INCEPTION AND SUBSEQUENT DEVELOPMENT OF CONDUITS IN THE CUILCAGH KARST, IRELAND

VOLUME I

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Abstract

This thesis explores speleogenesis within the Dartry Limestone Formation of Cuilcagh Mountain by considering the hydrogeology of the aquifer in the modern setting but also by considering its evolution since it was deposited during Asbian (Dinantian) times. Due to the synclinal structure of the region, which gently plunges northwestwards, the aquifer remains buried beneath the upland and is not exposed to the south. However, the formation outcrops along its northern and eastern upland margins where resurgences drain the aquifer via an extensive network of cave systems, which include Marble Arch Cave. In the west, the aquifer lies near surface but a significant artesian resurgence, Shannon Pot Rising, emerges from the aquifer via c.20m of overlying sandstones and shales. Water tracing experiments undertaken during this research project have added significant clarity to the hydrological regime that operates within this karst aquifer. These tests have shown that whilst extensive conduit systems are present at the eastern and northern margins of the uplands, Shannon Pot Rising in the west is the outlet for a regional conduit system that operates beneath Cuilcagh Mountain where the aquifer remains buried and in places confined. Water tracing has also identified that the boundary between the regional and marginal systems correlates to an igneous intrusion, the Cuilcagh Dyke. Hydrochemical data from Shannon Pot Rising indicates that the regional system has both shallow and deep flow components. This and hydrogeological evidence indicates that Shannon Pot developed as an overflow and that it's conduits formed at depth and unrelated to surface processes. Study of the cave systems at the eastern and northern margins have identified a number of lithological discontinuities within the sequence that have guided conduit inception within the aquifer. These early systems were later modified when the aquifer became unconfined and surface karst landforms developed.

The author beneath the Marble Arch, at the head of the Cladagh Glen, County Fermanagh

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Chapter 1

Aims and Objectives

1.1. Introduction

This thesis is a study of the hydrogeological evolution of a karst aquifer. The study area for this research is Cuilcagh Mountain, an upland area that straddles the border between southwest County Fermanagh in Northern Ireland and northwest County Cavan in the Republic of Ireland. In many ways this study is site specific, in the sense that it considers why conduits have formed within particular parts of a carbonate sequence but also because the underground drainage systems, flow paths and hydrochemistry which are described and examined are unique to the hydrogeology of the study area. However, the fundamentals of conduit initiation and subsequent development that are discussed in this thesis have implications for speleogenesis in carbonates within other parts of Ireland, Europe and worldwide. As such, whilst the study area for this thesis is Cuilcagh Mountain, the concepts of this thesis contribute to a wider understanding of speleogenesis within carbonate strata.

Recent advances in speleogenesis theories by Worthington (1991), Lowe (1992), Lowe and Gunn (1997) and Klimchouk (2000) have shown the importance of hydrogeological and hydrochemical aspects of speleogenesis in karst aquifers. This research project was initiated following publications by these authors with the objective of considering the geological features that focus and guide the inception and development of conduits.

The karst of Cuilcagh Mountain was selected as a study area for this thesis primarily because there was very little in the way of published research on speleogenesis for the region. However, the mud mound limestones of southwest Fermanagh also provide an unusual limestone medium for speleogenesis. Although not unique, the sedimentology the Dartry Limestone Formation differs greatly from limestones in other parts of Great Britain and Ireland. As far as the author is aware this is the first time that speleogenesis has been extensively studied within mud mound limestones. Additionally, work by Gunn had identified the study area as having a particularly complex hydrological setting with individual sinks draining to multiple risings. Although it is not unusual for sinks to drain to two or three risings, individual sinks in the eastern part of Cuilcagh Mountain have been proven to drain to at least seven risings.

On this basis, this thesis has three major objectives.

1. To detail the geology of the karst aquifer.
2. To undertake an investigation of the modern karst hydrology.
3. To investigate conduit inception and development within the karst aquifer.

1.2. Methodology

Although the objectives of the project detailed above are related as an investigation into a karst aquifer the methodology to achieve each objective is different.

Objective 1: In order to detail the geology of the aquifer its stratigraphy and structure must be assessed. Although some geological information will be available from government agencies, the majority of information will be collated from observations both above and below ground. Collection of geological data will allow the construction of cross-sections to develop a 3-dimensional understanding of the aquifers extent.

Objective 2: Investigation of the modern hydrology will be based upon undertaking water tracing experiments to prove and disprove hydraulic connections between sink and rising. Catchment boundaries will be delineated and flow paths inferred from data collected in objective 1. Hydrochemical analysis undertaken by Neil Webber as part of a related project at the University of Huddersfield will be used.

Objective 3: Cave systems will be described in relation to lithology and geological structure, in order to identify any geological features that have guided conduit initiation on conduit development.

1.3. Thesis structure

This thesis has been subdivided into two volumes. Volume I contains the text whilst Volume II contains the figures, plates and tables.

Outline of chapter:

Chapter 1.	Presents aims and objectives
Chapter 2.	Reviews recent advances in speleogenesis theories since the 1990's.
Chapter 3.	Reviews the karst hydrogeology of the study area.
Chapter 4	Presents the authors work on the hydrogeology of the Cuicagh Karst.
Chapter 5.	Draws conclusions from chapter 5 and discuses conduit inception and development.
Chapter 6	Summarises the evolution of the Cuilcagh karst aquifer
Chapter 7	Conclusion

Chapter 2

Literature Review

2.1. Introduction

This chapter provides a brief summary of the advances that have been made in speleogenesis and the evolution of karst aquifers. A review of the literature on the hydrogeology of the study area is presented in Chapter 3.

Historically, the term speleogenesis has been used to describe the origin of limestone caves. However, the term 'cave' itself simply refers to 'a natural hole in the ground, large enough for human entry' (Lowe and Waltham, 1995). Over the last two decades speleogenesis has become more synonymous with the evolution of a karst aquifer, from the initiation of preferential flow paths, through the transition to conduit, to the development of caves and ultimately their abandonment and destruction. The practical study of speleogenesis is restricted by the fact that caves themselves are the only part of karst aquifers that are accessible by man. As such, speleologists only observe the later stages of cave development. The earliest stages of speleogenesis are theoretical and based upon the hydrogeological and hydrochemical aspects of the aquifer in which they form.

Modern studies such as those by Lowe (1992), Klimchouk (2000), Palmer (2000) consider karst aquifers in terms of their primary, secondary and enhanced permeabilities. The primary permeability comprises the rock matrix, including any heterogeneity within the limestones, whilst the secondary permeability consists of fracture networks that dissect the rock matrix. The enhanced permeability (or tertiary permeability) consists of conduits that have formed by solution along preferential pathways within the aquifer where the matrix permeability and/or the fracture permeability have guided flow. In this thesis the geological features that guide and focus the development of conduit are referred to as inception horizons (Lowe, 1992), or inception planes. Inception horizon is used to refer to lithological guidance and inception plane is used to refer to a tectonic guidance of conduit initiation.

Although many rock-types have a dual permeability of both matrix flow and fracture flow it is the potential for solutional conduits, and hence triple permeability properties, that is characteristic of a karst aquifer. The distinction between conduit flow and fracture flow is that conduits have an aperture size greater than 10mm (Worthington and Smart, 2004) and transfer turbulent flow (Groves and Howard, 1994a and 1994b, Howard and Groves, 1995), whilst fractures typically have apertures of between 0.01-0.1mm and transfer laminar flow. Klimchouk (2004) describes the transition between laminar and turbulent flow to occur at between 5-15mm but an aperture size of 10mm is generally considered to represent the 'breakthrough' and as such used to define conduits. At the breakthrough of turbulent flow carbonic acid dissolution is enhanced and the rate of enlargement increases substantially. Additionally turbulent flow is able to transport sediment allowing erosional processes to modify and enlarge the pathway. Where pathways have developed along inception horizons or planes but have not yet achieved an aperture of 10mm then these pathways are termed channels (Worthington and Smart, 2004). By these definitions then conduits also include caves.

In considering the Carboniferous limestone at Mammoth Cave, Kentucky USA, Worthington (1999) attributes permeabilities of $2x10^{-10}ms^{-1}$, $1x10^{-5}$ ms^{-1} and $3x10^{-3}$ ms^{-1} and porosities of 2.4%, 0.03% and 0.06% for matrix, fractures and conduits respectively. Carboniferous limestones typically have a particularly low matrix permeability caused by poor interconnectivity between pore spaces. Fractures have less total porosity in the rock mass than the rock matrix but due to their two dimensional nature they have substantially greater interconnectivity and hence greater hydraulic conductivity. However, flow in fractures is laminar and therefore provides a lower hydraulic conductivity than the turbulent flow of conduit.

Worthington (1999) also presents the properties of a younger carbonate aquifer, the Cretaceous Chalk of Southern England. The chalk has matrix permeabilities and porosities that are measured at $1x10^{-8}ms^{-1}$ and 30% respectively, which are considerably higher than those for Carboniferous limestone. However, permeability and porosity values for fracture flow in the Cretaceous Chalk are calculated at $4x10^{-6}$ ms^{-1} and 0.01% respectively, which are significantly lower. Permeability and porosity values for conduit flow in chalk are also significantly lower at $6x10^{-5}$ ms^{-1} and 0.02% respectively. As such, whilst both Carboniferous limestone and Cretaceous chalk are karst aquifers the Carboniferous limestone has a more extensive and efficient fracture flow and conduit flow system. This is largely due to the higher matrix permeability and greater homogeneity within the chalk, which reduces the likelihood of preferential flow paths developing.

2.2. Advances in the study of karst aquifers and speleogenesis (1930-2004)

In the last 100 years the most significant advances in speleogenesis have been with the recognition of hydrogeological and hydrochemical aspects of conduit initiation and development. Early karst studies considered speleogenesis as a wholly shallow (vadose) process but by the turn of the 20th century the concept of speleogenesis in a deep phreatic setting was becoming increasingly recognised as a major factor. Davis (1930) was one of the first workers to suggest that the enlargement of flow paths may occur within a deep phreatic setting. Davis's 'The origin of limestone caverns' was also one the first papers to emphasise the 'potentially vast timescales of cavern formation' over tens or even hundreds of millions of years. Other authors of the time such as Swinnerton (1932) acknowledged the importance of phreatic speleogenesis but stated that most dissolution takes place at the transition zone between the shallow phreatic and vadose. With many of these early papers there is substantial overlap between theories, and many descriptions of speleogenesis were specific to cave development in different parts of the world.

Pathways and flow paths have long been described in the context of the initial stages of cave development. Water was first ascribed to be the driving force behind cave formation during the 18th century, although during these times it was erosion and not dissolution that was considered to be the main process of enlargement. By the end of the 19th century dissolution was acknowledged as being a fundamental concept behind speleogenesis. However, a number of authors remained objectors to dissolution being the driving force behind speleogenesis due to saturation being achieved 'everywhere except close to the surface' (Shaw, 2000). Observations associating joints (fracturing) with cave development had been made 100 years before Davis's 'The origin of limestone caverns' (1930) by geologists of the time, such as Charles Lyell (Shaw, 2000). However, less emphasis appears to have been focused on lithological guidance of caves during these times. Gardiner (1935) (Figure 1) was one of the first to identify that cave development favours certain lithological members within a limestone sequence. Although he referred to these 'favourable' beds as aquifers and carrier beds, which in the modern context would suggest a phreatic setting, he discussed them in the context of promoting vadose speleogenesis. Observations of lithological guidance of conduit and caves were also made by Moneymaker (1941), who found that levels of voids intersected by boreholes were associated with shales. He suggested that these cavities indicated initial dissolution below the water table followed by subsequent development above it. These observations bear some similarity with modern views on speleogenesis. Observations of cave passages forming levels or tiers in northwest Yorkshire were studied by Sweeting (1950). However, these levels were discussed in the context of caves developed at the water table with each cave tier being related the sequential down cutting in local valleys rather than their geological setting. During these times dissolution remained the driving force behind cave development. However, authors such as Howard (1963) highlighted the issues of carbonic acid dissolution achieving rapid saturation. However, unlike earlier theories that had objected to carbonic acid dissolution theories Howard concluded that for dissolution to occur at any significant depth then the aggressiveness of the water had to be created within the rock rather than derived from the surface. It was not until the 1960s and 1970s that the kinetics of dissolution was investigated and understood (Dreybrodt, 1981, 1992 and 2000). An important discovery was that although dissolution proceeded rapidly when meteoric waters came into contact with limestone, as the reaction approached equilibrium the rate slowed by several orders of magnitude (White, 2000). This phenomenon allowed carbonic acid dissolution to proceed deeper within the aquifer than had previously been conceived (see Figure 2 for general karst hydrology). A further discovery was made by Bögli (1971 and 1980), when the concept of additional dissolution by mixing corrosion was recognised.

At the same time advances were also being made in hydrogeology. The work of Ford (1968, 1971) and Ewers (1966) culminated in the Ford and Ewers paper 'The development of limestone cave systems in the dimensions of length and depth' (1978). This paper identified that 'cave systems may comprise of vadose, phreatic and water table components contemporaneously'. The model comprises of four states (cave types) with phreatic and water table caves being end-members, where the type of cave developed as a function of the fracture frequency (and availability of bedding discontinuities (Lowe, 2000b)) penetrable by groundwater (Figure 3). A state 1 cave has low fracture frequency and as there are less pathways available between sink and rising the resultant route is more likely to be less direct and deeper, hence a phreatic cave forms. A state 4 cave has very high fracture frequency and the abundance of pathways allows a more direct and shallow route from sink to rising, resulting in a vadose cave that is approximately coincident to the water table. Ford and Ewers also qualify a state 0 setting where fracture frequency is very low and caves do not develop, instead surface streams cross the limestone surface without sinking.

In the last two decades the study of speleogenesis has changed from the concept of deep-phreatic, shallow-phreatic, vadose and water table settings to the concept of unconfined and confined hydrogeological settings. With hindsight, earlier studies have tended to focus on the development of caves, whilst recent studies have focused upon the initiation of primary pathways and the development of conduits.

Confined karst develops where groundwater is under pressure in a carbonate aquifer that is buried beneath less permeable strata. Speleogenesis in this setting tends to be deep-seated (Klimchouk, 2000) and unrelated to surface topography. As such, processes of inception are factors of the hydrochemistry and hydrogeology of the aquifer. In confined settings the term hypogenic is often used and refers to the hydrochemistry of dissolution at depth. Confined karst may also be referred to as artesian or interstratal karst.

Palmer (1991) states that 'the hydrogeological setting of a karst aquifer is the most significant factor in determining the cave patterns within it'. In his 1991 paper several types of solutional cave patterns, including angular passages, curvilinear passages, fissure networks, spongework, ramiform and mazes, were considered in terms of the geological features that guided the flow path, and their subsequent development, and the source of the recharge (1991) (Figure 4). Cave passages and patterns were assessed in terms of guidance by either fracture and bedding partings or whether dissolution occurred within the intergranular rock matrix. The origin of the recharge was attributed to karst depressions, diffuse flow or hypogenic sources. In considering passage morphologies Palmer identified that in the vadose setting water flows by gravitational forces and as such will follow the steepest flow paths, usually via vertical fissures. As such, caves formed in the unconfined vadose setting tend to include shafts and linear passages. In the phreatic setting, either confined or unconfined, Palmer concluded that the downward hydrostatic pressure nullifies the gravitational effect and as such groundwater has a tendency to flow via the path of least resistance. As such phreatic caves tend to 'wander' in plan view forming sinuous passage networks that may be by a combination of fracture networks and/or bedding plane discontinuities. Palmer (2000) also identified that cave passages (and conduit) can be obscured by multiple phases of development. This is particularly the case with conduit and caves developed in the phreatic zone that are drained, overprinted and modified by vadose systems.

Although Palmer states that 'the great majority of caves have patterns determined almost entirely by the flow of rather shallow meteoric water' he also acknowledged that dissolution does occur at depth by either the deep circulation of meteoric waters or from hypogenic sources. Deeply circulating meteoric waters will retain a low state of dissolution for considerable time and depth. As such, and given time, flow paths will become solutionally enlarged by carbonic acid dissolution alone. Although this process is slow, mixing with other groundwaters may enhance it. Palmer (2000) states that: 'Hypogenetic caves are formed by water in which the aggressiveness has been produced at depth beneath the surface, independent of surface or soil CO_2 or other near-surface acid sources'. Whilst this covers caves formed by hydrothermal waters and rising H_2S (Hill, 2000) it also includes strong acid inception (Lowe, 1992) whereby H_2S is derived from pyrite-rich horizons within the limestone succession.

In the last decade several authors, in particular Worthington, Lowe and Klimchouk have advanced the understanding of deep-seated karst processes. Worthington (1991) observed high sulphate levels within springs in the Canadian Rocky Mountains and attributed their occurrence to sulphate dissolution as a mechanism for initiating conduit initiation along deep flow paths by H_2S dissolution. Lowe (1992) identified inception as the earliest phase of conduit development (1992) (Figure 5). This earliest phase marks the transition from rock without void to rock with solutional void. Based upon field observations and a re-evaluation of published work Lowe identified specific bedding partings within limestone sequences that were related to cave development. Lowe identifies these 'favourable' beds as inception horizons, i.e. horizons that have guided preferential flow paths within a limestone sequence. Lowe also identifies that subsequent to inception the development of conduit occurs within the surrounding 'high purity limestones'. Inception horizons tend to be minor partings in the context of the limestone sequence that have anomalous lithological, aquifer and/or hydrochemical properties. These bedding horizons tend to be related to hiatuses in depositional cycles and are commonly either clastic or impure limestones. Considering the low permeability of limestones (especially Carboniferous limestones) these interbeds are no less impervious and commonly more permeable than the surrounding rock. Historically these interbeds have been referred to as aquicludes (Gardiner, 1935) and the limestone bedrock as the aquifer but in reality the limestone may well be the less permeable and effectively be the aquiclude. Interbeds may also include anomalous chemical attributes when compared to the surrounding limestone bedrock, such as the inclusion of gypsum, which will dissolve or be reduced to form H_2S, or sulphide minerals, which may be oxidised to form H_2S. Although the amounts of H_2S are likely to be small they will locally enhance the permeability of the limestone above and/or below the source horizon by strong acid dissolution (Bottrell *et al.*, 2000). Depending on the depositional nature, frequency and lateral extent of these horizons Lowe's Inception Horizon Hypothesis identifies that preferential flow paths may form early within the evolution of a karst aquifer, potentially as early as during the burial of the sediment sequence.

Although the Ford Ewers 'fracture frequency model' is still referred to in modern texts it has largely been replaced by the most recent advancements in speleogenesis by Palmer, Worthington, Lowe and Klimchouk. These recent advances encompass the hydrochemical and hydrogeological aspects of inception and development processes that occur when the aquifer remains confined. These confined dissolution processes often precede unconfined speleogenesis i.e. those dissolution processes that occur near surface by the circulation of meteoric waters. Many aspects of the Ford Ewers 'fracture frequency model' remain valid for unconfined speleogenesis.

Chapter 3

Previous Research on the Cuilcagh Karst Aquifer

3.1. Introduction

This chapter serves to introduce the setting of the Cuilcagh karst aquifer and provides a review of published research. Geological and hydrological investigations undertaken by the author as part of this research project are presented in the following chapters.

In the modern setting approximately 45% of Ireland is underlain by Carboniferous limestone, the majority of which underlie the Irish Midlands buried glacial subsoils. Surface outcrop of the Carboniferous sequence largely occurs in the western uplands of counties Limerick, Clare and Galway and in the northwestern uplands of counties Fermanagh, Cavan, Leitrim and Sligo. In these upland areas, the terrains are renowned for their distinctive karst landscapes, of sinking streams, dolines, cave systems and risings. However, discoveries of karst landforms buried beneath glacial subsoils of the Irish Midlands are becoming increasingly common.

At 665m AOD, the summit of Cuilcagh Mountain is the highest point in the northwest uplands of Ireland, which encompasses southwestern County Fermanagh, northern County Cavan, northern County Leitrim and northern County Sligo. Cuilcagh Mountain, together with Belmore and Tullybrack, form the most eastern extent of the uplands, which border upon Upper and Lower Lough Erne and the provincial town of Enniskillen.

The stratigraphy of the region belongs to the Carboniferous system. Whilst, mountaintops are generally composed of sandstones, conglomerates and shales the lower slopes and the valley floors tend to be composed of limestones and shales (Figure 6). Two main limestone formations occur in the region: a lower limestone named the Ballyshannon Limestone Formation, which has a maximum thickness of 345m, and an upper limestone named the Dartry Limestone Formation, which has a maximum thickness of 360m (Geological Survey of Northern Ireland (GSNI), 1998). The two formations are separated by a sequence of shales, sandstones and argillaceous limestones (GSNI, 1998), which hydraulically isolates them as two distinct karst aquifers. This research project focuses on the hydrogeology of the Dartry Limestone Formation. However, it is worthy to note that the Ballyshannon Limestone Formation, whilst tending to be poorly exposed due to a thick and extensive cover of glacial subsoils, has significant karst landforms (GSNI, 1998; Peter Bennett, Hydrogeological and Environmental Services Ltd, *pers. comm.*, 2000), including the only turloughs in Northern Ireland (Kelly *et al.*, 2003).

Several major valleys including the MacNean Valley, the Erne Valley and the valley of the Shannon River transect the upland area of southwest County Fermanagh and northwest County Cavan. These valleys incise into the Carboniferous stratigraphy so that the Dartry Limestone Formation crops out on Cuilcagh Mountain, Belmore and Tullybrack. In these uplands the Formation forms wide expanses of the topography and has developed an extensive surface karst and an equally extensive underground drainage via conduit systems, making it a well-developed karst aquifer.

Due to the regional geological structure, outcrop of the Dartry Limestone Formation is restricted to the lower northern and eastern slopes of Cuilcagh Mountain, where it forms escarpments that overlook the MacNean and Upper Erne valleys respectively. The eastern escarpment is termed the East Cuilcagh Escarpment in this thesis and it forms a gently inclined dip slope at the top of the Formation. The karst geomorphology of the East Cuilcagh Escarpment includes several large pot holes, numerous small suffosion dolines, and a number of risings at the base of the scarp. A number of the pot holes form entrances to cave systems although these tend not to be particularly extensive (Jones *et al.*, 1998). On the northern escarpment, locally known as the Marlbank, the limestone comprises of an extensive accumulation mud mound limestones (Kelly, 1996), which gives the escarpment and undulating topography comprising of several large knoll-shaped hills. The karst geomorphology of the Marlbank includes large collapse and suffosion dolines as well as several major stream sinks (Gunn 1982, Kelly 1989 and Jones *et al.*, 1998). All rivers and streams that drain onto the Marlbank sink underground into conduit systems, and emerge at risings at the base of the escarpment. A number of these conduit systems are explorable as caves. These include the Marble Arch Cave System (4.5km) and the Prod's-Cascades Cave System (4.1km), which are the longest caves on Cuilcagh Mountain and the sixth and seventh longest caves in Ireland respectively (Kelly *et al.*, 1995).

Martel and Jameson undertook the first scientific study of Cuilcagh karst during their initial exploration of Marble Arch Cave in 1895 (Martel, 1985); and since then geologists, geomorphologists, speleologists and hydrologists have explored and studied the caves and karst of the region. However, compared to many other karst regions in Europe, Cuilcagh Mountain has received relatively little scientific focus. Since Martel's first survey of the Marble Arch Cave local and visiting cavers have systematically surveyed the caves of Cuilcagh Mountain as the systems have been explored. Coleman (1965) was the first to summarise the main cave systems in the region. Then, with the discovery of many new caves during the 1970's and 1980's, Burns (1989) produced a compilation map showing all cave surveys of the known systems on Cuilcagh Mountain. However, the first comprehensive guide to the caves and karst of Cuilcagh Mountain only became available in 1997 when Jones *et al.* produced 'The Caves of County Fermanagh and County Cavan'.

3.2. Geological review

Mapping of the surface geology was first undertaken by Symes and Wilkinson (1886) and then by Wilkinson and Cruise (1886), which let to the subdivision of the succession into a broad differentiation between the Upper Limestone, the Calp (or Middle) Limestone and the Lower Limestone (Figure 7). Padget (1954) undertook a detailed investigation of the Upper Carboniferous stratigraphy of Cuilcagh but did not consider the limestone sequence, which were not reviewed until Oswald (1955) modified the 1886 nomenclature using type localities in the Sligo Syncline. The Upper Limestone was renamed the Dartry Limestone Formation, The Calp Limestone was subdivided into the Glencar Limestone Formation, the Benbulben Shale Formation, the Mullaghmore Sandstone Formation and the Bundorran Shale Formation. Whilst the Lower Limestone was renamed the Ballyshannon Limestone Formation. Sheridan (1972) used a combination of Symes and Wilkinson's (1886) and Oswald's (1955) nomenclature to describe the Northwest Carboniferous Basin. In his paper he refers to the Upper (Dartry) Limestone and the Lower (Ballyshannon) Limestone. The Calp Limestone was subdivided into upper, middle and lower. Brunton and Mason (1979) reverted to Oswald's nomenclature by grouping the Dartry Limestone Formation, the Glencar Limestone Formation and the Benbulben Shale Formation as the Dartry Group and the Mullaghmore Sandstone Formation and the Bundorran Shale Formation (including the Dowra Sandstone Member) as the Ballyshannon Group. Kelly (1989a, 1989b and 1996) retained Brunton and Mason's nomenclature as did the GSNI (1998). However, the GSNI (1998) combined the whole sequence as the Tyrone Group rather than using the differentiation between the Dartry and Ballyshannon groupings.

3.2.1. <u>Northwestern region of Ireland during the Carboniferous</u>

By the end of Devonian times, the basement rocks (Dalradian) upon which the modern Irish landmass is founded (hereafter referred to simply as "Ireland") lay close to the palaeo-equator as part of the continental landmass of Laurasia. During early Carboniferous (Dinantian) times Ireland formed part of the central southern margin of Laurasia where several major sedimentary basins had developed and been invaded by shallow tropical seas (Bridges *et al.*, 1988; Bridges *et al.*, 1995).

3.2.1.1. Early Dinantian (Courceyan to Arundian stages)

The earliest Dinantian sedimentation in Ireland occurred in the south during early Courceyan times, in response to the onset of the Dinantian marine incursion (GSI, 1996). The marine transgression advanced northwards across the southern margin of Laurasia reaching the area that is now the Irish Midlands by the middle Courceyan, and eventually reaching the counties of Sligo, Leitrim and Fermanagh by late Courceyan times. As the transgression advanced a thick sequence of carbonate mud mounds [the Ballyshannon Limestone Formation] was deposited (Figure 8). Accumulation was widespread and largely unrestricted across Ireland, which resulted in complex build-ups of great thicknesses (780m near Limerick, Lees (1961 and 1963) and 600m in County Cork and County Kerry, GSI (1997)). Deposition is considered to have been contemporaneous with that of similar carbonates found in Staffordshire (Bridges and Chapman, 1988), South Wales and the Bowland Basin in Northern England (Gawthorpe *et al.*, 1988).

3.2.1.2. Middle Dinantian (Holkerian to early Asbian stages)

During late Arundian times a submarine fault block topography developed in northwest Ireland in response to tectonism. Increased subsidence during Courceyan to Arundian times caused these basins to deepen and as a result carbonate accumulation was reduced. This deepening of the basin continued during the Holkerian and sequences of shales with thin interbedded limestones and sandstones were deposited. Tectonism continued throughout the Holkerian but by the early Asbian the rate of subsidence was gradually overtaken by the rate of sediment deposition. As such, upward through the early Asbian sequence the carbonate component gradually increased and eventually caused the re-establishment of micrite deposition and mud mound accumulation.

3.2.1.3. Late Dinantian (Asbian to Brigantian stages)

The uneven submarine fault block topography, that developed during Arundian and Holkerian times, generated several different environments in which carbonates were deposited [the Dartry Limestone Formation] (Figure 9). Mud mounds accumulated at the shelf setting of the basin margins below the storm base and at structural highs and near-shore environments bedded limestones were deposited (Kelly 1989a, 1989b, 1996). As a result, mud mound accumulations became localised and developed as centres of growth separated between areas of bedded limestone. These mud mound accumulations are considered similar to build-ups on the Derbyshire carbonate platform (Bridges and Chapman, 1988) and in the Midland Valley of Scotland (Pickard, 1992).

The sediment build-up gradually began to fill the sedimentary basin, so that by late Asbian times shallow water conditions prevailed. By late Asbian and Brigantian times sabkha conditions were established.

3.2.1.4. Silesian

Through Pendleian and Arnsbergian times a deltaic environment advanced southwards into the now retreating sea, resulting in the deposition of sands, silts, muds and gravels. In County Leitrim at Arigna the upper most sediments of the Carboniferous comprise of sandstones and shales with coal seams.

3.2.2. Cuilcagh Mountain during the Dinantian

The geology of Cuilcagh Mountain forms part of the Lough Allen Basin, which is one of a number of sub-basins within the regional Northwest Basin of Ireland. To the west the Lough Allen Basin is bounded by the Castle Archdale–Belhavel Fault System and to the east by the Curlew Mountain Fault and the Clogher Valley Fault (Figure 10). All of these faults were active within the basement rocks of the Dalradian Supergroup before Dinantian times (Millar, 1990; Kelly, 1996). During Dinantian times movement along these faults led to the development of the Northwest Basin and the sub-basins therein, including the Lough Allen Basin.

Southwest Fermanagh records a near complete sequence of Irish Carboniferous stratigraphy (Figure 6), from the Courceyan Ballyness Formation exposed in the western bank of Lower Lough Erne to the Arnsbergian Lackagh Sandstone Formation, which forms the summit ridge. The Dartry Limestone Formation forms part of the lower sequence on Cuilcagh Mountain, which comprises of (from oldest to youngest) Benbulben Shale Formation, Glencar Limestone Formation, Dartry Limestone Formation, Meenymore Formation and the Glenade Sandstone Formation.

The Benbulben Shale Formation (Holkerian) is the lowest formation in the Cuilcagh area and represents deposition in a deep basin environment. During the early Asbian, the basin shallowed, leading to a gradual change from the deposition of the Benbulben Shale Formation to the Glencar Limestone Formation. The early Asbian also saw a period of increased subsidence and the development of half graben structures, which generated a tilted fault block-type topography on the sea floor (Kelly, 1996). The westward thickening of both the Glencar and Dartry formations reflects the gradual development of one of these half-graben structures in this part of the Lough Allen Basin. The pivot for the half graben was located near the area that is now East Cuilcagh (Kelly 1999, *pers comm.*), where the Glencar and Dartry formations are at their thinnest, whereas the greatest subsidence occurred in the west, where the Glencar and Dartry formations are at their thickest. Tectonism continued throughout the Dinantian leading to the development of the facies variation observed in the Dartry Limestone Formation. With continued basin shallowing during the late Asbian the depositional environment changed from shallow marine to sabkha and then deltaic leading to the deposition of the Meenymore Formation and the Glenade Sandstone Formation.

