworking, i.e. they are characterised by alternation of phases of sheet sandstone deposition (possibly during high discharge from distributaries, i.e. flooding) and more quiescent periods in which the sediments were reworked by bioturbators and waves. The siltstones and sandstones are compositionally uniform, comprising quartz-rich sand with only 1.2% feldspar. The sediments exposed at the Cliffs of Moher represent mouth-bar deposits.

Delta slope fronts were most unstable where rivers fed sediment to the shelf-slope break. The marine mudstones represent repeated transgressions due to glacio-eustatic changes in sea level; a distinctive band of marine mudstones, known locally as the "Moher Shales", occurs immediately above the prominent Moore's Bay Sandstone that forms a platform at the top of the cliffs close to the Cliffs of Moher Visitor Centre (Fig. 22).

In summary, the sedimentary succession in the Burren region records the evolution of the depositional environment from a shallow marine carbonate shelf to a deep marine basin, into which a massive delta system prograded from the SW. The limestones are typically massive, bioclastic and fossiliferous to crinoidal and were formed in a clear, open-water setting distant from sources of terrigenous sediment. The apparent uniformity of the limestone succession belies subtle variations in lithology that reflect high frequency, glacioeustatic, fluctuations in sea level. These changes in sea level continued during deposition of the overlying siliclastic sediments of the Clare Basin.

Deep basinal shales are overlain by slumped slope deposits and then by deltaic shelf sediments deposited in a humid, brackish, tropical basin with few connections to the ocean. The shelf sediments were derived from rivers flowing from the southwest and include prominent intervals of mudstones that represent fully marine conditions that developed during a rise in sea level. Fig. 23 is a detailed summary of those events that occurred during the Carboniferous.

*Figure 22. The upper part of the Cliffs of Moher close to the Cliffs of Moher Visitor Centre, showing the Moore's Bay sandstone (thick bed) and overlying marine mudstones ("Moher Shales")*

