



Mississippian (Dinantian) of Ireland and its geothermal potential

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Abstract: The Mississippian (Dinantian) rocks of Ireland are a main target for deep geothermal exploration in Ireland. Exploiting their potential as a future energy source is largely dependent on our understanding of their stratigraphy and structure. This article summarises the Lower and Middle Mississippian succession of Ireland incorporating new data from Geological Survey Ireland work in central-western Ireland. It includes a short summary of geothermal potential of the Dinantian basins derived from limited previous exploration and the GeoERA HotLime Project.

Keywords: Ireland, Carboniferous, Mississippian, Dinantian, Tournaisian, Viséan, shelf, Dublin Basin, Shannon Trough, Lough Allen Basin, marine transgression, stratigraphy, HotLime, geothermal energy

1. Regional setting

Ireland's palaeogeographic position during Dinantian times was in the tropics. During the early Carboniferous, global sea levels started to rise resulting in a marine transgression in Ireland from the south, leading to most of the country becoming a shallow-water carbonate shelf. Extensional tectonism during the early Carboniferous formed deeper water basins locally, e.g. the Shannon Trough and Dublin Basin (Fig. 1); their location is probably related to older basement structures. Mixed siliciclastic and carbonate sediments were deposited along the margin of the transgressive shelf sea as it spread over successively more northern areas. In the south of Ireland, terrigenous sediments continued to accumulate during most of the Courcayan (Tournaisian) in the South Munster Basin (Fig. 1). The carbonate shelf can be traced eastwards across Wales, England, the North Sea, northern France, and Belgium into northwest Germany. The rocks in the South Munster Basin are similar to the Culm facies of southwest England (Pharaoh *et al.*) and the Rhenish Mountains in Germany (Arndt 2021). To the west, Dinantian rocks of shelf facies are recorded as far as the Porcupine Basin.

The Dinantian succession is described in stratigraphical order, which is based on conodonts, corals, miospores, and foraminifers (Fig. 2). The palaeogeographic and correlation diagrams for the various time intervals produced by Sevastopulo & Wyse Jackson (2001) and the published 1: 100,000 scale maps and book series by the Geological Survey of Ireland are used as the basis for this contribution. The detailed microfacies analysis presented were carried out by I. D.

Somerville on samples collected by one of the authors (MP). First, the sediments of the initial marine transgression across the Irish shelf resulting in mixed siliciclastic and shallow-water shelf limestone are discussed, subdividing the area into “Provinces” (Philcox 1984; Sevastopulo & Wyse Jackson 2001). This is followed by a brief summary of Waulsortian buildups/mudbanks. The Viséan succession of the main shelf area is followed by brief descriptions of Shannon Trough, Dublin Basin and Northwest Basin/Lough Allen Basin. Emphasis lies on describing the carbonate successions that have recently become the main target for deep geothermal exploration. Two recent case studies are summarised in the final part. Locations printed in **bold** can be found on Fig. 1 or Fig. 7. Underlined formation names mark the location of their discussion.

Extensive drilling by the Geological Survey of Ireland in recent years has led to a better understanding of the shelf development in the Dunmore and Western provinces (DP and WP) and the importance of major structures in the area (Fig. 7). The Castlemine borehole (total depth 849.5 m) and Springfield borehole (total depth 332 m), in the northern part of the Dunmore Province (see Fig. 1) penetrated most of the Dinantian succession (MFZ1 to MFZ13). In the Castlemine borehole, the Dinantian succession rests unconformably on early Palaeozoic “basement” rocks, which are exposed to the east in the Strokestown Inlier. Of the combined drilled 1,040 m of Dinantian rocks, c. 574 m are of Tournaisian age and c. 466 m of Viséan age. Lithologically, c. 455 m of the drilled Tournaisian rocks are dominated by siliciclastics and evaporites, c. 585 m by limestone (Fig. 3).