3.2.3. Stratigraphy of the Dartry Limestone Formation

The Dartry Limestone Formation has its 'type' locality in the Dartry Hills of northwestern County Leitrim (Oswald, 1955), where the Formation is more than 300m thick and composed entirely of thinly bedded, cherty limestone. However, on Cuilcagh Mountain, c. 30km east of the type locality, these thinly bedded cherty limestones only form a minor part of the formation. The GSNI sheet (1991) refers to six members of the Dartry Limestone Formation on the Cuilcagh Mountain. These are, from base to top: the Knockmore Member, the Carrickmacsparrow Member, the Cloghan Hill Member, the Dartry 'Type' Limestone, the Cloghany Member and the Carn Member. This nomenclature has also been used in recent publications by the GSNI (1996). Kelly (1996) also refers to six members of the Dartry Limestone Formation (Figure 11) but his classification differs from that of the GNSI (1991) by referring to the Gortalughany Beds and not the Carricknacoppan Member. The Gortalughany Beds, which refer to a sequence in the Gortalughany Townland of East Cuilcagh, comprise a 50m-thick sequence of carbonate mudstones, cherts, thin shales and grainstones (originally termed 'Facies A' by Kelly (1989a and 1989b)). In this thesis, the format proposed by Kelly is used with the Gortalughany Beds informally referred to as the Gortalughany Member. The lithostratigraphic descriptions of the different members to the Dartry Limestone Formation are presented below as a synthesis of geological mapping and analysis completed by GSNI and Kelly. The authors work on the Dartry Limestone Formation are presented in the following chapters.

3.2.3.1. Knockmore Member

The Knockmore Member comprises an extensive and complex sequence of mud mound accumulations. The mud mounds of the Knockmore Member contain little bioclastic material; most of the rocks being composed of carbonate mud. As the mounds lack a rigid skeletal frame they are not considered as typical 'reefs' (Schwarzacher, 1961). Kelly (1996) reports that the mud banks of the Knockmore Member are divided into two distinct forms, tabular-sheets and knoll-shaped banks.

The knoll-shaped mud banks stack up to form a series of distinctive hills on the Marlbank Escarpment. The mud banks are reported by the GSNI (1997) and Kelly (1996) to contain few shale horizons and to be massive but poorly bedded. Infilled stromatactis cavities are extensively found throughout the mud mound limestones.

3.2.3.2. Cloghan Hill Member

Whereas the micrite of the Knockmore Member form a complex accumulation of mud mounds, the Cloghan Hill Member is composed of isolated mud banks with an abundance of bioclastic material. These mounds display a high level of fragmentation and an abundance of intraclasts derived from the bank, which have been interpreted by Kelly (1996) to indicate a high-energy, storm base environment. The transition from Knockmore Member to Cloghan Hill Member represents a shallowing of the environment, suggesting that the rate of carbonate accumulation had exceeded that of basin subsidence and that the basin was filling with sediment.

3.2.3.3. Gortalughany Member

The Gortalughany Member has only been identified on the East Cuilcagh Escarpment. Kelly (1996) reports the member to comprise of mudstones, grainstones, cherts and thin shales that have a restricted fauna typical of a hyper-saline environment, such as that of a lagoon. The grainstone beds within the sequence are interpreted as sandbars and include vertical fissures that are filled with bioclastic sediment; inferring that emersion occurred.

3.2.3.4. Dartry 'Type' Limestone

The Dartry 'Type' Limestone occurs extensively across Cuilcagh Mountain. The limestone is similar to that described at the type location in the Dartry Hills of northwest County Leitrim (GSNI, 1997). Like the type location, the Dartry Limestone on Cuilcagh is comprises of carbonate mudstones, packstones and cherts. Chert is abundant throughout the limestone occurring as well-bedded and irregular nodules. (Kelly 1996) attributes this unit to widespread shallow water conditions and the near filling of the sedimentary basin towards the end of the Asbian.

3.2.3.5. Cloghany Member

The Cloghany member has a maximum thickness of 1.3m (GSNI, 1991). Kelly (1996) identified the member to have an abundant and diverse fauna and, with the presence of glauconite mud, attributed it to shallow-water deposition.

3.2.3.6. Carn Member

The Carn Member is a series of unfossiliferous thinly bedded limestones and shales, which is interpreted as possible emersion prior to deposition of the unconformably overlying Meenymore Formation.

3.2.4. Tectonic structure and igneous intrusions

The major faults of the Northwest Basin of Ireland include the Castle Archdale-Belhavel and Clogher Valley fault systems, all of which have northeast-southwest trends (Figure 10). These faults are continuations of the Scottish Highland Boundary and Southern Uplands fault systems, respectively, which initiated as strike slip faults towards the end of the Caledonian Orogeny (c.380 Ma). These long-lived structures exhibit evidence of many phases of reactivation and movement. During the Dinantian, subsidence relating to movement along these faults controlled deposition in the Northwest Basin (Millar, 1990). During the Variscan Orogeny (c.290 Ma), at the end of the Carboniferous and beginning of the Permian, these faults were again active and movement along them contributed to the folding of the Carboniferous strata.

There have been several minor tectonic episodes since the Variscan Orogeny, the most notable being during the Triassic and Jurassic periods. However, a major tectonic episode occurred at the end of the Cretaceous associated with the intrusion of many dykes, some of which may have originally propagated to the surface as volcanic feeder pipes. This event corresponds to the opening of the Atlantic Ocean, and its associated volcanism that is preserved in the northeast of Ireland.

3.2.4.1. Geological structure

The Lough Allen Syncline is bounded to the northwest by the Ox Mountains, where it meets metamorphic rocks of the Moinian and Dalradian supergroups, up thrown along the Castle Archdale-Belhavel Fault System, which forms a zone of disturbance approximately 3km wide. To the east the syncline is bounded by the Clogher Valley Fault and to the south by faulting in the Curlew Mountains.

The GSNI (1998) have produced a simplified structural map of southwest Fermanagh based upon deep exploratory boreholes and geophysical data, largely seismic reflection surveys (Figure 12). The map shows the depth of the Ballyshannon Limestone Formation below an arbitrary seismic datum of 50m AOD, and reveals a steady southwestward increase in depth that is related to the Lough Allen Syncline. When topography is overlain on this map, the top of the Ballyshannon Limestone Formation is calculated to be c.1750m below the ridge of Cuilcagh Mountain.

Geological surveying by the Geological Survey of Ireland (GSI, 1996) and the GSNI (1991 and 1998) as well as work by Kelly (1986, 1989a and 1989b) and Millar (1990) identifies several major faults and numerous minor faults across Cuilcagh Mountain (Figure 13). Faulting generally follows three major orientations, eastnortheast-westsouthwest, north-south and westnorthwest-eastsoutheast. Surprisingly, fractures with the Caledonide trend (northeast-southwest) observed in the Castle Archdale-Belhavel and Clogher Valley fault systems are locally uncommon.

3.2.4.2. Igneous intrusions

Two igneous intrusions are identified in the Cuilcagh uplands, the Cuilcagh Dyke (named by GSNI, 1998), which cross cuts Cuilcagh Mountain westnorthwest-eastsoutheast, and an unnamed dyke mapped by the GSNI (1991) that lies at the southern margin of the East Cuilcagh Escarpment (Figure 13).

The Cuilcagh Dyke forms part of a dyke swarm in southwest Fermanagh (Figure 14), in which individual dykes extend for up to 80km. Smaller dykes, such as the Cuilcagh Dyke, do not exceed 20m in width but others have a width of 100m (Johnson and Rundle, 1993). The dykes of the southwest Fermanagh swarm have attracted the attention of several workers, as these represent some of the earliest activity in the Irish Tertiary Igneous Province during an early, but failed, spreading centre for rifting prior to the opening of the Atlantic Ocean. Past studies of the dyke swarm have included petrological analysis (Preston, 1967 and Walker, 1959), radiometric dating (Johnston and Rundle, 1991) and surveying by proton magnetometer (Gibson and Lyle, 1993).

It was hypothesised by Preston (1967), on the evidence of a gravity-high (Cook and Murphy, 1952) that a large body of basic plutonic rock exists beneath southwest Fermanagh. By modelling the gravity anomaly, Gibson and Lyle (1993) suggested that the top of this intrusive igneous body lies some 3km below the present surface. Gibson and Lyle (1993) also showed that the southwest Fermanagh dyke swarm is centred upon this gravity anomaly. Given that radiometric dates for the dykes have ranged between 75 and 60 million years ago (Johnston and Rundle, 1993), the up welling and injection of the magma was initiated during late Cretaceous to early Tertiary times. Preston (1967) suggested that some of the larger dyke intrusions were feeder dykes to surface volcanism during Tertiary times.

3.3. Hydrological review

'The karst hydrology of the [Cuilcagh] Upland is of considerable interest, for the divide between Shannon and Erne basins passes through the district'

Williams (1970, P121)

The River Erne is partially sourced from several large springs that emerge at the base of the eastern and northern limestone escarpments. The largest of these include Marble Arch and Cascades risings (Gunn, 1982 and 1985), both of which are located in the Cladagh Glen (a steep sided valley that has incised into the northern margin of the Marlbank Escarpment). Whilst Marble Arch Rising is located within the Dartry Limestone Formation, Cascades Rising is located within the stratigraphically lower Glencar Limestone Formation (Kelly1989a). The Shannon River also partially gains its source from the Cuilcagh karst aquifer. Shannon Pot Rising, which is located on the western margin of the mountain, is the most northerly source of the river and is known, in Ireland, as the Source of the Shannon. Unusually, Shannon Pot is located within the shales of the Meenymore Formation, which stratigraphically overlie the Dartry. The catchment boundary between risings that drain to the River Erne and Shannon River occurs within the karst systems of Cuilcagh Mountain, and is also influenced by the Cuilcagh Dyke (Gunn, 1996), which cuts across the northern slope of Cuilcagh Mountain and has intruded through the Dartry Limestone Formation. Williams (1970) was the first to consider the implication of the Cuilcagh Dyke (although he refers to dykes P.119) cross cutting the Dartry. However, he concluded that the influence of the Cuilcagh Dyke on the karst hydrology was undetermined.

The first scientific water-tracing experiments in the Cuilcagh karst aquifer were undertaken on the Marlbank Escarpment. In 1908 by Brodrick proved that the Monastir stream sink drained to Marble Arch Rising using florescent dye (Gunn, 1982). Between 1908 and 1974 a total of four other successful traces are recorded; in 1954 Holgate proved a connection from Cats Hole to Marble Arch Rising, in 1956 Wynn proved that Pollasumera drained to Marble Arch Rising, in 1970 Devoy and Orr proved that Prod's Pot drained to Cascades Rising and in 1974 Jones proved that Whiskey Holes sink drained to Tullyhona (Gunn, 1982). These first experiments appear to have been single tests to either prove or disprove connection to a specific rising (Gunn, 1982). Between April 1979 and September 1980 Gunn undertook a series of water tracing experiments on the Marlbank Escarpment (Gunn, 1982 and 1985). These tracer tests were the first on Cuilcagh Mountain in which multiple tracers (Fluorescein and Rhodamine WT) were used. Gunn used the results from these tests to determine connectivity between sinks and risings, to calculate average linear velocities and to determine catchment boundaries. On the basis of these experiments Gunn delineated the catchment areas for those Springwell, Marble Arch, Cascades and Tullyhona risings on the northern part of the Marlbank and Shannon Pot Rising on the southern part of the Marlbank (Figure 15 and 16). Results from Gunn's and earlier workers water tracing experiments as are presented in Tables 1, 2 and 3.

Whilst, most of Gunn's experiments during the 1970's and 1980's were conducted on the Marlbank Escarpment he undertook additional tracer tests during the 1990's that focused upon the East Cuilcagh Escarpment (Gunn, 1996 and 1997). Although the earlier experiments on the Marlbank Escarpment had indicated that stream sinks drained to single risings, tracer tests conducted by Gunn at Pigeon Pot II and Badger Pot on the East Cuilcagh Escarpment showed that drainage from single stream sinks flowed to multiple risings, including two risings distal to the escarpment. This complex karst hydrology indicated from Gunn's results is further compounded by the fact that one of the distal risings, Cascades Rising, is located on the opposite side of the Cuilcagh Dyke to the stream sink (Gunn, 1995, *pers comm.*). The other distal rising to Pigeon Pot II and Badger Pot is Shannon Pot Rising. As such, streams sinking at Pigeon Pot II and Badger Pot drain to both the Erne and Shannon drainage basins.

3.4. <u>Summary</u>

The Cuilcagh karst aquifer is defined as comprising of the Dartry Limestone Formation, which crops out on the lower slopes of Cuilcagh Mountain. The Formation forms an escarpment to the east and north of the mountain that have an extensive surface karst and an extensive system of caves and conduit systems. It is noted that conduit development is also recorded within the underlying Glencar Limestone Formation and the overlying Meenymore and Glenade Sandstone Formations. Surface karst landforms also are recorded in the Ballyshannon Limestone Formation that forms the floor of the Erne and MacNean valleys. However, the karst of the Ballyshannon Limestone is beyond the scope of this project.

Review of the geological setting of Cuilcagh Mountain identifies that the Dartry Limestone Formation has a particularly complex stratigraphy (Kelly, 1996 & GSNI, 1997) with lateral variation caused by its deposition within a tectonically active sedimentary basin. Mud mound limestones dominate the northern outcrop of the Formation but bedded cherty limestones dominate the east.

Reference is made to the regional geological structure of the Lough Allen Syncline and the intrusion of multiple dykes, including the Cuilcagh Dyke, into southwest Fermanagh during late Cretaceous to early Tertiary times. The Cuilcagh Dyke cuts through the Dartry Limestone Formation complicating the hydrology of the karst aquifer (Williams, 1970).

Study of the karst hydrology by Gunn (1982, 1996) has shown that whilst the conduit systems on the Marlbank Escarpment tend to form simple courses to single risings, those on the East Cuilcagh Escarpment are complex, with sinks draining to multiple risings. Pigeon Pot II and Badger Pot have been proven to drain to a number of local risings in the East Cuilcagh Escarpment but also two distal risings, Cascades Rising and Shannon Pot Rising. As Cascades Rising drains to the River Erne and Shannon Pot Rising to the Shannon River, then the stream sinks at Pigeon Pot II and Badger Pot have divergent flow that flows to two separate drainage basins.

Chapter 4

Hydrogeology of the Cuilcagh Karst Aquifer

4.1. Introduction

The review in Chapter 3 showed that research into the Cuilcagh karst aquifer began in the early 1970's with hydrological (including hydrochemical) study by Williams (1970) and Gunn (1982), with subsequent geological investigation by Kelly (1986, 1989a, 1989b and 1996) and the GSNI (1991 and 1998). The work completed by these authors has led to a greater understanding of many hydrogeological aspects of the Cuilcagh karst aquifer. However, the review also identified many aspects of the aquifer that remain incomplete. Gunn (1982 and 1996) made significant contributions to delineating catchment boundaries to springs around the mountain using water-tracing experiments. Additionally, Kelly (1986, 1989a, 1989b and 1996) and the GSNI (1991 and 1998) made substantial advances in explaining the extensive lithological variation that is evident across the aquifer. However, no interpretations have been made as to how the geology of the aquifer may have guided the initiation and subsequent development of the conduit systems that are observed as caves in the modern hydrological setting.

The hydrological investigation into the Cuilcagh karst included 14 water-tracing experiments and although a number of Gunn's original tracer tests were repeated, nine new sinks were traced by the author. The majority of experiments were undertaken on sinks in the East Cuilcagh Karst using multiple tracers (Fluorescein and Rhodamine WT). Also incorporated, is unpublished research into the chemistry of surface water and groundwater in the Cuilcagh Karst by Webber (Neil Webber, Limestone Research Group, *pers. comm.*, 1997). In parallel with this thesis Webber commenced a research project to investigate the hydrochemistry of the Cuilcagh Karst. The results were never written up but the raw data were made available to the author to assist the interpretation of speleogenesis. Webber measured temperature, electrical conductivity, pH and HCO_3 in the field and collected water samples for laboratory analysis to determine Cl, NO_3, SO_4, Ca, Mg, Na, K, Fe and Sr. In addition, isotope analysis was undertaken to determine the influence of pyrite oxidation of the groundwaters. In all Webber undertook ten sampling rounds. However, only two of these sampling rounds are included in this thesis as being representative of low flow (base flow) and high flow conditions. These are presented in Tables 4 and 5. Where other data are referred to in the text they are from the authors individual measurements using portable handheld equipment.

The geological investigation into the Cuilcagh Karst includes descriptions of the stratigraphical levels that the caves are located at, including a number of stratigraphical logs where possible. Fracture orientations and frequency within cave systems have also been mapped in order to determine their relationship with the pattern of cave passages.

4.2. Regional hydrogeology

Cuilcagh Mountain forms the most northerly watershed to the Shannon River, where it forms a topographic divide with the River Erne. Although the topography of Cuilcagh Mountain suggests a distinct divide between run-off draining to the Shannon and to the Erne, most of the streams that drain the eastern, northern and western slopes of the mountain sink underground. Tracer tests undertaken by Gunn have shown that these karstic systems do not conform to the catchment divide dictated by topography and indeed karstic drainage crosses the topographic watershed.

The outcrop of the Dartry Limestone Formation stretches across the eastern, northern and western lower slopes of Cuilcagh Mountain, where it forms a wide plateau with a steep escarpment that overlooks Upper Lough Erne and Lower Lough MacNean. The outcrop has a total area of approximately 58km^2, covering about fifty percent of the mountain's northern flank. Although the outcrop is largely continuous, the Upper Carboniferous sandstones and shales of Trien Mountain split the limestone into two distinct escarpments, that of East Cuilcagh and the Marlbank (Figure 17). Based upon work by Gunn in delineating catchments to the major springs, the Marlbank Escarpment can be divided into two further areas, namely the Erne Karst and the Shannon Karst. Where the Erne Karst includes all landforms that drain to the Erne basin from the Marlbank, and the Shannon Karst, which includes all landforms that drain to the Shannon basin from the Marlbank. As such, in this thesis the surface karst and caves of Cuilcagh are considered as three areas, the karst of the East Cuilcagh Escarpment (here after referred to as the East Cuilcagh Karst) and the Erne Karst and Shannon Karst of the Marlbank Escarpment (Figure 18).

Sandstone cliffs form the summit ridge of Cuilcagh, and they overlook the upper slopes of the mountain that are covered by a great expanse of blanket bog (Plate 1). Incident rainfall and discharges from the blanket peat bog recharges the many streams that drain from the mountain. Limestone does not crop out on the southern flank of Cuilcagh, and as such, the surface water streams that drain these slopes discharge directly into the Owenmore River without sinking underground. The Owenmore River is a tributary to the Shannon River, which it joins near Glengevlin, County Cavan. Run-off from the eastern and northern slopes of Cuilcagh drains onto the karst landscape of the East Cuilcagh Escarpment and the Marlbank Escarpment. Several water courses drain onto the East Cuilcagh Escarpment and with the exception of the Swanlinbar River and the Swanlinbar Stream all streams sink underground and form point inputs into karstic systems. Three rivers, the Owenbrean, the Aghinrawn and the Sruh Croppa as well as several smaller streams drain onto the Marlbank Escarpment and all sink underground into conduit systems, most of which are explorable as caves. However, water tracing experiments by Gunn (1996) have shown that a major groundwater divide cross-cuts the Marlbank Escarpment and separates its drainage into the Erne Karst and the Shannon Karst. The catchment divide roughly corresponds to the Cuilcagh Dyke, which cross-cuts northern Cuilcagh in a westnorthwest-eastsoutheast orientation. Resurgences on the Marlbank Escarpment that drain to the

River Erne include Marble Arch, Cascades, Hanging Rock and Tullyhona. Shannon Pot Rising is the only discharge point to the River Shannon. Water-tracing experiments by Gunn (1996) have shown that sinks on the East Cuilcagh Karst, which topographically fall into the catchment of the River Erne, drain both northwards to risings in Erne Karst and westwards to Shannon Pot Rising. As such, Shannon Pot Rising also has a distal catchment on the East Cuilcagh Escarpment in addition to its local catchment on the southern part of the Marlbank Escarpment.

4.2.1. Aquifer stratigraphy

Although the main part of the Cuilcagh karst aquifer is the Dartry Limestone Formation, previous workers (Kelly 1989b and Gunn, *pers. comm.,* 1995) have identified that the karst of Cuilcagh is unusual in that the strata above and below the Formation also have some conduit development, although on a much lesser scale than in the Dartry itself. In total karst landforms and caves, some of them substantial in size, are located within the underlying Glencar Limestone Formation and the overlying Meenymore Formation and Glenade Sandstone Formation. A summary of the karst landforms and caves in the Cuilcagh sequence is presented below (from oldest to youngest).

4.2.1.1. Glencar Limestone Formation

The Glencar Limestone Formation (Asbian) is composed of thinly bedded argillaceous limestone with common shale interbeds. Near the top of the Formation bedding becomes more massive and less shale is present. Conduit development is observed in the Glencar Limestone Formation but only at the entrance series to Cascades Rising Cave (GR: 21228-33498) where c.250m of cave passage occurs entirely within the Formation.

4.2.1.2. Dartry Limestone Formation

The Dartry Limestone Formation (Asbian) has an extensive underground drainage system, with more than of 20km of surveyed cave passage, including some of Ireland's longest cave systems. Associated with the extensive underground drainage network is an equally well developed surface karst terrain that includes numerous dolines, stream sinks and resurgences. In contrast to the underlying thinly bedded argillaceous Glencar Limestone Formation, the Dartry Limestone Formation is largely a massive mud mound limestone with rare shale horizons.

4.2.1.3. Meenymore Formation

The Meenymore Formation (Asbian) has a thickness of 30m and is composed of an interbedded sequence of thinly bedded shale, sandstone and limestone. Gypsum is reported to occur in this formation in parts of the Northwest Basin (GSI, 1997) but not on Cuilcagh Mountain. A number of karst landforms are present within the Meenymore Formation, including the Owenbrean Upper Sinks (GR: 21277-33172) and Shannon Pot Rising (GR: 20533-33176).

4.2.1.4. Glenade Sandstone Formation

The Glenade Sandstone Formation (Asbian) comprises of thickly bedded deltaic sandstone with rare shale interbeds and no carbonate units. Three karst landforms occur within the Glenade Sandstone Formation and these are large cover collapse dolines. The largest of these landforms, Tullynakeeragh Gravel Lake (GR: 20975-33187), swallows a surface stream.

4.2.2. Aquifer thickness

Across the northern flank of Cuilcagh Mountain, the Dartry Limestone Formation increases in thickness westwards, from c.120m on East Cuilcagh, of which 90m is exposed, to a maximum of 360m in the MacNean Borehole (GR: 20473-33839) in the west near Blacklion, County Cavan. The rapid thickening of the Dartry Limestone Formation confirms the fault control on the western boundary of the sedimentary basin by movement along the Belhavel-Castle Archdale Fault as suggested by Kelly (1996).

The Dartry Limestone Formation also has significant lithological variation from east to west across the mountain (Figure 19 and 20). The mud mounds, such as those of Gortmaconnell Rock, Limekiln Rock, Skreen Hill and Cloghan Hill, dominate the escarpment of the Marlbank (Plates 2 and 3) but they are not present in the East Cuilcagh Escarpment (Figures 7 and 8) where the formation comprises c.50m Dartry 'Type' Limestone and at least 50m of the underlying Gortalughany Member (Plate 4) and the topography forms a planar dip slope (Plate 5). Between the East Cuilcagh Escarpment and the Marlbank Escarpment the Knockmore Member must rapidly thicken both northwards and westwards. Similarly, the Gortalughany Member must rapidly thicken southwards and eastwards. This lithological change from well bedded to mud mound is not exposed.

4.2.3. Geological Structure

The geological structure of the region presented in this thesis is an interpretation of the geological maps published by the GSNI (1991) by the author.

The Dinantian strata of Cuilcagh Mountain form the northern limb of the Lough Allen Syncline, near the axis of the MacNean Anticline (Figure 21). Both are major structures with their axes aligned northwest-southeast and parallel with the ridge of Cuilcagh Mountain. Flexures within the northern limb of the Lough Allen Syncline form minor anticlines and synclines. These include the Owenmore Anticline and the

Cuilcagh Syncline (Figure 21). Throughout the Northwest Uplands the lines of valleys typically correlate with anticlinal axes, whilst upland ridges correlate with synclinal axes. The Owenmore Valley is aligned with the axis of the Owenmore Anticline, whereas the ridge of Cuilcagh Mountain follows the axis of the Cuilcagh Syncline. Like the Lough Allen Syncline and the MacNean Anticline, both the Owenmore Anticline and the Cuilcagh Syncline plunge westwards by 1°. The valley-anticline and mountain ridge-syncline relationship reflects the effects that compressional and extensional forces have upon the resistance of strata to erosion, where extensional forces make a rock more prone to weathering and compressional forces increase the rock strength. Due to the shape of the Cuilcagh Syncline and the Owenmore Anticline the Dartry Limestone Formation only crops out on the northern and eastern margins of the mountain (Figures 22 and 23). The Dartry Limestone Formation is at its highest in the east and decreases in altitude westwards. At Tullyhona Rising Cave, the contact between the Dartry Limestone Formation and the Glencar Limestone Formation lies at 155m AOD; further west at Hanging Rock the contact lies at 60m AOD, where it crops out before being submerged beneath Lower Lough MacNean. Down dip to the south and the west the Formation remains buried, until eventually cropping out on the periphery of the Lough Allen Syncline. The Formation continues to crop out up dip along the northern periphery of the Lough Allen Structure at Upper Lough MacNean. At White Father's Cave in County Cavan, the top of the Dartry Limestone Formation lies at 70m AOD, however, by Glenfarne, in County Leitrim, the Formation becomes buried.

4.2.4. Cuilcagh Dyke

The Cuilcagh Dyke has intruded for its entire length along the Cuilcagh Fault. This dolerite dyke is poorly exposed, being visible only on the East Cuilcagh Escarpment and in the Owenbrean, Aghinrawn and Sruh Croppa rivers of the Marlbank Escarpment. The contact between the dyke and limestone is typically sharp, with rapidly chilled margins. From the scattered exposures, a westsouthwest-eastnortheast line has been predicted for its surface trace by the GSNI (1991). Where the dyke is exposed it is typically highly weathered, in contrast to the surrounding country rock, and it is best described as 'rotten'. Although the intense weathering reduces information about the nature of the intrusion, it does assist in tracing its outcrop both in the field and in aerial photographs, as it forms a negative landscape feature. It is generally blanketed by thick drift in the valleys but is most noticeable as a gentle col upon ridges where subsoil cover is at its thinnest.

Aeromagnetic surveying carried out by the GSNI (1997) highlighted the southwest Fermanagh dyke swarm as a series of prominent lineations that display strong magnetic anomalies. The large 100m-wide intrusions in Fermanagh are represented clearly by prominent lineations but the Cuilcagh Dyke appears to be more diffuse in form, although indisputably a strong magnetic anomaly. The reasons for such an unclear image of the Cuilcagh Dyke may be partly the thick blanket peat bog covering the lower slopes of Cuilcagh Mountain and partly interference from the regional Cuilcagh structural high (I. Legg, GSNI, *pers. comm.*, 1997). The magnetic anomaly of the Cuilcagh Dyke stretches from the Slieve Rushen ridge, across the Erne Valley to the East Cuilcagh Escarpment and then past Benaughlin and Trien, extending as far northwest as the Burren Forest, where it appears to end. Approximately 30km away in County Leitrim (GSI 1:100 000 sheet 7 Sligo and Leitrim (GSI, 1996)), and along the line of the Cuilcagh Dyke (Figure 21) lies the Glenfarne Dyke (Brandon, 1973) which may be its continuation.

Geophysical survey of the outcrop of the Cuilcagh Dyke by Dr Paul Lyle (University of Ulster, *pers. comm.*, 1997) has shown that the dyke exposed in the Sruh Croppa River has a negative magnetic anomaly. However, the same survey in the Aghinrawn River showed the dyke to have a positive anomaly. This suggests that the intrusion is not a simple single injection, but a multiple series of injections that took place over at least one reversal of the Earth's magnetic field.

Due to the lack of exposure, and results of a number of water tracing experiments from the East Cuilcagh Escarpment that show underground flow paths to cross the GSNI predicted line, the author conducted a survey to determine the continuity of the Cuilcagh Dyke. Initially the survey was undertaken by desk study, using published aerial photographs, including the aeromagnetic survey work conducted by the GSNI

(1997). A geophysical survey was then undertaken along the length of the dyke using a hand held proton magnetometer, kindly provided by the Geological Survey of Northern Ireland. The position of the dyke was located using differential GPS (accurate to <5m) and imported into MapInfo GIS (Figure 24). The geophysical survey included 15 transects and a total of 29 spot readings. These readings (presented in Table 7 and Figures 25-28) show that Lyle's observations of both positive and negative magnetic readings in fact occur along the length of the intrusion. At one location in the Owenbrean River (Chart 10) the magnetic properties of the dyke are measured to be part positive and part negative, confirming its origins by multiple dyke injection.

The geophysical survey proved the dyke to trend from the East Cuilcagh Escarpment to the Burren Forest along the general trace drawn by the GSNI (1991). However, at two locations the dyke forms a sinuous sidestep that offset it from the GSNI trace. The first occurs in the Owenbrean Valley where a faulted break was identified and the second occurs in the area of Legalough where the trace of the dyke appears to be continuous (Figure 24). Approximately 250m south southeast of the Owenbrean River, the magnetic survey shows the Cuilcagh Dyke to be displaced so that a gap of c.150m exists (Chart 11 and 12), after which it continues along its original trend towards the East Cuilcagh Escarpment. This 'gap' in the trace of the dyke correlates to the line of a fault, named the Brookfield Fault in this thesis. Field mapping by the author and the GSNI has highlighted the Brookfield Fault as a major zone of disturbance at the northern base of Trien. Within this zone the Meenymore Formation, and the Glenade Sandstone Formation (I. Mitchell, GSNI, *pers. comm.*, 1996), are faulted against the Dartry Limestone Formation, with a displacement of up to 50m. Preston (1967) notes that faulting, typically orientated northeast-southwest displaces several other dykes in the southwest Fermanagh swarm.

4.3. <u>The East Cuilcagh Karst</u>

The East Cuilcagh Karst (Figure 29) comprises the outcrop of the Dartry Limestone Formation that forms a north-south trending escarpment along the eastern margin of

Cuilcagh Mountain, from Florence Court Forest (GR.: 2165-3330) in County Fermanagh towards the R200 regional road at Altinure (GR.: 2154-3232) in County Cavan.

The dip slope of the East Cuilcagh Escarpment inclines westsouthwest by 5-7° and marks the upper contact of the Dartry Limestone Formation, which has a thickness estimated at 120m. The majority of the succession (Figure 11) comprises of the Gortalughany Member, which is measured at 50m thick without the base exposed, and the overlying Dartry 'Type' Limestone, which forms a unit up to 50m thick. The Carn Member and Cloghany Member, overlie the Dartry 'Type' Limestone at the top of the sequence and have a combined thickness of no more than 8m. The Gortalughany Member is largely a sequence of cherty carbonate mudstones that includes units of medium-grained bioclastics and grainstones. The carbonate mudstones are well-bedded with thin horizons of chert and shale. The overlying Dartry 'Type' Limestone is a crinoidal limestone with abundant cherts and bioclastics in which bedding is irregular with the occasional interbeds of massive micrite.

The East Cuilcagh Karst is crosscut by four major fault lines, named in this thesis as the Brookfield, Swanlinbar, Aghaboy and Altinure faults (Figure 30). In the north the Brookfield Fault separates the East Cuilcagh Escarpment from the Marlbank Escarpment, whilst the Altinure Fault marks the most southern extent of outcrop for the Dartry Limestone Formation on Cuilcagh Mountain. Due to the throw of these four faults, the limestone outcrop forms a stepped topography composed of three benches, which are named the Low, Middle and High Escarpments (Figure 31). The High Escarpment is truncated by three minor faults, which are named in this thesis as the Pollnadad Fault, the Gortalughany Fault and the Cuilcagh Fault. The Cuilcagh Dyke has intruded along the length of the Cuilcagh Fault and cuts across the High Escarpment. Although poorly exposed the dyke forms a 40m-wide zone across the escarpment that is devoid of karst landforms.