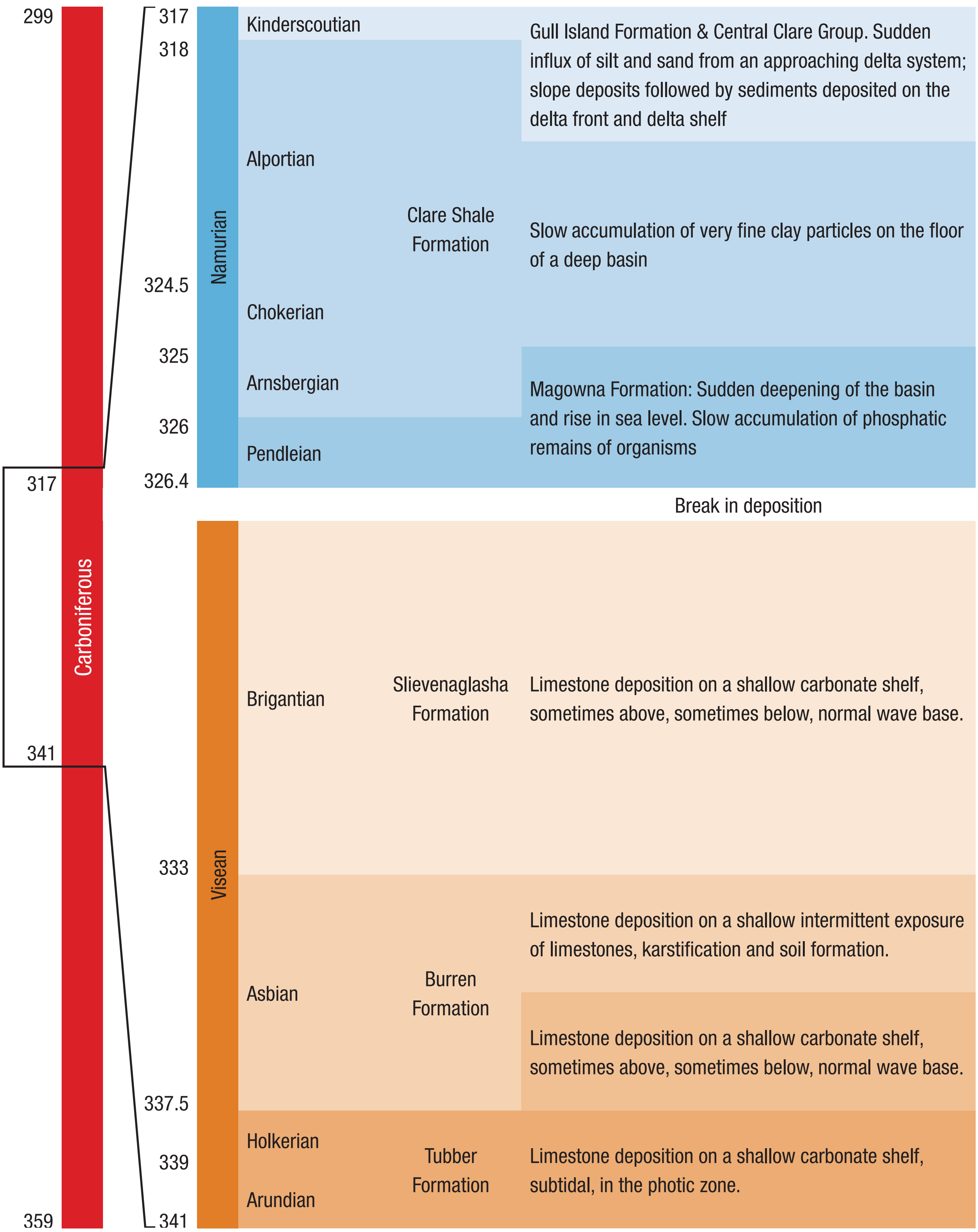


*Figure 23. Geological summary of the events affecting the Burren region during the Carboniferous*

## 3.4 Tectonic deformation (folding, faulting, and jointing)

The rocks of the Burren region are relatively undeformed. Nonetheless, they do exhibit evidence of the late Carboniferous Variscan orogeny (that resulted from the closure of the Rheic Ocean and subsequent collision of Laurussia and Gondwana) that formed the supercontinent Pangaea. The effects of this orogeny vary across the Burren region. In the north and west, the limestone beds dip by only 2-4° S, with minor 100 m - scale variations that reflect subtle flexure of the strata. This limited deformation may reflect the stabilising presence of the Galway Granite pluton underneath the sedimentary succession in this area. In the southeast of the Burren region, however, the dip of the limestone strata is often 10°S. This regional trend is superimposed by several km-scale asymmetric and monoclinal folds, such as those visible at Mullaghmore (Fig. 24), Slieve Roe and Clooncoose. The axes of these folds trend NNE-SSW, indicating that they may be the result of reactivation of northeast-southwest trending Caledonian structures.


*Figure 25. Google Earth image of Black Head showing prominent set of approx. N-S trending non-stratabound joints*

*Figure 24. Folded limestones of the Slievenaglasha Formation at Mulloughmore*

Subvertical fractures are extremely prominent, and abundant, features of the limestones of the Burren region as they are sites of preferential dissolution that have been exploited by rainwater to form fissures termed grikes (see Karstification, below). Contrary to popular belief, not all of the fractures represent joints. In fact, the dominant set of fractures, which trends approximately north-south, actually comprises mineralised veins (Figs. 25, 26). These veins are pervasive (both geographically and vertically through the sequence (non-stratabound)), clustered, and reflect north-south directed compression during the Variscan orogeny. Their non-stratabound character reflects their formation at depth within the crust (>1.25 km), in conditions that promoted fracture propagation across mechanical boundaries (bedding planes). Joints exhibiting other orientations are regularly spaced, stratabound, and restricted in their geographic extent. These structures are considered to have formed during uplift; their more variable orientation reflects local torsion or flexure of the limestone strata.

