



NORTHERN ENVIRONMENTAL
EDUCATION DEVELOPMENT

THE GEOLOGY OF THE BURREN REGION, CO. CLARE, IRELAND

part of WP2 of the NPP-funded Northern Environmental Education Project

by

Dr Maria E. McNamara

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1. INTRODUCTION

1.1. The Northern Environmental Education Development (NEED) project

The NEED project is a transnational geoscience education project funded under the Interreg Northern Periphery Program (see Fig. 1 for area covered by this program).

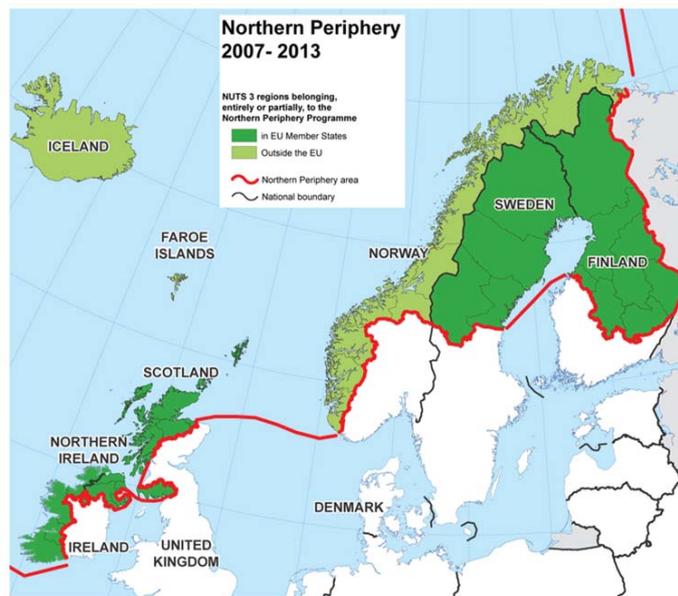


Fig. 1. Map of Northern Periphery Program area.

The NEED project is focussed upon the development of geoscience education facilities, programs, and technology, in key target areas in the northwestern periphery of Europe. The project aims to promote geoscientific and wider environmental education and educational tourism in the target areas and to increase skills and environmental awareness among local inhabitants.

Specifically, the project will:

- (1) develop geo-education programs for schools, local adults, visitors, and private businesses;
- (2) develop various digital tools (e.g. GIS and mobile technology) for educational purposes;
- (3) design and test geoscience learning methods that can be implemented in learning environments such as schools and visitor centres;

- (4) develop and enhance learning environments, e.g. provision of workstations, microscopes, and other scientific and technological equipment; and
- (5) assess, via surveys, the effectiveness of these programs.

The primary, or National, partners in the NEED project are the University of Joensuu (Faculty of Education) in Finland, the University of Iceland (Hornafjörður Research Center) in Iceland, Nordland National Park Centre in Norway, and Clare County Council in Ireland. The target areas are the Saimaa-Pielinen Lake-system (Finnish Lakelands), Vatnakökull National Park, Nordland, and the Burren region, respectively (Fig. 2).



Fig. 2. Representative images from each target area in the NEED project, from left to right: Vatnakökull National Park, the Saimaa-Pielinen Lake-system, the Burren region, and Nordland.

Each National Partner has several associate, or Regional, partners, drawn from the following sectors: education and research, regional and local authorities, private SMEs, and educational tourism. These Regional Partners work with the National Partner in each country in the planning and production of outputs of the project. In Ireland, the regional partners are the Geological Survey of Ireland, the Cliffs of Moher visitor centre, Shannon Development, National University of Ireland, Galway, the Burren Centre Kilfenora, Burrenbeo, and the Burren Outdoor Education Centre. Each regional partner provides in-kind contributions towards the project, e.g. time, expertise, and facilities.

The NEED project started in mid-2008 and will run until the end of 2010. The work program is divided into five distinct packages, each comprising a series of actions or goals. This report is a review of current geological knowledge of the Burren region in North County Clare, Ireland, and fulfills the work program under Action 7 of Work Package 2. Further details about the structure, aims, and outputs of the NEED project can be found at www.joensuu.fi/need and www.burrenconnect.ie/geopark/education.

1.2. The NEED target area in Ireland: the Burren region in North County Clare

The Burren region in North County Clare encompasses the landscapes of the Burren, the Cliffs of Moher, and the western part of the Gort-Kinvarra lowlands (Fig. 3). 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.

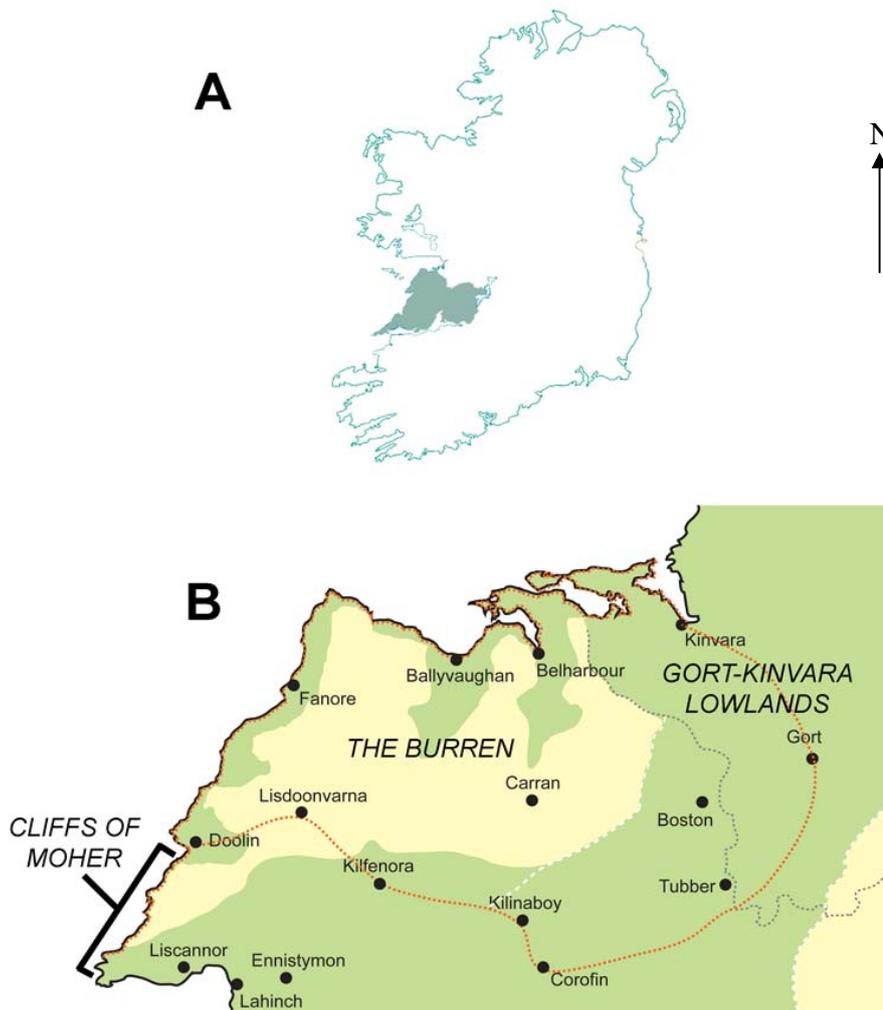


Figure 3. The NEED target area in Ireland. A: Map of Ireland with, shaded, County Clare. Box shows area in B. B: Map of the Burren region (orange dashed line), showing [continued overleaf]

the Cliffs of Moher, the Burren, and the Gort-Kinvara Lowlands (white dashed line). Areas below 60 m OD are shaded in green.