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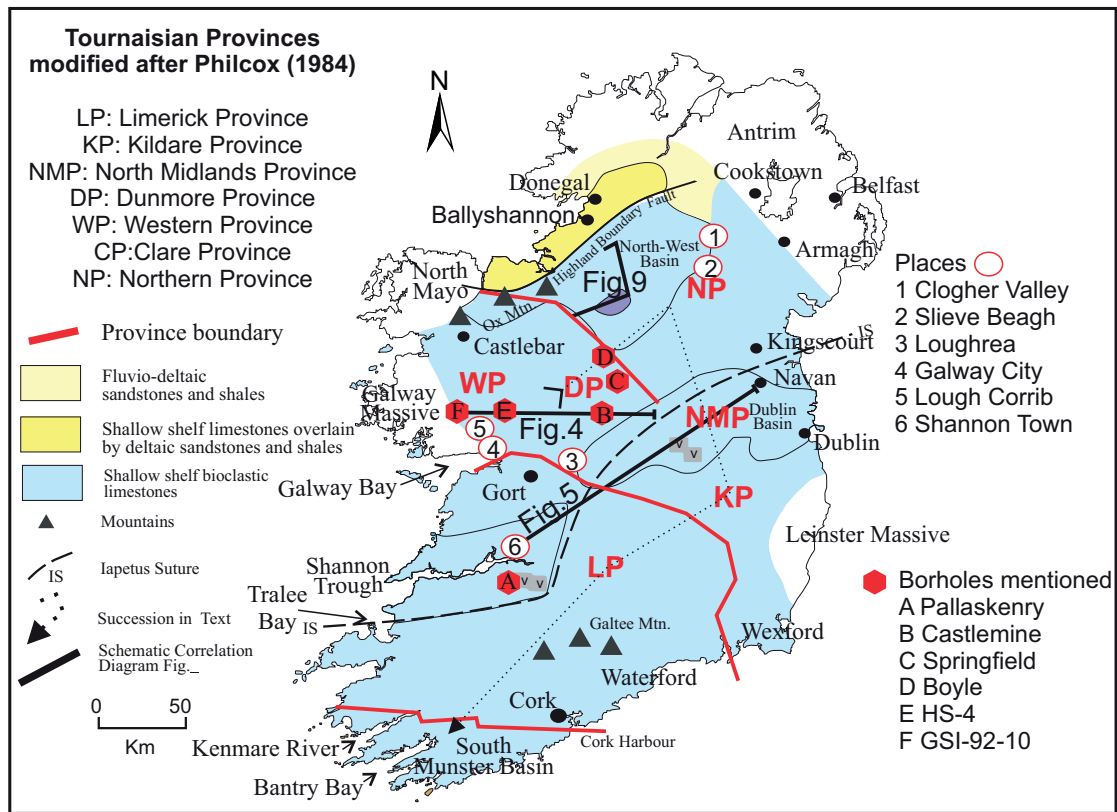


Fig. 1: Generalised Irish ramp/shelf extend during the Tournaisian with provinces, boreholes, shelf areas, and places mentioned in the text (modified after Philcox 1984, Sevastopulo & Wyse Jackson 2001).

2. Shelf areas during the Tournaisian ramp stage (MFZ1 to MFZ8)

As can be seen in Fig. 1, most of the shelf area is covered by late Tournaisian carbonates. The boundaries of the “provinces” are gradational. The first provinces described are the **Dunmore and Western provinces**. They have been subject to extensive research over the past decades with new data presented and are therefore described in greater detail. This is followed by brief summaries of the other provinces in a clockwise direction (arrow in Fig. 1).

Thickness variation in the Dunmore and Western provinces across NE to SW trending faults suggest intermittent tectonic activity after the basal unconformity had developed (Tournaisian MFZ1 to MFZ8), with the accommodation space being gradually filled. Major thickness variations along and across the Strokestown Fault, for example, in the siliclastic sediments of the Fearnaght Formation and its lateral equivalent “Red Beds” (MFZ1–3 approx.) and in the Meath Formation (approx. MFZ6) indicate possible differentiated subsidence along this structure (Philcox 2008). Alternatively, however, the thickness variations could be explained by infilling of palaeotopography and erosion mechanisms.