*Figure 26. N-S orientated calcite vein exposed at the coast at Gleninagh*

Faults are extremely rare in the Burren region. There are only three mapped examples, each of which is a normal fault with a slight sinistral sense of shear: at Black Head in the northwest, McDermott's Fault northwest of Carran, and Glencolumbkille, northeast of Carran. The apparent displacement on each fault is minimal, undoubtedly <200 m. Some workers consider that many lesser faults may exist in the Burren but are obscured by the extremely abundant fractures that permeate the succession.

## 3.5 Post-Namurian geology

There are no rocks younger than the Namurian in the Burren region, although comparison with the sedimentary succession in Kerry suggests that up to 2.5 km of sediments may have been deposited during the late Carboniferous, much of which may have been eroded during the Variscan orogeny. The lack of Permian and Mesozoic sediments in the region may reflect persistence of the latter above sea level. Furthermore, Ireland is considered to have been land throughout much of the Cenozoic, with unequivocal evidence of terrestrial sediments throughout the south of the country, and subaerial volcanics in the north. Because of the dearth of post-Carboniferous sediments in the Burren region, its uplift history is poorly resolved. Regardless of the data source, however, it is clear that several periods of uplift affected the Burren region, most likely during the late Carboniferous (~300 Ma), mid-late Jurassic (~170 Ma), and late Cretaceous-Early Cenozoic (~65 Ma). The region is considered to have been exposed to subaerial weathering and erosion processes since the early Cenozoic, i.e. 50-60 Ma. These terrestrial denudation processes are responsible for the removal of the Namurian siliciclastic cover from over much of the Burren region and are discussed in more detail in Section 4.1.

The Pleistocene glaciation began approximately 1.6 Ma. In Ireland, little evidence exists for all but the last two glacial advances, the Munsterian (which affected the whole country and ended ~100,000 years ago and the Midlandian (which affected the country as far south as Limerick, 70,000-13,000 years ago (the ice began to retreat ~15,000 years ago)). During the Midlandian glacial, ice sheets developed in Connemara, central Kerry and Donegal, and the east coast of the country was affected by ice sheets originating in Scotland. The ice sheet is considered to have achieved a thickness of up to 300 m. The effects of the Pleistocene glaciation on the landscape in the Burren region are discussed in detail in section 4.2. The primary events that have affected the landscape in the Burren region are summarised in Fig. 23.

# 4 Geomorphology

The landforms of the Burren region reflect denudation during the Cenozoic period (~1.6 Ma), including the recent Pleistocene glaciation (~1.5 Ma to 13,000 years ago in Ireland). The primary processes involved in denuding the landscape were freeze-thaw action and erosion by ice during the Pleistocene, but chemical solution and fluvial erosion earlier during the Cenozoic (and today). The gross evolution of the landscape in the Burren region reflects faster rates of limestone denudation via chemical solution than erosion of adjacent siliciclastic rocks during episodic, brief, high-energy storm events. The evolution of the landscape of the Burren region during the Cenozoic is described in detail below.

## 4.1 Pre-Pleistocene denudation and karstification

The primary controls on the evolution of the landscape in the Burren region during the Tertiary are the presence of the Slieve Aughty anticline to the east of the region and the persistence of a cover of siliciclastic rocks in the west of the region. During the early Tertiary, the entire Burren region would have been covered by siliciclastic sedimentary rocks of Late Carboniferous age or younger. Erosion of these rocks would have exposed the underlying limestones initially on the Slieve Aughty anticline to the east of the Gort-Kinvarra Lowlands, creating a karst window in the siliciclastics. Dissolution of the limestones would eventually have exposed the underlying Old Red Sandstones in the core of the anticline. The sandstones formed a stable catchment that allowed an extensive karst drainage system to develop in the adjacent limestones of the Gort-Kinvarra Lowlands. Average limestone dissolution rates for the Cenozoic were approximately 40-50 mm/1000 years, suggesting that lowering of the limestone surface of the Gort-Kinvarra Lowlands may have been ongoing for the last 30 Ma. This is consistent with the age of the limestones exposed at the surface in this area: the rocks in the Gort-Kinvarra Lowlands are the oldest in the entire Burren region.