The landscapes of the Burren region are underlain by different rock types: limestone 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 target area (Figure 4). 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 and is intended as an information resource for the various partners involved in the NEED project, and for those with a scientific background interested in the geology of the Burren region. Appendix 1 is a non-technical summary of sections 3 and 4 of this report that is intended as an information resource for the general public. Note that all geological dates quoted are sourced from the online IUGS GeoWhen database (<http://www.stratigraphy.org/geowhen/index.html>).

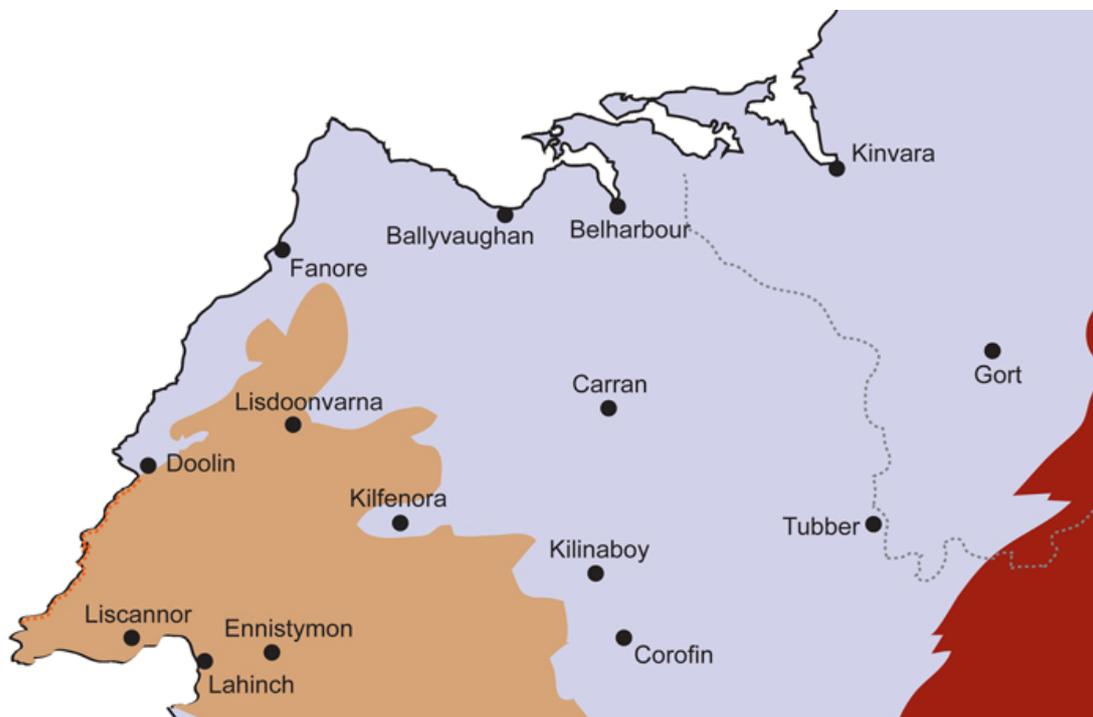


Figure 4. Simplified geological map of the Burren region and surrounding area, showing limestone (pale blue), younger siliciclastic rocks (pale brown), and older siliciclastic rocks (dark brown).

2. LOCATION AND EXTENT OF THE NEED PROJECT TARGET AREA IN IRELAND

The target area – the Burren region – is located 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. 3); the eastern boundary runs approximately from Kinvara in the north, through Gort, and to the border between Counties Clare and Galway just south of Tubber (Fig. 3). The southern boundary of the target area is an irregular east-west line that extends from the county boundary in the east (near the village of Tubber) through the towns of Corofin, Kilfenora, Lisdoonvarna, and Doolin at the coast, and also includes the coastline from Doolin southwards to Hag's Head. 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 Burren *sensu stricto* extends over most of the target area. The eastern boundary of the Burren 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. Its southern boundary follows broadly that of the target area and can be defined geologically as the contact between the limestones and the overlying younger siliciclastic rocks; at the coast, the contact occurs at Doolin. The Burren extends over ~ 360 km² and forms 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 Bellharbour. The Burren is considered a barren landscape and is characterised by a paucity of surface drainage, extensive areas of bare rock and rocky pasture, and cliffed and terraced hills.

The part of the target area that lies to the east of the Burren forms part of the Gort-Kinvarra lowlands, which extend further east (beyond the county boundary) to the Slieve Aughty Mountains. Within the target area, the lowlands cover ~ 130 km² and average less than 30 m OD. These 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.

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). Much of the bedrock of Ireland is today blanketed by glacial drift, i.e. unconsolidated sediments that were deposited during the most recent glaciation.

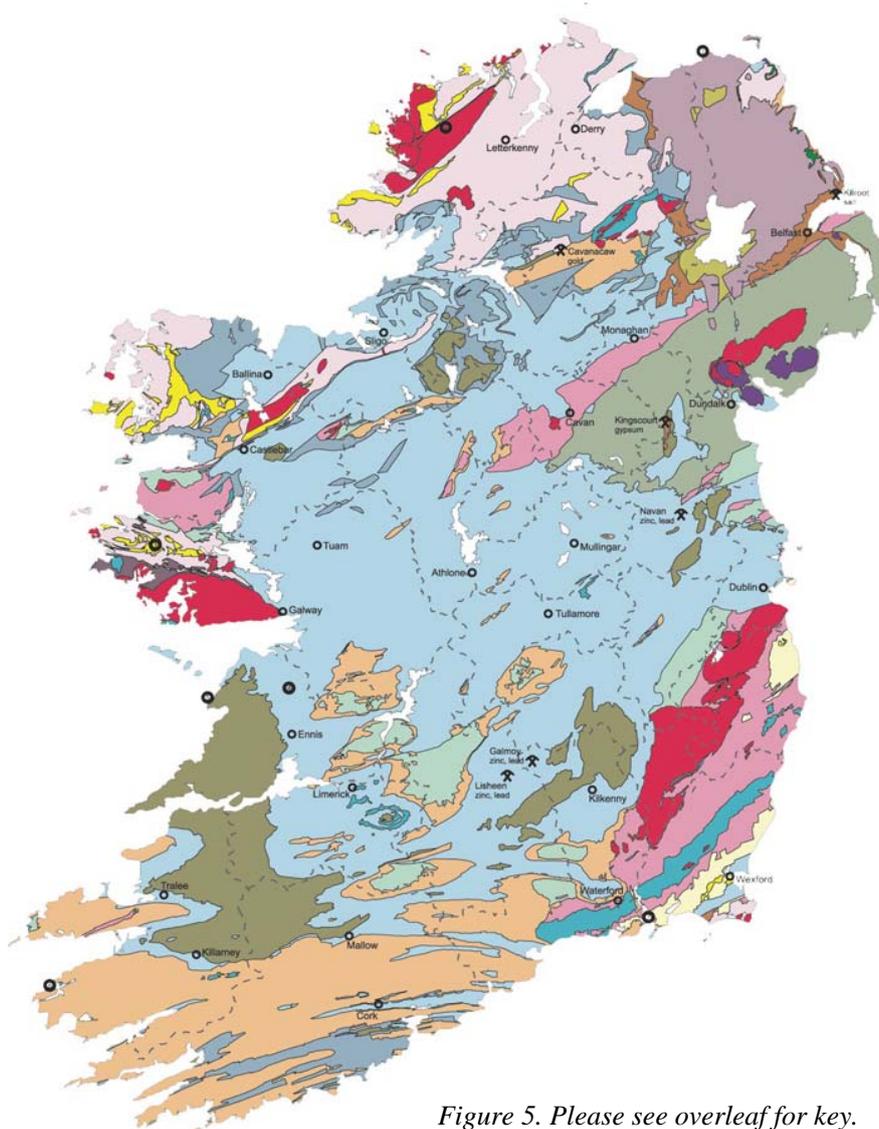


Figure 5. Please see overleaf for key.