With the exception of the Boyle Sandstone Formation and Fearnaght Formation, the siliclastic rocks of early

Tournaisian age (based on a CM miospore age) across the Dunmore Province (Fig. 4) shelf area are known as “undifferentiated basal clastic rocks” (Morris et al. 2003; Philcox 1984, 2008). These rocks, in some areas, rest conformably on probable Devonian siliciclastic rocks, in others are unconformable on highly deformed lower Palaeozoic rocks (Castlemine borehole). At Castlemine, c. 200 m of thick beds of coarse-grained, cross-bedded, red, pink, and white sandstone, siltstone, mudstone, breccia and conglomerate of the Fearnaght Formation are overlain by variously coloured sandstone, conglomerate, and mudstone with caliche carbonate nodules and gypsum beds of the Boyle Sandstone Formation. In the Western Province, the Tonweeroe Formation consists of c. 105 m of basal clastic rocks and rests unconformably on a wide variety of older rocks. The succession consists of red beds at its base, followed by a lithologically mixed unit and an upper grey sandstone and mudstone sequence. The “grey sandstone” is correlated with the Boyle Sandstone Formation. Mudstone from the base and top of this unit yielded a CM biozone age (Ivorian, approx. MFZ5 to MFZ8).

The onset of carbonate sedimentation across most of the Dunmore and Western provinces occurred in mid-Tournaisian (MFZ5 to MFZ6-Hastarian/Ivorian) time (Pracht & Somerville 2015). In the northern part, near Boyle, carbonate sedimentation started in the upper Boyle Sandstone Formation, further south at the base of the Meath Formation. The

Chronostrat.	SUB-STAGE UK&IRL	Foram. zones Poty et. al. 2006	Conodont zones		Rugose Corals		Miospore zones Higgs 1984		
			Conil et al. 1991		Jones & Somerville 1996				
MISSISSIPPIAN (pars.)	VISEAN	Warnantian	Brig.	MFZ15	<i>Gnathodus girtyi collinsoni</i> <i>Lochreia nodosa</i> <i>Mesognathodus bipleti</i>		J-K I H	<i>Orionastrea</i> spp. <i>Corwenia rugosa</i> <i>Palastrea regia</i> <i>Actinocyathus floriformis</i>	NC pars. VF
			Asbian	MFZ14	bilin.	<i>Gnathodus girtyi girtyi</i> <i>Gnathodus bilineatus bilineatus</i>	G	<i>Dibunophyllum bipartitum</i> <i>Haplolasma cf. dansum</i>	NM
				MFZ13			F	<i>Siphonodendron pauciradiale junceum</i> <i>Dibunophyllum bourtonense</i>	TC
		Liv.	Holkerian	MFZ12	? T. transatlanticus	<i>Taphrognathus</i> <i>Gnathodus cracoviensis</i>	E	<i>Lithostrotion vorticale</i> <i>araneum</i>	TS
			Molinciatic emend.	Arundian			MFZ11	D C B	<i>Siphonodendron sociale martini</i> <i>Clisiophyllum garwoodi</i> <i>Dorlodotia biarti</i>
		MFZ10			A	<i>Dorlodotia pseudovermiculare</i> <i>Carruthersella compacta</i> <i>Axophyllum simplex</i>			
		Chadian emend.	MFZ9	? T. transatlanticus			<i>Gnathodus homopunctatus</i>	A	
	TOURNAISIAN	Ivorian	Courceyan emend.	MFZ8	S. anchoralis coraliformis	<i>Mestognathus praebeckmanni</i> <i>Polygnathus bischoffi</i> <i>Doliognathus latus</i> [P. mehli latus] <i>Dollymae hassi</i> [Ps. multistriatus]	[P. mehli]	<i>Siphonophyllia cylindrica</i> <i>Synchoelasma urbanowitschi</i> <i>Caninophyllum patulum</i> <i>Cyathoclisia modavensis</i> <i>Synchoelasma hawbankense</i> <i>Synchoelasma konincki</i> <i>Caninia cornucopiae</i>	CM
				MFZ7					
				MFZ6					
				MFZ5					
				MFZ4					
		Hastarian		MFZ3	<i>Gnathodus</i>		<i>Zaphrentites delanouei</i>		PC
				MFZ2	upper obsoleta [P. inornatus]	<i>Zaphrentites vaughani</i> (<i>Saleelasma delepinet</i>)		BP	
				MFZ1	lower obsoleta [P. spicatus]			HD VI	
upper cooperi									
		MFZ1	duplicata - cooperi						