In contrast with the Gort-Kinvarra Lowlands, the limestones further west in the Burren region are younger and expressed as higher topography, suggesting that the overlying cover of siliciclastic rocks persisted until relatively recently, albeit dissected by surface streams and rivers, until ~1 Ma. The precise pattern of removal of the siliciclastic cover is highly speculative, but may reflect preferential removal by fluvial erosion superimposed upon a general trend of retreat from northeast to southwest. Furthermore, the geometry of the shale-limestone contact suggests that its present location may reflect supra-km-scale subtle folding in the succession, whereby siliciclastic rocks are exposed in shallow synclines (e.g. at Knockavoarheen and Clifden Hill) and the limestones, in anticlines (e.g. around Kilfenora, and northeast of Lisdoonvarna).

The ridge with which the Cliffs of Moher are associated reflects the relatively high mechanical strength of the siltstones and sandstones of the Gull Island Formation and Central Clare Group relative to the underlying Clare Shale Formation. The rate of coastal recession at the Cliffs of Moher has not been calculated but is approximately 0.4 m/year at the southwest coast of the Aran Islands. Lithological differences aside, these data suggest that the coastline along what today comprises the Cliffs of Moher may have been located several (some authors suggest as much as six) kilometres to the west during the late Pleistocene.

## 4.2 Pleistocene glaciation

Prolonged weathering of the shale cover that persisted in the Burren until the onset of the Pleistocene glaciation would have generated saprolites that may have been up to tens of metres thick but mechanically weak. Erosion of this weathered material prior to the glaciation would have been restricted to flood events and essentially minimal where it was covered by vegetation. Pleistocene ice sheets, however, would have removed the saprolite cover easily, exposing fresh surfaces of the shales underneath. Successive glacials and interglacials would have repeatedly exposed fresh surfaces of the shales that were subsequently weathered to sapropels and then eroded during the succeeding glacial. Climatic oscillations during the glaciation may have eroded a significantly greater volume of shale from the Burren than would have occurred otherwise.

Investigations of cave sediments have shed some light on events during the Pleistocene. Clasts of Namurian sandstone in sediments in Kilweelran Lower Cave on Aillwee Hill indicate that the caves formed when the Namurian cover was much more extensive. Quartz-rich sediments in the relict cave passage of Pol an Griancloch at Poulsallagh are considered to represent fluvially reworked Connemara-derived (i.e. NW-derived) till that pre-dates the most recent glacial advance from the NE.

The Pleistocene glaciation resulted in other modifications of the landscape of the Burren region. Erosion-related modifications include the smoothing of the steep slopes on the northern scarp of the Burren, shunting and plucking of limestone blocks on south-facing slopes in the Burren, and generation of glacial striae on exposed limestone outcrops. Deposition-related modifications include erratics and extensive deposits of glacial till that may be up to 20 m thick in some valleys (e.g. the Caher River and Rathborney valleys) and are often organised into drumlin fields (as in the east of the Burren region).

## 4.3 Common geomorphological features

Much of the Burren region today comprises an extensive glaciokarst landscape, i.e. a landscape where development of karst features has clearly been modified or influenced by the effects of glaciation. In the Burren region, karstification has been ongoing for several tens of millions of years in the Gort-Kinvarra Lowlands, and for thousands to a few million years in the Burren. The most common glaciokarst features visible in the Burren region include limestone pavements, grikes and clints, kamenitzas, karren, dolines, erratics, drumlins, dry valleys, turloughs, swallow holes, springs, and caves. Each of these features is described briefly below.