Figure 5. Simplified bedrock geological map of Ireland. 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.

The oldest rocks in Ireland are dated at 2.4 billion years and crop out in Co. Wexford, where they are part of the group of rocks termed the Rosslare Complex. 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 in the Gort-Kinvarra Lowlands 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.

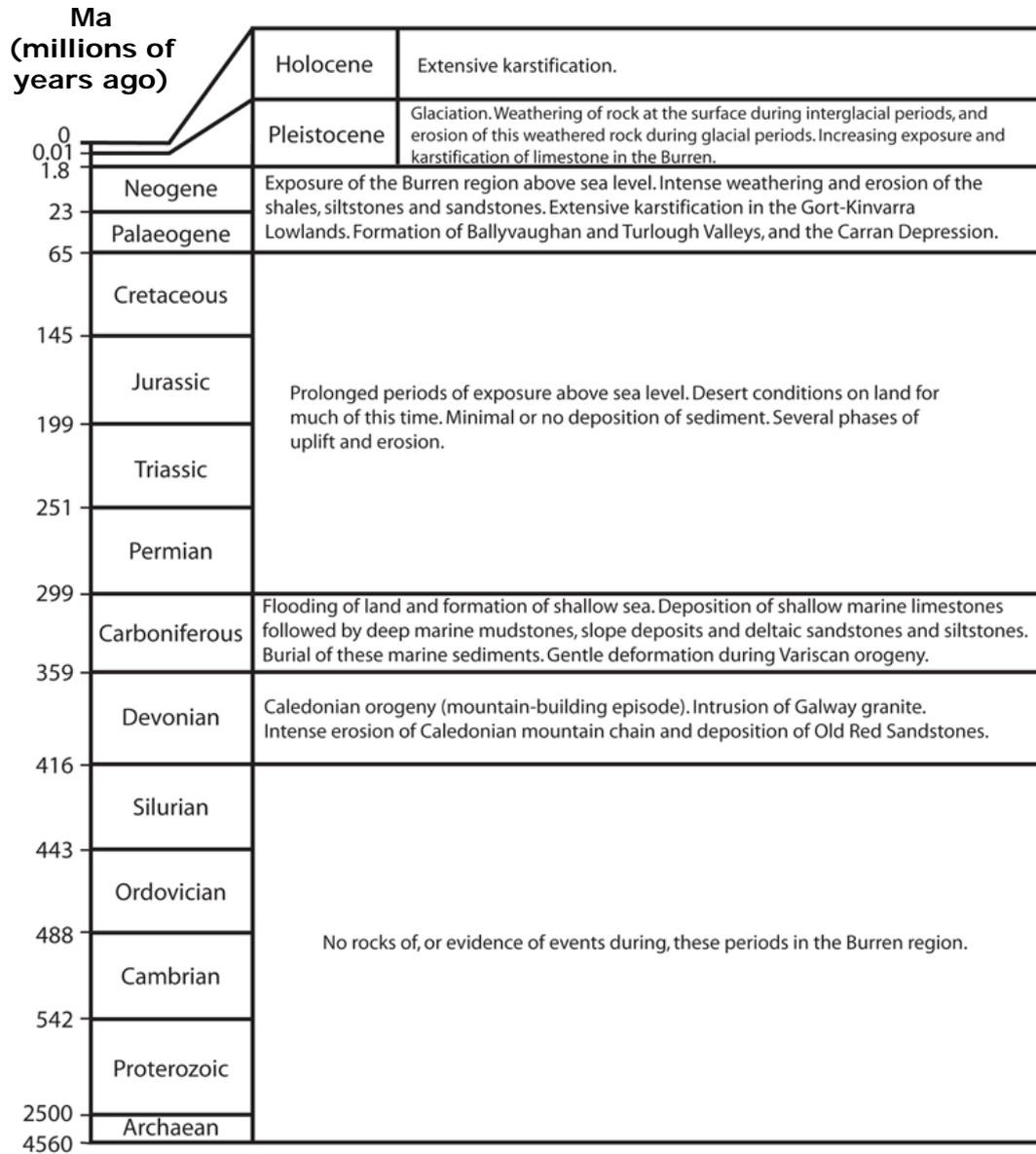


Figure 6. Geological timescale showing the major events occurring in, and affecting the rocks of, the Burren region.

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 (megaannum: millions of years ago). 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.

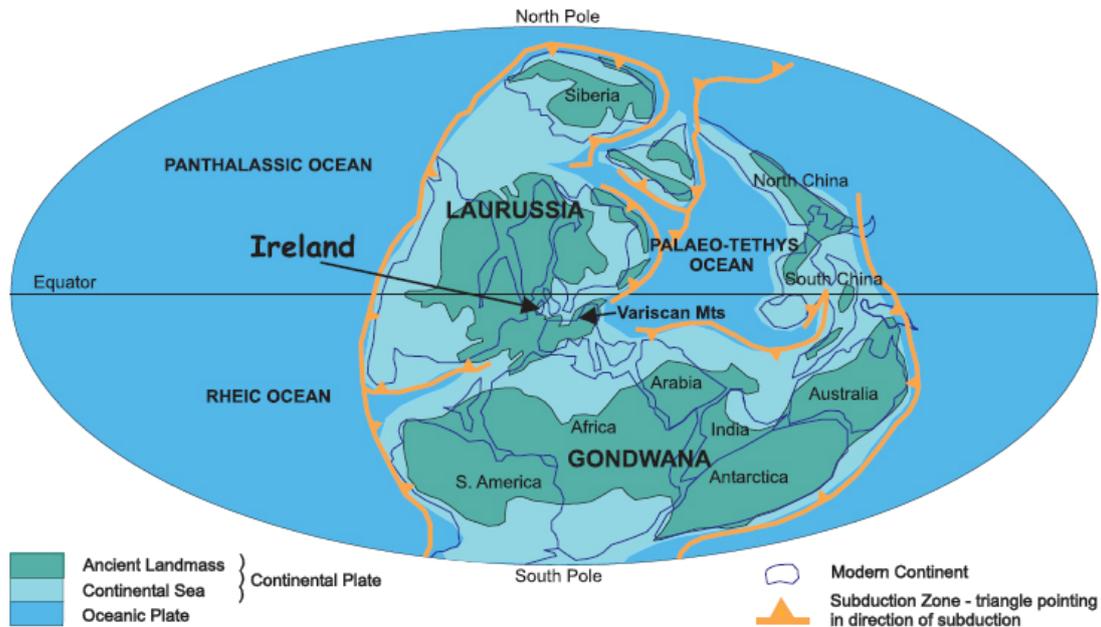


Figure 7. Plate reconstruction during the Early Carboniferous period. From “Understanding Earth processes, rocks and the geological history of Ireland” published by the Geological Survey of Ireland.

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 overleaf.