Fig. 2: Correlation of Irish Carboniferous (Dinantian) foraminiferal, conodont, coral, and miospore zonations. Modified after Poty et al. (2006, 2014) and Jones & Somerville (1996). Brig. – Brigantian, Liv. – Livian, emend. – emended range, [] – Irish Main Shelf taxa; abbreviated conodont names: S: - *scaliognathus*, Ps: - *Pseudoscaliognathus*, P: *Polygnathus*, selected species only.

Meath Formation consists of alternating beds of bioclastic/oolitic/peloidal and sandy limestone, siltstone, and evaporites. The main skeletal components are crinoids, brachiopods, bryozoans, ostracods, bivalves, and rare foraminifers. A sparse foraminiferal assemblage including *Endothyra*, *Earlandia*, *Tournayella*, *Eoforschia*, algal/cyanobacteria and microproblematica (*Girvanella*, *Salebra sibirica*) suggest a lower Ivorian age (MFZ5). A similar age was obtained from the Boyle borehole near the northern margin of the Dunmore Province and from borehole HS-4 in the Western Province (CM Biozone; Philcox 2008). In the Western Province, the change to carbonate sedimentation occurred rapidly, with only minor siliciclastic input. In the North Midlands Province to the east (Figs. 3, 5), the Stackallan Member at Navan yielded a similar age (Cf2; Strogon et al. 1990).

The early mixed succession in the northern part of the Dunmore Province was deposited in a nearshore, shallow-water siliciclastic-dominant shelf in which both fine- and

coarse-grained clastic sediments accumulated. Periodically, shelf limestone with a rich and diverse benthic fauna developed, when siliciclastic input onto the shelf was somewhat reduced. High-energy conditions prevailed during the formation of the limestone, as suggested by the transport and concentration of large shells and the presence of ooids. The presence of evaporites interbedded with red-bed clastic rocks that thicken towards the north and northeast of the Dunmore Province (Meath Formation) suggests an increasingly marginal-marine to lagoonal depositional environment. Gypsum is recorded as massive beds and nodules in several boreholes in northwest County Longford (Morris et al. 2003) and in the Castlemine borehole. Periods of influx of coarser grained siliciclastics interbedded with limestone highlight the mixed character of the lower succession whereas the limestone beds higher in the succession mark more turbulent higher energy conditions with open-marine stenohaline fauna (large brachiopods, crinoids, and bryozoans).