### 4.3.1 *Limestone pavements*

Limestone pavements (Fig. 27) are the classic glaciokarst landform and are typically horizontal or gently inclined surfaces of bare limestone dissected to varying extents by grikes and karren. They are formed by the erosion of overlying soil, weathered rock, and mechanically weak bedrock by the action of ice sheets or glaciers, thereby exposing subaerially fresh, unweathered (unkarstified), surfaces of limestone. Approximately 20% of the Burren comprises limestone pavement, with an additional 30% comprising a combination of pavement and rendzina (i.e. organic-rich, calcareous) soil. Limestone pavements

*Figure 27. Limestone pavement with clints and grikes at the Sheshymore*

are found only in areas that have been recently glaciated. In the Burren, the most pristine pavements (i.e. with few karren, kamenitzas and grikes) therefore occur near the boundary between the limestones and overlying shales.

### 4.3.2 *Grikes and clints*

Grikes are sub-vertical fissures in limestone pavement that develop via the widening of pre-existing fractures in the rock by dissolution. The blocks of limestone separated by grikes are termed clints (see Fig. 27). Grikes and clints are ubiquitous on the limestone of the Burren region; grikes are commonly up to 800 mm wide and up to 2 m in depth.

### 4.3.3 *Kamenitzas*

Kamenitzas (solution pans) are shallow, rounded, relatively flat-bottomed basins on exposed limestone surfaces that develop via dissolution of the limestone by standing water (Fig. 28). Some kamenitzas exhibit irregular, pointed, rims that extend up to 10 mm above the adjacent limestone surface; these rims reflect precipitation of dissolved calcium carbonate in the kamenitza splash zone. Kamenitzas occur throughout the limestone pavements of the Burren region and are well-developed in the north of the region and along the western coastline.

*Figure 28. Kamenitza (~20 cm diameter) on limestone pavement surface. A more newly developing kamenitza is seen to the right of the water filled solution hollow*

### 4.3.4 *Karren*

Karren are small-scale, mm- to m-sized features formed on the limestone surface. They are classified according to their shape and size, with the most common forms including rillenkarren (small runnels ~ 20 mm wide), rinnenkarren (larger runnels ~ 200 mm wide) (Fig. 29), and trittkarren (shallow sub-horizontal steps with a vertical separation of only a few mm) (Fig. 30). Despite their superficial similarity to erosional channels, karren are formed via dissolutional carving and not erosion.

*Figure 29. Rinnenkarren*

*Figure 30. Trittkarren*

### 4.3.5 *Dolines*

Dolines are roughly circular, bowl-shaped, enclosed depressions that can be several metres to several hundreds of metres wide (Fig. 31). They can form via dissolution of rock from the surface downwards, by the collapse of overlying rock into a cave, or by a combination of these processes. Complex or compound dolines used to be described using the term uvala, which has now largely fallen out of use. There are at least 1500 dolines in the Burren with an area >100 m$^2$, most of which occur in the east of the area; this reflects the fact that they are a feature of a mature karst landscape. In the Burren, only 25% of the dolines are circular and the remainder are elongate; only some of the latter are orientated parallel to the predominant set of fractures in the limestone. The Carran Depression is ~ 9 km$^2$ in area and is the best example of a doline in Ireland. It is considered to have formed early in the denudation history of the Burren, via the capture of surface drainage in a karst window formed on a shallow anticline. Enclosed depressions elsewhere in the Burren, however, do not appear to be related to the underlying geological structure.

*Figure 31. Doline on Knockaunsmountain*

### 4.3.6 *Erratics*

Erratics are pieces of rock that have been transported from their original location by moving ice; they can be up to several metres wide. In the Burren region, most erratics are of limestone (e.g. Fig. 32), but erratics of more exotic lithologies, e.g. granite and schist (each transported from Co. Galway) are common, particularly on the north coast of the region. Erratics occur at up to 200 m O.D. in the Burren region, indicating that the ice sheet that covered the area was at least a couple of hundred metres thick.