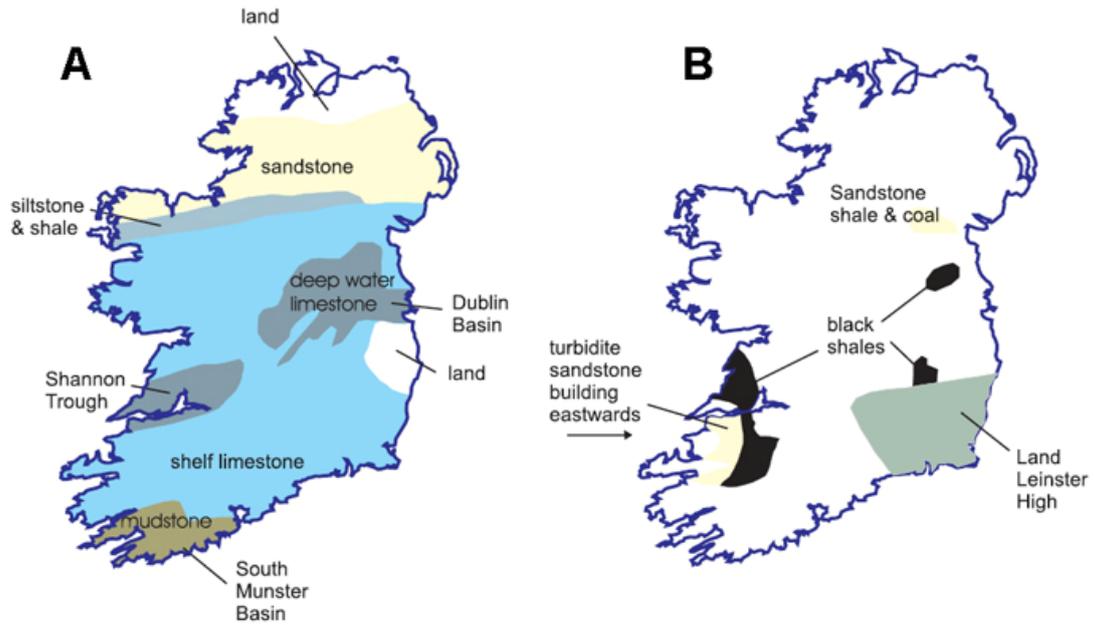


Figure 8. Palaeogeography ca. 330 Ma (A) and ca. 318 Ma (B). From “Understanding Earth processes, rocks and the geological history of Ireland” published by the Geological Survey of Ireland.

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 overleaf and described below in detail from oldest to youngest.

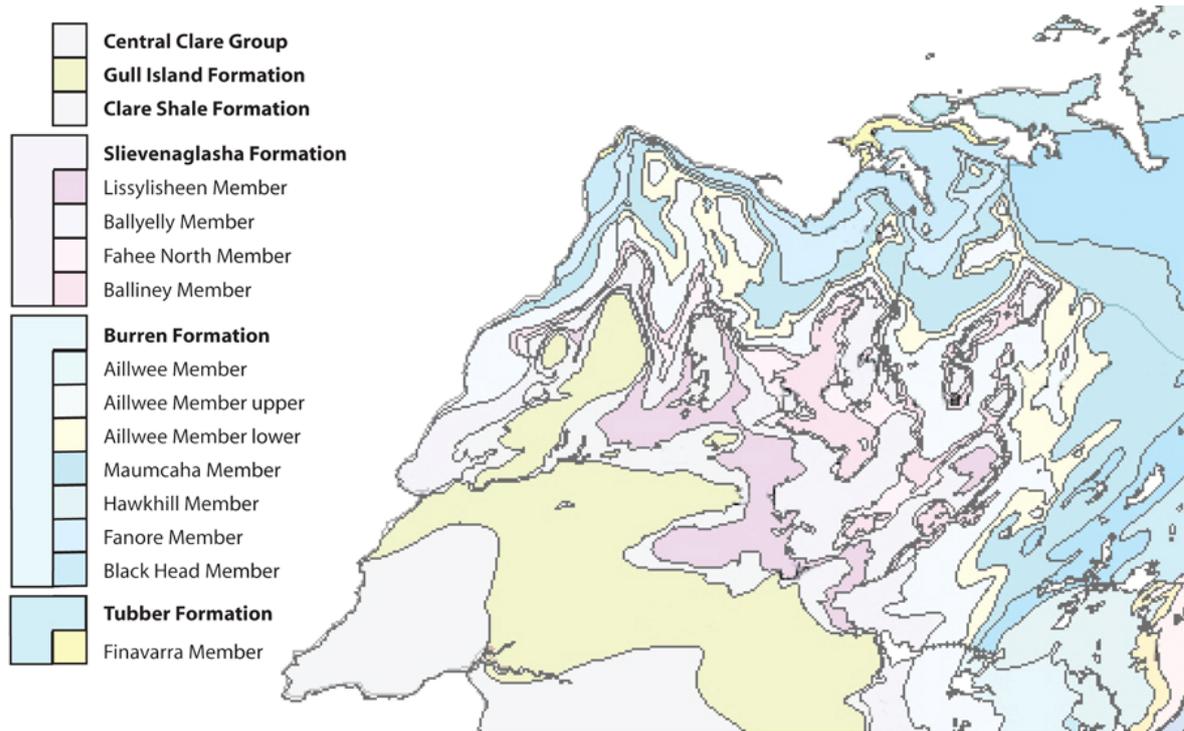


Figure 9. Detailed geological map of the Burren region with key to formations and members. Map is modified from GSI online database.

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, brachiopods and gastropods. Several beds with abundant *in situ* (Fig. 11) and overturned colonial



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. Coral on left is approx. 40 cm diameter.

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 (Fig. 12). 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.



Figure 12. Cerioid colonial corals of the Finavarra Member of the Tubber Formation exposed at Black Head. Each corallite is approx. 7-10 mm diameter.

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; 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, overleaf) 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.

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*.



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.



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

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 (*Gigantoproductus* (Fig. 15)) 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.



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

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.

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* with thin dark-coloured chert bands. 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.

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.



Fig. 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 Viséan 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.



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

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.

3.3.7. Central Clare Group

This group is ~ 200 m thick in the Burren region but ~ 900 m 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 syndepositional 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, overleaf). 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.



Figure 21. Horizontal traces of Olivellites / Scolicia, and vertical burrows, in siltstone at the Cliffs of Moher.

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, overleaf).

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.



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

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 overleaf is a detailed summary of those events that occurred during the Carboniferous.