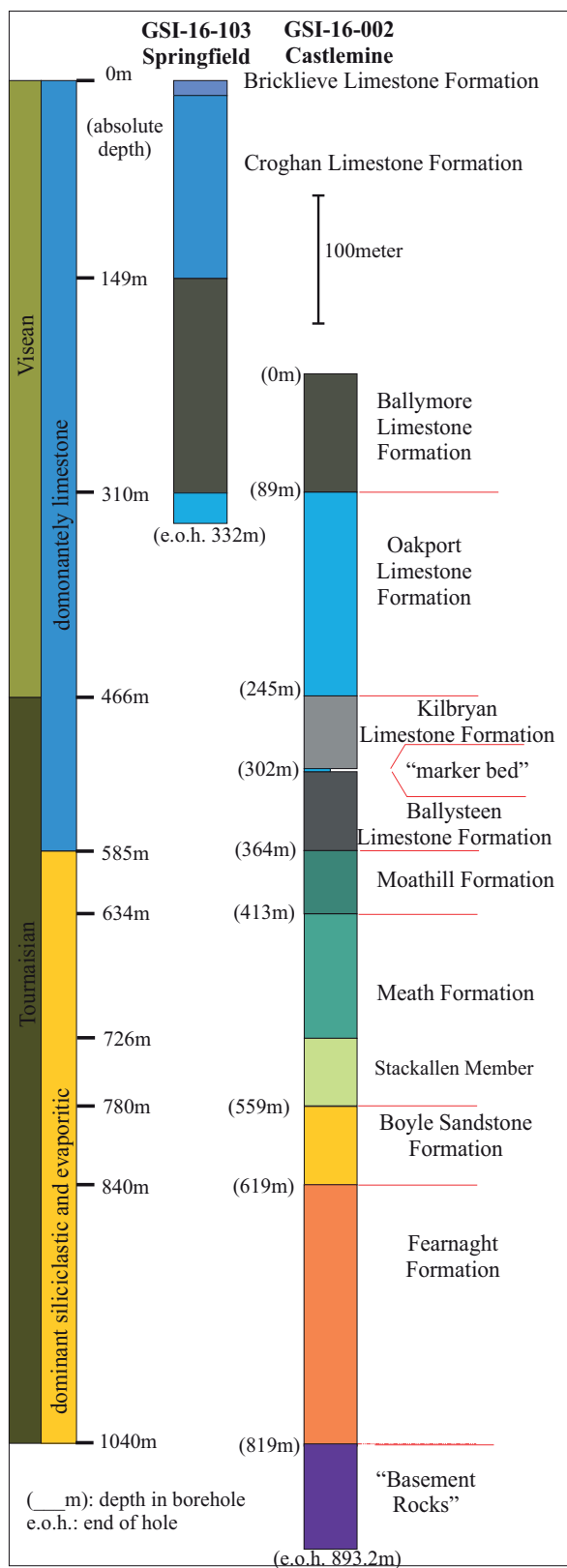


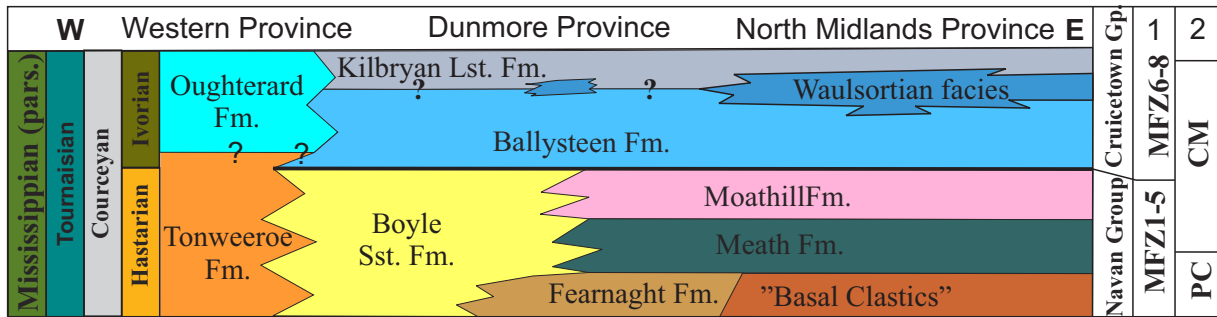
Fig. 3: Schematic diagram to show the combined lithostratigraphy and thicknesses of boreholes GSI-16-002, Castlemine and GSI-16-102, Springfield.

In the overlying Moathill Formation of mixed burrowed, calcareous siltstone, argillaceous, bioclastic limestone, calcareous sandstone, and mudstone (Strogen et al. 1990) a MFZ6 foraminiferal age (Tournaissian) is based on a sparse assemblage including *Endothyra*, *Septatournayella*, *Earlandia*, *Eoforschia*, algal/cyanobacteria, and microproblematica (*Girvanella*, *Salebra sibirica*). The main skeletal components are large brachiopods, crinoids, fenestellid bryozoans, ostracods, and rare foraminifers. The rocks of the Moathill Formation were deposited in a similar environment as the underlying Meath Formation but generally lack the evaporites and red beds. They represent the transition into the succeeding fully marine Ballysteen Formation.