*Figure 32. Limestone erratic near Poulnabrone*

Figure 35. The Glen of Clab gorge

### 4.3.7 *Drumlins*

Drumlins are low (usually 30-50 m high), elongate, rounded hills up to 1 km long comprised of unsorted glacial drift deposited by, and moulded, by ice. They typically have a steeply inclined side that originally faced "up-current", and a more gently inclined side that faced "down-current" (Fig. 33). Drumlins form during the latter stages of a glacial period, when ice begins to melt, and often occur in clusters or swarms, such as those that occur throughout the Gort-Kinvarra Lowlands.

*Figure 33. Drumlin near Kilshanny*

### 4.3.8 *Dry valleys*

Dry valleys are valleys that were eroded at some time in the past by surface rivers or streams but that now lack a permanent surface stream or river due to the capture of surface drainage by underground routeways. This may reflect the development of secondary permeability and cave systems, or access to pre-existing underground systems that were blocked by ground ice during glacial periods. The origins of many of the dry valleys and gorges in the Burren region are enigmatic; the features may represent simple stream capturem (as in the case of the Coolagh River Valley (Fig. 34)), collapsed cave passages, channels excavated by glacial meltwater, or elongate solutional depressions. The Ballyvaughan and Turlough valleys are among the oldest geomorphological features preserved in the Burren, and probably formed via prolonged dissolution of limestone exposed initially in river valleys draining northwards off the pre-existing shale margin into Galway Bay. These valleys, and many other dry valleys and gorges in the Burren, are now floored by a thick covering of glacial till.

*Figure 34. Coolagh River dry valley*

### 4.3.9 *Turloughs*

Turloughs are seasonal lakes that form in karst depressions; both the inlet and outlet are underground. In true turloughs, fluctuations in water level reflect variations in the level of the water table in response to high precipitation levels, or tides. Pseudoturloughs also exhibit fluctuations in water level, but in this case such fluctuations reflect the limited ability of the outlet to allow drainage underground following high surface runoff. Turloughs are common in Ireland but many have been drained artificially to reduce flooding. Examples in the Burren region include Lough Aleenaun and Knockaunroe.

*Figure 35a. Carron Turlough when empty (upper) and when full (lower)*

### *4.3.10 Swallow holes and springs*

Swallow holes and springs are the points at which surface streams or rivers pass underground, and re-emerge at the surface, respectively. In the Burren, swallow holes typically occur along the limestone-shale contact, where surface streams passing over the relatively impermeable shales sink upon reaching the more permeable limestones (note that this permeability is largely secondary, i.e. it relates to the high abundance of joints and veins as opposed to a high porosity), e.g. the Coolagh River swallow hole (Fig. 36) Springs occur throughout the Burren region and within a few tens of metres offshore; most have a flow rate of < 20 litres per second but some flow at > 500 litres per second, e.g. along the Fergus River. There are numerous smaller springs that rise at the surface where a bedding plane in the limestone is underlain by an impermeable layer such as clay or chert. There are nine major underground drainage systems in the Burren region, the largest being that of the Fergus River and Kinvara-Corranroo.

*Figure 36. The Coolagh River swallow hole*

*Figure 37. Stalactites and scallops in one of the many caves in the Burren*

### *4.3.11 Caves*

Caves typically develop along the boundary between permeable and impermeable rock masses. In the Burren region, most cave passages that have been explored have formed on a layer of impermeable chert or clay, and follow this bed downslope for considerable distances. Many of the cave passages also show evidence for the stream exploiting joints in the limestone, e.g. sharp bends and vertical drops. Most of the known caves in the Burren developed above the water table and exhibit characteristic vadose canyons along at least part of their length. Phreatic cave passages are relatively rare in the Burren; the best example is the Aillwee cave (Fig. 37), which is at least 350,000 years old. An extensive phreatic cave system underlies the Gort-Kinvarra Lowlands; much of this cave system is today extensively flooded and many parts are blocked by glacial deposits or collapsed.