There are few karst landforms on the Low and Middle escarpments but there are many on the High Escarpment. These include abundant small suffosion dolines as well as several deep potholes. In places, the landscape of the High Escarpment resembles that of a polygonal karst, where several dolines link together with only narrow ridges separating them. Both dolines and potholes are commonly elongate, reflecting the trends of faulting and fracturing along which they have developed. Potholes in the East Cuilcagh Karst are vertical, with open entrance shafts that swallow surface streams and penetrate up to 70m into the Dartry Limestone Formation. The caves show a high degree of breakdown and collapse, which commonly forms the termination of accessible passage. Streams can be followed for part of the way into the cave systems but are soon lost into breakdown debris and their waters are not observed again until they rise.

4.3.1. Identification of karst landforms and cave systems

Karst landforms and caves in the Cuilcagh Karst have previously been catalogued in Jones *et al.* (1997) 'The Caves of Fermanagh and Cavan'. The format used in this publication was to label the system with a letter (usually the first letter of the resurgences name) and then to number sinks and caves thought to be part of that drainage system. However, due to the complexity of drainage patterns in the East Cuilcagh Karst, where individual stream sinks have been proven to drain to multiple risings, this has proved awkward and difficult to manage. A cataloguing system for the East Cuilcagh Karst was developed by Burns (1989) and later used by Jones *et al.* (1997). In this thesis, Burns' system has been modified so that identification reflects the setting of each surface landform and cave within the fault blocks that form the East Cuilcagh Escarpment (Table 8).

The cataloguing system operates by listing individual karst landforms by a code consisting of a number with a lettered prefix. Distinction is made between risings (located at the base of the scarp), which are given the prefix 'R' and landforms on the dip slope. The lettered prefix of each landform denotes the fault block in which the karst feature is located, and within each block numbering progresses northwards. Karst landforms on the Middle Escarpment are given the prefix 'A' (Aghaboy), whereas the prefixes 'G' (Greenan), 'B' (Beihy) and 'F' (Florencecourt) denote the sub-blocks of the High Escarpment.

4.3.2. Hydrogeology of the East Cuilcagh Karst

The tracer tests undertaken during this research project have concentrated on the East Cuilcagh Karst to gain further information on the complex and multi-directional flow paths that typify drainage in this region. In addition to undertaking tracing at a number of original locations, several of Gunn's tracer tests were repeated to confirm results under a range of flow conditions. Average linear velocities from sink to rising were calculated when data permitted but when this was not possible fluocapteurs were left in place and changed on average every four days to simply prove or disprove connection. Results from water tracing experiments conducted as part of this research project are presented in Table 9 and are included with results from water tracing experiments by previous workers in Table 10. Based on these data, catchments for each rising have been delimited and are shown in Figure 32. Regional flow paths from the East Cuilcagh Karst are presented in Figure 33.

Due to the complex drainage of the conduit systems it is difficult to describe individual sink to rising systems. As such, the geological setting and hydrology of the stream sinks are first described and then followed by a description of the geology, hydrology and chemistry of the risings.

4.3.2.1. Stream sinks, dolines and associated caves

Due to the abundance of karst landforms in the High Escarpment the reader is directed to Jones *et al.* (1997) for a comprehensive summary of all landforms and caves. However, a number of caves in the East Cuilcagh Karst are frequently referred to throughout this thesis and these are described in detail below.

The Border Pots including Pollnadad cave (Greenan Fault Block) (Figure 34)

The Border Pots cave system comprises Pollprughlisk (G07), Pollnatagha (G08), and Polliniska (G09). All are located on the contact between the Dartry Limestone

Formation and the overlying Meenymore Formation. Pollprughlisk is a relict shaft but Polliniska and Pollnatagha are active. The Border Stream sinks at Polliniska and enters the chamber of Pollnatagha 12m below the surface, where it falls a further 37m to the floor and disappears into breakdown debris. Water from the Border Stream is not observed again until it emerges at Sumera Rising, 107m lower and c.2km away. Passage from Pollnatagha connects to Pollprughlisk via the Black Arrow Inlet and Old Man's Rift, a series of narrow dissolutionally enlarged vertical fractures. From Pollprughlisk the passage continues past the Well (a 24m-deep muddy shaft that has a short section of streamway at the bottom) into the West Wing and eventually the Unapproved Road and the Border Diner, which is blocked by collapsed boulders and is the existing limit to the system. Most passages between Pollnatagha and Pollprughlisk are relict but they have been observed by the author to become active as water rapidly backs up from depth, during flooding.

The lower phreatic part of the system is largely unknown, as water sinking into collapse debris at the base of the Pollnatagha shaft is not observed again until it rises at Sumera. A second, smaller, stream of unknown origin enters the system at the Unapproved Road but soon sinks into an inaccessible fracture. Jones *et al.* (1997) suggest that the streamway at the bottom of the Well is most likely a continuation of the water from the Unapproved Road, although no tracer tests have been performed.

On the surface, due south from the entrance of Polliniska, lies the course of a dry stream bed that can be followed for 180m directly to the entrance of Pollprughlisk, and then a further 180m south to a 15m drop down a cliff face into a dry valley, where the Border Stream at one time cascaded down a waterfall. At the base of the cliff face lies the entrance to Pollnadad (Plate 6), a short section of cave passage that is choked by sediment after only 25m. The entrance to Pollnadad lies within 10m of the major Pollnadad Fault, along which sandstone units from the Meenymore Formation are displaced against the Dartry Limestone Formation. At the end of Pollnadad, the passage changes its direction, from east-west to southeast-northwest and runs parallel with, and very close to (<2m), the Pollnadad Fault. This southeast-northwest trend is also pronounced in the Unapproved Road and Border Diner passages of the Border Pots system, which lie c.38m lower than Pollnadad Cave. The passages also lie within

10m of the Pollnadad Fault and are obviously influenced by it. The rest of the Border Pots cave system is also strongly influenced by fracturing, particularly by those orientated at between 170-185° and 030-045° (Figure 35). The 170-185° fractures have guided most of the passages in the Pollnatagha part of the system, including the Pollnatagha Chamber, Paris Passage and the Black Arrow Inlet, whereas, the passages in the Pollprughlisk part of the system, including Old Man's Rift, the Well and Frog Chamber, trend along fractures orientated at 030-045°.

The limestone sequence of the Greenan Fault Block is best exposed in the 52m-deep Pollnatagha shaft where the stratigraphy influences the shape of the chamber. The first 12m of the Pollnatagha shaft is only 3m wide being located within massive bedding of the Dartry 'Type' Limestone. The base of this massive bed forms the flat roof of the Pollnatagha Chamber, below which the chamber bellows out to c.20m wide and remains at this width for 40m to the chamber floor. The walls of the chamber are formed of irregularly bedded Dartry Type' Limestone, which contains abundant chert nodules with frequent chert horizons. The sequence has several depositional cycles changing gradually from being reasonably well-bedded with chert bands to poorly-bedded with chert nodules. At the base of the chamber lie large angular boulders (up to 4m across) of these cherty limestones that were once were part of the roof. The collapse of strata is due to mechanical failure of the cherty limestones. The roof of the chamber is formed from the massive beds of the Dartry 'Type' Limestone that form a solid beam that emphasises the change in lithology.

<u>The caves of the Peter Bryant's Hole area (Greenan Fault Block) (Figure 36)</u>

The caves of the Peter Bryant's Hole area comprise Peter Bryant's Bullock Hole (G10), Long Pot (G11), Tea Pot (G12), Black Pot (G13), Dig Swallet (G14), Small Pot (G15), Pollthanaclanawly (G16), an unnamed sink (G17) and Peter Bryant's Hole (G18). All are active sinks, located upon the boundary between the Dartry Limestone Formation and the overlying Meenymore Formation, and form part of the vertically extensive drainage system to Sumera Rising. Pollthanaclanawly, the deepest of the caves, has been explored to a sump at 63m below surface (232m AOD). Black Pot is the second deepest at 60m below surface, although the current terminus of surveyed passage is at the head of an unexplored shaft at 238m AOD. The 170-185° fracture set identified in the Border Pots cave system is also evident in Long Pot (G11), Tea Pot (G12) and Black Pot (G13) (Figure 37). However, Tea Pot (G12) and Black Pot (G13) are guided by fracture sets that trends at 035°, as have Dig Swallet (G14), Small Pot (G15), Pollthanaclanawly (G16), G17, and Peter Bryant's Hole (G18).

The Pigeon Pots cave system (Figures 38 and 39)

The Pigeon Pots system comprises three open shafts (Pigeon Pot II (B20) (Plate 7), Pigeon Pot III (B18) and Pigeon Pot I (B17)) all aligned along a line of 041° for a distance of 120m. Northeast from the Pigeon Pots lies Legacurragh Gap a 15m wide dry valley that is incised into the edge of the escarpment, which is remnant from a time when water cascaded from the escarpment. Three logs were completed on the geology exposed in the shaft sides of Pigeon Pot II, which are presented as Figures 40, 41 and 42. Additionally measurements of fracture trend are presented in Figure 43.

Pigeon III and I are relict shafts but Pigeon Pot II is active and swallows the Pigeon Stream, which can be followed down a series of shafts, with some horizontal development, before it sinks into debris that forms the floor of Rift Chamber. Tracer tests have proven connections to Sumera, Gortalughany, Gortalughany Farmyard and Gortalughany Intake risings in the East Cuilcagh Karst, but also to Cascades Rising in the Erne Karst and Shannon Pot Rising in the Shannon Karst.

The Pigeon Stream sinks at the contact of the Dartry Limestone Formation and Meenymore Formation where it enters a narrow gully that has incised through the Carn Member and Cloghany Member to the top of the Dartry 'Type' Limestone. At the end of the gully, the water cascades 18m into the entrance shaft. At 5m below the surface, the thinly but irregularly bedded limestones of the Dartry 'Type' Limestone are encountered. However, near the base of the shaft the limestone becomes increasingly well bedded with abundant chert bands. The base of the entrance shaft is located within thinly bedded limestone that dips gently towards southwestward by 5°. The dip of the limestone beds is opposite that of the stream flow and as a result causes the stream to pond in places. At the start of the second shaft, which descends into Rift Chamber, the bedding is less regular and nodular chert becomes abundant. However, 6m below the top of the shaft a 1.8m-thick massive micritic limestone bed occurs, with sharp upper and lower contacts to the irregular beds of chert. At the level of this micrite unit are a series of high-level passages, accessible from 9m down the second shaft. The micrite bed has some very well developed karren forms around the edge of Rift Chamber, which are c.4-7cm deep in places.

To the southwest, a high-level passage (termed Indiana Jones Series) continues for c.100m crossing the head of two shafts (shaft 3 and shaft 4, at 21m and 18m deep respectively: Jones *et al.*, 1997). The passage connects with The Temple of Mud, a large rift chamber that is c.70m beyond the limestone contact and below the cover of the Meenymore Formation. To the northeast of Rift Chamber, the high-level passage continues for a further 20m into a chamber before it becomes blocked by boulders and debris that has fallen in from Pigeon Pot III (Tim Fogg, *pers. comm.*, 1998). However, a relict dissolutionally enlarged bedding plane in the northwestern wall of this chamber connects to a narrow passage that trends northwestward for 40m. This passage is keyhole-shaped in cross-section and is c.0.60m wide and c.1.2m high. The passage has a flat roof set above a thin (4cm-thick) shaley mudstone horizon that forms the widest part of the passage. This passage, like all the high level passages, has developed within the massive micrite bed. The roof of the keyhole passage is composed of poorly bedded cherty limestone sequence of the Dartry 'Type' Limestone which has a fracture extending for the full length of the passage. Unusually for caves in the East Cuilcagh Karst the passage, although now relict, is worn very smooth from the flow of water. This passage also contains several speleothem deposits. The end of this water worn passage is marked by an intersection with a rift that trends along a fracture orientated at 038°, which is parallel to Rift Chamber. The fracture has been dissolutionally enlarged so that it extends vertically downward by approximately 8m and upward by 20m but is never more than 2m in width.

Badger Cave and Badger Pot (Figure 44)

Badger Cave (B23) is unusual in the East Cuilcagh Karst in that it is a short section of relict, horizontal passage located at the top of the Dartry Limestone Formation. All other passage at this stratigraphical level is vertical. *Siphonodendron* corals (Plate 8) are abundant in the walls of the passage and confirm its stratigraphical setting at the top of the Formation. The Cloghany Member forms the roof of the cave and directly above it lies the Carn Member, which in turn is unconformably overlain by the Meenymore Formation. The passage is up to 3.5m wide but only 16m long as it is blocked by thick flowstone (Plate 9). The cave has scalloping upon its walls and a half tube in the roof (Plate 10). Although the scallops are poorly preserved, a northeastward flow direction is indicated, and individual scallops are up to 7cm long.

To the southwest of Badger Cave lies Badger Pot (B22), a 7m deep steep-sided doline. Excavation at the southern corner of the doline has revealed that its base consists of large angular limestone blocks, up to 3m across. The steep-sided form of the doline and the large angular limestone blocks indicate that this doline formed by collapse. It's close proximity to Badger Cave and similar dimensions suggest that it may be part of the same system, and perhaps a now collapsed continuation of the passage. Badger Pot takes a small amount of drainage from Poll-na-mona (Turf Cave), a 1m-diameter peat pipe reported to be c.150m long (Jones *et al.*, 1997, p. 114).

Aghatirourke Pot

Aghatirourke Pot is a 28m shaft that lies c.170m northeast of Badger Cave. A stream enters from the northwestern side of the pot during high flow and sinks into collapse debris at the floor of the shaft. The shaft is initially developed within the Carn Member but the Dartry 'Type' Limestone is observed at c.8m down. At the base of the shaft the cave forms a long narrow rift, c.4m wide and 36m long. However, both ends of the rift terminate in small chambers.

4.3.2.2. Risings

Several risings lie at the base of the East Cuilcagh Escarpment, the largest being Sumera Rising. Tracer tests have shown the karst drainage of the escarpment to be complex and multi-directional. This is the only area in the Cuilcagh Karst where individual stream sinks have been proven to drain to multiple risings. In particular, Pigeon Pot II and Badger Pot drain to risings in the East Cuilcagh, Erne and Shannon karst areas.

<u>Aghaboy Rising (R01)</u>

Although small, Aghaboy Rising is the largest rising of the Middle Escarpment. The rising is located c.60m below and c.150m southeast of Pollnagollum Aghaboy, a 12m deep shaft into which two small allogenic streams sink. A passage at the base of the shaft trends eastwards for 70m before becoming blocked by peat. Although tracer tests have not been performed on the Aghaboy system, Webber (Limestone Research Group, *pers. comm.*, 1997) measured the electrical conductivity of the rising at 56μS/cm, which is only slightly greater than the streams sinking at Pollnagollum Aghaboy (47μS/cm). During heavy rainfall, the rising has been observed to rapidly increase in discharge, typically within one to two hours, and has been observed to rapidly return to its pre-flood flow, within approximately 24 hours. This indicates that the system has little storage and is likely to be simple.

<u>Aghaboy Springs (R02)</u>

These two very small springs emerge from a thin veneer of drift, near the base of the Middle Escarpment. Both have a near constant flow throughout the year. Their moderately elevated conductivity (Tables 4 and 5) suggests that they are fed entirely by autogenic percolation waters (Webber, *pers. comm.*, 1997).

Sumera Risings (R03)

The twin risings of Sumera have the lowest altitude of all risings in the East Cuilcagh Karst at 139m AOD. The upper rising is set within a steep-sided hollow, approximately 5m deep, whereas the lower has been capped as a water supply. No exposure is visible as the rock topography is lined by glacial drift. The drift thickness is unknown but may exceed 7m in such low-lying areas (GSNI, 1998). Sumera Rising lies along the fracture zone of the Swanlinbar Fault, a normal fault that has a displacement of approximately 65m. At Sumera, the footwall of the fault lies within the Gortalughany Member of the Dartry Limestone Formation, approximately 50m above the Glencar Limestone Formation. However, the hanging wall of the fault lies below the base of the Dartry Limestone Formation near the contact between the Glencar Limestone Formation and the Benbulben Shale Formation.

The upper and lower risings discharge water with the same chemistry. Electrical conductivity is only slightly elevated and reflects the low concentration of HCO_3 and Ca ions (Tables 4 and 5) suggesting a relatively short water-rock contact time. The lower rising is active all year round showing a maximum variance in stage of no more than 0.30m across its narrow channel (c.0.45m). In contrast, the upper rising dries up after approximately one week of no rainfall but reacts rapidly to heavy rainfall (often in less than three hours) and can discharge a torrent that fills a channel 2m wide and up to 1m deep. Whilst this response suggests rapid flow, water tracing experiments have shown flow-through times are in fact between three to four days over distances of up to 3km, which gives average linear velocities of up to 50m/hr (Table 10). This phenomenon of rapid response but relatively low flow-through times is commonly observed in systems that have an extensive phreas. Whilst the risings respond quickly to rainfall the tracer must pass through the phreas with the main body of flood water (Atkinson, 1986).

Sumera has a large catchment, which includes all sinks on the High Escarpment that are located south of the Cuilcagh Dyke. The sinks on the Gortalughany Fault Block drain exclusively to Sumera, whereas those that are on the Beihy Fault Block also drain to Gortalughany, Gortalughany Intake and Gortalughany Farmyard risings.

Gortalughany Springs (R04a, b and c)

The small risings that comprise the Gortalughany Springs are located along the 254m - 259m contour on the scarp slope of the Greenan Fault Block, where they emerge from a thin cover of glacial drift. Their flow shows little variance across the year and although R04a and R04b cease to flow during prolonged dry periods, R04c has not been observed to dry up. The close proximity and similar altitude of all three springs indicate a lateral influence upon flow, most likely guidance along horizontal discontinuities, such as chert horizons or massive interbedded micrite of the Dartry 'Type' Limestone.

Gortalughany Risings (R05)

The Gortalughany Rising complex issues from the Gortalughany Member, c.55m above the Glencar Limestone Formation. The complex comprises an upper rising, with approximately 12m of surveyed cave passage, and a number of lower risings that emerge from small pipes developed within a thin mantle of drift. During low flow, only the lowest of the pipes in the drift are active leaving the upper rising and remaining lower risings dry. During such low flow conditions, access can be gained to the upper rising, which consists of a series of low passages that terminate in a sump blocked by boulders. An increase in water levels causes the small drift pipes to become active up slope sequentially, until during moderate to high flow the upper rising becomes active. During very high flow events, the author has noted the development of several new pipes in the drift.

The upper and lower risings discharge water with identical chemical signatures. The conductivity of the waters has been measured at 150μS/cm during low flow conditions, which is indicative of a relatively short rock-water contact time. Tracer tests have isolated the catchment of Gortalughany Rising to stream sinks that are located within the Beihy Fault Block, as no dye has been detected at the rising from sinks located on either the Florencecourt Fault Block or the Greenan Fault Block. Like Sumera, discharge from Gortalughany Rising reacts quickly to heavy rainfall events, typically within 12 hours. Considering that tracer tests have estimated flow through times of between 2 to 4 days then most of the conduit system must be flooded.

Gortalughany Intake Rising (R06)

At Gortalughany Intake, a small rising has been capped for use as a local water supply. Flow shows little variance across the year, despite draining a catchment shown by water tracing experiments to include Pigeon Pot II, Badger Pot and B08, which all swallow surface streams that vary considerably in stage throughout the year. The water from Gortalughany Intake Rising has an electrical conductivity of between 300-350μS/cm, which reflects the elevated concentrations of Ca and HCO_3 ions (Table 4 and 5) and suggests a longer contact with the limestone bedrock. Tracer flow-through times indicate relatively slow average linear velocities with dye detection at the rising 5-7 days from injection at sinks located only 1000m away (Table 10). This indicates that the system is largely flooded and that the water is slow moving.

Gortalughany Farmyard Rising (R07)

Gortalughany Farmyard Rising is a small well, once used to supply water to the nearby farm buildings. The electronic conductivity of this rising has been measured at 370μS/cm during high flow. The chemical and flow characteristics are similar in many respects to Gortalughany Intake Rising, which lies 600m further downstream. Gortalughany Farmyard Rising has been proven to drain the part of the Beihy Fault Block that includes Pigeon Pot II and Badger Pot. Tracer average linear velocities from sink to rising are low, typically taking between 4-7 days to travel approximately 1000m to the rising (Table 10).

The Florencecourt Springs (R08)

Two streams that drain from the scarp of the Florencecourt Fault Block have their sources in boggy areas located in slight depressions at the base of the scarp. Whereas no distinct risings can be identified, traces of dye have been recovered from both streams during repeated traces from Pollmyalla I, confirming a groundwater input to the boggy areas. Flow velocities are very low, at less than 10m/h (Table 10).

4.3.3. Drainage catchments

Although the East Cuilcagh Escarpment is recognised as being hydraulically complex it can be simplified by subdividing it into three distinct catchments. The divides between these catchments are geological features that either restrict flow or guide flow elsewhere.

Aghaboy Rising and Aghaboy Springs on the Middle Escarpment are hydraulically separate from the Greenan Fault Block of the High Escarpment. The divide between these catchments is the Swanlinbar Fault. The fault guides all flow draining from the High Escarpment along its length towards Sumera Rising, preventing flow continuing southwards across it. Similarly, within the High Escarpment, the Florencecourt Fault Block is hydraulically distinct from the Beihy Fault Block. However, this is due to a dolerite dyke, the Cuilcagh Dyke, which has been intruded along the Cuilcagh Fault and separates the blocks. Although the Florencecourt and Beihy fault blocks are hydraulically distinct, they both have a number of sinks that drain to multiple risings. In particular, Pigeon Pot II and Badger Pot of the Beihy Fault Block drain to six risings, four of which are in the East Cuilcagh Karst (Sumera Rising, Gortalughany Rising, Gortalughany Intake Rising and Gortalughany Farmyard Rising), and one each in the Erne Karst (Cascades Rising) and Shannon Karst (Shannon Pot Rising). Streams sinks that lie north of the Cuilcagh Dyke, upon the Florencecourt Fault Block, drain northwards beneath Trien towards Cascades and Tullyhona risings in the Erne Karst, with a minor component of flow draining towards the Florencecourt Springs.

Tracer tests undertaken by the author and by Gunn (Table 10) show that all stream sinks and dolines south of the Cuilcagh Dyke, i.e. those on the Beihy and Greenan fault blocks, drain southwards to Sumera Rising. Those sinks on the Beihy Fault Block drain to multiple risings including Sumera and those on the Greenan Fault Block drain solely to Sumera Rising. As such, a major flow path(s) drains southwards from the Cuilcagh Dyke across the Beihy Block and through the Greenan Block to the Swanlinbar Fault and Sumera Rising. Flow paths to all other risings in the East Cuilcagh Karst are minor to the path to Sumera. As discussed in this chapter water tracing has proven a flow path from the Beihy Fault Block to Shannon Pot Rising and Cascades Rising. The distance between sink and risings and the relatively high average linear velocities compared to other flows in the East Cuilcagh Karst indicates that these flow paths like the flow path to Sumera are major flow paths. The flow paths to Shannon Pot Rising and Cascades Rising are discussed later on in this thesis.

4.3.4. Flow paths

The known part of the hydrological system within the East Cuilcagh Karst is restricted to potholes and dolines that drain the escarpment, and the risings where the waters are discharged. The potholes account for very little of the horizontal component of flow paths from sink to rising but they do account for much of the height difference. Most underground streams disappear into collapse debris and are not observed again until they rise; those sumps that have been discovered have not yet been explored. However, the depth of the cave systems is such that the upper 50-70m of the limestone has been drained and as such, the vertical extent of the phreatic zone must be restricted to the lower half of the limestone sequence.

From the descriptions of the cave systems earlier in this chapter, it is apparent that fracturing and faulting almost entirely guide the orientation of cave passage and surface landforms in the East Cuilcagh Karst. Horizontal guidance of passage is not common, and only in two caves to any extent. Pigeon Pot II includes a level of conduit development that is associated with a micrite bed within the Dartry 'Type' Limestone and Badger Cave includes a conduit half tube preserved in its roof at the top of the Dartry 'Type' Limestone. In all cave systems, particular fracture sets have been preferentially enlarged by dissolution so that they may be followed extensively through the system. The Border Pots and Pigeon Pot are good examples where particular fractures can be followed for much of the system with great vertical extent (52m in the Pollnatagha chamber and c.48m in the northeast extension to Pigeon Pot II). Those fractures that are dissolutionally enlarged tend to be those that are oriented from sink towards rising; this is particularly evident in the caves that drain only to one rising, such as the Border Pots, Black Pot and Pollthanaclanawly. Other caves, such as Pigeon Pot II, which drain to more than one rising typically have a more complex passage network with more than one dissolutionally enlarged fracture set.

Flood events in the East Cuilcagh Karst have been observed to cause rapid and extreme backing up within the system. In Pigeon Pot II, the author has witnessed water levels to rise over a range of 28m. Water levels have also been reported to rise by at least 23m in Pollprughlisk and an estimated 28m in Black Pot. The dissolutionally enlarged fractures that form the conduit network are at their widest near the surface. At depth the conduits tend to be narrower, such as the Well in Pollprughlisk and lower passages in the northeast extension of Pigeon Pot. Hence, the deeper phreatic parts of the system most likely comprise of narrow and constricted conduits, which is why these conduits are inaccessible. The complexity of this network and restricted width of the conduit are such that increased recharge at the stream sinks rapidly causes severe backing up in the system, with extensive flooding of the abandoned higher-level passages. Although the aperture of conduit decreases with depth it is considered unlikely that the aquifer extends below the base of the Dartry into the Glencar Limestone Formation. As the upper 40-60m is vadose, the phreatic zone of the aquifer has a thickness of 60-80m. The depth to which groundwater circulates is of particular interest with regard to Sumera Rising that lies on the downthrown side of the Swanlinbar Fault, which has a vertical displacement estimated at 65m by the author.

By modelling the phreas beneath the East Cuilcagh Escarpment as an extensive network of narrow flooded rifts it is possible to explain how single sinks drain to multiple risings. As the drainage from the Beihy Fault Block, specifically at the central part of the fault block near Pigeon Pot II and Badger Pot, has been traced to the greatest number of risings the piezometric surface must be higher here than elsewhere. More over as these sinks also drain to Shannon Pot Rising and Cascades Rising, then this piezometric surface within the karst aquifer is higher than anywhere else on Cuilcagh Mountain.

Hydraulic gradients to risings in the East Cuilcagh Karst are moderate to steep (44-102m/km) (Figure 45) but the systems typically have rather low average linear velocities (<10m/h-50m/h). In comparison, the hydraulic gradients from sinks on the East Cuilcagh Escarpment to risings in the Erne and Shannon karsts are lower (30-60m/km) but the average linear velocities are greater (50m/h -100m/h). The relatively low average linear velocities are characteristic of flooded maze-like conduit systems of the East Cuilcagh Karst. However, the higher average linear velocities to Shannon Pot Rising and Cascades Risings indicate pathways that are more direct, most likely as tributary conduits that are part of the branching systems behind both risings.

4.4. Erne Karst

The Marlbank Escarpment stretches westwards from Florence Court Forest in County Fermanagh (GR: 2165-3330) to the Barran Risings in County Cavan (GR: 2040-3355) (Figure 46). The Marlbank straddles the divide between landforms, caves and conduits that drain to the Shannon River and those that drain to the River Erne. In this thesis, the Marlbank is subdivided into its two catchments, the northern catchment of the Erne Karst and the southwestern catchment of the Shannon Karst. This section examines the hydrogeology of landforms, conduits and caves of the Erne Karst.

The strata overlying the Dartry Limestone Formation have been eroded to reveal the underlying, and more resistant, mud mounds of the Knockmore Member. These accumulations occur in two forms: horizontally extensive 'sheet-type' forms that occur near the base of the Member, and vertically extensive mounds that occur in the middle and upper parts of the Member. Several major vertically extensive mud mounds are observed as 'knoll-shaped' hills, such as Gortmaconnell Rock (Figures 19 and 20) that rise up above the limestone escarpment of the Marlbank (Plates 2 and 3). The lower part of the Knockmore Member is composed of horizontal-type mud mounds, which are only observed in the Cladagh Glen and resurgence caves at the base of the Formation. The horizontal- type mounds lack a reef skeleton and are composed almost entirely of micrite mud (Lees, 1963; Schwarzacher, 1961; Bridges *et al.*, 1995). Whilst, the vertical-type mounds include extensive accumulations of fenestellid bryozoans that locally may form a partial reef skeleton. Without a frame to bind and protect the mound, the mud would clearly have been disturbed by wave action; as such, the horizontal mud mound accumulations must have occurred at a depth below the storm-base (c.200m) within the sedimentary basin (Figures 47 and 48). There is no physical evidence to suggest what influenced the siting of the mud mound accumulations, although any irregularities on the sea floor would suffice to initiate mud collection.

The lower 30-50m of mud mounds in the Knockmore Member are horizontally extensive and are best observed at the head of the Cladagh Glen as well as in Marble Arch Cave and Cascades Rising Cave. Individual mounds are typically no more than 10m in height but may extend laterally for several hundreds of metres. Laterally-extensive mounds grew during conditions where sea level was relatively stable. Sediment accumulation was restricted in height by the storm base, and growth largely propagated horizontally (Figure 49). The remainder of the Knockmore sequence (>60m) comprises vertical-type mounds, which form the knoll-shaped hills of the Marlbank Escarpment. Vertical growth of a mud mound occurs as a response to a relatively gradual increase in the rate of sea floor subsidence over the rate of sediment deposition, most likely by tectonic subsidence in the half graben structure (Figure 47). As the storm wave base rises away from a mud mound it will no longer be restricted in height and so will grow upwards (Figure 50) to remain in the photic zone. The result of this gradual subsidence is development of an undulating submarine topography with numerous knolls that accumulated up to 80m in height above the sea floor. However, if subsidence occurred rapidly, the base of the photic zone would rise above the mud mound and accumulation would be reduced (Lees, 1961 and 1963). A reduction in carbonate deposition such as this would increase the relative proportion of non-carbonate particulate being deposited. As such, these episodes of carbonate result in shaley horizons. Within an accumulation of mud mounds these shaley horizons are referred to as intramound horizons.

Intramound horizons occur as thin bands, or beds, of carbonate-rich shale in between mud mound complexes (Figure 51). They represent a cessation in mud mound accumulation that may have been short lived (such as an erosional event caused by a turbidity current) or long lived (caused by rapid subsidence and dramatic reduction of carbonate deposition). In the Knockmore Member, intramound horizons have been identified at three locations, namely Skreen Hill I in Marble Arch Cave, at the end of Mainstream Passage in Cascades Rising Cave and parts of Tullyhona 1, of Tullyhona Cave.

In all three locations the intramounds mark the junction between the horizontal and vertical mud mounds and are interpreted by the author as marking a sudden reduction in carbonate accumulation. The event or events leading to their deposition were caused by increased subsidence that lowered the mud mound accumulation below the base of the photic zone. Carbonate forms up to 60% of the intramound horizon with the remaining 40% of the rock being comprised of terrigenous particles, such as terrigenous muds, bioclastic debris and sulphide mineralisation. Schwarzacher (1961) reports that sulphides are rare in all mud mound accumulations, and the mud mounds of Cuilcagh Mountain are no exception to this statement. The bioclastic debris of an intramound horizon comprises of broken brachiopod, crinoid and bryozoa fragments (Plate 11). Centres of mud mound accumulation are typically unfavourable for sea floor dwelling species due to the soft and unstable ground conditions and rapid rates of sediment accumulation.