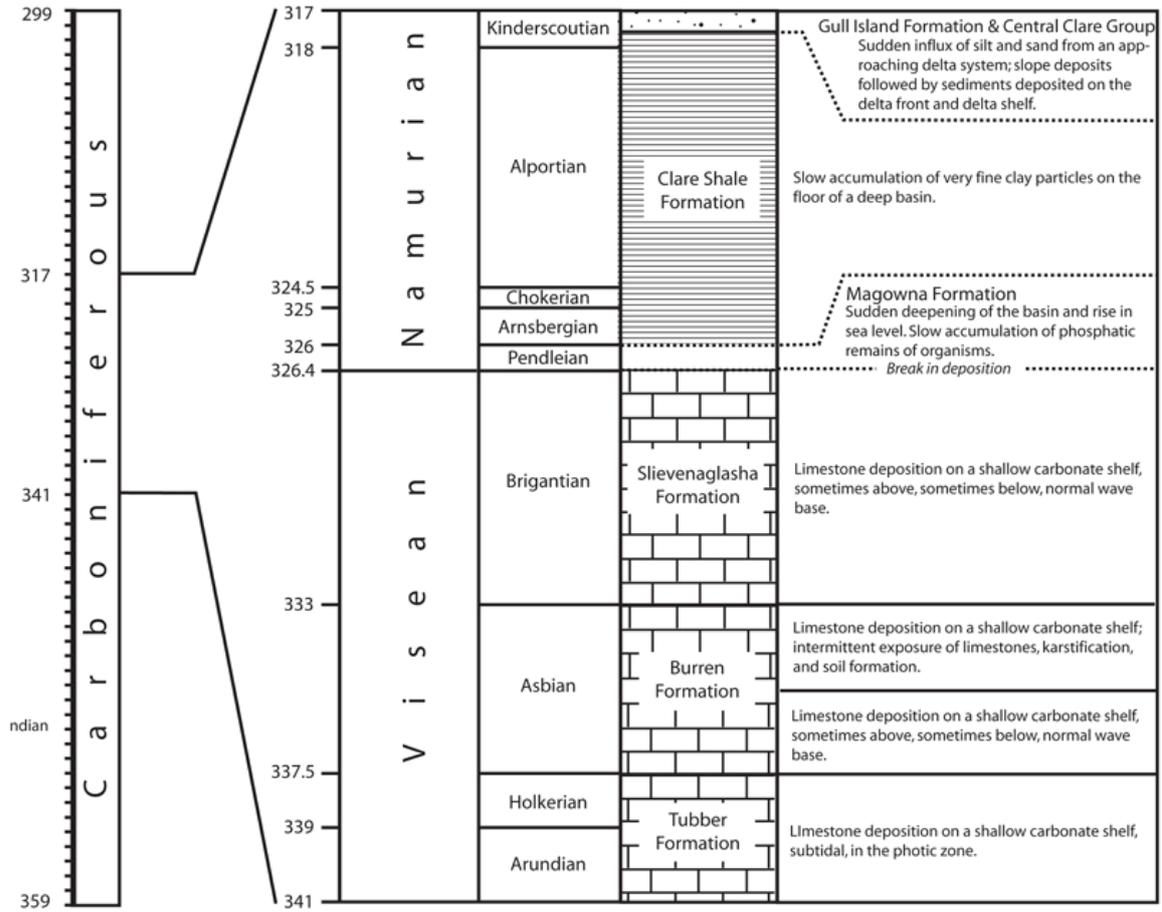


Figure 23. Geological summary of the events affecting the Burren region during the Carboniferous.

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 monoclinical folds, such as those visible at Mullaghmore (Fig. 24, overleaf), 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 24. Folded limestones of the Slievenaglasha Formation at Mulloughmore.

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.

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, overleaf). 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



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



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

(continued from overleaf)

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.

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. Further, 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 ~ ka) and the Midlandian (which affected the country as far south as Limerick, 70-13 ka (the ice began to retreat ~15 ka)). 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 (65-0 Ma), including the recent Pleistocene glaciation (~1.5 Ma to 13 ka 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 ka⁻¹, 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 a^{-1} 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 *s.s.* 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 *s.s.* 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 Grianloch at Poulsallagh are considered to represent fluviially 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, overleaf) 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 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.



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

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, overleaf). 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 on limestone pavement surface. Approx. 150 mm diameter.

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, overleaf), and trittkarren (shallow sub-horizontal steps with a vertical separation of only a few mm) (Fig. 30, overleaf). 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, overleaf). 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 *s.s.* with an area $>100 \text{ m}^2$, 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 *s.s.*, 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 $\sim 9 \text{ km}^2$ 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.

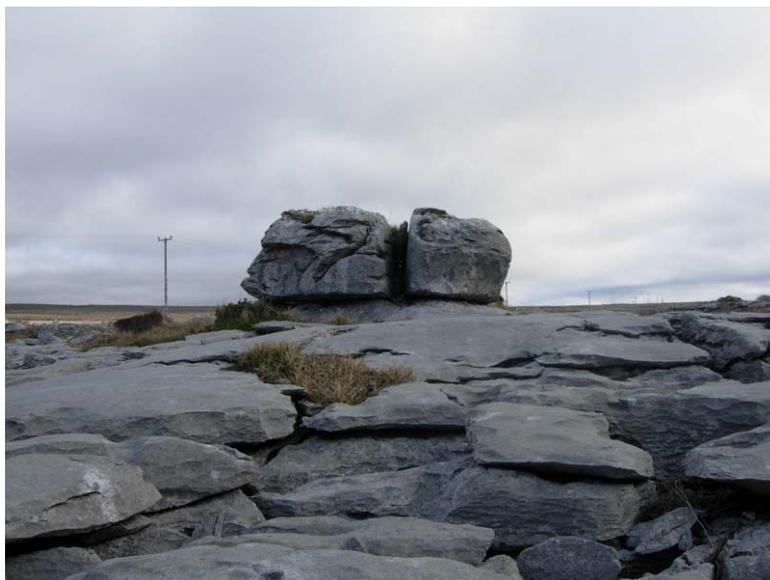


Figure 32. Limestone erratic near Poul nabrone.

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 capture (as in the case of the Coolagh River Valley (Fig. 34, overleaf)), 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.



Figure 35. The Glen of Clab gorge.

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.

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 $<20 \text{ l s}^{-1}$ but some flow at $>500 \text{ l s}^{-1}$, 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.

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.



Figure 37. Entrance passageway at Aillwee Cave. The rounded roof profile represents the original geometry of phreatic tube.

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. The deposits at Doolin (Fig. 38) and Noughaval were worked during the 1940s for chemical fertiliser and produced 75,000 t, and 30,000 t, of phosphate, respectively; total reserves are estimated at 3 million tonnes. 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.



Figure 38. Ruins of the phosphate factory, Doolin.

5.2. Calcite

Calcite occurs as veins 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, Kylecreeen, Mogouhy, Moneen, Mortyclogh, Murroughtoohey, and Poulawack. The vein at Ballyheha contains the largest deposit of calcite in the region; that at Murroughtoohey (Fig. 39) is extremely pure (99% calcite). Calcite extracted at these and other localities was used predominantly in the glass-making process.



Figure 39. Calcite vein at Murroughtoohey.

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 t 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 Zn), quartz, smithsonite, cerrussite, malachite, chalcopyrite, and greenockite. Veins containing sphalerite and smithsonite have been exploited for Zn; malachite and chalcopyrite, for Cu; and greenockite, for Cd.

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Appendix: Non-technical summary of sections 3 and 4

The Geology of the Burren region in Co. Clare

Introduction

The Burren region in North County Clare encompasses the landscapes of the Burren, the Cliffs of Moher, and the western part of the Gort-Kinvarra lowlands (Fig. 1). The landscapes of this region are underlain by different rock types. Limestone occurs in the north and east, i.e. the Gort-Kinvarra lowlands and most of the Burren. Sandstones, siltstones and shales occur in the south and west, i.e. the Cliffs of Moher, and high ground in the west and centre of the Burren e.g. Slieve Elva (Fig. 2, overleaf). Variations in the landscape across the region reflect not only rock type, but also the more recent geological history, such as the effects of the most recent glaciation (ice age) and the length of exposure of the rocks at the Earth's surface.



Figure 1. Map of the Burren region (orange dashed line), showing the Cliffs of Moher, the Burren, and the Gort-Kinvarra Lowlands (white dashed line). Areas below 60 m OD are shaded in green.