The Burren region, like all karst regions, has a distinctive hydrology that is markedly different to that found elsewhere in Ireland. A review of the hydrology of the Burren is, however, beyond the scope of this report. Suggestions for further reading on this topic are given in the bibliography.

# 5 MINERAL DEPOSITS

The primary minerals that occur and have been exploited in the Burren region are phosphate, calcite, fluorite, and galena.

## 5.1 Phosphate

The phosphate deposits that occur in the lowermost six metres of the Clare Shale Formation constitute one of the most important sedimentary phosphate deposits in Ireland. The phosphate occurs as lenses or discontinuous layers of phosphorite at five discrete horizons, and comprise granules of fluorapatite and cellophane in a calcite-silica-pyrite-carbonaceous matrix.

Phosphate deposits were discovered in Doolin (Fig. 38) and at Noughaval, near Kilfenora in 1924. Phosphates were largely used as chemical fertilizer in Ireland. These deposits, and their shale host rocks, have an average uranium content of ~ 150 ppm (with an estimated total mass of 450 tonnes of uranium) and therefore represent a notable radon source.

Prior to the 1940s, most of the phosphate used in Ireland originated in North Africa. However, the outbreak of World War 2 in 1939 brought an end to the import of phosphate supplies from overseas. Pre-War consummation of phosphate in Ireland was around 100,000 tonnes per year. By the end of 1941, 300-400 tonnes of phosphate were being supplied from County Clare per week. However, the Doolin phosphate deposits were not as high in quality as the phosphate imported from North Africa. With the end of the war, phosphate imports resumed and the phosphates from Doolin were no longer in high demand.

The Doolin phosphates were extracted by mining and the Noughaval phosphates were quarried. The phosphate deposits were last worked in 1947. Total reserves are estimated at 3 million tonnes.

*Figure 38. Ruins of the phosphate factory, Doolin*

## 5.2 Calcite

Calcite occurs as veins (Fig. 39) in the limestones of the Burren region and, although widely distributed, does not occur in considerable volumes at any one locality. Known localities include Aghawinnaun, Ballyhehan, Fahee North, Gortlecka, Kylecreen, Mogouhy, Moneen, Mortyclogh, Murroughtoohy, and Poulawack. The vein at Ballyheha contains the largest deposit of calcite in the region; that at Murroughtoohy is extremely pure (99% calcite). Calcite extracted at these and other localities was used predominantly in the glass-making process.

*Figure 39. Calcite vein (yellow) at the Flaggy Shore*

## 5.3 Fluorite

Fluorite occurs as veins (associated with calcite mineralisation) and, more rarely, replaces the host limestones; all deposits are minor. Vein-hosted fluorite occurs at Addergoole, Castletown, Crossard, Doolin, Kilweelran, Lisnanroum, Mogouhy, Sheshodonnell East, Sladoo, and Tullycommon. The most significant deposits are those at Kilreelan and Doolin, which were worked during the 1960s and 1940s, respectively. The Doolin deposit yielded 31 tonnes of fluorite that was used as a flux in the manufacture of steel.

## 5.4 Galena

Galena occurs as an accessory mineral in calcite or calcite-fluorite veins in the Slievenaglasha Formation at the following localities: Addergoole, Castletown, Crossard, Doolin, Moheraroon, Sheshodonnell, and Tullycommon. The deposits at Crossard and Doolin were exploited commercially.

## 5.5 Other minerals

A variety of minor accessory minerals occur in calcite veins throughout the Burren region, including sphalerite (source of zinc), quartz, smithsonite, cerrussite, malachite, chalcopyrite, and greenockite. Veins containing sphalerite and smithsonite have been exploited for zinc; malachite and chalcopyrite, for copper; and greenockite, for cadmium.