Stromatactis filled cavity structures are common within the micrite of the Knockmore Member. These cavities formed within the mud mound when it was soft and had not lithified (Schwarzacher, 1961). The cavity structures are commonly seen in two settings: as part of an interconnected network and as separate, individual shadow cavities associated with fenestellid bryozoans or other bioclastic material. Those stromatactis features that form part of an interconnected network differ in their structure from those that are isolated, as they typically contain reworked micrite (commonly of a different colour) that lines or fills many of the voids. Shadow-type stromatactis cavities are common in the vertical type mud mounds, which have a greater bioclastic component, specifically of fenestellid bryozoans (Kelly, 1989a, 1989b and 1992). As carbonate deposition continues on the sea floor and burial proceeds the voids are filled in, and preserved, by radiaxial fibrous calcite, an early stage precipitate from the formation waters. Later stage precipitation is typically as sparry calcite (Plate 12).

Cementation of mud mound complexes occurs relatively rapidly following deposition (Bathurst, 1982 and 1987). During diagenesis the complexes undergo increasing mechanical stresses, which cause compaction. Further to this as diagenesis continues the newly lithified rocks are introduced to migrating fluids other than formation waters. The first part of this section examines the effect of burial in the mud mound complex, whilst the second section considers evidence for migrating fluids.

Within the sediment sequence, lithological units react differently to the compressional forces applied. Whilst the subdivision of Dartry Limestone Formation into members is based upon lithology, each member has its own lithological variations. As such, during burial deformation (Maltman, 1984) varies throughout each of the members. In the case of the Knockmore Member, whilst the majority of the sequence is composed of mud mounds that are uniform in lithology, the intramound horizon(s) introduce heterogeneity into the sequence.

Mud mounds undergo cementation soon after the onset of burial, as shown by the infilling of stromatactis cavities by radiaxial fibrous calcite. In addition, the calcite precipitates that infill stromatactis cavities form a secondary reinforced framework, increasing the resistance of the mound to compression. In comparison intramound horizons do not appear to undergo cementation at such an early stage and are thus more susceptible to compression than the mud mounds (Bathurst, 1982 and 1987). As such, whilst the rock thickness of the mud mound complexes is likely to be similar to that of the original sediment, the intramound horizons are likely to be severely compacted.

During burial, mechanical compaction is concentrated along the more susceptible horizons within the sediment column. This focuses the effects of compaction to particular horizons that develop pressure dissolution-seams perpendicular to the stress being applied. Dissolution-seams are not observed within the mud mound limestones but they are abundant within intramound horizons (Plate 13). There is evidence of some compaction within the mud mound limestone in the form of stylolites (Simpson, 1985). However, these indicate a far lesser degree of compaction compared to the severely compacted strata with dissolution-seams. During the pressure-dissolution process soluble carbonate is removed leaving an insoluble (non-carbonate) residue. The resultant higher non-carbonate component and abundance of dissolution seams parallel to bedding also increases the lateral permeability of the intramound horizon.

Evidence of fluids reacting with the host rock is provided by the presence of secondary mineralisation. Secondary dolomite is common and associated with faults and fractures along which metasomatic fluids have migrated altering the wall rock chemistry. The GSNI (1998) report that this dolomitisation is inferred to have occurred during late Palaeozoic times. Although evidence for the replacement of calcite by dolomite is observed throughout the Dartry Limestone Formation, its effect is most pronounced in the Knockmore Member, where dolomitisation has occurred along most faults and major fractures. It is also notable that the greater the movement or disturbance along fault or fracture, then the greater the extent of dolomitisation. Whereas fractures have only a narrow zone of wall rock alteration that extends no more than a metre into the host, large faults have a zone of alteration that may extend for 5m. In surface, or subsurface, exposure the dolomitisation is particularly obvious where it crosscuts through the network-type stromatactis as dissolutional processes remove the calcitic infill of the stromatactis leaving the surrounding dolomitised micrite behind (Plate 14).

4.4.1. Identification of karst landforms and cave systems

Jones *et al.* (1997) catalogued the karst landforms and caves in the Cuilcagh Karst by giving each system a name and a letter (usually the first letter of the resurgences name) and then numbering sinks and caves thought to form part of that drainage system. This format is used in this thesis but because most karst landforms and caves in the Erne Karst are named, the names are used more frequently than the numbers. Where subsequent tracer tests have proven drainage to a different rising than in Jones *et al.* (1997) then the catalogue is modified.

4.4.2. Hydrogeology of the Erne Karst

All of the rivers and streams that drain the northern slopes of Cuilcagh Mountain sink and re-emerge at risings located at the margin of the escarpment. The Erne Karst incorporates most of the known cave passage in the Cuilcagh Karst, including the two longest cave systems, Marble Arch (6.5km) and Prod's-Cascades (4.5km). The Erne Karst also includes most of the risings in the Cuilcagh Karst. There are 18 main risings and many other smaller risings some of which are ephemeral. Of these Tullyhona, Cascades, Marble Arch and Hanging Rock are discussed in detail in this thesis. Due to the abundance of caves and karst landforms, the Erne Karst is subdivided under the headings of Eastern, Central and Western Marlbank (Figure 46).

The abundance of cave passages in the Erne Karst allows a greater understanding of its hydrology compared to the karst of the East Cuilcagh and Shannon areas. However, with the exception of the three short sections of cave passage that form the White Father's Caves, none of the streams can be followed in their entirety from sink to resurgence. The largest risings (Cascades, Marble Arch and Hanging Rock) are located in the eastern and central parts while the risings in the western part are largely impenetrable.

The catchments for risings in the Erne Karst were initially delimited by Gunn (1982 and 1984) following a series of water tracing experiments. However, these catchment boundaries were modified during the early 1990s when it was discovered that sinks on the East Cuilcagh Escarpment also drained to risings in the Erne Karst of the Marlbank (Gunn, 1996 and 1997). Table 6 details the results of water tracing experiments conducted by the author. The authors results are combined with those undertaken by previous workers to for a complete table of all water tracing results undertaken in the Erne Karst (Table 11). These are compiled into Figure 52, which shows the estimated surface water catchment boundaries for individual risings. These boundaries were determined on a topographic basis by combining the catchments of each sink that drains to the same rising.

4.4.2.1. Eastern Marlbank

The Eastern Marlbank extends northwards from Trien Mountain. Tullyhona Rising Cave is the only major rising in the area.

Tullyhona Rising Cave (Figure 53)

Oxbow Inlet and Up The Junction form the two tributaries to this branching cave. Streams sinking at Whiskey Holes and Brookfield 1 have been traced to Oxbow Inlet, whereas Dick's Sinks have been traced to Up the Junction inlet (Table 11). Water sinking at Goat Pot and Pollmyalla I on the East Cuilcagh Escarpment also drains into Tullyhona, although it has not been proven to which tributary passage the water drains. The rising reacts rapidly to rainfall, typically within 2 hours, but flow levels also subside quickly, typically within 24-48 hours.

From Whiskey Holes and Dick's Sinks to Tullyhona Rising the cave passage almost traverses the entire thickness of the Dartry Limestone Formation. Only the Dartry 'Type' Limestone is missing from the sequence, being 'faulted out' by the Brookfield Fault. Fracture patterns within Tullyhona Rising Cave are presented in Figure 54 and show a dominant 350-010° and 120-140°, which shows a close relationship on passage orientations. The cave passage in Tullyhona is developed entirely within a single vertical mud mound of the upper Knockmore Member (Jones *et al.*, 1997). The lower Knockmore Member, composed of horizontal-type mound accumulations, is not represented in the Dartry Limestone Formation in this area. The rising lies close to the base of the Formation, above the underlying Glencar Limestone Formation, within a soft calcareous mudstone. Whiskey Holes and Dick's Sinks are located near to the Brookfield Fault, which extends from east to west across the Marlbank Escarpment. The most easterly of the Brookfield Pots (Brookfield 1 (Gunn, 1982)) is also located near the Brookfield Fault and marks the western limit of drainage to Tullyhona.

4.4.2.2. Central Marlbank

The central part of the Marlbank includes the Marble Arch Caves, the Prod's-Cascades cave system, the Cladagh West risings, the Carricknacoppan caves, Schoolhouse Cave, Springwell cave and rising and the Hanging Rock system (Figure 55). Schoolhouse Cave and Springwell are short and simple caves with relatively little difference in elevation between sink and rising. However, the Marble Arch, Prod's-Cascades and Hanging Rock systems have greater vertical range are more extensive and more complex.

<u>The Cladagh Glen</u>

At the head of the Cladagh Glen, in the eastern bank, lies the Marble Arch, through which the Cladagh River flows after rising from Marble Arch Cave. The Marble Arch is a natural bridge that is a short remnant of an east-west oriented cave passage once part of Marble Arch Cave but now separated by a collapse doline that forms a karst window between the arch and cave. After rising, and passing through the Marble Arch, the Cladagh River turns at a right angle northwards towards the MacNean Valley. Downstream of the Marble Arch the Cladagh River is joined by several other karst waters, including water from Springwell Rising, the Cladagh West risings and Cascades Rising.

From its head at the Marble Arch the floor of the Cladagh Glen steadily lowers by some 65m to the Arney River in the MacNean Valley. On route the Cladagh cuts through the basal part of the Dartry Limestone Formation, through the underlying Glencar Limestone Formation and into the Benbulben Shale Formation. Marble Arch Rising is located c.4m above the Dartry/Glencar contact, as is the Cladagh West 1 rising, which lies in the western bank of the Cladagh just downstream of the Marble Arch. The Cladagh West 2 rising lies c.9m above the floor of the Cladagh Glen, perched at the Dartry/Glencar contact. Cascades Rising lies c.5m above the valley floor but located c.15m below the Dartry/Glencar contact. Comparison of these elevations suggests that a fault exists along the line of the Cladagh Glen.

Prod's Pot and Cascades Rising cave system (Figures 56 and 57)

The Cascades Rising (Plate 15) issues from a dissolutionally enlarged, but inaccessible, bedding plane within the Glencar Limestone Formation, some 15m below the base of the Dartry Limestone Formation. Above the active rising, at 4m and 9m, are two tiers of partially relict risings. The lower of the two relict risings becomes active during very high flow, whereas the upper only becomes active during exceptionally high flood events. The upper relict rising also gives access to the Entrance Series of the Cascades Rising Cave. The Entrance Series comprises approximately 180m of maze-like stream passage that has developed within the Glencar Limestone Formation. The remaining 3900m of surveyed passage in the Cascades-Prod's Pot system have developed within the Dartry Limestone Formation. Measurement of fracture orientations (Figure 58 and 59) show a close comparison with the orientations of cave passage. However, it is noticeable that the fracturing at 120-140° is less abundant in the west than it is in the east, which makes the 350-010° fracture trend to be more dominant in the western part of the system.

Historically, the Prod's Pot and Cascades Rising cave system has been described in two sections (Jones *et al.*, 1997) reflecting the nature of its discovery and exploration. The initial breakthrough was via Prod's Pot, which has given its name to the upstream part of the cave system. Divers exploring the downstream sumps in Prod's Pot also discovered most of the Brandywine and Main Stream Passage, which are now attributed to the Cascades Rising Cave following the subsequent access to the upper relict rising. Together, Prod's Pot and Cascades Rising Cave form a branching cave system with three main tributaries, namely Cascades Inlet Passage, Formations Passage and Papist Passage. All tributaries unite within the Prod's Pot section of the cave and flow via Main Stream Passage towards the Cascades Rising. The Prod's-Cascades system is the deepest in the Cuilcagh Karst, at 94m (Kelly and Jones, 1995). Dye tracing experiments have shown the Cascades Rising to be fed by streams sinking in the East Cuilcagh Escarpment as well as in the Erne Karst giving a vertical range from highest sink to the rising of 209m

The catchment of Formations Passage incorporates Smokey Mountain sink and the Owenbrean Upper Sinks on the Marlbank together with Pigeon Pot II and Badger Pot on the East Cuilcagh Escarpment. Aghatirourke Pot and Goat Pot have also been traced to Cascades Rising and are expected to enter the system via Formation Passage. Formation Passage includes the tallest sections of cave in Prod's Pot; although only 4m wide the passage height frequently exceeds 15m. Beyond the first upstream sump, is a second sump that marks the present terminus of passage. At this location a tributary enters the system, which can be followed for 30m. The boulder choke at the end of this tributary lies close to Gortmaconnell Pot and is likely to be the downstream continuation of the 50m-long stream passage found in Little Gortmaconnell Pot. No dye has been recovered from Papist Passage and Cascades Inlet Passage but several dolines that lie above these passages have yet to be traced.

The catchment of Cascades Rising is unusual in the Cuilcagh Karst in that it includes stream sinks both north and south of the Cuilcagh Dyke, whereas in all other catchments the dyke forms a barrier to conduit flow. Where other karst systems cross the dyke, such as in the Carricknacoppan and Schoolhouse cave systems, flow does so as a surface stream that rises before the dyke and sinks after it. As well as being fed by stream sinks from the East Cuilcagh Escarpment, Formation Passage is also fed by water sinking into the bed of the Owenbrean River, where it crosses the Meenymore Formation. The Owenbrean Upper Sinks (Figure 60) lie 2km upstream of Pollasumera, a large stream sink that is the downstream limit of surface flow in the

Owenbrean River and part of the Marble Arch Cave system. The Upper Sinks consist of one main sink and several small sinks, all of which are impenetrable. In low flow, all water enters the Upper Sinks and the total flow continues underground to the Prod's Cascades system (Figure 61). As the discharge of the Owenbrean River above the Upper Sinks increases, the capacity of the conduit(s) taking flow to the Prod's-Cascades cave system is exceeded and the excess flow is discharged from a series of springs about 200m downstream of the Upper Sinks. With a continued increase in discharge, the capacity of the conduit(s) taking flow to the springs is also exceeded, and the Upper Sinks are overtopped and submerged. Approximately 400m downstream of the Upper Sinks, the Owenbrean River cuts perpendicularly through the Cuilcagh Dyke, which is well exposed in both sides of the riverbank. A further 400m downstream of the dyke the river bears northwards towards Pollasumera. At this prominent bend in the river, in the eastern bank, lie a second series of sinks named the Owenbrean Lower Sinks. These, like the Upper Sinks, are impenetrable and drain to Formations Passage of Prod's Pot, most likely via the streamway in Little Gortmaconnell Pot. The Lower Sinks are rapidly overtopped by anything other than base flow.

From its Owenbrean Upper Sinks to its rising in the Cladagh Glen the Prod's-Cascades system traverses the full thickness of the Dartry Limestone Formation, which in this area comprises the Dartry 'Type' Limestone and the Knockmore Member. The cave gradually descends through the lithological sequence of the Knockmore Member, exposing a number of vertical mound accumulations including the Gortmaconnell Rock mound. The main streamway continues to traverse through vertical mounds until the Mudbank Chamber, where an intramound horizon at the top of the horizontal-type mud mounds is encountered. Passage size increases at the Boulder Series and the streamway disappears into a collapse of limestone blocks that fill the cave to the roof in places. The boulder series is a large-scale collapse that extends for 190m. The collapse indicates failure of the roof support due to widening and under cutting at the base of the chamber. The form of the cave passage changes dramatically at the end of the Boulder Series becoming much smaller. Approximately 30m downstream of the Boulder Series the stream crosses the Dartry/Glencar contact and enters passages that are more like a maze cave than a branching cave system.

The complex hydrology of the Cascades Rising catchment is reflected in the reaction of the rising to rainfall, as a single heavy rainfall event generates two flood pulses. The first pulse arrives at the rising within 24 hours of heavy rain and the second pulse arrives approximately 24 to 48 hours later. The first pulse is the result of increased flow from sinks on the Marlbank, from the Owenbrean Upper Sinks, Owenbrean Lower Sinks, Smokey Mountain sink and the Brookfield sinks. The second pulse, which is smaller in volume, is a result of increased flow into the sinks on the East Cuilcagh Escarpment c.4km away. The delay in time for the second flood pulse to reach the Prod's–Cascades system indicates that the system between East Cuilcagh and Formations Passage includes vadose passage. In January 1997 a temperature and electrical conductivity study (Table 6) was undertaken in the Prod's Pot system to compare these characteristics of the waters in the tributaries to the Main Stream Passage. Temperature was measured at 10.6°C and electronic conductivity at 297µS/cm in Formation's Passage, compared to 9.5°C and 207µS/cm in Papist Passage and 6.3°C and 114µS/cm in Cascade Inlet. On the day of the study, the stream sinking into Gortmaconnell Sink was measured at 4.9°C and 89µS/cm. This indicates that water draining via Formations Passage has been in contact with limestone for a longer period than the other two passages.

Actual flow velocities within the vadose cave passage in the Prod's-Cascades systems are estimated at 300-400m/h, which is moderate for open linear cave passage but reflects the low gradient of the cave system. The average linear flow velocities from the many sinks to the Cascades Rising show a wide variation. Flows from the Brookfield area of the Marlbank Escarpment have the fastest average linear velocities, up to 300m/h compared to sinks in the East Cuilcagh Escarpment, which have average linear velocities of c.70m/h. However, the Brookfield area is located only 200m from Cascades Inlet whereas the sinks in the East Cuilcagh Escarpment lie c.4km away. The close proximity of the Brookfield sinks to cave passage and the rapid flow through time suggests a linear flow path, similar in form to passage in the known part of the system. The greater distance between the East Cuilcagh sinks and the Prod's–Cascades system allows for a flow path of greater complexity. Whilst, the geology between Brookfield and Cascades Inlet is similar the geology between the East

Cuilcagh pots and Formations Passage is lithologically and structurally complex, and separated by the Cuilcagh Dyke. The average linear velocities from the Brookfield Pots are likely to accurately reflect the average velocity into the Cascades Inlet whereas the average linear velocity from sinks in the East Cuilcagh Escarpment are likely to underestimate the average velocity in the conduits draining to Formation Passage.

Marble Arch Cave (Figure 62 and 63)

Three rivers, the Owenbrean, Aghinrawn and Sruh Croppa, as well as several small streams and flow from the Carricknacoppan caves and Aghinrawn Cave, unite underground to feed the Marble Arch Rising, which is one of the largest in the British Isles (Gunn, 1982). Marble Arch Cave is an active system with four main tributary passages. Approximately 6.5km of cave passage has been explored, of which the Skreen Hill section has been developed as a show cave, operated by Fermanagh District Council. The show cave runs from the Wet Entrance via the Castle and Skreen Hill I to Journeys End.

The Pollnagollum-Skreen Hill III and Legnabrocky Way tributaries combine and flow through Skreen Hill II and Skreen Hill I passage. The Upper Cradle and the Sruh Croppa tributaries drain via Lower Cradle having united beneath a large collapse doline, Cradle Hole. The tributaries of Skreen Hill I and Lower Cradle meet at the Junction and flow downstream to the sumped resurgence. On route, the passage is intersected by three large steep sided dolines, named C, D and E (Figure 62) by Martel (1895), which, like the karst window of the Marble Arch, have formed by collapse. In all cases collapse occurred along fractures, which form planes of weakness in the rock. In order to determine the dominant fracture trends in the area of Marble Arch Cave those fracture observed within the cave system and also exposed on the surface were recorded. These observations show that fracturing at 350-020° is dominant in the area (Figure 64), which conforms with the orientations of major surface landforms such as the Cladagh Glen and the branch passages to Marble Arch Cave. However, Skreen Hill I passage does not conform to these trends (Figure 65).

Skreen Hill I and its tributaries

The main feeder to Skreen Hill I is the Owenbrean River, which sinks at Pollasumera (Plate 16). However, the hydrology of Pollasumera is complicated by the Owenbrean Upper and Lower sinks, which drain the base flow of the river to Cascades Rising. From Pollasumera, the Owenbrean flows through Pollnagollum of the Boats to Skreen Hill III and then via Sump 2 to Skreen Hill II, where it unites with water from Legnabrocky Way and flows through Sump 1 to Skreen Hill I. Under high flow, floodwater backs up at Pollasumera to a depth of c.10m, as measured by a water level recorder maintained by Marble Arch Caves, but there are no historical records of the sink being overtopped.

The small stream that flows through Legnabrocky Way has been traced from Peruvian Pot, the terminal sink of the Carricknacoppan caves. Peruvian Pot is located approximately 1km south and 55m higher than the end of Shiver Passage, the farthest extent of Legnabrocky Way. In between the sink and Shiver Passage is a thick overburden of glacial sands and gravels. Passage in Legnabrocky Way also contains extensive sequences of fluvio-glacial sand and gravel deposits, which block the passage at its present terminus.

From the stream sinks of Pollasumera and Peruvian Pot to Skreen Hill I, the tributaries pass through the vertical-type mounds of the Knockmore Member. Pollasumera is located within the Gortmaconnell Rock mud mound complex and on its route to Skreen Hill I the Owenbrean River also flows through several other vertical mound sequences, as does the Legnabrocky Way tributary. At the start of Skreen Hill II, the cave passage changes direction, from northwards to westwards when it intersects an intramound horizon that lies at the top of a horizontal-type mud mound. The passage follows along strike downstream to the Junction.

Lower Cradle and its tributaries

Cradle Hole is a steep-sided collapse doline c.40m across that marks the underground confluence of the Aghinrawn and Sruh Croppa rivers. On the southern side of Cradle Hole, in Upper Cradle cave, is the Aghinrawn River. At the downstream end of Upper Cradle the Aghinrawn River sumps, the water emerging at the northern side of Cradle Hole in Lower Cradle, united with the Sruh Croppa.

During times of low discharge the Aghinrawn River sinks a few metres upstream of the base of Monastir cliff into gravel and boulders in the riverbed. In higher flows the river sinks into a short section of cave at the base of the cliff, whilst in extreme floods the cave cannot take all the flow and water backs up to an estimated depth of 12m. However, the cliff is 33m high and has not been overtopped in living memory. In the cave, the passage becomes blocked by boulders after c.45m and the Aghinrawn River is next encountered in the Monastir Way sumps, and then in the upstream section of Upper Cradle Hole. Divers surveying the Monastir Way sumps found that the passage does not trend directly towards Cradle Hole but instead trends westwards towards Pollreagh, a large suffosion doline that lies between the Aghinrawn and Sruh Croppa Rivers (Jones *et al.*, 1997).

The Sruh Croppa River sinks at various points in its bed, depending on discharge. In normal flow, it sinks at Bank Sink a 4m-wide depression in the side of the riverbed filled with glacial boulders. Under moderately high flow the capacity of Bank Sink is exceeded and the river flows further south to Zero Sink. In 1995 Bank Sink had a capacity of 40% base flow but following a major flooding event during early October 1999 this subsequently opened up to 70%. During March 2000, Bank Sink subsided even further so that by July 2001 it took 95% of base flow. The underground waters of the Sruh Croppa River are observed in Cat's Hole, Pollthananarees, Mastodon, Pollasillagh, and then John Thomas's Hole before joining with the Aghinrawn River beneath Cradle Hole and flowing into Lower Cradle and Marble Arch Cave. During intense or prolonged storm events, the Sruh Croppa sequentially overtops several sinks in the base of the river and eventually cascades 9m into Cats' Hole. During periods of extreme flow Cats' Hole, Pollthananarees and Mastodon are filled and overtopped by the Sruh Croppa, which eventually sinks near Pollasillagh.

Average linear flow velocities from Monastir and the Sruh Croppa to Marble Arch Rising have been recorded at 32m/h and <34m/h respectively (Gunn, 1982), only one tenth of the average linear velocity recorded from Pollasumera. In the known vadose part of the flow path from Monastir and the Sruh Croppa to Marble Arch, flow velocities are typically in excess of 250m/h. Hence, the unknown part of the system must be largely flooded.

From the Monastir and Sruh Croppa stream sinks, the Aghinrawn and Sruh Croppa Rivers traverse the Knockmore Member to Marble Arch Rising. The route taken is direct, so that the passage traverses through vertical mounds and only intersects the Lower Knockmore Member and the horizontal-type mounds at the Grand Gallery. At the Marble Arch Rising the Cladagh River emerges at the foot of a 15m-high cliff face, in which the bedding planes of the horizontal-type mounds are exposed (Plate 17). In the natural limestone arch a phreatic tube, 1m wide, lies upon one of these planes. The rising lies approximately 5m above the Glencar Limestone Formation.

The water emerging from Marble Arch Rising has a low electrical conductivity and has been only slightly enriched with respect to Ca, Mg and HCO_3 ions (Table 4 and 5). This is due to the relatively fast flow-through times from Pollasumera to Marble Arch Rising and because the streambeds within the system are armoured by glacial debris so that the water has minimal contact with limestone.

<u>Hanging Rock</u>

Two risings are located at Hanging Rock, the main rising and a west rising, called Pollnasalac, which is an overflow that only becomes active during high flow. Hanging Rock main rising is one of the lowest risings in the Cuilcagh Karst at 83m AOD; only Barran Rising (77m AOD) is lower in elevation. Behind the rising lies c.15m of cave passage that ends abruptly in a mud-lined chamber with water entering from below into a pool. Behind Pollnasalac, some 50m of largely water filled cave passage has been explored. Legacapple is the furthest sink from the rising and lies approximately 3km distant, although the limestone catchment extends 5km away. Compared to Tullyhona, Marble Arch or Prod's-Cascades, only a very short length of accessible cave passage is known at Hanging Rock, although the rising has one of the largest limestone catchment areas on the Marlbank, extending from Crossmurin westwards to Legalough (Figure 52).

The only other accessible conduit in the Hanging Rock system is 100m of flooded passage in Hammer Pot explored by cave divers, initially J. Philips and M. Farr, and then by J. Corrigan (Jones *et al.*, 1997). The passage found was quite large (>3m in diameter) but lined with glacial muds similar to those found in the cave passage at Hanging Rock (Joel Corrigan, Birmingham University Caving Club, *pers. comm.*, 1997). The Hanging Rock risings react rapidly to rainfall, but this is likely to be due to the conduit behind the risings being water filled rather than rapid flow through times. Analysis of the water rising at Hanging Rock shows that electronic conductivity is relatively high and that Ca, Mg and HCO_3 ions are significantly elevated compared to Marble Arch Rising (Table 4 and 5). Average linear velocities range between 50m/h from Cow Skull Pot and 150m/h from Legacapple (Table 4). However, the streams that feed the Hanging Rock rising all drain across limestone and/or limestone-rich till, which they traverse for up to 2km before sinking, so that the waters already have relatively high concentrations of Ca, Mg and HCO_3 ions before they sink. As the explorable parts of the system are reported to be mud lined, the underground flow may have limited contact with limestone, reducing post-glacial rates of conduit solutional enlargement.

Both the main and Polnasalac risings are located near the bottom of the Dartry Limestone Formation, c.3m above the Glencar Limestone Formation. From the Legacapple sink to the risings, the Hanging Rock system traverses the full thickness of the Knockmore Member, from the vertical-type mounds through to the horizontal–type mounds where the risings lie.

4.4.2.3. Western Marlbank

In the western Marlbank, there are several small risings, including Marlbank East, Marlbank West, Ture, Cornagee Lower, Cornagee and Barran risings. Most are multiple risings but none give access to cave passage. Solution and suffosion dolines are abundant across the whole area, being typically less than 8m in diameter, although the Lost Valley doline (GR: 2077-3354) has a diameter of approximately 500m and a depth of up to 50m and is probably an ancient stream sink.

Considering the size of the Western Marlbank, very little cave passage has been explored. Most of the known passage is in the 1000m long Pollnagossan cave (Figure 66). The stream that sinks into the cave system at the Car Wash is lost in the sediment fill of the Main Chamber and is not observed again until its water rises at Barran. However, a second untraced stream emerges into the system at Boothroyd's Bit before being lost at sump 10 of Cripple Creek. The water that rises at Barran flows northwards for some 2km before it passes through a series of three caves that form the White Father's Cave system. The first cave is a short remnant of passage and stands as a natural arch, the second cave is 60m long, and the third is some 270m in length.

All of the known cave passage of the Western Marlbank lies within the Knockmore and Cloghan Hill members of the Dartry Limestone Formation. Pollnagossan is developed within the Cloghan Hill Member, as are Super Star Pot, Barran Rising and the karst landforms of the Burren. Marlbank Rising, Holy Hour Pot, Ture Rising, Cornagee Rising and the White Father's caves are all developed within the Knockmore Member. As the base of the Dartry Limestone Formation lies at an estimated depth of 100m at Blacklion (55m below OD) the Lower Knockmore Member is not exposed.

Chemical analysis of these risings of the Western Marlbank show higher electrical conductivities compared to risings in the eastern Marlbank. Values for the western Marlbank range between 254μS/cm at Barran Rising 1 to 710μS/cm at Barran 3. Water tracing experiments have shown that Barran Rising 1 is fed by the streams sinking at both Pollnagossan and Pollnaskeoge. Those risings that have highly elevated electrical conductivities, i.e. Ture East and Barran Rising 3, have not been traced from any stream sinks and probably receive only dispersed recharge. Many sinks in the area have yet to be traced. Most notable are those in the area of the Lost Valley doline, where several streams sink into drift.

4.4.3. Drainage catchments

Catchment mapping on Cuilcagh Mountain was first undertaken by Gunn (1982). Subsequent tracer experiments by Gunn during the 1980s and 1990s refined these catchment boundaries and identified the complexity associated with the divergent flows in the Owenbrean River, Pigeon Pot II and Badger Pot. The water tracing experiments undertaken by the author as part of this thesis are intended to assist the understanding of these divergent flows and to further refine the catchment boundaries identified by Gunn (1982). Of the sinks on the East Cuilcagh Escarpment traced by the author, Aghatirourke Pot and Sheep Pot on the Beihy Fault Block as well as Goat Pot, Pollmyalla I and Pollmyalla II on the Florencecourt Fault Block were proven to drain to Cascades Rising. All of these sinks drain to multiple risings. However, the sinks on the Beihy Fault Block drain to multiple risings such as Sumera and Gortalughany risings, which lie to the south, compared to Goat Pot and the Pollmyalla sinks which also drain to Tullyhona Rising. Topographically Goat Pot and the Pollmyalla sinks should follow the dominant southward flow path observed by all sinks that lie south of their location. However, they do not drain to any risings south on the East Cuilcagh Karst. Along the contact between the Beihy and Florencecourt fault block lies the Cuilcagh Dyke and although it has been shown to be displaced by faulting elsewhere along its intruded length the results from water tracing indicate that conduit flow does not traverse the Cuilcagh Dyke on the East Cuilcagh Escarpment. As such, these sinks on opposite sides of the dyke that all drain to Cascades must do so by separate flow paths. The flow paths from Sheep Pot and Aghatirourke Pot to Cascades are likely to converge with flow from Pigeon Pot II and Badger Pot on route to Cascades. However, this convergence can only occur after the flow from Pigeon Pot II and Badger Pot has diverged into its separate flow paths.

Marble Arch system and Prod's-Cascade systems have the first and third largest surface water catchments in the Cuilcagh Karst at $25km^2$ and $10.4km^2$ respectively. Shannon Pot Rising is the second largest with a catchment of $15.2km^2$. Due to the complexity of the Owenbrean Upper and Lower Sinks both Marble Arch and Prod's-Cascades share the catchment of the Owenbrean River upstream of the Lower Sinks. As discussed earlier, during periods of low discharge all flow in the Owenbrean drains to Formation Passage of Prod's Pot. However, with increased run-off the capacity of the Upper and Lower sinks are exceeded and the overflow from these sinks drains to Pollasumera. As such, whilst the catchment to Prod's-Cascades remains essentially constant, the catchment of the Owenbrean River that drains to Marble Arch Rising is dynamic. During low discharge the Owenbrean does not drain to Marble Arch and as such the catchment is reduced by $8.1km^2$ to $16.9km^2$. However, as discharge increases above the capacity of the conduit draining to Cascades, Marble Arch Rising gains an increasing proportion of the total catchment discharge.