The story of the rocks (geological history)

The rocks in the Burren region were deposited when Ireland was located ~ 10°S of the Equator, during the Carboniferous period in Earth history, which spans 359-299 Ma (megaannum: millions of years ago). The limestones were deposited during the

Viséan stage (345-326 Ma) of the Carboniferous, and the sandstones, siltstones and shales, during the Namurian stage (326-315 Ma).

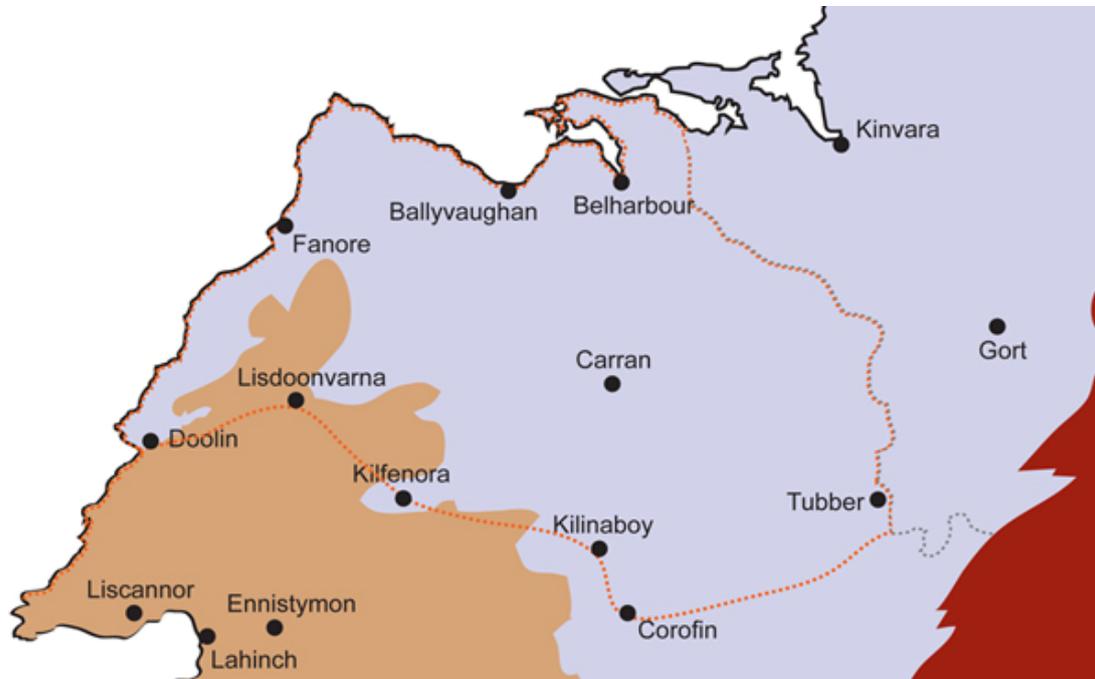


Figure 2. *Simplified geological map of the Burren region and surrounding area, showing limestone (pale blue), younger siliciclastic rocks (pale brown), and older siliciclastic rocks (dark brown).*

A shallow tropical sea teeming with life

The limestones of the Burren region are about 800 m thick. Only about 500 m, however, is exposed at the Earth's surface; the rest is below ground. The limestones formed in a warm, shallow, tropical sea that once extended across most of Ireland, the UK, and large parts of northeast Europe. The limestones contain the fossilised hard skeletons of a variety of marine organisms; the soft tissues of these organisms decayed and are not preserved. The most common fossils are crinoids (relatives of starfish), corals (very similar to those alive today), brachiopods (a filter-feeding animal with two shells that is found today on the ocean floor in the deep sea), and gastropods (snails) (Fig. 3, overleaf). Most of the fossils are broken to some degree, and very few are found in their life position. These features indicate that the fossils were transported or moved around in a high-energy environment and show that the floor of the shallow tropical sea was agitated by waves. Fossils make up only a small

proportion of the limestones, however. Most of the grey mass of the limestones is composed of microscopic particles of calcium carbonate. These particles have a variety of origins: some precipitated directly out of the water column, others are the faecal pellets of zooplankton and other invertebrates, and others still represent microscopic ground-up fragments of the hard skeletons of marine animals such as corals and brachiopods. There are very few particles of clay and sand in the limestones. This shows that there were no major rivers flowing into the tropical sea in the Burren region, possibly because the climate was too dry.

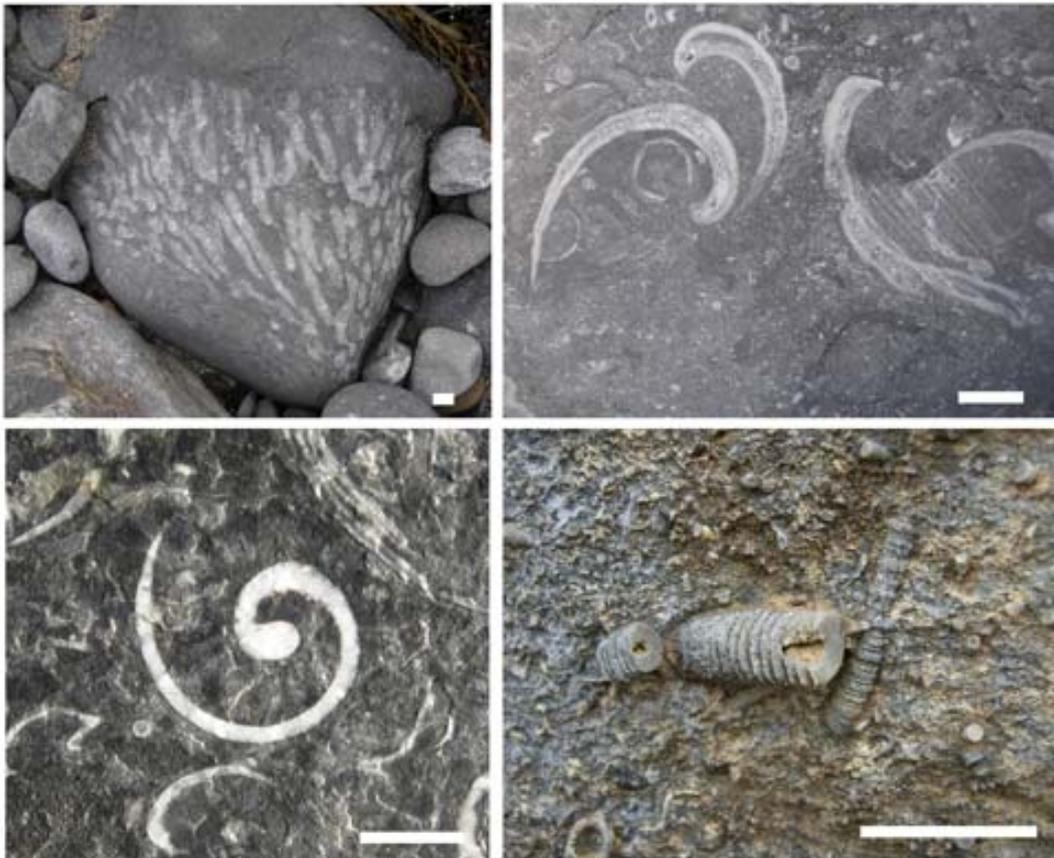


Figure 3. Common fossils in the limestones of the Burren. Clockwise from top left: corals, brachiopods, crinoids, and gastropods.