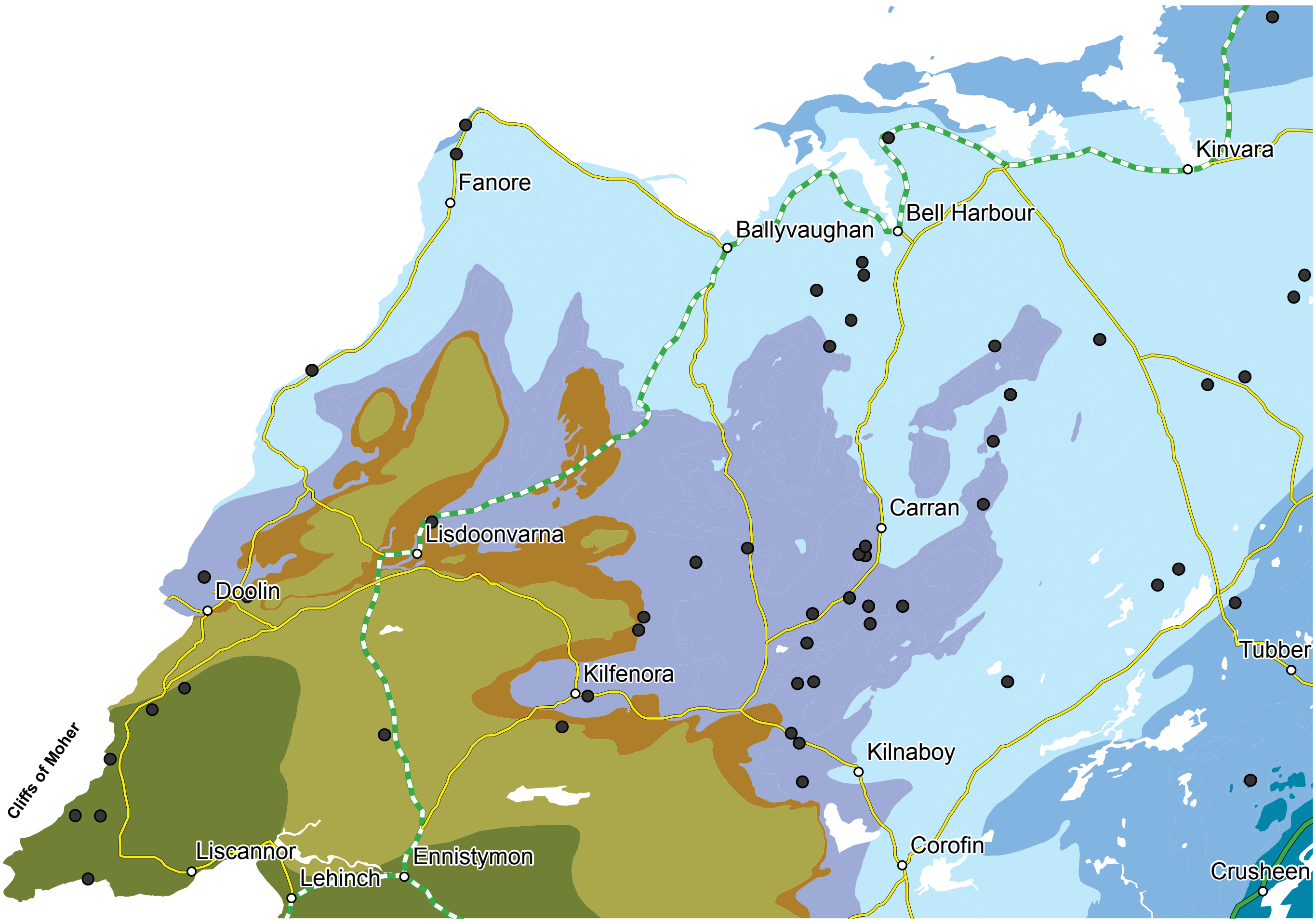


*Figure 40. Distribution of mines and quarries in North Clare (see www.GeoNeed.org)*

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