In MFZ6-7 times (Ivorian), fully marine conditions were established across the Dunmore and Western provinces with the deposition of the Ballysteen Limestone Formation. On the western margin of the province (Fig. 4), the Tournaisian-Viséan boundary (identified by the appearance of *Eoparastaffella simplex*) lies 30.6 m below the top of the Oughterard Limestone Formation (155 m thick) and most of the formation is of ?MFZ6 to MFZ9 age (Devuyst & Hance unpubl.). Here, the Waulsortian facies is absent. Mapping indicates that the Oughterard Limestone Formation thins towards the northeast (Lough Corrib) and that the siliciclastic content decreases in the same direction. In the Dunmore Province, the age is based on a sparse foraminiferal assemblage including *Tetrataxis*, the rare microproblematicum *Sphaerinvia piai*, and the rugose coral *Caninophyllum patulum* (Castlemine). Irregularly bedded and nodular bedded, fine-grained, argillaceous bioclastic limestone, interbedded with bioclastic calcareous mudstone was deposited. The limestone beds are commonly bioturbated. Large crinoids along with brachiopods and bryozoans are the main macrofaunal elements. In thin section, the limestone typically comprises poorly sorted, fine-grained, argillaceous, and skeletal wackestone/packstone with main skeletal components of crinoids, brachiopods, fenestellid bryozoans, tubular foraminifers, ostracods, sponge spicules, trilobites, gastropods, and cyanophytes.

The sediments of the Ballysteen Limestone Formation were deposited mostly in an offshore open shelf to middle ramp environment, below fair-weather wave-base but above storm wave-base, in which fine-grained carbonate accumulated with some fine siliciclastic input. The limestone beds of the Ballysteen Limestone Formation are associated with a major deepening episode following the deposition of the shallow-water siliciclastic-rich sediments of the underlying successions (Meath and Moathill Formations). The lack of sedimentary structures, poor sorting of bioclasts and abundance of bryozoans implies low-energy, relatively quiet water conditions. Many of the limestone beds are interpreted as debris flow or grain flow deposits derived from nearby shallower water areas.

Within the Dunmore Province, the succession thickens and becomes increasingly argillaceous from west to east and north to south (Philcox 2008) before passing laterally into the Lucan Formation of the southwestern part of the Dublin Basin (Gatley et al. 2005). Locally, the early Palaeozoic inliers appear to control the rate of accommodation, with thin-



1 Foraminiferal zonation based on Poty et al. (2006 and 2014). 2 Miospore zonation based on Higgs (1984). MFZ: Mississippian Foraminiferal Zones.

Fig. 4: Schematic Tournaisian lithostratigraphic correlation diagram from West to East. Fm – Formation; Correlation line see Fig. 1.

ning towards the inliers suggesting they formed palaeo-highs. Waulsortian facies is locally developed, but where absent, the Ballysteen Limestone Formation is overlain by the Kilbryan Limestone Formation which consists of thinly bedded, argillaceous, bioclastic limestone, calcareous mudstone of late Tournaisian (MFZ8) to early Viséan (MFZ9) age (CM/PU Biozone miospore assemblage age; Philcox et al. 1992). This is confirmed by the first appearance of the foraminifer *Eoparastaffella simplex* in the upper part of this unit in the GSI boreholes. Other foraminifers recorded are *Pseudolituotubella*, *Tetrataxis*, and *Eotextularia diversa*. The recorded coral fauna (*Siphonophyllia cylindrica*, *Clisio-phyllum sp.* and *Siphonophyllia sp. cf. garwoodi*) indicate a similar age range.