Changes in sea level and an ancient ice age

Although the limestones appear relatively uniform, different layers do show subtle changes in composition. These changes reflect variations in environmental conditions. During deposition of the limestones, the Earth was in the grip of an ice age, with alternating advances and retreats of polar ice caps. As a result, global sea level fluctuated constantly, and occasionally was low enough to expose the limestones of

the Burren at the Earth's surface. When this happened, the limestones were weathered and dissolved by rainwater, forming ancient karst landscapes (Fig. 4). Sometimes these exposed limestones were covered by soil. These ancient soil layers are visible today as thin bands of mudstone ("clay wayboards"; < 1 m thick) that occur at several horizons in the limestone sequence (Fig. 4). The mudstones contain particles of volcanic ash that were probably transported by wind from volcanoes in Co. Limerick that were actively erupting at the time.



Figure 4. An undulating ancient karst surface (white arrow) covered by a thin layer of mudstone, i.e. an ancient soil layer (black arrow).

The limestones also contain occasional thin (50-200 mm thick) bands of dark grey to black chert (Fig. 5, overleaf). Chert is a hard rock composed of silica (which makes up most sand) and so it often stands proud of the limestones by a few centimetres. Unlike the clay wayboards, the bands of chert were not deposited along with the limestones. In fact, the chert formed much later, from the remains of the silica-rich shells of microscopic algae that lived in the tropical sea and were deposited in the lime sediments. The pressure of the overlying layers of sediment caused the silica in the shells of these algae to dissolve and to form a gel that flowed through the limestone along bedding planes, where it eventually precipitated out as hard, silica-rich layers of chert.



Figure 5. Thin dark-coloured chert bands in limestone; each is ~ 5 cm thick.

The sea deepens and all is quiet

Over time, the shallow tropical sea in which the limestones were forming began to deepen as the sea floor slowly subsided (lowered due to stretching of the Earth's crust). Eventually, despite ongoing fluctuations in sea level due to the glaciation, the limestones that were forming ceased being exposed at the Earth's surface; as the sea deepened, the limestones were no longer affected by waves, except during storms (which can agitate sediments in deeper waters). Suddenly, ~ 326 Ma, there was a major rise in sea level as the basin deepened very rapidly, and formation of limestone ceased abruptly. For several million years, almost no sediment was deposited on top of the limestones in this deep sea, except for the teeth and bones of fish (and other marine vertebrates) that settled out of the water column above. These hard tissues are rich in phosphate, and because of the very low inputs of other types of sediment, the phosphate from these tissue remains was concentrated into a thin band of black, phosphate-rich sediment on top of the limestones. These phosphate deposits are up to 2 m thick near Doolin and were once mined as an ingredient for fertiliser. Later on, small amounts of very fine clay particles began to settle to the sea floor, forming black shales. The clay particles probably came from very fine river sediments carried far away from the coast by currents, and were the only sediment deposited in the region for about five million years. At this time, the deep sea floor was extremely inhospitable to life: there was no light, very low oxygen levels, abundant dissolved

sulphides, and no organic matter in the sediment. The only fossils found in the shales are therefore the remains of animals that lived higher up in the water column, close to the water surface, e.g. cephalopods. Pyrite (fool's gold) also occurs in the shales, and often replaces the shells of the cephalopod fossils (Fig. 6)



Figure 6. Pyritised goniatite fossils in black shales. Specimen top left is ~ 2.5 cm wide.

A delta approaches

About 318 Ma this quiet, deep-water environment was overwhelmed by the influx of extremely large volumes of silt and fine sand. These coarse-grained sediments built up a slope in front of a massive, complex delta system that was prograding from a land mass to the west. The sediments on this slope were deposited so quickly that they became gravitationally unstable, and slid and slumped down the slope before they were fully lithified. The results of this can be seen in the spectacular slump folds in the rocks on the south side of Fisherstreet Bay (Fig. 7, overleaf).

In the delta

As the delta approached, sediment was being deposited faster than the basin was deepening, and so the environment became progressively shallower. As a result, the slope sediments are overlain by sandstones and siltstones that were deposited on the delta itself, both on the shallow-water delta shelf and at the delta front (where the

shelf slopes down to the basin floor). The rate of deposition was extremely fast: hundreds of metres of sediment were laid down in less than 2 million years – compare this to the black shales, where it took ~ 8 million years to deposit only 12 metres! The deltaic sediments are exposed spectacularly at the Cliffs of Moher, where repeating cycles of sandstone, siltstone and mudstone are visible. These cycles reflect changes in sea level that were caused by the same glaciation that affected deposition of the limestones. Each time sea level rose, the delta shelf was flooded by the sea, and marine mudstones were deposited on top of the deltaic sands and silts. After the rise in sea level, however, the delta would have continued carrying sand and silt out into the ocean, resulting in sandy sediments being deposited on top of the mudstones. The siltstones and sandstones were laid down during flood events; in between the flood events, the sea floor was relatively calm, allowing current ripples to form on the sediment surface, and organisms to make trails in the sediment (Fig. 8, overleaf). The siltstones and fine-grained sandstones of Liscannor show extremely abundant trails (trace fossils) made by an extinct arthropod (a woodlouse-like animal) and / or a gastropod (snail).



Figure 7. Slumped, folded sandstones and siltstones of the Fisherstreet Slide. Cliff is ~ 10 m high.



Figure 8. Ripples (left) and horizontal trace fossils (right) in siltstones at the Cliffs of Moher.

There are no rocks younger than these deltaic sediments in the Burren region. However, it is thought that an additional 2.5 km of sediments were deposited on top of the deltaic sediments, but were later eroded away (see below).

Burial, gentle squashing and uplift

After deposition, the rock sequence of the Burren region was gradually buried up to depths of ~ 2.5 km below the surface. About 300 Ma, there was a mountain-building episode in southern Europe that caused compressive (squashing) stresses to travel through the Earth's crust. By the time these stresses reached the Burren region, they did not have enough energy to bend the rocks into tight folds, but only to tilt them slightly and fold them gently. The rocks are usually tilted at between 2 and 5° to the south, and gentle folds can be seen at Slieve Roe and Mulloughmore (Fig. 9, overleaf).

The tectonic forces that caused this tilting and folding also resulted in the formation of many joints, or fractures, in the limestone. These fractures were initially microscopic but were widened by hot mineral-rich fluids that forced their way through the rocks during burial. Evidence of these fluids is seen today in the mineral-bearing veins that

run roughly N-S through the entire limestone sequence. In most cases, the minerals have been weathered away and the spaces widened by dissolution of the limestone to form N-S fissures. Some of the veins, however, still contain minerals such as calcite, fluorite, galena and pyrite.



Figure 9. Folded limestones at Mulloughmore.



Figure 10. Veins in the limestones of the Burren. Left: A cluster of calcite veins (yellow-white). Top right: Close-up of a calcite vein. Lower right: A calcite vein (dark line running from centre left to centre right) weathering away to leave a thin fissure (centre to centre).

The rock sequence is thought to have been uplifted in several phases over approximately 250 million years. Each phase of uplift would have eroded rocks exposed at the surface, relieving the pressure on the rocks underneath. This “depressurisation” would have allowed the underlying rocks to relax and expand, forming microscopic fractures in the rocks. Such fractures are extremely abundant in the limestones of the Burren region and are visible today as fissures; unlike the fissures formed by the N-S veins, however, these younger fissures have no regular orientation. In fact, these younger fissures often run in different directions in successive limestone beds. This reflects slight differences in the way different limestone layers relaxed according to their precise composition.