Although no quantitative measures are available the size of the risings appears to be proportional to the area of the catchment draining to them. However, while the catchment of Cascades Rising is broadly constant, the catchment to Marble Arch Rising is dynamic. Thus the range of flows is much larger at Marble Arch Rising, with lower low flows and much larger flood discharges than Cascades Rising. The discharge from Hanging Rock appears to be broadly proportional to the estimated $7km^2$ catchment. There is only one main stream sink draining to Hanging Rock but there are many dolines in the catchment so drainage is probably via a branching conduit network.

The estimated $1.8km^2$ catchment to Tullyhona Rising is rather small considering the size of the rising and hence the catchment may be larger than shown in Figure 52. Although surface streams drain the area directly east of Tullyhona Cave, the most northern part of the East Cuilcagh Escarpment lacks any surface water drainage, including sinking streams, and as such incident rainfall is likely to recharge Tullyhona Rising. In contrast the catchment for Springwell Rising is slightly larger than would be expected for its small size. However, the boundary between Springwell and Hanging rock catchments may lie further east than shown in Figure 52. Further water tracing experiments will be required to refine this catchment boundary.

Water tracing data is more sparse on the Western Marlbank than it is in the Central and Eastern Marlbank, and as such the surface water catchment for each rising will most likely need be modified following additional water tracing experiments. The risings at Hanging Rock have the largest catchment size (7km^2), followed by Barran (3.5km^2), Ture (2.7km^2), Cornagee (1.6km^2) and Marlbank risings (0.8km^2).

4.4.4. Flow paths

From east to west, the base of the Dartry Limestone Formation dips southwestward, so that beyond Hanging Rock Rising the base of the formation dips below level of Lough MacNean. However, in the eastern and central part of the Marlbank the base of the Formation is elevated up to 80m above the valley floor. The conduit systems in the eastern and central Marlbank have extensively drained the limestone so that they are explorable as networks of cave passages. All cave passages form tributary systems with many sinks draining to a single rising. Where the base of the limestone is exposed above the valley floor then the major risings occur near the base of the Dartry Limestone Formation, with the exception of Cascades Rising, which occurs 15m below it. To the west of Hanging Rock Rising the Western Marlbank risings tend to occur at various different stratigraphic levels in the formation but usually along fractures and at the break of slope at the foot of the escarpment. As such, in terms of the evolution of the karst aquifer and the evolution of the landscape, those systems in the east, such as Marble Arch, Prod's-Cascades, Tullyhona and Hanging Rock, which drain the full height of the aquifer are more mature than those in the west that only partially drain the aquifer.

The chemical signatures of the emergent waters provide information on the hydrology of the karst systems. The emergent water from risings that have extensive cave passages, such as those in the Eastern and Central Marlbank, tend to have lower electronic conductivities and lower ionic concentrations, reflecting the more rapid flow though times and relatively short contact time with the bedrock. However, those systems in the western Marlbank tend to have higher conductivities and higher ionic concentrations reflecting dispersed recharge, slower flow through times and greater contact with the bedrock. The lowest conductivity (63uS/cm) was recorded at Marble Arch Rising during high flow and the highest conductivity (710μS/cm) was recorded at Barran Rising 3 during low flow. The conductivity of emergent waters generally increases to the west in the Erne Karst. An exception is Barran Rising 1, which is fed by sinking streams and has a relatively low conductivity (c.260μS/cm).

The cave systems in the Erne Karst form branching tributary systems but they are all single tier branching cave systems. The only rising that has an abandoned rising or risings is Cascades, where the active risings and the abandoned risings are located within the Glencar Limestone Formation. Geological mapping within Tullyhona, Cascades and Marble Arch shows that intramound horizon(s) occur near the base of the Formation, and that these horizons form the roof of passages in these caves for significant distances. In Tullyhona, the series of entrance passages, including the resurgence itself, are located at the elevation of an intramound horizon. In Cascades, an intramound horizon is frequently observed within the Boulder Series and as far upstream as Mud Chamber, whilst, in Marble Arch, an intramound horizon forms the roof of Skreen Hill I.

The risings and passages at the downstream end of the cave systems tend to be located at intramound horizons near the base of the Dartry Limestone Formation whereas the upstream parts of the system, including stream sinks and dolines are located at various different stratigraphic levels. As such, whilst there appears to be a horizontal guidance upon the downstream sections of cave passage and the level of emergence, there is no horizontal guidance in the location of the upstream section of passage, including stream sinks and dolines. All stream sinks, dolines and upstream passages are located upon prominent fractures, which are usually north-south trending,

Due to the southwestward dip of the limestone and the northward drainage of the underground systems, all cave systems gradually descend through the stratigraphy towards the base of the Formation and the margin of the escarpment. From stream sink to rising, the hydraulic gradients through the cave systems are moderate at c.40-

60m/km (Figure 67), with average linear velocities up to 400m/h. The streamways of all caves tend to be particularly uniform in their gradient, with no pitches and few waterfalls. The 5m waterfall downstream of Sump 1 in Tullyhona and the series of 1m-high cascades in Cascade Inlet of Prod's Pot are the only known underground waterfalls within the active main stream passage. The passages in the upper parts of the cave systems tend to be particularly linear, draining northwards and northwestwards directly towards the margin of the escarpment via solutionally enlarged fractures. However, in the lower parts of the caves systems, typically when the intramound horizon is intersected, the passages tend to change direction and drain down strike rather than towards the margin of the escarpment.

Streams sinking at Goat Pot and Pollmyalla on the Florencecourt Fault Block in the East Cuilcagh Karst have been proven to drain to Tullyhona Rising, although it has yet to be determined to which tributary passage the water drains. The average linear hydraulic gradients from East Cuilcagh to Tullyhona Rising and Cascades Rising are lower that those observed on the Marlbank (30m/km compared to 60m/km) (Figure 45 and 67), similarly average linear velocities are also lower (30-40m/h compared to 50m/hr). Tullyhona is unusual in that it has the highest sink to rising gradients of up to 120m/km.

4.5. <u>Shannon Karst</u>

In this thesis, the Shannon Karst is defined as the southwestern area of the Marlbank, which drains to Shannon Pot Rising, Lag Na Sionna, (GR.: 20534-33176), the 'traditional' source of the River Shannon (Figure 68). Shannon Pot is probably the most famous karst spring in Ireland, not only because it is the source of the country's longest river but also because of its place in Irish folklore and religion. The local legend of Lag Na Sionna tells of a holy man wandering in search of water during times of a terrible plague. Unable to find water he became unconscious and collapsed but he awoke to find water trickling from the earth and drank his fill. The legend goes on to say that since then the rising of Shannon Pot has never gone dry.

The Dartry Limestone Formation is poorly exposed in the Shannon Karst (Figure 69), largely due to an extensive cover of glacial drift and peat. Based upon maps produced by the GSI (1996), the Upper Knockmore Member, the Cloghan Hill Member and the Dartry 'Type' Limestone crop out in the Shannon Karst. Due to the southwestward dip of the sequence, the karst landforms of the Shannon Karst are located stratigraphically lower than Shannon Pot Rising. Whereas dolines and stream sinks are located within the Dartry Limestone Formation, Shannon Pot is set within the overlying shales of the Meenymore Formation. The strata of the Marlbank forms the northern limb of the Cuilcagh Syncline, the axis of which lies along the ridge of Cuilcagh Mountain, and plunges northwestwards by approximately 1°. Due to steepening of the regional structure, at the western margin of the uplands the Dartry Limestone Formation dips beneath the cover of the Meenymore and Glenade Sandstone formations. In contrast to the Erne Karst, the mud mounds of the Knockmore and Cloghan Hill members do not stand out from the modern Shannon Karst landscape instead they remain buried beneath the Dartry 'Type' Limestone and overlying clastic rocks. At Shannon Pot (106m AOD) the Dartry Limestone Formation is estimated to be 300m thick, with the Glencar Limestone Formation located c.180m below OD.

4.5.1. Identification of karst landforms and cave systems

Considering the catchment size of Shannon Pot Rising there is remarkably little known cave passage. The only known cave passage comprises Shannon Cave (2600m), Polltullyard (380m) and Pollboy (75m). Although Badger Pot and Pigeon Pot II have been proven to be part of the Shannon drainage system they are described in the section on the East Cuilcagh Karst.

Jones *et al.* (1997) catalogued the karst landforms and caves in the Cuilcagh Karst by giving each system a name and a letter (usually the first letter of the resurgences name) and then numbering sinks and caves thought to form part of that drainage system. This format is used in this thesis but because most karst landforms and caves in the Shannon Karst are named, the names are more frequently used.

4.5.2. Hydrogeology of the Shannon Karst

Prior to 1980, very little cave passage was known in the Shannon Karst. Most exploration was focused on the major sinks in the area and on Shannon Pot itself. As part of a programme of water tracing experiments in the area, Gunn (1982) showed that water sinking at Pollnahune, a remote sink on the slopes of Tiltinbane, drained to Shannon Pot Rising. The relatively high average linear velocities (<90m/h)) and shallow gradient between sink and rising (36m/km) (Table 3) suggested that open passage was likely. Excavation in the Pollnahune doline eventually led to the discovery of Shannon Cave. Following the exploration of Shannon Cave, further tracer tests by Gunn (1982, 1984 1996 and 1997) proved that sinks in the Killykeegan and Tullynakeeragh townlands also to drain to Shannon Pot via Shannon Cave. Subsequent tracer tests showed that the Killykeegan and Tullynakeeragh sinks marked the known easterly extent of underground drainage to Shannon Pot Rising at that time (Figure 70).

During the early 1990s, at about the same time as the Entrance Series of Shannon Cave collapsed and became impassable, Gunn (1996) began a series of water tracing experiments on the East Cuilcagh Escarpment. Of the many landforms on the East Cuilcagh Escarpment one stream sink, Pigeon Pot II, and one doline, Badger Pot, were identified as draining to Shannon Pot Rising. The water tracing experiments undertaken by Gunn the author are presented in Table 9 and presented in Table 12 with data from previous tests. Between the Killykeegan sinks and the East Cuilcagh Karst, there are several karst landforms, including sinks in the Owenbrean River. However, all landforms between East Cuilcagh and Killykeegan drain northwards into the Prod's-Cascades and Marble Arch systems. As such, Shannon Pot Rising has two catchment areas, an immediate catchment that extends eastward from the rising as far as the townland of Killykeegan and a distal catchment on escarpment of East Cuilcagh (Figure 70). The distal catchment comprises of only part of the East Cuilcagh Karst, and the drainage is not exclusively to Shannon Pot Rising. Between the main catchment and the distal catchment is an extensive area where sandstones and shales that overlie the Dartry Limestone Formation crop out. The three largest rivers of the Cuilcagh uplands, the Owenbrean, the Aghinrawn and the Sruh Croppa, which drain this area, are tributaries River Erne.

4.5.2.1. Stream sinks, dolines and associated caves

Shannon Cave is the longest cave in the Shannon Karst at 2600m in length. Polltullyard cave is the second longest cave at 380m and was discovered following the survey of Shannon Cave, which showed it to be the upstream extension of JCP Passage. The only other cave in the Shannon Karst is Pollboy, which is located 2km northwest of Shannon Cave and forms a separate tributary to Shannon Pot Rising.

<u>Polltullyard (Figure 71)</u>

Polltullyard lies upstream of JCP Passage in Shannon Cave but is separated by a boulder choke, estimated to be 10m long. The Tullyard stream drains a small catchment on the lower slopes of Cuilcagh and sinks at the contact of the Meenymore Formation and the Dartry Limestone Formation into the 9m-deep Polltullyard doline. Although the active stream sink is impenetrable, access to the system is via a relict passage located 6m higher. The entrance lies within the Dartry 'Type' Limestone and has developed along a prominent fracture set in the passage roof. The Dartry 'Type' Limestone is only 11m thick in the Tullyard townland and the entrance is located 3m below the top of the Formation. The entrance passage to Polltullyard descends at a gradient of 5° with several steps at prominent chert horizons, until the unit is traversed and a 33m deep shaft has developed into the Knockmore Member (Plate 18). The author logged the geology of the shaft, which is presented in Figure 72. At the foot of the shaft, the Tullyard stream enters via a 4m waterfall in the eastern wall, known as Fossil Pot. This stream has increased in volume since the Polltullyard stream sink being augmented by drainage from the Killykeegan townland. Upstream the passage extends for 140m before ending in a choke of sandstone boulders. Westwards from the foot of the shaft to the boulder choke that separates Polltullyard from Shannon Cave the passage is partially filled with boulders, cobbles, pebbles and sand that locally reach the roof.

Shannon Cave (Figure 71)

The Reyfad [caving] Group discovered Shannon Cave in 1980 by engineering a route through a boulder choke, known as the Entrance Series, from Pollnahune (S2a) to Main Stream Passage. This remains the only known entrance to the cave system, although since a collapse in the early 1990s it has become impassable. Unfortunately, as the present study did not begin until October 1995, the author has not been able to make observations in Shannon Cave. Descriptions of the system are based upon published observations and photographs, together with oral accounts from cavers who have explored the cave.

The Hune stream sinks into an impenetrable boulder mass at Pollnahune (S2b) and is next visible in Pollnahune (S2a) the Entrance Series of Shannon Cave, some 50m west and 12m lower. The Entrance Series of Shannon Cave is c.45m in length and has been excavated largely through a boulder dominated glacial drift to solid rock. The instability of such debris is reflected by numerous collapses in the entrance series, including the major collapse that has prevented access to the cave since the early 1990s. Pollnahune (S2a) and the Entrance Series have developed within an accumulation of glacial debris, which buried an ancient depression (most likely to have been a valley, or perhaps a steep sided gorge) during the retreat of the last Pleistocene ice sheet. Shannon Cave has developed within the upper vertical-type mounds Knockmore Member. The horizontal-type mounds of the Knockmore Member lie at an estimated depth of 220m below Shannon Cave.

JCP Passage is the upstream section of Shannon Cave, from where the entrance series meets Main Stream Passage. The passage is 445m long and leads from the Polltullyard choke, where boulders fill the passage to the roof. Sediments in the cave largely comprise sandstone debris, ranging from medium sands through to large boulders (>1.5m in diameter), with some limestone and shale debris present. However, the volume and individual size of sandstone boulders is greater than in any other cave system in the region.

Mistake Passage is a tributary of Main Stream Passage, which was traced by Gunn (1982) from Tullynakeeragh Gravel Lake, a large caprock doline and stream sink developed in the Glenade Sandstone Formation. Mistake Passage terminates after only 168m where boulders, largely of sandstone, fill the passage to the roof. The end of Mistake Passage lies c.840m horizontally away from and an estimated 45m below Tullynakeeragh Gravel Lake. The Hune Stream is unusual in that it is a bifurcating stream (Plate 19), with the western branch sinking at Pollnahune and the eastern branch sinking at Tullynakeeragh Gravel Lake. Although the eastern branch sinks c.100m after bifurcation, the western branch continues on the surface for 2km before it sinks. In terms of flow, the majority of flow, c.65% drains to Pollnahune under moderate to high flow. Under low flow, this increases to c.80%. The sloping rock faces of Tullynakeeragh Gravel Lake indicate that the depression is actively subsiding and suggest that it is a relatively recent surface feature in terms of landscape evolution.

Two sinks east of Tullynakeeragh Gravel Lake, Pigeon Pot II and Badger Pot, have been traced to Shannon Pot Rising. However, the first water tracing experiments proving the connection between East Cuilcagh and Shannon Pot Rising occurred almost contemporaneously with the collapse in the Entrance Series of Shannon Cave. Therefore, it remains unproven if this drainage flows through Mistake Passage and Shannon Cave or if it bypasses the known cave and flows to Shannon Pot by a different flow path. The stream in Pigeon Pot II can be followed to a depth of 246m AOD and Mistake Passage is estimated to lie at 200m AOD. The linear distance between the two points is 8km, which gives a very low gradient of only 6.6m/km (Chart 18). The average linear gradient between Shannon Pot Rising and the end of Shannon Cave is calculated to be 19.4m/km, which is similar to the average gradient within Shannon Cave. On this basis it may be argued that the water from Pigeon Pot is unlikely to target Shannon Cave but instead flows via a lower route to Shannon Pot at an average gradient of 13.1m/km

Main Stream Passage is 900m long and like both JCP Passage and Mistake Passage, contains large boulder chokes, largely composed of sandstone boulders, which have no surface expression. The abundance of large rounded and semi-rounded boulders in

Polltullyard and Shannon Cave suggests a major input to the system. Although the topography is covered by drift that blankets the rock topography, the only way for the boulders to enter the system is from the surface. Within the system, there are several potholes, similar in size to Polltullyard, but filled with boulders. As such, there are likely to have been several large sinks to the system, of which only Polltullyard was not blocked by glacial debris.

The Main Stream Passage of Shannon Cave includes a large relict oxbow (Reyfadtwo Chamber), perched some 10m above the active streambed. Main Stream Passage ends at a major boulder choke, George's Choke, which marks the start of the Mayfly Extension (c.920m). The Mayfly Extension includes some of the largest passage in the Cuilcagh Karst, such as Fin McCool's Boulder Store, which is some 200m long, 20m wide and 20m high. Three sumps are present in the Mayfly Extension. The third of these has not been dived and marks the limit of exploration in Shannon Cave.

4.5.2.2. Risings

Shannon Pot Rising is the only outlet from the Shannon Karst. However, there are several small risings (S15, Legeelan (S16B) and S5) up gradient of Shannon Pot but all eventually sink to finally rise at Shannon Pot Rising.

<u>Shannon Pot Rising (Figure 71)</u>

Shannon Pot Rising is a circular pool 9.5m deep and 16m in diameter in the lowlands 4km northwest of Tiltinbane, the most westerly point on the Cuilcagh ridge. Regionally, the Dinantian stratum of the Marlbank dips between 5° and 8° southwestwards and forms the northern limb of the Cuilcagh Syncline. The Cuilcagh Ridge marks the axes of the syncline and as such the southern flanks of the mountain forms the southern limb of the syncline. The location of Shannon Pot places the rising upon or very close to the axis of the Cuilcagh Syncline. The geological map (GSI, 1996) for the Sligo and Leitrim area confirms that Shannon Pot is located within the most westerly part of an outcrop of the Meenymore Formation at the top of the formation near the contact between the overlying Glenade Sandstone Formation.

The rising is located at the head of a shallow valley, which is lined with drift. The pot itself is also lined with drift, with the exception of the steep eastern side where rock crops out and which is also the deepest part of the pot. Water flows from a horizontal but inaccessible fissure at the base of the bedrock, which is identified as sandstone from the Meenymore Formation. The survey of Shannon Pot by Elliot and Solari (1972) shows the outcrop to be thinly bedded and to be dipping by approximately 20° to the south. In the vicinity of Shannon Pot the local dip is measured at between 18° and 24° westwards. This relatively steep dip is associated with the Derrylahan Fault, which forms the eastern part of a fault complex that trends north-south from Lough MacNean towards the Owenmore Valley. The complex is approximately 600m in width and straddles Shannon Pot Rising. Displacement across the complex is c.30m, which is accommodated by the steeply dipping strata at Shannon Pot Rising.

Several karst landforms are located in close proximity to Shannon Pot Rising, including a small overflow rising located 2m higher and 15m to the east. Approximately 60m east of Shannon Pot Rising, and 15m higher, there is a north-south line of dolines, all of which have sandy floors in which there is little or no vegetation growth. During times of low flow, several small streams drain into the dolines and sink. During high flow, water enters the dolines from below and they gradually fill with water, forming deep pools. During very high flow, the dolines fill completely and flow is discharged from them. The coarse sand that lines these dolines also accumulates around the outflow of the rising, which is unusual as there is no sand source in the area. However, the catchment to Shannon Pot Rising includes many sinks that drain from sandstone, and as such, the sand at the rising and the dolines is probably sourced at some distance and transported by conduit to emerge during high flow. For water to rise into the dolines, then at least 15m of hydraulic head must build up during high flow events. During such events, the depth of water in Shannon Pot Rising has been observed to rise by over a metre with a pressure dome on the surface. The rising has also been observed to react rapidly to heavy rainfall, typically within a few hours.

Average linear velocities to Shannon Pot Rising vary widely from 50m/h for Derrylahan 1 to 250m/h for Pollboy (Gunn, 1982). Sink to rising gradients are typically low (Figure 73) and reflect the wide area but low gradient across the catchment (Table 12). Badger Pot and Pigeon Pot II the sinks furthest from Shannon Pot Rising have the lowest sink to rising gradients of less than 20m/km. Average linear velocities for Badger Pot and Pigeon Pot II are moderate at 85m/h and 100m/h respectively. As there is little or no known cave passage between sink and rising, average linear velocities are likely to be a gross underestimate of true velocities. Especially when considering that Pigeon Pot II and Badger Pot are located 10.5km and 10.3km from Shannon Pot Rising respectively.

The water emergent at Shannon Pot has a relatively low conductivity reflecting only a moderate enrichment of HCO_3, Ca and Mg ions by dissolution of the limestone (Tables 4 and 5). In addition to the chemical analysis undertaken on the risings Webber also undertook investigation into the ratios of light and heavy sulphate isotope of the emergent waters. The aim of this work was to determine the influence of pyrite oxidation on the sampled waters. Sulphate sulphur derived from the oxidation of pyrite is depleted in $\partial^{34}S$ relative to rainwater sulphate, and therefore has a lighter isotopic composition. Hence, waters that have been influenced by pyrite oxidation show a lighter $\partial^{34}S$ value than rainwater. All of the samples show a lighter $\partial^{34}S$ value and higher SO_4 concentration than would be found in rainwater. This suggests that the isotopically light sulphur is being added to the rainwater between catchment and rising. The most probable source of this light sulphate is the oxidation of pyrite minerals within the aquifer. However, whilst Shannon Pot has an isotopically light $\partial^{34}S$ signature during low or normal flow conditions, during high flow conditions the emergent water has a significantly heavier $\partial^{34}S$ value (+17.9 $\partial^{34}S_{CDT}$) and higher concentration of sulphate (from 2.7 mg/l to 7.6 mg/l). This indicates that an additional influence is being exerted during high flow events. The only process that can produce $\partial^{34}S$ values at this level is sulphate reduction (Neil Webber, *pers. comm.*, 1997). During this process, the lighter ^{32}S is preferentially removed and the resulting sulphate is thus enriched in ^{34}S and the heavier isotopic composition is observed. Sulphate reduction is a process that only occurs in anoxic conditions, which tend to be found deep within the aquifer. This suggests that part of the water emergent at Shannon Pot Rising during high flow events has been circulating deep in the aquifer. This observation is supported by the relatively high concentration of strontium at 1.19 mg/l. It is most likely that the origins of the sulphate are by pyrite oxidation but that following the oxidation the waters were influenced by sulphate reduction. Interpretation of this chemical variance suggests that a deep underflow, with slow moving long residence time waters, and a shallow overflow, with rapid moving short residence times exists (as defined by Worthington, 1990) but that the deep flow only emerges at Shannon Pot Rising during flood events and by mixing with the shallow flow.

Although it is unusual for conduit to have developed in the Meenymore Formation it is not unique, as the Owenbrean Upper Sinks have developed at a similar level within the Formation. Limestone forms interbeds within the formation between shale and sandstone units. Like the Owenbrean Upper Sinks, Shannon Pot Rising is developed within a fracture zone. In this case the Derrylahan Fault Zone. Water rises by at least 15-20m above the top of the Dartry Limestone Formation although the main conduit is likely to be far deeper. Shannon Pot Rising is a relatively recent development in the evolution of the Shannon Drainage System. It is related to the modern topography which formed by the incision of the Shannon Valley during glacial times. However, as no other active or relict risings to the system are known it is unclear where water drained to prior to the development of Shannon Pot.

4.5.3. Drainage catchments

The Shannon Karst is unique on Cuilcagh Mountain in that all recharge drains to a single major karst rising, Shannon Pot, which is the traditional 'Source' of the River Shannon. The proximal surface water catchment of Shannon Pot Rising is 15.2km^2, whilst the distal catchment on the East Cuilcagh Escarpment measures 0.9km^2. The combined area of 16.1km^2 makes the surface water catchment of Shannon Pot Rising the second largest catchment in the Cuilcagh Karst, Marble Arch Rising being the largest (25km^2 high flow, 16.9km^2 low flow). The Shannon karst is also unusual in that over much of its area the surface comprises non-karstic rocks. Many karst landforms have developed by caprock collapse and the main cave system, Shannon Cave, has largely developed beneath this cover.

The Shannon Karst is set upon the gentle dip slope of the Marlbank escarpment and gradients from sink to risings are low, typically less than 30m/km. As the Dartry Limestone Formation dips southwestwards at a slightly steeper angle than the topography, the formation dips beneath the cover of the Meenymore Formation at the western margin of the uplands. In terms of the regional dip and the topography, Shannon Pot Rising lies at one of the lowest points in the valley where the Dartry Limestone Formation is buried at a very shallow depth (<20m). Further west, where the topography of the valley is lower, the Dartry Limestone Formation is buried far more deeply. Hence, Shannon Pot has developed at the shallowest point for water to rise to the surface from the Dartry Limestone Formation in the Shannon Valley.

4.5.4. Flow paths

The lateral extent of the underground drainage to Shannon Pot Rising suggests that an ancient and mature conduit system exists. Shannon Pot Rising provides an overflow from a much deeper system. Hence it must represent a recent modification of the system that pre-dates the topography of the region. At Shannon Pot Rising the limestone has a thickness of c.320m, which provides significant scope for deep-seated groundwater circulation. The small number of accessible caves in the near and distal catchments of the modern system allow only a partial study of the conduit that forms the branching network that drains to Shannon Pot Rising. None of these in the proximal catchment have lithological guidance and all are entirely developed along faulting and fracturing within the Dartry 'Type' Limestone and the Knockmore Member. In the distal catchment, Pigeon Pot II and Badger Pot are all guided by fracture patterns. However, a high-level passage in Pigeon Pot II is located within the Dartry 'Type Limestone at a massive micrite interbed that lies below a thin shale. This passage is unusual in the East Cuilcagh Escarpment as it extends laterally for c.150m. Badger Cave, near Badger Pot, also has lateral passage that has developed upon a bedding plane. However, this plane is located at the shaley contact between the Dartry 'Type' Limestone and Carn Member. The occasional phreatic shaped roofs of lateral passages in both Pigeon Pot II and Badger Cave indicate that their origins are different to the deep rift passages that dominate the caves on the East Cuilcagh Escarpment. The hydrology of the East Cuilcagh Escarpment is complex due to the divergence of several flow paths. However, when the flow path to Shannon Pot Rising is compared with the flow path to risings in the East Cuilcagh Escarpment then its greater average linear velocity, lower sink to rising gradient and relatively long flow path largely beneath non-limestone cover all indicate a more ancient drainage system. It is also perhaps not unusual that Pigeon Pot II and Badger Cave include the only relict phreatic sections of passage in the East Cuilcagh Karst. It is hypothesised that the inception of this ancient conduit system pre-dates the modern topography and that the original conduit was lithology guided, as opposed to the systems that drain to risings at the base of the East Cuilcagh Escarpment, which are related to topography and guided entirely by fractures and faulting.

The proximal and distal catchments of Shannon Pot Rising are separated by a wide expanse of non-limestone rock outcrop. However, the development of caprock dolines, such as Tullynakeeragh Gravel Lake, and the location of Shannon Cave partly beneath the non-limestone strata demonstrates that conduit, and indeed caves, extend well beneath this cover. From the work undertaken as part of this research project, it is apparent that the Cuilcagh Syncline guides the Shannon system. However, the Cuilcagh Syncline is not restricted to Cuilcagh Mountain, and it continues to plunge westwards from Shannon Pot Rising, perhaps as far as the Castle Archdale-Belhavel Fault system at Manorhamilton.

4.7. Summary

Catchment mapping, using tracer tests, has subdivided Cuilcagh Mountain into the East Cuilcagh Karst, the Erne Karst and the Shannon Karst. A summary of all water tracing experiments is presented in Figure 74. On the Marlbank, the Erne and Shannon drainage systems are separated by the Cuilcagh Dyke, which forms a major part of the groundwater divide. Where the dyke is intact it forms a hydrological barrier that is not penetrated by conduit flow. The East Cuilcagh Escarpment has a complex hydrology with divergent groundwater movement to risings in the east as well as Cascades Rising on the northern side of the dyke and to Shannon Pot Rising in the west.

The drainage of the East Cuilcagh Escarpment is hypothesised to be via an extensive maze-like network of fracture-guided conduit. This narrow but vertically extensive network is partially flooded with its upper half drained and accessible as potholes. The local risings in the East Cuilcagh Karst represent leakages from the phreas within the highly fractured limestone escarpment. It is further hypothesised that drainage from the East Cuilcagh Escarpment to Cascades Rising is focused on the Owenbrean valley where the dyke is faulted permitting conduit flow to pass and continue to Formation Passage of the Prod's-Cascades cave system. For much of its length this conduit passes beneath non-limestone strata.

The route from the East Cuilcagh Escarpment to Shannon Pot Rising, proven by repeated water tracing experiments, is also largely beneath non-limestone strata. Water tracing, geological and geochemical evidence suggests that the Shannon System has at least two components, one deep and one shallower. Shannon Pot Rising discharges water largely from the shallow system but with pulses of deeper water during storm events. The ultimate destination of the deep drainage is uncertain. Conduit inception of the deep system is thought to be ancient and unrelated to the modern topography. In contrast eastward drainage from the East Cuilcagh Escarpment is shallow and has developed in response to the incision of the Erne Valley.

With the exception of the complex at the Owenbrean Upper Sinks there are no divergent flows in the Erne Karst and instead groups of sinks focus on a single rising. In the Eastern and Central Marlbank the caves are generally larger with a greater lateral flow component. This reflects their age, the geological context and particularly the large inputs of concentrated allogenic recharge from sinking streams.

This chapter has presented geological, tracer test and hydrochemical evidence to develop hypotheses that explain the relatively complex karst hydrology of Cuilcagh Mountain. The next chapter, Chapter 5 "Conduit Inception and Development" furthers the discussion by providing processes for the origin of conduits and their subsequent enlargement.

Chapter 5

Conduit Inception and Development

5.1. Introduction

The conduits that form the drainage systems of the East Cuilcagh, Erne and Shannon Karst areas have been shown to differ in their geological setting. This chapter explores inception and development processes of conduits in each karst area by studying the setting of the modern caves in terms of their hydrogeology.

Fundamental to inception and development are the processes of transition from rock without conduits to rock with conduits. Intermediate between rock without conduits and rock with conduits are the origins of preferential flow paths, which by natural selection develop into channels (as defined by Worthington, 2004). Upon achieving a diameter of 1cm turbulent flow occurs and upon this breakthrough channels become conduit. With the onset of turbulent flow conduits become increasingly enlarged largely by carbonic acid dissolution but also by erosion from sediment transport. As such, although caves may enlarge over relatively short periods the inception processes themselves are particularly slow. Hence, the evolution of a karst aquifer from preferential flow path to cave may span considerable geological time.

One aim of this thesis is to identify the geological features where inception is initiated and to determine how they develop as preferential pathways. Lowe (1992), termed the lithological discontinuities that guide conduit initiation as 'inception horizons'. However, tectonic guidance is also important in terms of aquifer evolution, in this thesis fractures where conduit has initiated are referred to as inception planes. Whilst the pathway of a primary conduit is likely to be simple, the consideration of time vastly increases its complexity so that inception processes are increasingly masked by subsequent, and continuous, development.

This chapter discusses the factors that have guided the inception and development of conduits in the karst of Cuilcagh Mountain. The guidance that geological features have had upon the location of conduit inception is assessed and considered within the context of modern and pre-existing settings. This chapter follows the format of previous chapters in that each of the three karst areas are described individually.

5.2. The East Cuilcagh Karst

From field observations of karst landforms and cave passage on the East Cuilcagh Escarpment it is apparent that fracturing is the main guidance for conduit development. Caves, such as the Border Pots (Figure 34) and Pigeon Pot II (Figure 38 and 39), characteristically form vertically extensive, angular networks of rift-like shafts and passages. Drainage via these systems has lowered groundwater levels so that vadose conditions penetrate up to 70m below the escarpment. Rift-like conduits, as well as extensive fracture flow, provide a well inter-connected network within the rockmass. As such, the phreatic part of the system exhibits the typical triple permeability characteristics of a karst aquifer. During high recharge events the phreatic zone responds rapidly by rising up to 30m.

Like the karst landforms and cave passages, the risings of the East Cuilcagh Karst, which lie near the base of the scarp slope, are also guided by fracturing. No guidance by lithology is observed at any of the risings and each have different elevations, with the notable exception of the spring cluster at R04 a, b and c. The large risings, Sumera Rising and Gortalughany Rising, are located upon significant faults, with Sumera being located upon the Swanlinbar Fault, which has a throw estimated at 65m. Based upon the triple permeability characteristics of a karst aquifer, risings are most likely to occur where the topography intersects significant flow paths. Larger risings develop where larger conduit is intersected. Evidence that conduit pre-dates the modern topography is best observed in Badger Cave where a phreatic half-tube forms part of the roof, which lies near the top of the Dartry Limestone Formation. The phreatic half-tube shows that the flow path existed prior to the shaping of the modern landscape and the incision of the Erne Valley but also that conduit development occurred before the Dartry Limestone Formation cropped out in the area of the East Cuilcagh Escarpment. However, the phreatic tube in Badger Cave is atypical of the majority of cave passage on the East Cuilcagh Escarpment as it is located upon a shaley horizon within the sequence and has developed down the dip of its bedding plane. Differences between the Badger Cave phreatic tube and the more typical rift-like passages indicate that at least two phases of conduit inception and development have occurred. The first phase being along inception horizons and the latter along inception planes.

Based upon field observations this section examines the inception and development processes of the caves in the East Cuilcagh Escarpment. In order to assess the evolutionary sequence of conduit inception and development, three caves are studied in detail, Badger Cave, Pigeon Pot II and the Border Pots,

5.2.1. Case study: Badger Cave

The relatively short section of passage that forms Badger Cave is unusual on the East Cuilcagh Escarpment as it comprises entirely of horizontal passage but also because it is one of the few places on the escarpment where evidence of an early phase of conduit development can be observed. The phreatic half-tube in Badger Cave is c.0.35m in diameter and lies c.5m below the surface where a prominent shaley bedding plane is intersected by a fracture. The shaley horizon occurs above the *Siphonodendron* layer c.2m below the top of the Dartry 'Type' Limestone. Over the length of the passage the bedding plane and half-tube dip westsouthwest by approximately 3°. Although the Badger Cave phreatic tube lies close to the surface the phreatic system lies some 40m deeper.

The semi-circular form of the Badger Cave conduit is centred upon the intersection between the shaley horizon and the fracture plane, suggesting that whilst the properties of both features may have promoted preferential flow it was their combined properties that led to development of conduit. The subsequent development within the phreatic setting led to the dissolutional enlargement of the conduit equally across its cross-section to form a circular shape. For inception to have been guided at the shaley horizon, then the horizon itself must have formed a preferential flow path to groundwater flow compared to the overlying and underlying strata. As such, the aquifer properties of the shaley horizon, over those of the limestone, promoted conduit inception. Whilst, shales tend to have a vertical permeability similar to that of micrite, due to their laminar nature they tend to have a higher lateral permeability (Neuzil, 1994). Additionally they have a potential for the genesis of strong acid from sulphide minerals that are relatively abundant within such shaley beds, when compared to micrite.

For phreatic conditions to prevail at the high stratigraphical level of Badger Cave then the piezometric level must have been higher than the Dartry Limestone Formation. For this to be the case the aquifer must have been buried and confined. Clearly for these conditions to prevail then the modern topography could not yet have formed.

5.2.2. Case Study: Pigeon Pots

The Pigeon Pots consist of three potholes, named (from southwest to northeast) II, III and I, which are located along the same fracture in the Beihy Fault Block (Figure 38 and 39). Pigeon Pot II swallows a stream, whilst I and III are relict. However, the development of each pothole along the same fracture indicates that the modern stream originally sank at pothole I and then pothole III before eventually sinking at pothole II. Whilst potholes I and III are simple shafts, pothole II includes multiple shafts that form part of a network of rift passages. All three potholes are part of the same system. However, as each new pothole developed the previous sink became blocked by collapse and sediment fill.

Pigeon Pot II consists of a series of rift-like shafts developed along a series of parallel northeast-southwest orientated fractures that are joined by a series of northwest-southeast orientated fractures. The cave forms an angular network of passage that descends to a depth of 52m. The cave swallows a stream that falls down a series of shafts before disappearing into the boulder floor of Rift Chamber. On route, the stream falls past the Badger Cave inception horizon c.4.1m down the entrance pitch (Plate 7) and although a substantial undercut occurs the author has not observed any conduit or phreatic form at this horizon in the Pigeon Pots. However, in Rift Chamber, at a depth of 35m from the escarpment surface, a sub-horizontal passage, aligned along dip, extends for c.70m from its northeastern end and c.110m from its southeastern end. Both of these passages are high-level extensions from Rift Chamber that have developed in a 1.4m-thick micritic horizon that has a thin, weathered, shaley horizon above it. This second shaley horizon lies 31m below the inception horizon observed in Badger Cave.

From the northeastern part of Rift Chamber, the passage trends northwestwards and includes c.40m of relict keyhole passage, c.1.4m in height (Fogg, 1998). This passage links between a series of rift passages and chambers similar in form to Rift Chamber. Whilst the keyhole passage has incised into the massive micrite horizon, a phreatic half-tube, c.0.65m in diameter, remains at the top of the micrite unit along the thin (<4cm) shaley parting. Whilst the passage was only entrenched into the micrite bed when the conduit became vadose, inception of the conduit occurred along the shaley horizon, specifically at the intersection between it and a fracture orientated at 120°. Similar phreatic remnants are also evident in the southwestward series of passage (the Indiana Jones Series) where remnants of the original conduit are observed along the intersection between the shaley horizon and a fracture orientated at 55°. However, the southwestward series has been deeply incised into so that although the passage continues at the level of the shaley horizon a number of shafts, up to 20m deep, have formed in its floor. The Indiana Jones Series extends beneath the Meenymore Formation cap for c.60m. This passage beneath the cap includes an aven that rises for >12m, which has flowstone lining its walls and peaty seepage from the surface. The position of the aven c.15m upstream of the active sink indicates that this will eventually form the location of a new sink to the Pigeon Stream as the cap continues to be striped back.

As the high-level passage from Rift Chamber exhibits phreatic features, its development pre-dates that of the active and relict stream sinks. Further to this, as the high-level conduit developed at the intersection between the shaley horizon and a fracture, it was the combined aquifer properties that promoted its development as a preferential flow path. As such, inception occurred because of the higher permeability at the junction of the bedding plane and fracture. This being the case then the conduit associated with these high-level passages, like the Badger conduit, also pre-dates the development of the rift-like conduits, which are guided solely by fracture planes.

5.2.3. Case study: Border Pots

With a depth of 70m the Border Pots cave system (Figure 34) is the deepest on the East Cuilcagh Escarpment. Whilst the system is entirely developed within the Dartry 'Type' Limestone, the lowest parts of the cave system lie near to the transition into the Gortalughany Member. The Polliniska, Pollnatagha and Pollprughlisk entrance shafts are all guided by fractures that are orientated at 160-190° and/or 030-045° (Figure 35). Fractures at these orientations have also guided the development of the angular passage network that joins the potholes together. Lithological variations have guided some of the development of cave passage, specifically in Pollprughlisk where a short horizontal section is guided along the Badger Cave inception horizon at c.3m below the surface. This shaley horizon is also observed in Polliniska and Pollnatagha although in these potholes the shaley horizon is simply crosscut by each shaft. In Pollnatagha, the horizon forms an undercut causing the overlying massive limestone beds to overhang, as it does in Pigeon Pot II. An additional lithological discontinuity similar to the Badger Cave inception horizon occurs c. 12m below the surface. This horizon guides the stream that sinks at Polliniska into Pollnatagha and influences the flat roof of the Pollnatagha Chamber. The second shaley horizon identified in Pigeon Pot II is not present within the stratigraphy exposed in the Border Pot cave system. Black Arrow Inlet Passage, which joins the Pollnatagha and Pollprughlisk shafts, has developed as a series of sub-horizontal rift passages along particular fracture planes. Unlike the horizontal passage in both Pigeon Pot II and Badger Cave, where specific horizons have guided conduit, Black Arrow Inlet Passage has no lithological guidance.

The entrance shafts of the Border Pots, like the Pigeon Pots, have evolved with the landscape. The stream that presently sinks at Polliniska originally discharged southwards from the escarpment across the surface towards Pollnadad cave (Figure 34) where a dry valley forms a misfit tributary to the Swanlinbar Stream. The potholes developed as flow paths within the limestone became sufficiently enlarged to swallow the stream. The original stream sink was Pollprughlisk and then, as Polliniska-Pollnatagha developed, Pollprughlisk became abandoned. The path of the stream to Pollprughlisk is still present as a slight surface depression that can be traced back 'upstream' to Polliniska.

5.2.4. Inception and development of conduit in the East Cuilcagh Karst

Prior to the incision of the modern Erne Valley, the Dartry Limestone Formation remained buried, and phreatic conditions prevailed at the top of the formation. The relict phreatic tube in Badger Cave at the top of the Dartry 'Type' Limestone is a remnant from these pre-incision times and indicates that significant conduit development had occurred prior to the evolution of the modern topography. The inception of these early conduits, as identified in Badger Cave and Pigeon Pot II, occurred at shaley interbeds in the sequence, especially where the aquifer properties of the horizon were enhanced by fracturing. In the modern setting rift-like shafts and passages cut through these shaley horizons (inception horizons) and are entirely guided by fracturing (inception planes).

The conduit remnants in Badger Cave and in Pigeon Pot II are both located along depositional breaks in the limestone. The depositional break exposed in Badger Cave is widespread across the escarpment and is observed in many potholes and surface exposures, especially at Legacurragh Gap where the top of the Dartry 'Type'

Limestone, identified by the abundance of *Siphonodendron* colonial corals, forms the dip slope of the escarpment. The horizon exposed in Pigeon Pot II is not widespread, and is assumed to be a localised depositional feature.

Whilst the development of conduit along inception horizons in the East Cuilcagh Karst pre-dates the modern topography the inception of conduit occurred far earlier. The shaley horizon and fracture set along which the conduit developed have existed since middle Dinantian and late Silesean times, respectively. Although the horizon may have formed a preferential flow path during Dinantian times it is unlikely to have been substantially enlarged until much later. As discussed in Chapter 4, relatively stable hydrogeological conditions prevailed within the aquifer for substantial parts of its Mesozoic history. During these times 'Ireland' remained an upland area with recharge input. Although the aquifer remained buried groundwater circulated within the sequence. Considering the low permeabilities of the sequence advancement from preferential flow path to channel would require considerable geological time. Recharge to the limestone aquifer was most likely from a combination of interstratal and up-gradient basin marginal sources. Discharge from the aquifer was likely to have been at the continental margin and down-gradient basement margins.

Without the valleys that separate and isolate Cuilcagh Mountain the karst aquifer would have extended further across southwest County Fermanagh, northern County Cavan and northern County Leitrim. Geological mapping has shown that the aquifer is gently folded with axes orientated eastsoutheast-westnorthwest and a gentle westnorthwest dip of 1°. Elements of these structures combined with the westward thickening of the formation would have guided flow within the confined body of the aquifer from higher elevations in the east to lower elevations in the west. Additionally local flows would be guided away from the anticlinal ridges and down the dip synclinal troughs.

Whilst a significant thickness of limestone has been removed from the valley, a substantial thickness of cover has also been removed from the uplands themselves. This is particularly important when considering Shannon Pot Rising, which Badger Pot and Pigeon Pot have both been proven to drain to. By applying the thickness of rock eroded in the Erne Valley to drain the Badger conduit (>300m) to the topographical setting of Shannon Pot Rising in its valley floor and its geological setting within the Meenymore Formation then the inception of the Shannon conduit system must have been particularly deep-seated.

The abundance of fracturing within the East Cuilcagh Escarpment indicates that fracture flow is undoubtedly a major component of groundwater flow within the karst aquifer. However, it is hypothesised that the inception of these rift-type conduit along fracture planes only developed when elevation of the Dartry Limestone Formation was significantly shallow. In this shallow setting unloading of the non-limestone cover would have increased the aperture of fractures and allowed meteoric waters to circulate. As the Erne Valley incised into the Dartry Limestone Formation these fracture flow paths were intersected and formed risings, which further facilitated drawdown within the aquifer. This relatively recent phase of conduit development along fracture planes modified the earlier phase conduit. Prior to the incision of the modern landscape groundwater flow was largely westward, guided by the regional synclinal structure. However, subsequent to the incision of the modern landscape, and removal of cover, flow paths began to bifurcate as the westward flowing groundwater was gradually captured towards the local risings in the east. Drawdown occurred within the aquifer as the eastward flow paths increased in capacity causing the phreatic zone to lower and gradually reduce the component carried by the westward flow path. Although in the modern setting flow still drains westward, as proven by water tracing experiments, ultimately all flow in the East Cuilcagh Escarpment will drain eastward to the local risings.

5.3. Erne Karst

The caves and karst landforms of the Erne Karst were described in Section 4.4. Eighteen risings have been identified in the Erne Karst; each located at or near the northern edge of the Marlbank escarpment. The largest of these risings are Tullyhona, Cascades, Marble Arch and Hanging Rock. In the case of Tullyhona, Cascades and Marble Arch the conduit behind each rising is explorable as cave passage. However, the conduit behind Hanging Rock Rising is blocked by muds that have remained within the system since glacial times. The only explorable passage in the Hanging Rock system is that of Hammer Pot where passage is water filled and only explorable by cave divers.

Throughout this thesis, the Marble Arch Cave and the Prod's-Cascades Cave have been the focus of study in the Erne Karst. The ease of access into these systems and the extensive passages that they include allows a more detailed study of these caves than others on Cuilcagh Mountain. The geological information exposed in the cave walls of both Marble Arch and Prod's-Cascades caves provides a detailed study of the lithostratigraphy of the Knockmore Member, in which the majority of known caves exist. Although most caves has developed within the Knockmore Member, caves are also found in the Cloghan Hill Member and the Dartry 'Type' Limestone. It is also important to note that the Entrance Series of Cascades Resurgence Cave is uniquely developed in the Glencar Limestone Formation.

In the eastern and central parts of the Marlbank all stream sinks, with the exception of the Smokey Mountain sink and the Owenbrean Upper Sinks, are located within the Knockmore Member. Smokey Mountain stream sink is located within a faulted block of the Dartry 'Type' Limestone that forms a displaced pod along the line of disturbance of the Brookfield Fault, whilst the Owenbrean Upper Sinks are located within the Meenymore Formation. Further west in the Burren Forest, several sinks have developed within the Cloghan Hill Member, which overlies the Knockmore Member.

The stream sinks of the Erne Karst can be subdivided into three groups, those that are located in the Meenymore Formation, those located at or near the margin between the Meenymore Formation and the Dartry Limestone Formation, and those that drain across the limestone for 1km before sinking. Importantly, the three largest stream sinks in the Cuilcagh Karst, namely the Owenbrean, Aghinrawn and Sruh Croppa, all fall into this latter grouping.

The setting of stream sinks and dolines in the Erne Karst has been strongly guided by fracturing and faulting. Those sinks in the Meenymore Formation and its contact with the Dartry Limestone Formation are all located upon fracturing associated with the Brookfield Fault; the best examples are Gortmaconnell Pot, Little Gortmaconnell Pot, Smokey Mountain Sink and the Whiskey Holes. Those stream sinks and dolines located within the outcrop of the Dartry Limestone Formation are also strongly guided by faulting or fracturing. The best examples are Pollasumera (Plate 16), the terminal sink of the Owenbrean River, which has developed along a major north-south fracture set, and Monastir the terminal sink, of the Aghinrawn River, which has developed along a major east-west fracture set. Cave passage in the Erne Karst has also been guided by fractures and faulting, especially the upstream sections of cave, which typically form tall but narrow canyon-type passages. However, downstream sections of the cave are also guided by particular bedding horizons that give the passage a wider profile with a lower, flat roof.

There is no correlation between the stratigraphic levels at which the stream sinks have developed other than that they form within the upper vertical-type mud mound accumulations, of the Knockmore Member. However, the risings in the Eastern and Central Marlbank are clustered near the base of the Knockmore Member. Jones (1972) attributed the levels of the risings to the fact that the underlying Glencar Limestone Formation controls the base level of flow within the karst aquifer. However, of the risings in the Erne Karst only Tullyhona Rising and the Cladagh West 2 Rising are located at the contact between these two formations. Of the other risings, Cascades lies c.15m below the contact, whilst Marble Arch Rising, Cladagh West 1 and Hanging Rock lie c.4m above the contact.

Most risings within the Eastern and Central Marlbank have formed along one or more intramound horizon(s) that occur at the top of and within the horizontal-type mud mounds, at the lower part of the Knockmore Member. Whilst several thin (<4cm) intramounds are observed within the horizontal mud mound sequence, one relatively thick (15-30cm) and laterally extensive intramound horizon exits at the top of the horizontal mud mound complex, which in this thesis is referred to as the Knockmore intramound. The depositional environment of this thick horizon was discussed in

Section 3.4, where it was described as being the product of a basin-wide cessation or reduction of carbonate deposition. As such, this intramound has a basin-wide extent. The intramound is a shaley carbonate mudstone that is enriched with non-carbonate sediment, which under normal carbonate deposition forms a minor component of mud mound sediment. Although the best exposure of this intramound horizon is within Skreen Hill I of Marble Arch Cave and the Boulder Series to Mudbank Chamber of Cascades Resurgence Cave, a shaley carbonate mudstone is also exposed within the entrance series of Tullyhona Rising Cave. In Cascades Resurgence Cave and Marble Arch Cave the intramound horizon occurs at the top of the horizontal mounds, above which the vertical mounds dominate. At Tullyhona Rising, the horizontal mounds have a thickness of c.3m and as such the intramound occurs very close to the base of the Knockmore Member. As in Marble Arch and Cascades the intramound is overlain by a vertical mound accumulation, suggesting it is the same horizon. Further east and southeast from Tullyhona there is a lithological change to the shallow water/lagoonal carbonates of the Gortalughany Member that dominate the East Cuilcagh Escarpment. As both horizontal-type mounds and intramounds are indicators of deeper water environments in the basin then Tullyhona Rising must lie close to the easterly extent of their deposition; as such, the intramound horizon is unlikely to extend further east.

5.3.1. Case study: Prod's-Cascades Cave and Marble Arch Cave

The longest cave system on Cuilcagh Mountain is Marble Arch Cave (6.5km) and the Prod's-Cascades Cave System (4.5km) is the second longest. At the head of the Cladagh Glen, in the eastern side of the valley, lies the Marble Arch Rising, which is surrounded by cliffs that are up to 15m in height. Water emerges from the rising into a karst window and flows beneath the Marble Arch, a remnant southeast-northwest trending cave passage (Plate 17), before turning and flowing due northwards down the Cladagh Glen. Approximately 400m downstream from the Marble Arch lies Cascades Rising from which the waters from the Prod's-Cascades Cave resurge.

5.3.1.1. Inception

The intramounds of the Knockmore Member, and specifically the Knockmore intramound, have had a strong guidance upon the inception and development of conduit but they are only located within the lower 20m of the Dartry Limestone Formation. Due to the southwestward dip of the formation, and the northward drainage of the cave systems, from sink to rising the conduit systems drain through the full thickness of the formation and only intersect the intramounds near the formation base. Above the stratigraphic elevation of the Knockmore intramound, within the vertical-type mud mounds, the lithology is largely homogenous and all conduit that has developed is guided solely by fracturing. Within the entire length of main streamway passage in both the Prod's-Cascades Cave and Marble Arch Cave systems there are no waterfalls or sudden drops; all passage has developed at a steady low gradient. Shafts such as Prod's Pot link the surface to the systems but the main streamways themselves continue at a gradient of approximately 30m/km throughout most of the system. The only exceptions to this gradient are in Cascades Inlet of Prod's Pot where the gradient is c.70m/km and the Entrance Series of Cascades where the gradient is c.60m/km.

The conduit of Skreen Hill I is located upon the intramound horizon but it is typically located at the intersection of the intramound horizon and fracturing. Although the horizon is followed for almost the entire length of the passage, several fracture orientations are used. As a result, the Skreen Hill I passage is not linear but is meandering and sinuous. The permeability of the horizon is sufficient for it to form a preferential flow path but this permeability is further enhanced where fractures crosscut the horizon. Hence, the intersection of the intramound and fracturing provides the most favourable conditions for the development of conduit. Considering the abundance of fractures that cross-cut the intramound horizon only those fractures that trend along the hydraulic gradient of the aquifer will be selected for the inception of conduit. It is the natural selection of these flow paths that ultimately form conduit which subsequently develops as cave passage.

The Knockmore intramound is first observed in Marble Arch Cave downstream from Sump I, which lies in between Skreen Hill II and Skreen Hill I (Figure 63). At this location the morphology of the cave passage changes from those that have a high vertical profile and taper in towards the top (often exceeding 8m in height) such as Skreen Hill III, Skreen Hill II and Legnabrocky Way, to the wide flat roofed passages of Skreen Hill I. Downstream from Sump I the passage meanders along the intramound horizon for c.700m. At the end of Skreen Hill I (called Skreen Hill Corner) a small fault offsets the intramound and the Owenbrean River enters a narrow impenetrable sump developed along the fault zone. The river descends to a lower flow path, re-emerging of the other side of the fault zone at the Junction (Figure 62), where it joins with the waters of the Aghinrawn and Sruh Croppa rivers. A static sump in New Chamber marks an earlier flow path of the Owenbrean River. However, this sump has been descended for 7.5m to conduit that connects through to the other side of the sump in Pool Chamber. A high level passage, the Flyover (Figure 62) also connects across the fault. Whilst the Flyover has developed along the deformed line of the intramound horizon the lower flow paths have developed along a horizon c.4m above the base of the Dartry Limestone Formation. This stratigraphic level corresponds to a minor intramound horizon along which a remnant phreatic tube is located at the Marble Arch.

In general terms the Knockmore intramound dips gently southwestwards, although as the horizon was deposited across a gently undulating mud mound topography it has many slight troughs and peaks. The passage has a general westward trend and as such it is oriented slightly down dip. Whilst the intramound is always present at roof level the stream descends at a slightly greater slope than the dip of the intramound. As such, whilst the intramound is at stream level at the upstream end of Skreen Hill I by the Grand Galley (Figure 62) the passage roof, and the intramound, lies c.8m above the streamway. Vadose entrenchment has been most significant in the downstream parts of the cave and is most likely due to development at the modern Marble Arch Rising.

The remnant half tube remains in the roof all the way among Skreen Hill I and identifies the intramound as the inception horizon from which the cave has developed

(Plate 20). The full circumference of the phreatic conduit is also observed in a number of locations throughout the system, specifically near the Paddy Fields of Skreen Hill I, in New Chamber (Figure 63) and in the natural 'Marble Arch', which lies downstream of the Marble Arch Rising. The phreatic tube at the Paddy Fields is marginally elliptical in shape, being 2m in horizontal diameter and 1.6m in vertical diameter, the tube is centred upon the intramound horizon. The phreatic tube in New chamber is also centred upon the intramound horizon but is circular in shape with a diameter of 1m. At the Marble Arch the phreatic tube has the same size as that observed in New Chamber. However, this phreatic tube is located upon a minor intramound horizon located c.4m above the base of the Dartry Limestone Formation.

Upstream from the end of Skreen Hill I the roof steadily lowers until it intersects the stream surface at Sump I. This occurs because the passage orientation changes from east-west to north-south, and lowers southwards along the dip of the intramound. On the upstream side of the sump in Skreen Hill II the passage lies stratigraphically higher than the intramound along a prominent fracture zone. Upstream of Skreen Hill II lies Sump II, the depth of which corresponds to the stratigraphic elevation of the Knockmore intramound. Similarly at the down stream end of the Grand Gallery the roof lowers down towards the surface of combined Aghinrawn and Sruh Croppa rivers. The dip of the roof corresponds to the Knockmore intramound, which then descends below Cradle Hole. The unexplored conduit that exist at depth beneath Cradle Hole, where the Aghinrawn and Sruh Croppa converge, are most likely via conduit developed along the Knockmore intramound.

In Cascades Cave the intramound horizon is best exposed immediately upstream of the Boulder Series, where it forms a 0.20m thick unit. This section of cave passage lies within 200m of the exposure of the intramound horizon in Marble Arch Cave and as it lies at a comparable stratigraphic setting it is very likely to be a continuation of the Knockmore intramound. The horizon can be followed upstream to the canals (Figure 57) where the roof descends close to the surface of the streamway. Downstream the horizon can be followed part of the way through the Boulder Series until the stream cuts through the horizon. Several smaller intramound horizons are observed within the horizontal mounds until the stream descends along fractures and into the Glencar Limestone Formation.

The tributaries of the Marble Arch Cave system, including Prod's-Cascades Cave, are guided along particular north and northwestward trending fracture sets that form long linear sections of cave passage. When the passages intersect the intramound horizon their general passage shape changes from straight, narrow and high to meandering, lower and wider passages with a flat roof. The only passage to cut through the intramound is in Cascades Cave where the passage dissects the intramound horizon and continues along the same fracture set through the Glencar Limestone Formation and to the Cladagh Glen. All other passages, including the abandoned tributary between Cascades and Marble Arch caves are directed along the intramound. As the fracture guided conduit are all focused towards the intramound then the intramound guided conduit must from a more efficient flow path than those developed solely along fractures. It is therefore hypothesised that the intramound horizon represents an early phase flow path and that other flow paths have developed towards it.

When examining the intramound horizon, specifically in the area of the Paddy fields and Moses Walk, the horizon corresponds to a significant deposition of speleothem, particularly helictites, stalactites and curtains. The speleothem deposits derive from seepages that discharge from the intramound horizon (Plates 21 and 22). However, the speleothem only occurs in abundance on the up dip side of the passage and not on the down dip side (Plate 23). Hence, the permeability of the intramound horizon is higher than that of the surrounding micritic mud mound rocks and it is intercepting water migrating from the surface and diverting it down dip to where it emerges in the side of the passage wall. This intramound seepage is confined to the horizon itself and the deposition of speleothem from this seepage indicates that the water is enriched with respect to calcium and carbonate ions.

The mud mound micrites are chemical sediments and as such have a low permeability. The shaley intramound horizon is also essentially a micrite but it has a higher component of terrigenous particles and as such is partially detrital in origin. Although permeability testing was not undertaken, mud mound limestones typically have a primary permeability, c. 1 x 10^{-9} to 1 x 10^{-11} m/sec. The detrital component of the intramound suggests that it has a greater permeability than the pure micrites and it is apparent from both outcrop and hand specimen that the intramound has a greater horizontal permeability. Additionally sulphide minerals are rare in mud mound accumulations in general but they are relatively common in the Knockmore I intramound. This abundance of sulphide minerals within the horizon speculates a potential for the generation of strong acid by their oxidation. Lowe and Gunn (1996) discuss the potential of strong acid dissolution as an important phase in the inception of conduit. Strong acid dissolution will enhance the permeability of the rockmass above and/or below the source rock depending upon the hydraulic gradient. As such, although the Skreen Hill I intramound horizon is considered an inception horizon due to its relatively higher permeability compared to the mud mound rocks, which overlie and underlie it, the permeability of the intramound may also have enhanced the permeability of the surrounding micrites by the production of strong acid.

The Knockmore intramound and other intramounds within the sequence are features that theoretically may have formed preferential flow paths since the lithification of the sequence during Dinantian times. However, the hydrogeological conditions during these early times (Chapter 4) are unlikely to have substantially enlarged the pathways. However, the stable circulation of meteoric water that prevailed during Mesozoic times promoted some solutional development, although as the formation remained confined flows would only have been slight. The stable geological conditions that prevailed during Mesozoic times ceased at the start of the Tertiary when the Cuilcagh Dyke intruded into the Dartry Limestone Formation, trapping the groundwater in the area that is now Marble Arch between the dyke and the MacNean Anticline. Subsequent to the intrusion of the dyke groundwater flows within this part of the aquifer would have been reduced as flow paths where isolated from the remainder of the synclinal structure.

The next significant phase of conduit development occurred during Pliocene times when the Dartry Limestone Formation was exposed to the surface by uplift and erosion. As the modern valleys incised into the sequence and the modern topography began to form groundwaters where drained from the aquifer. Those groundwaters trapped between the Cuilcagh Dyke and the MacNean Anticline began to drain and the early phase of conduit inception along the Knockmore intramound became reactivated by meteoric waters circulating within the aquifer. As the modern topography formed inception occurred along fracture zones and flow paths propagated through the upper parts of the formation towards the intramound horizons which provided lateral flow paths to discharge points.

5.3.1.2. Development

Cascades Rising is unique on Cuilcagh Mountain, as it the only active rising in the whole region that has developed within the Glencar Limestone Formation (Plate 15). Associated with the rising, also in the Glencar Limestone Formation, are two higher relict risings as well as a number of smaller seepages and c.180m of cave passage, the Entrance Series of the Prod's-Cascades Cave, which lies behind the second abandoned rising. However, the Entrance Series passage represents <8% of the Prod's-Cascades Cave system with the remainder being developed within the Dartry Limestone Formation. It is suggested by the author that conduit only developed in the Glencar Limestone Formation subsequent to events that are specific to its location. These events are related to down-cutting of and deepening in the Cladagh Glen as evinced from the abandonment of the two upper risings. Whilst Prod's-Cascades Cave is a mature and extensive system, the risings, both active and relict, and the passages that form the Entrance Series are more recent in their development. Hence, prior to the development of the Cascades Entrance Series flow of the Prod's-Cascades stream must have been directed elsewhere.

The passages of Marble Arch Cave and Cascades Rising Cave come to within 200m of each other at their closest point (Figure 55). This corresponds to Sand Cavern in Marble Arch Cave and a relict side passage that runs c.35m southwards from Mudbank Chamber in Cascades Resurgence Cave. Sand Cavern is a relict tributary to Skreen Hill II and part of the Sump I Bypass Series, which is a large abandoned passage with extensive roof collapse. A static sump, the Green Pool, is located at the most northern extent of the passage, which is also the closest point to Cascades

Resurgence Cave. The remaining section of the bypass series, namely Crab Passage and Organ Chamber, is markedly different in profile and size to Sand Cavern. Whilst the Sand Cavern is linear, trending north-south, and often exceeding 4m in width by 5m in height, Crab Passage is notably sinuous in length and keyhole in section but is less than 1.2m in height and 0.6m in width. Crab Passage enters at roof level into Sands Chamber above the Green Pool, and although now relict, the trench was formed by a small stream flowing to Sands Passage from the near surface Organ Chamber. However, the Crab Passage is only a small tributary to the larger passage of Sand Cavern and as such is a recent modification to the system. Although Sand Cavern terminates at the Green Pool, investigation by divers (Tim Fogg, *pers. comm.,* 1997) under very poor visibility due to thick accumulations of mud reports the sump to be continuing along a trend towards Cascades Rising Cave.