Exposure at the surface

The Burren region has probably been above sea level for the past 50-60 million years, and so more sediments did not accumulate. Instead, the exposed rocks experienced prolonged weathering and erosion at the Earth’s surface. These processes removed the siltstones and sandstones from over much of the region, and eventually the underlying shales. The shales in particular are easily weathered to friable (crumbly) masses of rock fragments and would easily have been eroded, thus exposing the limestone at the surface. The limestones of the Gort Lowlands were exposed about 20-30 Ma, and their surface has been lowered to only a few tens of metres above sea level by slow but continuous dissolution of the limestone. It is thought that shales still covered the Burren until the start of the most recent ice age (the Pleistocene glaciation). The ice sheets would easily have eroded most of the weathered shale, exposing limestone at the surface in places. The Pleistocene ice age ended in Ireland ~ 13,000 years ago, at which point parts of the Burren may have had a soil cover of some description. Evidence from pollen suggests that much of this soil cover was removed during the Bronze age ~ 1600 BC.

Faults (surfaces in which the rocks on either side have moved past each other) are extremely rare in the Burren region.

Common features of the rocks and landscape

The Burren region is relatively unusual as many of its landscape features have been formed not by erosion or deposition, but by *dissolution* of the underlying limestones. Such regions are termed “karst”, after the Kras region in Slovenia where this type of dissolution-dominated landscape was first described. Today, many people think of the Burren as a typical karst landscape when, in fact, it is not typical at all! The karst

features of the Burren have been developing for only a few thousand to a few million years. In geological terms, these are very young features and so the landscape of the Burren is an “immature” karst. A good example of a “mature” karst landscape is the Gort-Kinvarra lowlands, in which karst features have been developing for much longer, i.e. several tens of millions of years.

The Burren is most correctly termed a “glaciokarst” region. This is an area where the development of karst features (karstification) has been influenced by the effects of glaciation. 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, and springs. Each of these features is described briefly below.

Limestone pavements

Limestone pavements are the “classic” glaciokarst landform. They are horizontal or gently sloping surfaces of bare limestone that are dissected by surface features such as grikes and karren (see below). Limestone pavements are formed by the erosion of overlying soil, weathered rock, and weak bedrock by the action of ice sheets or glaciers, thereby exposing fresh surfaces of limestone. Approximately 20% of the Burren is limestone pavement, with an additional 30% consisting of a combination of pavement and rendzina (an organic-rich, calcareous soil). Limestone pavements occur only in areas that have been glaciated recently. In the Burren, the most pristine pavements occur near the boundary between the limestones and overlying shales.



Figure 11. Limestone pavement with clints (blocks of limestone) separated by grikes (fissures).

Grikes and clints

Grikes are vertical or near-vertical fissures in limestone pavement that develop by the widening of pre-existing fractures in the rock by dissolution. The blocks of limestone separated by grikes are termed clints. Grikes and clints occur throughout the limestone of the Burren region; grikes are commonly up to 800 mm wide and up to 2 m deep.

Kamenitzas

Kamenitzas (solution pans) are shallow, rounded, flat-bottomed basins on the surface of exposed limestone; they are usually a few centimetres to 30 centimetres wide. They develop by dissolution of the limestone by standing water. Kamenitzas occur throughout the limestone pavements of the Burren region and are particularly well-developed in the north of the region and along the western coastline.



Figure 12. Kamenitza on limestone pavement surface. Approx. 15 cm diameter.

Karren

Karren are small-scale, mm- to m-sized features formed on the limestone surface. They are classified according to their shape and size: the most common forms are rillenkarren (small runnels or channels about 20 mm wide), rinnenkarren (larger

runnels about 200 mm wide), and trittkarren (shallow horizontal steps). Despite their apparent similarity to channels formed by erosion, karren are formed by the dissolution of limestone by water flowing off the pavement surface.



Figure 13. Rinnenkarren.



Figure 14. Trittkarren.

Dolines

Dolines are bowl-shaped depressions in the land surface that can be several metres to several hundreds of metres wide (see Fig. 15, overleaf). 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, but this term has now largely fallen out of use. There are at least 1500 dolines in the Burren with an area greater than 100 m². Most of these large dolines occur in the east of the area; this reflects the fact that they are a feature of a more mature karst landscape. The Carran Depression is ~ 9 km² in area and is the best example of a doline in Ireland. It began to form several tens of millions of years ago, as a river flowing over the surface of the shales eventually eroded through to the limestone underneath and disappeared underground.



Figure 15. Doline on Knockaunsmountain.

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, as in the examples around Poulsallagh and Murroughtoohey, but many smaller, pebble- or cobble-sized erratics also occur in the Burren. Most erratics in the Burren region are of limestone, 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 above sea level in the Burren region, indicating that the ice sheet that covered the area was at least a couple of hundred metres thick.



Figure 16. Limestone erratic near Poul nabrone.

Drumlins

Drumlins are long, low, rounded hills up to 1 km long and 30-50 m high. They consist of unsorted glacial drift deposited 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”. 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 17. Drumlin near Kilshanny.

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 water flow as the stream now flows underground. The origins of many of the dry valleys and gorges in the Burren region are enigmatic. Some may have formed during glacial advances, when underground drainage channels were blocked by ice and surface water was forced to flow overground. Other dry valleys formed simply because dissolution of limestone at the surface formed fissures large enough to capture surface streams. Yet other dry valleys may represent collapsed cave passages. A combination of two, or all three, processes could have occurred in some cases! The Ballyvaughan and Turlough valleys are among the oldest landscape features preserved in the Burren. They probably reflect the original position of ancient rivers that flowed over the land surface when it was still covered by shales, several tens of millions of years ago. These valleys, and many other dry valleys in the Burren, are now floored by thick deposits of glacial till.



Figure 18. Coolagh River dry valley.

Turloughs

Turloughs are seasonal lakes where both the inlet and outlet are underground. In true turloughs, fluctuations in water level reflect variations in the level of the water table due to changes in rainfall. In some turloughs, water level changes occur because the lake is connected by underground passageways to the sea, and therefore is affected by the tide. Other lakes with a varying water level can appear similar to turloughs, but in this case, the changes in water level reflect a buildup of water in the lake following high rainfall as the outlet is too small, or too blocked, to allow the water to escape fast enough. Turloughs are common in Ireland but many have been drained artificially to reduce flooding. Examples in the Burren region include Lough Aleenaun and Knockaunroe.

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 are common along the limestone-shale contact, where surface streams passing over the relatively impermeable shales sink upon reaching the more permeable limestones. Springs occur throughout the Burren region and also within a few tens of metres offshore. Most springs here have a flow rate of less than 20 litres per second but some

flow at more than 500 litres per second, e.g. at springs of the Fergus River. There are numerous smaller springs that rise at the land 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 19. The Coolagh River swallow hole.

Caves

Caves typically develop where water flow through a rock mass is prevented by an impermeable (water-tight) layer. 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 caves in the Burren developed above the water table and are termed “vadose” caves. Phreatic cave passages, which form below the water table, are relatively rare in the Burren; the best example is the Aillwee cave, which is at least 350,000 years old. An extensive phreatic cave system underlies the Gort-Kinvarra Lowlands, but many parts of it are extensively flooded, blocked by glacial deposits or collapsed.



Figure 20. Entrance passageway at Aillwee Cave. The rounded roof profile represents the original geometry of phreatic tube.