In Cascades Rising Cave, the Boulder Series marks the penultimate 220m of cave passage within the Dartry Limestone Formation before the Cascades Stream traverses into the Glencar Limestone Formation. The Cascades Main Stream Passage flows through the Mudbank Chamber but is rapidly lost at the start of the extensive roof collapse that marks the start of the Boulder Series. The stream is only encountered again at the end of the Boulder Series, some 50m before the start of the Entrance Series. The extensive debris of large (greater than 4m and up to 14m) angular limestone blocks along the c.170m length of the Boulder Series is entirely due to roof collapse. Passage in the Boulder Series is formed along two distinct orientations: the first is orientated north-south, and the second orientated northwest-southeast. The north-south orientated passage is aligned to the passages of the Sand Chamber of Marble Arch Cave, whereas the line of the northwest-southeast boulder collapse trends towards the Cascades Rising in the Cladagh Glen. It is hypothesised by the author that the stream gradually charged its flow path from away from Marble Arch and towards Cascades Rising and in doing so it undercut the support of the roof, causing it to collapse and thereby forming the Boulder Series. Downstream, the passage lowers to a chamber, which is the final part of the system developed in the Dartry Limestone Formation. From this chamber, the stream flows down an enlarged fracture to the passage of the Entrance Series and into the Glencar Limestone Formation. A number of relict narrow passages also connect to the Entrance Series, all via fractures that crosscut the contact between the Dartry Limestone Formation and Glencar Limestone Formation. Passage that has developed within the Glencar Limestone Formation is generally less than 1.5m in height, and although several small chambers are encountered these are all located near the top of the formation and associated with small-scale mud mound development. The passages of the Entrance Series form a maze-like system rather than the branching passage observed in the Prod's Pot and Cascades Main Stream Passage. Flow in the Entrance Series is dispersed along several small passages all of which are guided by fractures. No single conduit has developed to carry the flow through the Glencar Limestone Formation as the thinly bedded and shaley nature of the rock promotes collapse.

The lack of a relict rising to the Prod's-Cascades system, and its nearness to Marble Arch, indicates that before emerging at Cascades in the Cladagh Glen the passage was part of the Marble Arch system. As such, the Prod's-Cascades Cave System is an ancient tributary of the Marble Arch Cave System that has been separated by the incision of the Cladagh Glen. Capture of the Cascades tributary from Marble Arch Cave has extensively modified the drainage system, enlarging flow paths towards the Cladagh Glen via the Glencar Limestone Formation and inducing the collapse of the Boulder Series. As the drainage from Prod's-Cascades had previously been part of the Marble Arch System then prior to capture Marble Arch Rising had a substantially greater discharge.

The morphology of the glen suggests that the greatest down-cutting occurred down-stream of Marble Arch Rising itself. The cliffs (up to 15m high) about the Marble Arch Rising form a step above which a dry 'hanging' valley continues towards Cradle Hole. It is suggested that incision of the valley 'up-stream' of Marble Arch, where the dry valley now exists, intersected the conduit of the Marble Arch Cave System. This perpendicular intersection led to the development of a rising, which in turn rapidly increased the discharge draining down what is now the Cladagh Glen. This increased flow substantially increased incision and ultimately also developed Cascades Rising, as a capture from the Marble Arch system itself.

Although the active Cascades Rising emerges into the Cladagh c.5m above the valley floor, the highest relict rising lies c.10m higher. As such, the valley has continued to be significantly deepened subsequent to the Prods-Cascades tributary of the Marble Arch System being diverted to Cascades Rising. The steeper gradient of the Entrance Series to Cascades Rising Cave, which is twice that of either Marble Arch or the remainder of the Prod's-Cascades Main streamway is the product of incision by the Cladagh Glen through the Glencar Limestone Formation. It is unusual to encounter conduit in the Glencar Limestone Formation but the example of Cascades Rising Cave indicates that flow paths do occur. Although preferential flow paths exist within the Glencar it is the potential for preferential flow paths to evolve into conduits that is particularly low. Conduit development in the Glencar Limestone Formation would appear to be particularly site specific and essentially due to relatively recent geomorphological processes. Ultimately, the incision of the glen has captured Prod's-Cascades Cave systems and as the connection was severed the conduit that had joined Prod's-Cascades to Marble Arch Cave became relict. However, as observed in both Marble Arch Cave and Prod's-Cascades Cave subsequent inundation by glacial melt filled these 'relict' passages with sediments, preventing exploration by cavers.

The 30-m wide dry valley at the head of the Cladagh Glen indicates that a significant surface flow drained across the Marlbank Escarpment, and down the route of the Cladagh Glen. This landform is likely to be a remnant of early surface drainage patterns from the upland that is now Cuilcagh Mountain. As the less-resistant cover of the Dartry Limestone Formation thinned these drainage routes will have become increasingly influenced by the position of the mud mound hills emerging from the landscape. During these times the proto-routes of the Owenbrean, Aghinrawn and Sruh Croppa rivers would have been initiated. In the modern landscape these three rivers all sink into the Marble Arch Cave system, with the Owenbrean also sinking into the Prod's-Cascades Cave System. The relatively large passage sizes in Marble Arch Cave can be attributed to these rivers. However, the rivers have continuously modified their routes as the surface karst of the Marlbank evolved. At an earlier stage of landscape development, all rivers traversed the escarpment without sinking and by tracing dry valley and known cave entrances, a number of relict routes and stream sinks have been identified.

The hanging dry valley above the Marble Arch can be traced southwards towards Cradle Hole and from there towards Monastir, suggesting that at one time the Aghinrawn and/or the Sruh Croppa Rivers discharged from the escarpment by way of the Cladagh Glen. Additionally the Fosstra, a dry valley above Hanging Rock also discharged surface water from the upland. The Owenbrean River may also have drained from the Marlbank by route of what is now the Cladagh Glen, either via the surface depression that lies above Skreen Hill III or via a route to Monastir and the Aghinrawn. Another potential route is via a shallow dry valley above the Prod's Pot streamway. As the limestone began to be uncovered these rivers began loose flow into the conduit systems developed within the karst aquifer. The Aghinrawn River is likely to have sank at Cradle Hole before sinking at its present location at Monastir. The Sruh Croppa River may also have sank into Cradle Hole, and then as the landscape evolved and the size of pathways increased it would have sank sequentially at John Thomas' Hole, Pollasillagh and Cat's Hole (into which it still sinks during high flow) before its present main sink at Zero Sink. The Owenbrean River has perhaps the most complex history as it previously sank into Legnabrocky Way, which is a now a largely relict tributary to the Marble Arch Cave System, fed by a misfit stream but blocked by glacial sediments that fill the cave passage to the roof. Prior to its present terminal sink at Pollasumera (Plate 16), the Owenbrean River also sank at McGovern's Boulder Cave, which is a likely feeder to Legnabrocky Way.

As mentioned, Legnabrocky Way and also many other parts of the Marble Arch System contain extensive glacial sediments. These deposits remain preserved within the system where the passages that were active became relict prior to glacial events, so that the fluvio-glacial sediments flowing into these passages during periods of melting still remain. The timing of Pleistocene glacial events are not as well documented in Ireland as in the rest of the British Isles. However, in this thesis speleothem dating has been undertaken that does improve the understanding of cave evolution during this period. Uranium series dating kindly undertaken by Stein Erik Lauritsen, University of Bergen, Norway, on six samples collected from parts of Marble Arch Cave. These samples included whole non-active stalagmites, displaced stalactites and broken flowstone some of which was embedded in partially consolidated fluvio-glacial gravels. Of the six samples collected dates were able to be determined on four of the samples, namely sample numbers MAC 1, 3, 4 and 6.Sample numbers MAC 2 and 5 did not contain uranium in a significant enough concentration to undertake the dating.

Photographs of the samples are presented in Plates 27-30 (Figures 75 and 76) with the results are presented in Table 13. Sample MAC1 was a displaced stalactite that was no longer active. It was located in Skreen Hill II on a mud bank c. 5m above the emergent sump from Skreen Hill II (Plate 27, Figure 75). The sample was lying on its side and partially covered I mud. The uranium series dates from the base of the sample indicate that it's growth began c.32.6ka. Sample MAC 3 (Plate 28) is a stalagmite located within 2m spatially and 1m vertically of MAC 1 but it was in situ and was active. The base of MAC 3 was covered with a fine sand, suggesting that in flood the river 4m below did flood the sediment bank MAC3 had precipitated on. Uranium series dates for MAC 3 indicate that this speleothem is only 12.3ka in age. Sample MAC 4 comprises of a collection of well-rounded fragments of broken flowstone located in partially consolidated gravel mid-way up Legnabrocky Way (Plate 29). Dates derived by uranium series analysis indicate ages of 240.8ka and 251.0ka for two of the cobbles. Sample MAC6 (Plate 30) is a large fragment of broken flowstone lying in the bed of Legnabrocky Way passage. Three samples from MAC6 (termed A, B and C) were analysed. Sample MAC6A gave a resultant dates of 210.2ka. However, MAC 6B and C both recorded dates of >350ka, which is the present limit on this type of dating methodology (Stein Erik Lauritsen, *pers. comm.*, 1999).

As the flowstone sample was taken from glacial till it is assumed that a glacial melting event was responsible for the destruction of the flowstone and cessation of its growth. Thus the date of >350ka corresponds only to a date before the glacial outwash entered the cave passage breaking apart the flowstone within it. Hence, Legnabrocky Way had already formed and been drained by this time. Considering the relatively low gradient of the Marble Arch System then most if not all of the vadose system had probably already developed by this time. As such, at the time when this flowstone was active the Owenbrean River is likely to already have been diverted from Legnabrocky

Way by being captured upstream at Pollasumera and routed via Pollnagollum of the Boats and Skreen Hill III to Skreen Hill II where it is joined by Legnabrocky Way.

In the modern setting the Owenbrean River also looses water through its bed at the Upper Sinks and Lower Sinks. Thus the next phase of capture has already been initiated and all flow will eventually be captured upstream and the Pollasumera-Skreen Hill III-Skreen Hill II-Skreen Hill II tributary will become relict, as Legnabrocky Way has. When this occurs a significant component of the modern discharge at Marble Arch Rising will be lost.

Whilst the Marble Arch Cave System has a large catchment, recharge is largely via the three main rivers. By comparison the catchment of Prod's-Cascades is also large but is fed by many smaller streams. One of the consequences of this is that whilst Marble Arch Rising is prone to rapid water level rises (i.e. a flashy discharge), Cascades Rising is not, although the more constricted passages of the Entrance Series often flood to the roof. The size of the stream passage in the Prod's-Cascades Cave System would be considered large in southwest Fermanagh but not as large as the Marble Arch Cave System. This reflects the modern setting where no large rivers sink entirely into the Prod's-Cascades Cave system.

As the Prod's-Cascades Cave system itself was a previous tributary to Marble Arch Cave then it, like Legnabrocky Way and the Pollasumera tributary, was drained >350ka. The draining of Marble Arch Cave and Prod's-Cascades Cave System was initiated as incision in the MacNean Valley intersected conduit systems present within the karst aquifer. Considering that passages in the Marble Arch Cave System had already been drained before 350ka ago then valley incision must significantly pre-date this. Evidence from palaeokarst in Ireland suggests that substantial surface karst had developed during the Pliocene following substantial stripping of its non-limestone cover during the Miocene. Erosion during these periods initiated the intersection of the karst aquifer and modern surface drainage patterns become imprinted on the topography. It is suggested by the author that during these times a major surface drainage route from Cuilcagh Mountain was by a river that discharged from the upland via what is now the Cladagh Glen. This route would have formed a negative landscape feature and been one of the first points where the karst aquifer was intersected. Due to the southwestward dip of the limestone, and the slope of the evolving topography, the margins of the escarpment were first exposed, with the modern stream sinks of the Owenbrean, Aghinrawn and Sruh Croppa remaining buried. Incision induced drawdown within the aquifer. However, it was only when the near full thickness of the Dartry Limestone Formation had been incised through that the conduit associated with the intramound horizons were intercepted. This first occurred at Tullyhona Rising (193m AOD), where the intramound is at its highest elevation. Subsequently the intramound was exposed further west at Marble Arch Rising (128m AOD) and then Cascades Rising (119m AOD). At Hanging Rock the elevation of the intramound is relatively low (83m AOD) and close to the elevation of Lough MacNean (c.55m AOD) and as such it is more likely that the conduit at Hanging Rock was intersected more recently.

The hanging dry valley above the Marble Arch Rising represents the remains of this river as it drained from the upland. Considering that a substantial thickness of ice covered Cuilcagh Mountain during the Pleistocene then it is likely that the advance and retreat of ice sheets across the region caused significant erosion on the landscape, including the hanging dry valley above Marble Arch Rising. Glaciation at this latitude of western Europe occurred during the Pleistocene. Hence, the intersection of the Marble Arch conduit occurred between 1.8Ma and 350ka years ago. Considering that the >350ka years ago date refers to the deposition of flowstone then in order to accommodate the sequence of events from phreatic to vadose then the intersection of conduit most likely occurred closer to c.1Ma than 350ka ago. However, the age for the cessation of speleothem growth is only a minimum limit on its age, as such intersection and draining may have occurred much earlier.

As discussed, the development of Cascades Rising is due to incision of the Cladagh Glen which captured the Prod's-Cascades Cave tributary to Marble Arch Cave. An indication of the size of passage that existed in the system at the time of capture is provided by the large vadose passage in Sands Chamber, which was once the streamway connecting Cascades Mudbank Chamber Cascades Cave to Skreen Hill II of Marble Arch Cave and also by the extensive collapse that was induced in the

Boulder Series of Cascades Rising Cave as the capture of the streamway first caused it to bifurcate and then entirely flow towards the Cladagh Glen. Additionally, a rock step (Plate 25) of 0.75m between Sands Chamber and Skreen Hill II shows the extent of down-cutting that has occurred in the Marble Arch System subsequent to the capture of the Prod's-Cascades tributary. Fundamentally, the size of the relict passage and the down-cutting subsequent to the capture shows that prior to separation the Marble Arch Cave System was not dissimilar in form to its modern passage.

Prior to the development of the Marble Arch Rising at the head of the Cladagh Glen, water from the system must have drained elsewhere. At this level near the base of the Dartry Limestone Formation the inception and development of conduit is associated with intramound horizons that are located within the horizontal-type mud mounds. In Marble Arch Cave, and in the Marble Arch itself, remnants of the original phreatic conduits are located upon intramound inception horizons for approximately 1km upstream of the rising. Prior to the capture of the system by the Cladagh it is suggested by the author that conduit 'downstream' of the Marble Arch Rising would also have developed from conduit inception upon this intramound horizon. Continuation of the conduit northwestward from the Marble Arch Rising, as indicated by the remnant phreatic tube in the Marble Arch, trends towards Hanging Rock Rising, which has a similar stratigraphic setting to Marble Arch Rising, near the base of the Knockmore Member. Although no cave passage is known between Marble Arch and Hanging Rock it is suggested by the author that the Marble Arch Cave formed as part of a far larger branching conduit system with flow focused towards conduit that now forms Hanging Rock Rising. Whilst, the modern catchment of Hanging Rock Rising does not include Marble Arch Cave or Prod's Cascades Cave it still has a particularly large limestone catchment, which extends some 4km from the rising. Based upon the low elevation of Hanging Rock Rising, compared to the valley floor, it is hypothesised by the author that the Hanging Rock conduit was not intersected until a later stage in landscape development after Marble Arch Rising

Although the Prod's-Cascades system, the Marble Arch system, and Hanging Rock Rising, are not connected under the present hydrological regime, the evidence presented indicates they formed part of a significantly larger conduit system that has subsequently been segmented by incision of the Cladagh Glen. Cascades and Marble Arch are now separated hydraulically, but also physically due to glacial muds that fill the passage that once connected them. Similarly, the incision that separated Hanging Rock from the upstream passage of Marble Arch occurred after the system was filled by glacial debris. Following the incision of the glen the sediment fill was largely flushed out from the conduit as surface drainage was activated following glaciation. Those sections of cave that became isolated or cut-off from their feeders have substantial remnants of the glacial fill. Particularly good examples of these sediment fills are found in Legnabrocky Way and Sands Passage in Marble Arch Cave, Mudbank Chamber in Cascades Cave and Hanging Rock East Rising. In these cases it is possible to piece together parts of the sedimentary sequence of the cave deposits. In the case of Marble Arch Cave there are numerous cases of 'false floors', which are speleothem (flowstone) that was deposited over a sediment bank that has subsequently become washed away (Plate 25). However, in a number of cases, especially where the sediment was coarse and became cemented into the flowstone, then part of the sediment bank is preserved. Two excellent examples of this are found in Marble Arch Cave.

Example 1 (Plate 26) is located in Legnabrocky Way at the junction with Skreen Hill II and the Owenbrean River. In this example the sediment bank that the flowstone precipitated upon is an accumulation of well-rounded sandstone cobbles. The bank was approximately 1.8m in height, all of which has been removed with the exception of the cobbles cemented into the flowstone. This short sequence indicates that the cobbles were laid down first during a period of very turbulent erosive flow. Subsequently during a period of low flow speleothem was deposited. However, the cave environment has subsequently become erosional again and now the cobble bank, and the speleothem is being slowly removed. It may be the case that the cave system became blocked by fluvio-glacial debris allowing the flowstone to deposit in the time that it took modern streams to r-invade the cave system and remove the fill.

Example 2 (Plates 34 and 35) is located 5m upstream from the Moses Walk in Skreen Hill I. This flowstone is suspended c.1.8m above the stream bed. Unlike example 1 it does not have cobbles cemented to its underside suggesting that the sediment bank had finer grained debris. Plate 35 show a small remnant of the consolidated gravel bank that the flowstone once developed over. The smaller sediment size and location right next to the Owenbrean River suggest this sediment bank has been remobilised relatively easy.

Other examples in Marble Arch Cave indicate *this shift from depositional to the* modern erosional environment. Rimstone pools at the 'Paddy Fields' are attributed to low energy environment where calcite precipitates to form dams (Plate 36). Close inspection of the site shows that well-rounded sandstone cobbles are embedded within the calcite rims. The rimstone pool was deposited during a period of low energy. However, the environment became more erosional and cobbles were moved onto the dams during events. Following these events the dams were deposited again cementing the cobbles into the dams. In the modern environment very little deposition is occurring and the dams are steadily being eroded away with each flood event. The degradation of the deposition has also been increased by a reduction in the flow of water onto the dams, thereby reducing growth rate. The switching of flow has also led to the degradation of a rimstone pool at the Castle (Plate 33). In summary a sequence stratigraphy is provided in Figure 77 to illustrate the chronology of sediment deposits in the cave system.

5.4. Shannon Karst

The caves and karst landforms of the Shannon Karst were described in Chapter 4.5. The only known discharge from the Shannon Karst is Shannon Pot Rising and all known stream sinks and cave passage in the Shannon Karst have been proven by water tracing experiments to drain to it. The largest known cave in the Shannon Karst is Shannon Cave (2.6km), which forms part of a dendritic system that includes Polltullyard although the two caves are separated by a boulder choke. Shannon Cave and Polltullyard form one of several tributaries that makes up this dendritic system. Water tracing experiments have shown that another tributary to Shannon Pot Rising drains the catchment in the area of Garvagh Lough, whilst another drains from the distal catchment of East Cuilcagh.

The geological setting of the karst landforms and caves is ascertained from rock outcrop observed both above and below ground. At the time of this study the only significant length of cave explorable in the Shannon Karst is Polltullyard, as Shannon Cave has become inaccessible since the collapse of the only known entrance in the early 1990's. As such, the geological setting of caves and conduit is based upon observations from Polltullyard, descriptions of Shannon Cave by the original cave explorers and by interpretation of the surface geology. The MacNean No. 1 borehole at Blacklion in the western part of the Cuilcagh uplands provides a detailed stratigraphy of the Dartry Limestone Formation, with only the uppermost part of the sequence missing.

As discussed, Cuilcagh Mountain lies upon the northern limb of the Lough Allen Syncline near the axis of the MacNean Anticline, which forms the margin of this regional structure (Figure 14). Within the northern limb of the Lough Allen Syncline are smaller structures, which include the Owenmore Anticline and the Cuilcagh Syncline. Both of these smaller structures measure c.7km in width and plunge northwestwards along their axis by approximately 1°. The Cuilcagh Syncline underlies Cuilcagh Mountain with the axis of the fold aligned along the line of the ridge from the summit to Tiltinbane. The dip on either flank of the Cuilcagh Syncline is similar but the northern limb extends much further than the southern. As such, the Dartry Limestone Formation only crops out on the northern slopes of the Cuilcagh ridge where it forms the Marlbank escarpment.

The Cuilcagh Syncline forms a northnorthwest-southsoutheast orientated trough at the northern edge of Lough Allen Syncline. However, the base of the Dartry Limestone Formation is only exposed in the east and north of the uplands as further to the south and east the formation remains buried. As such, the eastern and northern outcrop of the Dartry Limestone Formation mark the extent of the recharge to the karst aquifer. To the south recharge is reduced due to cover by non-limestones and any interstratal recharge that does occur will encompass the area only as far south as the ridge of the Owenmore Anticline which forms the catchment boundary. However, to the west the structure remains open and may extend as far as Manorhamilton and the Belhavel-

Castle Archdale Fault. The plunge of the Cuilcagh Syncline forms an inclined trough in the Dartry Limestone Formation that guides groundwater flow from the highest elevation in the east to the lowest in the west. This hydraulic gradient imposed by the geological structure of the region guides groundwater flow down dip from the northern and southern limbs of the syncline, as well as the eastern margin of the structure at East Cuilcagh, along the axial plunge of the structure. As the Dartry Limestone Formation remains buried at the western margin of the uplands, groundwater flow is likely to extend further west than Shannon Pot Rising.

5.4.1. Case study: Polltullyard (Shannon Cave)

Polltullyard and Shannon Cave are both developed in the upper part of the Knockmore Member of the Dartry Limestone Formation which is composed of vertical-type micrite mud mounds. Study of the lithology of the Knockmore Member in the Shannon Karst has revealed that the member is homogeneous in its composition. A 34m section from the top of the unit exposed at the head of the Polltullyard shaft did not identify any intramound horizons or anomalous lithologies. However, within the shaft numerous stylolites and en echelon calcite veins were observed. The stylolites are a product of the compaction and diagenesis of the limestone but the en echelon veining is a product of fracturing within the unit. This fracturing, which trends east-west, has guided the development of both passage and shaft. The survey of Shannon Cave (Figure 71) shows a similar profile to that of Polltullyard, passages tend to be linear and typically higher than they are wide, suggesting further guidance by fractures and /or fault planes.

In the area of Shannon Cave the Dartry Limestone Formation comprises of <15m of the Dartry 'Type' Limestone and approximately 180m of the Knockmore Member. Shannon Cave is located within the upper c.40m of the Knockmore Member. The lithology of the Knockmore Member is similar across Cuilcagh Mountain with the middle and upper parts being composed of vertical-type mud mounds and the lower part being composed of horizontal-type mud mounds. The best outcrop of the Knockmore is in the passage of the Marble Arch and Prod's-Cascades cave systems as they both traverse the near full thickness of the member, with only the very top of the sequence missing. The known caves of the Shannon Karst have developed within the vertical-type mud mounds of the Knockmore Member and tend to form linear passages that are guided by fracturing and faulting.

Further west of Shannon Cave, the Dartry Limestone Formation increases in thickness to c.340m thick, as measured in the MacNean No. 1 borehole near Blacklion. The thickening of the Dartry limestone Formation between Shannon Cave and Shannon Pot is largely by the inclusion of the Cloghan Hill Member into the sequence between the Dartry 'Type' Limestone and Knockmore Member. Surface outcrop of the Cloghan Hill Member is best observed between Cloghan Hill in County Fermanagh, its type locality, and the Burren Forest, in County Cavan. In this locality several cave and karst landforms have formed within this member including Holy Hour Pot, Super Star Pot and the Lost Valley doline. However, like the Knockmore Member the surface karst and caves developed within the Cloghan Hill Member have developed by guidance along fractures and faults. The similarities observed between passages developed in both members are expected, as the Cloghan Hill Member is also a mud mound limestone.

Shannon Pot Rising lies upon the axis of the Cuilcagh Syncline and is down gradient of all karst landforms and caves that form the Shannon Karst. Topographically the rising is set in the eastern side of the Shannon Valley at the western margins of the Cuilcagh Uplands, c.3km northwest from Tiltinbane. The Dartry Limestone Formation does not crop out in the Shannon Valley and remains buried beneath younger non-limestones. Shannon Pot is a large karstic rising, the resurgence itself being located within the Meenymore Formation, which also includes several other karst landform on Cuilcagh Mountain but is not normally considered as a karst aquifer. Further westwards, the Dartry Limestone Formation is increasingly buried beneath non-limestone cover. Based upon geological cross-sections shown in Figure 7, Shannon Pot Rising lies at the point in the Shannon Valley where the Dartry Limestone Formation is buried at its shallowest along the line of the synclinal axis.

The northern extent to the Shannon Karst is generally accepted to be the Cuilcagh Dyke, which forms a hydrological divide to conduit flow. However, a gap in the dyke at the Owenbrean River facilitates flow northwards from the distal part of the Shannon catchment to Formations Passage in the Prod's-Cascades system of the Erne Karst. Whilst this breach in the dyke is exploited by the Owenbrean Upper Sinks, a number of sinks in the East Cuilcagh Karst have also been proven to drain to Formations Passage in Prod's Pot. As the dyke also forms a divide to conduit flow on the East Cuilcagh Escarpment flow from these sinks is also likely to exploit this break. Drainage through the Cuilcagh Dyke to the Erne Karst demonstrates that flow from the distal East Cuilcagh catchment of the Shannon Karst has been partially captured by drainage to the Erne Karst. Additionally, as individual sinks in the East Cuilcagh Karst have been proven to drain to both Cascades Rising and Shannon Pot Rising flow must bifurcate into two flow paths at or near the break in the dyke. The extensive faulting in the Owenbrean Valley that has led to the development of the Owenbrean Upper Sinks and the flow path through the Cuilcagh Dyke is also likely to provide the flow path that has captured part of the flow draining from the distal part of the Shannon catchment.

The underground drainage of the Shannon Karst spans the length of the Cuilcagh Uplands from stream sinks in the East Cuilcagh escarpment to Shannon Pot Rising at the western margin of the upland area. In Section 4.5 the karst water emergent at Shannon Pot Rising is described as comprising of deep and shallow components, based upon chemical analysis by Webber (*pers. comm.*, 1998). During low flow the emergent waters from Shannon Pot Rising are entirely derived from the shallow system but during high flow the emergent waters comprise of discharge from both the shallow and the deep systems. The shallow system is characterised by relatively low concentrations of calcium, magnesium and bicarbonate ions in the emergent waters. The conduit associated with the shallow system allows for rapid flow through times from sink to rising, which is measured in periods of days by tracer tests. The shallow system has been shown to include all of the known cave systems and stream sinks in the Shannon Karst, including those draining from the East Cuilcagh Karst. In contrast, deep systems are characterised by relatively higher concentrations of calcium, magnesium and bicarbonate ions but also the presence of other less common ions such as sulphate and strontium. The greater concentration of such ions in the deep groundwaters infers that flow in these systems is slow moving. The shallow system can be explored and the geological setting of conduit studied but the deep systems are not explorable, and the geological setting of the deep path has been inferred from the lithology and geological structure of the Dartry Limestone Formation as well as chemical analysis undertaken by Webber (*pers comm.,* 1998).

5.4.2. Inception and development in the Shannon Karst

Shallow pathways have developed within the upper part of the Dartry Limestone Formation, where inception is guided by a network of fracture and fault planes but the deep paths have developed within the lower part of the sequence where conduit has been shown to be guided both by inception along particular bedding horizons and by fracture and fault planes.

The lower part of the Knockmore Member is composed of horizontal-type mud mounds accumulated within the Carboniferous Cuilcagh basin. The vertical-type mud mound accumulations overlie these horizontal accumulations, and mark a change in the depositional environment. The two types of mud mound accumulation are separated by a thin (<0.50m) intramound horizon, which represents a period where carbonate did not accumulate in the basin. As such, the carbonate-rich shale horizon that forms the intramound horizon was deposited across the basin. The intramound horizon is best observed in Marble Arch Cave where it has had a strong influence upon the guidance of the conduit from which the modern cave passage has evolved. In Section 6.2, it was concluded that the intramound horizon acts as a preferential pathway compared to the massive micritic mud mound accumulations. Due to extensive pressure dissolution parallel to bedding the horizon provides a far more efficient path for groundwater flow than the overlying and underlying mud mounds. In addition, the abundance of sulphide minerals within the horizon suggests that strong acid dissolution may have further enhanced the lateral permeability of the horizon, effectively forming a basin wide lithologically guided preferential flow path.

As such, this horizon is most likely to provide the flow path for the deep system as identified by the chemical analyses of from Shannon Pot Rising.

Interpretation of the geology at Shannon Pot Rising places the base of the Dartry Limestone Formation at c.200m below OD. Based on the location of the intramound horizon in the Marble Arch Cave System this places the horizon at c.180m below OD. Where fractures intersect the horizon permeability may be further enhanced. Natural selection will lead to the preferential enlargement of those flow paths with the most efficient transfer of flow. The Cuilcagh Syncline drives the hydraulic gradient of the groundwaters in the limestones of Shannon Karst from east to west. As such, the flow paths that guide flow down-dip and down the synclinal plunge will naturally be selected and enlarged as conduit. With all flow being focused towards the axis of the Cuilcagh Syncline, conduit developed along the axis will be increasingly enlarged 'downstream' as the groundwater volume increases. It is well recognised within synclinal systems that compressional forces are focused in the upper beds whilst tensional forces become focused on the lower beds. The Cuilcagh geology is a particularly good example of this as compression of the upper beds has made them more competent, particularly along the line of axis, and as such they have guided the landscape evolution and assisted in shaping Cuilcagh Ridge. However, at depth the lower beds of the sequence, including the Dartry Limestone Formation, will have increased tensional fracturing, potentially further enhancing the permeability of the rockmass along the synclinal axis and guiding the inception and development of conduit.

It has been shown that two conduit systems exist in the Shannon Karst, a shallow and a deep system. Both systems are guided by the Cuilcagh Syncline which focuses groundwater flow towards the axis of the syncline and down its plunge. Shannon Pot lies upon the synclinal axis and acts as resurgence for the shallow system during low flow and for both shallow and deep waters during high flow. The two conduit systems have similarities but their inception is different. The shallow system has developed as a conduit system that drains flow from several stream sinks to one rising. The paths that facilitate this flow appear to be strongly influenced by a network of fractures and faults that guide flow down dip and down plunge. The deep system has no known point recharge and hence only responds slowly to rainfall. Its chemical signature, that has been detected during high flow events in the shallow system is more likely a factor of the shallow flow reaching a greater depth in the aquifer and mixing with the deep flow rather than the deeper waters rising into the shallow system.

The location of the intramound near the base of the Dartry Limestone Formation provides a horizon of higher permeability and a preferential pathway to groundwater flow. This geological feature is particularly long lived and may have guided groundwater flow since Carboniferous times. The Cuilcagh Syncline formed subsequent to the folding of the strata at the end of the Carboniferous and as such, the hydraulic gradient imposed by the structure is also particularly long lived. The longevity of this hydraulic gradient has provided substantial time for the inception and development of flow paths.

5.5. Summary

Surface karstification was widespread in Ireland during the Pliocene following the evolution of the modern Irish landscape during Miocene times. However, even before Miocene times preferential flow paths had already developed within the Dartry Limestone Formation. During these early stages of conduit inception groundwater movement was part of a deep regional system where flow was guided by lithology and structure. These guiding constituents have been present within the rockmass since late-Carboniferous times when the formation was buried to its maximum depth. As such, when the modern surface evolved conduit systems were already well-developed in the karst aquifer. With the thinning of cover, recharge was able to form point inputs to the aquifer, which increased and enlarged but also modified the pre-existing conduit. As incision continued conduit became intersected and risings formed, leading to an even greater truncation and isolation of the conduit systems.

Chapter 6

A Conceptual Model for the Evolution of the Cuilcagh Karst Aquifer

6.1. Introduction

This chapter summarises the research undertaken as part of this thesis in the sense of Klimchouk *et al.* (2000), viz. 'The Evolution of Karst Aquifers' and advances a conceptual model for the confined and unconfined evolution of the Cuilcagh Karst Aquifer. This forms the basis for examining the development of surface karst and caves, which are discussed in the following chapter.

6.2 Confined Evolution

There has been a lack of certainty as to when the Dinantian limestones of Ireland changed from being confined to be unconfined. Palaeokarst evidence suggest that certain parts of the country were stripped of the strata that covered them as early as late Jurassic and early Cretaceous times, if not earlier. However, in the case in the northwestern uplands and the Dartry Limestone Formation of Cuilcagh Mountain evidence suggests that the aquifer remained confined until approximately the end of the Miocene. As such, this section on the confined evolution of the Dartry Limestone Formation encompasses Dinantian to late Miocene times. Evidence from around Ireland is presented to provide both a local and regional context.

6.2.1. Palaeozoic

The evolution of the limestone sequence as a karst aquifer began during the lithification of sediment to rock. The lime muds that form the Dartry Limestone Formation are chemical precipitates and as such these lithified rapidly relative to detrital sediments. However, the Dartry Limestone Formation is not homogeneous in its lithology (Chapter 3 and 4). The formation contains several different carbonate types, which has led to its sub-division into several members. In addition, all members have small-scale variations, either as interbeds or, in the case of the Knockmore and Cloghan Hill members, intramounds which provide further heterogeneity and complexity in terms of lithification, diagenesis and aquifer evolution.

The lateral lithological variability of the limestone sequence is largely due to tectonic activity in the Lough Allen Basin, which formed as a half graben-type sub-basin within the Northwest Basin (Chapter 3 and 4). Subsidence was greatest at the western margin of the Lough Allen Basin, where the Castle Archdale-Belhavel Fault System was active. As such, the basin deepened westwards building up a thick accumulation of mud mound limestones beneath the storm-base. In contrast, shallow water and lagoonal conditions prevailed in the east resulting in the deposition of a sequence of bedded limestones. Of several interbeds and intramound horizons within the formation, an intramound horizon near the base of the Knockmore Member is particularly extensive (Chapter 4). This intramound, termed the Knockmore intramound in this thesis, was deposited at depth below the storm-base during a period when carbonate deposition had been reduced. As such, it had an increased component of silts and sands, which were derived from a landmass that lay to the north and east. Other interbeds and intramounds where deposited within the sequence but these were less extensive than the Knockmore intramound and represent localised, not basin wide, events.

The increased terrigenous component of the interbeds and intramounds caused their lithification to occur at a slower rate than the cementation of the lime muds that formed the bulk of the sequence. During early burial the soft sediment interbeds and intramounds became increasingly deformed between the mud mounds, which as chemical sediments had lithified soon after burial. As a result of this deformation, the thicknesses of the interbeds and intramounds were reduced. A significant proportion of carbonate may have been mobilised and lost during burial, which further increased the non-carbonate component of the residual horizon. Whilst the majority of the interbeds and intramounds within the Dartry Limestone Formation remain carbonates they are distinctly shaley or slightly sandy in their composition, and have abundant laminations or pressure dissolution seams that are parallel to bedding. The increased terrigenous component and laminar form of these horizons is of importance in terms of the aquifer properties as they form lateral zones of higher permeability within a rock mass dominated by low-permeability massive micrite. This is particularly the case for the Knockmore intramound due to its basin-wide extent. In contrast, intramounds within the Cloghan Hill Member tend to be more discontinuous being isolated around the patch mounds that form the member. Those interbeds within the limestones of the Gortalughany Member extend over hundreds of metres but are isolated to the member and only located in the very east of the basin.

As the western part of the basin was subsiding along the Castle Archdale-Belhavel Fault System some uplift occurred in the east, most likely a consequence of rotational subsidence along the fault. These minor episodes of uplift caused the shallow-water lagoonal limestones to be exposed to the atmosphere. This is evinced by small-scale eogenetic palaeokarst in the Gortalughany Member (Kelly, 1989b). Although the Dartry Limestone Formation may have been exposed more than once during Dinantian times this was restricted to the eastern extent of the basin and did not occur in the deeper water limestones.

Deltaic advancement from the northern landmass gradually filled the basin during the Dinantian and the limestone sequence became increasingly buried beneath non-limestones, so that they had reached their maximum burial depth, estimated to be upwards of 3km, by the latest Carboniferous (Green *et al.*, 1998 and 2000). As the delta advanced the setting of the basin changed from being marine to being continental margin and as this transition occurred meteoric waters began to recharge the sequence. At the advancing interface meteoric waters formed a mixing zone with formation waters until all formation waters had been expelled. It is widely accepted that the aggressiveness of meteoric water is enhanced at the mixing zone between meteoric water and formation water (Mylorie and Carew, 2000). Hence, it is likely that during the late Dinantian, an interface of enhanced dissolution would have formed, Even at this early stage groundwater would have migrated through certain parts of the sequence more rapidly than others, particularly where heterogeneities occurred, such as the relative higher permeability of the Knockmore intramound. Fracturing and faulting may have been present at this early stage of aquifer evolution, caused by tectonism that was active throughout deposition. As the sequence continued to be buried a second transition occurred as the burial depth exceeded the depth to which meteoric waters where able to circulate. At these depths deep basinal brines would have been introduced to the sequence.

A potential for strong acid dissolution by sulphuric acid exists within many limestone sequences as metal sulphides, typically iron sulphide, are frequently present. Although, these sulphides, commonly in the form of pyrite (Berner, 1985), are widely distributed they are rarely concentrated enough to source a strong acid. Whilst this is true for the bedded limestones and mud mounds limestones of the Dartry Limestone Formation, the abundance of iron sulphide is significantly higher within the Knockmore intramound (Chapter 4). For sulphuric acid to be generated the iron sulphide must be oxidised to sulphate. This is most likely to occur within the oxygen-minimum zone of meteoric groundwater circulation, which typically only extends to a depth of a few hundred, or perhaps thousand, metres (Tucker and Wright, 1990). Bottrell *et al.* (1990 and 2000) suggest that the enhanced aggressiveness at the base of the mixing zone would also promote sulphuric acid genesis where sulphides are present within the rock mass. Thus, it is the interface of the advancing meteoric water, as well as the oxidising meteoric water itself, that will promote sulphuric acid genesis. Sulphuric acid produced at a particular horizon, such as the Knockmore intramound, may not have been great in quantity but would have been sufficiently concentrated to cause dissolution to the carbonate component of the intramound as well as limestone immediately above and below. Strong acid dissolution such as this would have enhanced aquifer permeability, and considering the extent of the Knockmore intramound then the enhancement would have occurred basin-wide as the mixing zone migrated through it. As such, the permeability of the horizon may have been enhanced at an early stage in the evolution of the karst aquifer. However, strong acid dissolution is most viable in a shallow burial setting and as the Dartry Limestone Formation was rapidly buried the window for the oxidation of pyrite and genesis of sulphuric acid was particularly short.

Fission track studies (Green *et al.*, 1998) confirm an extensive period of uplift in Ireland towards the end of the Carboniferous due the Variscan Orogeny, which was followed by a period of accelerated erosion. By early Permian times uplift within the region had gently folded the Carboniferous strata and reactivated movement along the Castle Archdale-Belhavel Fault System. The regional Lough Allen Syncline formed during this time, as did several smaller scale folds, including the Cuilcagh Syncline and the MacNean Anticline. Prior to folding groundwater flow would have been restricted only by the extent of the sedimentary basin. However, the episode of folding altered the shape of the strata and formed several troughs and ridges. These 'new' structures affected groundwater movement by guiding flow away from the anticlinal ridges and toward the synclinal troughs. In the context of Cuilcagh Mountain, groundwater flow in the Dartry Limestone Formation would have been guided down the limbs of the Cuilcagh Syncline towards its axis. The folding also caused a major phase of faulting within the strata that generated a network of faults, fractures and micro-fractures.

By the Early Permian uplift had raised the Carboniferous strata of the Lough Allen Basin so that the sequence formed part of an upland landmass. During this period, most of the younger Carboniferous strata overlying the Dinantian sequence would have been eroded, so that the limestones rapidly became elevated to a relatively shallow depth of 1km below the contemporary surface (Green *et al.*, 1998; Gries and Meshri, 1998). At this relatively shallow depth meteoric waters would again have been reintroduced to the sequence and the deep basinal brines displaced. With the circulation of meteoric waters within the basin dissolution, by carbonic acid, would have occurred within the carbonate parts of the sequence. Although less efficient at depth, due to rapidly achieving saturation, the kinetics of the reaction maintained a low level of dissolution within the aquifer. As such, with continued groundwater recharge by meteoric waters carbonic acid dissolution would have facilitated enlargement of favourable flow paths.

6.2.2. Mesozoic

During the Triassic and Jurassic periods, sandstones and mudstones were deposited, but these are now only preserved in northeastern Ireland (Figure 78). Evidence of palaeokarst from southern parts of Ireland, such as at Pilltown, near Carrick-on-Suir, County Kilkenny, indicates that Dinantian Limestones were exposed following an episode of erosion during late Jurassic and early Cretaceous times (Higgs and Jones, 1998 and 2000). However, the Dinantian limestones of the Northwestern Basin were not uncovered by this episode of erosion and remained buried throughout the Mesozoic.

During the Cretaceous Period the area now encompassing Ireland was inundated by shallow seas, and the Ulster White Limestone Formation, equivalent to the Chalk elsewhere in the British Isles, was deposited. Although the Ulster White Limestone Formation is reported to crop out only beneath the Palaeogene basalts of the Irish Tertiary Igneous Province in northeastern Ireland, recent studies suggest that it once covered most, if not all, of Ireland (Clayton and Naylor, 1998). This modern view is based largely upon recognition that exposures of Mesozoic sediments within the Kingscourt, Wexford and Ballydeenlea outliers are remnants of a more extensive cover of Mesozoic sedimentary rocks. For example the Ballydeenlea Formation, discovered by Walsh (GSI, 1997), is an unbedded breccia with chalk matrix that lies some 200km from the nearest exposure of the Ulster White Limestone. The Geological Survey of Ireland (1997) report that the chalk breccia, which is of Campanian (late Cretaceous) age, was preserved only because it was deposited in solutional hollows in the Dinantian limestone. Palynofacies analysis of the Ballydeenlea Formation reveals little terrigenous input, suggesting that a 'Chalk sea' covered much of Ireland. Vitrinite reflectance studies of the Ballydeenlea Formation inlier indicate that 1-1.5km of late Cretaceous sediment cover, subsequently buried it, and the surrounding Dinantian limestones.

With the exception of the Cretaceous Period, when shallow seas dominated, a mountainous or upland land surface remained above the Dartry Limestone Formation during the Mesozoic. As such, a relatively stable but slow circulation of meteoric waters prevailed within the sequence for c.145 million years, from early Permian to late Jurassic times. These stable conditions further promoted the development of preferential flow paths along particular geological discontinuities. As the formation remained buried, the enlargement rate of preferential flow paths would have remained low but it is possible that over this substantial geological period breakthrough from laminar to turbulent flow may have been achieved. As such, conduit is likely to have become increasingly abundant during this period and with it turbulent flow. During Cretaceous times the transgression from land to tropical sea would have reduced recharge of meteoric waters to groundwater and re-introduced basinal connate waters into the groundwater system. The Cretaceous sea existed until early Tertiary times when uplift began and reverted the region to an upland terrain.

6.2.3. Cainozoic (Palaeocene to Miocene)

Uplift continued during early Palaeocene times, exposing the Cretaceous Ulster White Limestone to an aerial environment and it became extensively karstified (Simms, 1998). This was followed by initiation of volcanism during the middle Palaeocene when a mass out-pouring of basaltic lava occurred flooding the karst landscape of the Ulster White Limestone and preserving it as a palaeokarst. These flood basalts are preserved as the Irish Tertiary Igneous Province of northeastern Ireland. Although the Cuilcagh Dyke was unlikely to have been a feeder to volcanism, others in County Fermanagh such as the 100m-wide Doraville Dyke, north of Enniskillen, were. Consequently, the thick flood basalts found in County Antrim are likely to have extended across the northern part of Ireland, including County Fermanagh.

The Cuilcagh Dyke intruded via a prominent east-west fault zone (named the Cuilcagh Fault in this thesis) through the full thickness of the Dartry Limestone Formation and into the overlying non-carbonates. Prior to this intrusion groundwater was unrestricted within the Cuilcagh Syncline but focused along particular flow paths. Subsequent to the intrusion, flow was divided into two bodies of groundwater separated by the dyke. Although the Cuilcagh Dyke is the only intrusion observed on Cuilcagh Mountain, it is possible that other dykes also intruded and these may also impact on groundwater movements. The separation of the aquifer into two groundwater bodies influenced the development of the regional groundwater system by isolating groundwater north of the dyke to the northern limb of the Cuilcagh Syncline. Whilst groundwater south of the dyke continued to flow towards the westward plunging axis of the Cuilcagh Syncline, flow north of the dyke was restricted, being trapped between the Cuilcagh Dyke and the axis of the MacNean Anticline.

Continuing uplift during the Oligocene and Miocene times caused the erosion of c.2500m (G. Ll. Jones, Conodate, Dublin, *pers. comm.*, 1997) and 3000m (Gries and Meshri, 1998) of strata in the northwestern uplands of Ireland. In the south of Ireland the transition from confined to unconfined occurred earlier than in the northwest uplands. An exploratory borehole into sediments filling a palaeokarst pipe at Aughinish Island, County Limerick (Figure 79) was abandoned after drilling 62m without encountering solid rock; pollen and spores from a lignitic part of the fill were identified as being of Tertiary (sub-period unspecified) age (Mitchell, 1985). Similar fossiliferous fills in pipes at Tynagh, County Tipperary, and Holymount, County Carlow, (Figure 79) have been identified as Oligocene and early Pliocene respectively (Mitchell *et al.*, 1980). Evidence suggests that during these times Dinantian limestones began to be exposed across most of Ireland. Whilst, other limestone to the south had been exposed previously (such as at Ballydeenlea) this was the first time that the Dartry Limestone Formation cropped out to the surface since the Carboniferous. At the same time subsidence occurred in a number of basins in northeastern Ireland as uplift continued through the Cainozoic. As such, the rock sequence of these basins was protected from erosion and they have remained preserved in modern times (Figure 78). Tectonism during these times reactivated a number of fault systems within southwest Fermanagh but also initiated new faulting and fracturing, some of which cross-cut and truncated earlier phases of faulting, including that of the Cuilcagh Dyke.

6.3. Unconfined evolution

The mass erosion of the upland landscape during Oligocene and Miocene times incised deep valleys into the topography. As the cover of the Dartry Limestone Formation became increasingly thinned the ease and aggressiveness of meteoric waters to recharge the aquifer would also have increased. Following the removal of cover, the Dinantian limestones of Ireland were subject to widespread Pliocene karstification. Surface karst landforms developed across the rock landscape. Many landforms were destroyed as the landscape evolved but others were buried by sediment deposition and preserved as palaeokarst.

6.3.1. Cainozoic (Pliocene to Holocene)

Within the karst aquifer of Cuilcagh Mountain flow paths became enlarged at an increasing rate and eventually the succession was incised into and conduits began to be drained. The modern topography shows that valleys were incised to the north, east, south and west of what is now Cuilcagh Mountain. However, due to the structural form of the Dartry Limestone Formation only those valleys to the north and east incised into the formation. These valleys drained conduits within the northern limb of the MacNean Anticline, north of the Cuilcagh Dyke, as well as conduit in the east. Where connectivity existed across the Cuilcagh Dyke then conduits south of the Cuilcagh Dyke also began to be drained.

The lack of relict risings in the escarpment is due to the main conduits being located upon the Knockmore intramound, which is located near the base of the formation. As such, whilst localised risings developed in the scarp slopes as the valley was incised into, the major risings only formed when valleys incised through the Dartry Limestone Formation, exposing the Knockmore intramound and intersecting the conduit developed at it.

In response to the Miocene erosion, the original conduit system was extensively modified. New flow paths developed along fractures within the upper part of the formation and these propagated towards the deeper pre-existing conduit at the Knockmore intramound. As such, the subsequent caves formed as a combination of conduit guided by fracture and intramound.

Vadose drainage of the southern part of the aquifer, the Shannon System under the context of the modern topography, only occurred in the north where fractures facilitate flow across the dyke and in the east where valley incision has captured the eastern periphery of the system. In the eastern part of this system the flow paths are complex due to multiple fracture developed flow paths within the Gortalughany Member and lack of a single major flow path. In the modern setting the Shannon system remains protected from capture by the Cuilcagh Dyke. However, it is only observable by its stream sinks and caves in the East Cuilcagh and Shannon karsts, by Shannon Pot Rising the only known outlet from the system and by the tracer tests that have repeatedly proven connection from east to west across the mountain (Chapter 4).

During the Pleistocene, ice and periglacial action modified the rock landscape, deepening valleys and changing the courses of rivers. Most mountain masses exhibit the well-known erosional features attributed to Alpine-type glaciation, cut both by ice and glacial meltwater. Glacial deposits (Figure 80) derived from the ice and meltwater, cover wide areas, reaching thicknesses of over 20m. However, the underlying trends of valleys and upland areas have remained largely unchanged since pre-glacial times. Glaciation has had a significant effect on the pre-glacial caves and karst landforms of Ireland. In particular the sides of glacially deepened valleys commonly expose relict dissolutional cave passage segments, truncated by cliff faces, at elevations well above the valley floors. Dermot and Grania's (Diarmaid and Grainne's) Cave (GR: 17250-34715) provides a fine example at an elevation of 480m ASL, c.250m above the floor of Gleniff in County Sligo. Further to this, the fluctuation between cold dry periods and wet warm periods resulted in periodic inundation of cave and karst systems with fluvial and mass flow deposits, which partially filled many of them, e.g. Marble Arch Cave, County Fermanagh and Crag Cave, County Kerry.

The landscape of Cuilcagh Mountain, from lough to mountain ridge, is typical of the northwestern uplands, being essentially a rock topography that is overlain directly by glacial subsoils which form a thick blanket in the valleys in the northwest of Ireland (Figures 81 and 82), all of which have abundant drumlins that indicate the direction of ice movement. On Cuilcagh Mountain, glacial drift is restricted to the lower and middle slopes where it tends to form a thin covering, although its thickness is locally variable, with common glacial erratics. The steep upper slopes reflect severe periglacial action that shattered cliff faces, leaving a rock landscape scarred with deep *(>10m) gulls.*

The MacNean Valley, like the Erne Valley, is dominated by an abundance of drumlins that formed during the last (Midlandian) (Figure 83) glacial advance in northwest Ireland. Ice flow was from the east to west towards the Atlantic along the MacNean and Lower Erne valleys. Glacial deposits from the retreat of this ice mass cover the region (GSNI, 1998), and consist largely of till. There is no evidence of any older glacial deposits.

6.4. Summary

By the end of the Carboniferous the Dartry Limestone Formation was buried to a depth of c.3km. It is likely that pathways had been initiated at, and along, particular geological horizons shortly after the Dartry Limestone Formation had been deposited and buried. However, as the window for meteoric water circulating within the aquifer was short it is unlikely that flow paths became significantly solutionally enhanced. During the Permian uplift and erosion raised the formation to within 1km of the surface allowing meteoric waters to recharge the sequence. Relatively stable conditions prevailed within the sequence for c.145 million years, from early Permian to late Jurassic times. These stable conditions further promoted the development of preferential flow paths along particular geological discontinuities At the end of the Cretaceous the stability ceased, initially by further uplift and erosion and then by the intrusion of at least one igneous dyke, the Cuilcagh Dyke. This intrusion and others like it are associated with a period of igneous activity that included the mass outpouring of flood basalts in the northern part of Ireland. Extensive uplift and erosion followed the volcanism, with an estimated 2500-3000m of cover removed during the Oligocene and Miocene. The upland terrain that was carved during this period of uplift and erosion exposed the Dinantian sequence to the surface.

Chapter 7

Conclusions

7.1. Introduction

The research project was initiated following recent hydrogeological and hydrochemical advances in the concepts of speleogenesis within karst aquifers. When speleogenesis was being considered in the late 19th century Edward Martel (1896) suggested that 'no theory about the origin of caves is universal'. Whilst this statement remains largely true in modern times it is becoming increasingly recognised that one common feature with many caves is that they have developed over significant periods of geological time and involve both confined and unconfined aquifer evolution.

In Chapter 1 the objectives were outlined as:

1. To detail the geology of the karst aquifer.
2. To undertake an investigation of the modern karst hydrology.
3. To investigate conduit inception and development within the karst aquifer.

7.2. Key findings of the thesis

This thesis explores speleogenesis within the Dartry Limestone Formation of Cuilcagh Mountain by considering the hydrogeology of the aquifer in the modern setting but also by considering its evolution since Asbian times. Whilst, the Dartry

Limestone Formation is divided into several members based upon lithology, it can be divided into two main units in terms of its hydrogeology. The majority of the formation is composed of mud mound limestone sequences but part of the formation, which forms the East Cuilcagh Escarpment, is composed of bedded grainstones and finely laminated cherts.

In the modern setting extensive conduit systems have developed within the mud mound limestones, these include the caves of the Marlbank Escarpment. As many of these systems are vadose, groundwater levels within the aquifer have been lowered as the conduits have drained. As the piezometric levels in individual conduits, caves, fractures and rock matrix are largely unrelated is not practical to describe the aquifer beneath the Marlbank Escarpment as having a water table. This is typical of most mature karst systems.

Conduits have also developed within the bedded and laminated limestones of the East Cuilcagh Escarpment, where they form an extensive maze-like network of narrow but vertically extensive conduit, some of which are explorable as pot holes. Those pot holes that swallow surface streams penetrate the aquifer by up to 70m depth and from sink to resurgence the conduit systems of the East Cuilcagh Escarpment have particularly high flow gradients. However, most of the vertical difference comprises of the depth of the pot holes themselves. Whilst these systems have drained much of the aquifer its lower parts still remain water-filled. Even with the high degree of interconnectivity between conduits it remains inaccurate to describe the aquifer as having a water table. However, the interconnectivity and vertical extent of the fracture-guided conduit system allows a piezometric surface to exist beneath the East Cuilcagh Escarpment. As the piezometric surface has a relatively shallow gradient, the point recharge inputs from each stream sink disperse laterally within the groundwater body.

The water tracing experiments undertaken during this research project have added significant clarity to the hydrological regime that operates within the modern setting of the karst aquifer. These tests have shown that local hydrological systems operate at the margins of the uplands but that a regional conduit system operates within the main body of the aquifer. Whilst the local systems drain towards the marginal scarps, the regional system drains from east to west beneath the upland guided by the gently westnorthwest plunging Cuilcagh Syncline. Although the regional system is largely developed within the mud mound type limestones the most easterly extent of the regional system lies within the bedded and laminated limestones of the East Cuilcagh Escarpment. However, due to the high degree of interconnectivity and presence of a low gradient piezometric surface within the conduit system, groundwater flows laterally to several different risings. These include four local risings found at the eastern edge of the escarpment as well as two regional risings, Cascades Rising in the northwest and Shannon Pot Rising in the west. In this way sinks on the East Cuilcagh Escarpment form part of both the River Erne and the Shannon River drainage.

The hydrology of the karst aquifer is further complicated by the intrusion of the Cuilcagh Dyke during late Cretaceous and early Tertiary times. This regional drainage system has in many ways been 'preserved' by the Cuilcagh Dyke, which has prevented its flow paths from being captured and overprinted by routes draining northwards towards Lough MacNean. However, partial capture has occurred where the dyke is faulted in the valley of the Owenbrean River. At this location flow from the regional system bifurcates, with one flow path continuing to drain westwards to Shannon Pot Rising and the other, younger, flow path draining via the fault in the dyke into the Prod's-Cascades Cave System.

The differences between the conduit systems in the East Cuilcagh and the Marlbank escarpments occur due to their differing geological setting, which have guided their inception and subsequent development. The most significant difference being the lithology that comprises the formation at each location. However, other differences also exist, such as fracture frequency. The mud mound limestones form the bulk of the Dartry Limestone Formation on Cuilcagh Mountain. Of the mud mound sequence the Knockmore Member in particular is extensive and forms most of the Marlbank Escarpment. The Knockmore Member comprises of a thick accumulation of mud mounds (up to 220m), several of which dominate the escarpment forming knoll-shaped hills up to 70m high. Within the member there is little lithological variation. However, the lower c.20m of the member comprises of horizontal-type mounds rather than the typical vertical-type. The contact between the two mound types is particularly extensive and is marked by an intramound horizon, which is a shaley carbonate and has a maximum thickness of c.0.30m. Within the horizontal-type mud mounds several minor bedding planes also occur. However, none are as extensive as the main 'Knockmore intramound' horizon.

Whilst the Knockmore Member contains the majority of cave passage on Cuilcagh Mountain this main intramound horizon is the only inception horizon that has been identified. Unlike karst areas such as the Yorkshire Dales or parts of Derbyshire (Sweeting, 1950; Beck, 1980) where tiered systems are present the caves of the Marlbank Escarpment are typified by a single tier streamway that has a relatively shallow hydraulic gradient from sink to rising. Sinks are located at various levels high within the stratigraphy but risings tend to be clustered near the base of the formation. All cave systems are branching tributary systems, with each tributary forming a linear passage that descend through the vertical-type mud mounds of the Knockmore Member. However, the tributaries converge when they reach the stratigraphic level of the intramound and their passage morphology changes from high and narrow to low, wide and meandering. This change in passage morphology represents the change in the geological factors that have guided flow. Prominent fracturing has guided flow to form the tributary passages. However, when the intramound is intersected the guidance of flow switches from away from the fractures and along the strike of the intramound. Frequently this means that cave passages turn at right angles when the tributaries intersect the intramound. Importantly although of all the fractures crosscut the intramound their cease to guide the flow path as soon as the intramound is intersected. Based on these observations then the intramound horizon provided a significantly more efficient preferential flow path than the fracturing. This being the case then the flow paths that developed the tributaries to the system formed because they targeted the intramound horizon, which had formed as a preferential flow path at an earlier stage of aquifer evolution. The abundance of sulphides within the intramound relative to the rest of the mud mound sequence makes inception by strong acid a potential and important process for the initiation of conduit. However, other properties of the horizon such as its incipient higher lateral permeability also promote it as an inception horizon. Individually both of these concepts promote the intramound as a significant inception horizon within the limestone sequence. The fracture guided conduit was initiated and developed by the circulation of aggressive meteoric waters from sink to inception horizon as the aquifer became unconfined.

Within the East Cuilcagh Escarpment the majority of cave passage is guided by fracturing. Some lithological guidance is observed in Badger Cave and Pigeon Pot II. However, due to the changes in lithology the Knockmore intramound does not occur within the East Cuilcagh Escarpment. The lithological guidances that are observed are of importance but they do not have the regional extent of the Knockmore intramound and as such can only be found locally. In the modern setting these conduits have been intersected and drained by the deep vadose systems that dominate the escarpment. Previously when water levels remained above the top of *the formation groundwater* flow was guided by conduit that had developed along up to two inception horizons. However, when these now relict conduits were active groundwater levels remained above the top of the Dartry Limestone Formation. Considering the high elevation of these conduits on the eastern margin of the escarpment then they must pre-date the modern topography. This means they must also pre-date all of the risings at the base of the East Cuilcagh Escarpment, which have developed as solutionally enlarged conduit within the aquifer were intersected by the deepening valley. Prior to these risings developing flow drained elsewhere, most likely westwards as part of the regional drainage system, which it still partially drains too. Without the modern Erne, MacNean and Shannon valleys that encircle Cuilcagh Mountain then the present outcrop of the Dartry Limestone Formation would have remained buried. As such, the drained conduit of Badger Cave developed under confined conditions.

In the modern setting Shannon Pot Rising is the only resurgence of the water that drains from east to west beneath Cuilcagh Mountain. However, its location on the shallow floor of the valley to the west of Cuilcagh Mountain within shales that overlie the Dartry Limestone Formation suggests that it is a relatively recent landform in terms of landscape evolution. Hydrogeologically Shannon Pot is an example of an artesian rising emerging from a confined setting. A significant proportion of its catchment, between it and its distal catchment of the East Cuilcagh Escarpment, remains confined. Hydrochemical evidence suggests that a shallow flow system and a deep flow system operates at Shannon Pot. This evidence suggests that a source of sulphide is present within the deeper flow path and based upon geology of the sequence the most likely source of sulphide is from the Knockmore intramound, observed within the caves of the Marlbank. However, this would place the deep flow system c.300m below the landscape at Shannon Pot (c. 200m below OD).

7.3. Wider conclusions and implications

The key findings of this thesis indicate that the evolution of the Dartry Limestone Formation as a karst aquifer is particularly long lived. Evidence suggests that a regional system has developed and still partially operates under confined settings. As such, the inception and early development of this system has occurred unrelated to surface process. In the modern setting this regional system is slowly being intersected by surface processes. Where valley incision has intersected its conduits then risings form. In terms of the speleogenesis theories discussed in Chapter 2 the regional system cannot be adequately described by the Ford-Ewers model, which is intended by its authors only for describing caves in unconfined settings that have formed solely by meteoric waters sinking and circulating in carbonate rocks. However, Lowe's inception horizon hypothesis can be applied to explain how conduit may develop at depth and within a confined setting.

In the modern setting the caves of the East Cuilcagh and Marlbank escarpments exist where the aquifer is unconfined. According to the Ford-Ewers model state 3 (cave with mixture of phreatic and water table levelled components) and state 4 caves (ideal water table cave) are common in situations such as Cuilcagh Mountain where bedding has a low dip. Whilst the use of water table is not favoured by the author to describe the karst of Cuilcagh Mountain all systems upon the northern Marlbank characteristically have low gradient stream ways and some comparison may be drawn between them and the Ford-Ewers state 3 cave. Although the Ford-Ewers model does show some comparison with the cave systems of the Marlbank its use on the East Cuilcagh Escarpment is inaccurate, as caves tend to be vertical with no stream passage. Additionally two streams on the East Cuilcagh Escarpment do not sink underground but discharge from the escarpment solely by surface flow, which is equivalent to the state zero rather than state 3 or 4.

Importantly Lowe's inception horizon hypothesis (1992) as well as Klimchouk's (2000) descriptions of confined aquifers identify the wider evolutionary concept that although most caves are reported within unconfined settings, often the flow paths that the cave systems have formed from initiated and developed within confined settings. This concept is particularly appropriate for Cuilcagh Mountain where a single but particularly extensive inception horizon guides the location of cave systems at the northern, unconfined margin of the aquifer and as evinced by hydrochemical data the horizon also focuses flow in the deeper, confined parts of the aquifer. This being the case then the cave systems that are accessible from the escarpment margins are considered to be modifications of older flow paths that developed when the aquifer was confined. As such, the Ford-Ewers model only portrays the final stages of conduit development on Cuilcagh Mountain and it does not consider its wider evolution as a karst aquifer.

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