The Kilbryan Limestone Formation (or its equivalents) can be traced from the northern part of the shelf (Boyle) to the west (Lough Corrib) (Pracht & Somerville 2015). In the northwest of the region (Castlebar Syncline) the unit is absent. To the east (east of the Shannon), the formation passes into the informal “Argillaceous Limestone” of the Cruicetown Group (Morris et al. 2003). The unit contains evaporite replacement, birds-eye textures, soft-sediment deformation, and bioturbation. Main faunal components are crinoids, brachiopods, bryozoans, trilobites, ostracods, gastropods, solitary rugose corals, and tabulate corals (*Syringopora*, *Michelinia*), sponge spicules, foraminifers (typically: *Earlandia*, *Endothyra*, *Eotextularia*), and algae (typically: *Nanopora*, *Kamaena*, *Stacheoides*, and some encrusting algae). Microproblematica and calcispheres are also recorded. The beds are usually ungraded with diffuse bed contacts. Chert and distinct black, non-calcareous mudstone beds occur locally.

The Kilbryan Limestone Formation was deposited in a moderately deep shelf to ramp setting above storm wave-base, within the photic zone, in which both fine-grained carbonate mud and siliciclastic mud accumulated. Low-energy conditions prevailed during the formation of the limestone, as inferred by the presence of sponge spicules, bryozoans, and the mudstone beds. Episodic high-energy events led to coarse, crinoidal, unsorted deposits. The presence of the rare microproblematicum *Sphaerinvia piai* is notable, as it is usually associated with Waulsortian mud-mounds and adjacent

strata. It is likely that the Kilbryan Limestone Formation is, in part, coeval with, and lateral to, Waulsortian limestone (see Morris et al. 2003; Pracht & Somerville 2015).

The area to the north of the Longford Down early Palaeozoic inlier and as far west as Donegal is loosely referred to as the **Northern Province (NP)** (Fig. 1; Sevastopulo & Wyse Jackson 2001). In the Clogher Valley – Slieve Beagh area, the Tournaisian rocks are assigned to the Tyrone Group (Mitchell 2004). Up to 240 m of fluvial red, purple and grey sandstone and conglomerate of the Ballyness Formation are overlain by c. 470 m of shallow-water interbedded grey mudstone, sandstone micrite, dolomite, and evaporites of the Clogher Valley Formation. Kelly & Jones (pers. com.) show the top of the Ballyness Formation to be of VI Miospore zone age (= MFZ1) whereas the top of the Clogher Valley Formation yielded late Courceyan age (emend. = MFZ8). These rocks are equivalent to the red beds and overlying Navan Group in the North Midlands Province and record the Tournaisian (Ivorian) transgression in this area. Further east (Armagh area, Belfast, Cookstown), terrigenous and marginal marine conglomerate, sandstone, mudstone, and limestone of Ivorian age have been recorded. A mudstone in this area yielded a CM Biozone age (Ivorian) (Geological Survey of Northern Ireland 1985; Sevastopulo & Wyse Jackson 2001; Mitchell 2004). To the west, in the Omagh Syncline, <600 m of conglomerate, sandstone, and shale are recorded. In County Donegal, an isolated thick succession of conglomerate and sandstone (Edergole Formation, Eske Sandstone Formation) yielded a CM miospore biozone (Ivorian; Graham & Clayton 1994). In the west, the Tournaisian marine transgression reached the southeast flank of the Ox Mountains – Ballyshannon Height during PU miospore biozone times (Higgs 1984).

In the Lough Allen Basin, the lowest Tournaisian rocks are conglomerate, red sandstone, and mudstone containing pedogenic carbonate, locally topped by the upper sandstone of the Kilcoo Formation. These “Basal Clastics” become finer-grained towards the south (basin centre) and can be traced as far southwest as Boyle. At Boyle (see Dunmore Province), grey sandstone of the Boyle Sandstone Formation rests on thinly developed Kilcoo Formation.

The **North Midlands Province (NMP)** covers approximately the area of the later Dublin Basin (Fig. 1). The succession can be divided into fluvial red beds at the base and a marine succession on top comprising the Navan Group (Andrew & Ashton 1985) of shallow-water origin and the overlying Cruicetown Group (Rees 1992) of deeper water origin. Variations in the proportion of the lithologies in the Navan Group occur across the North Midlands Province but the overall sedimentation follows the basic depositional pattern outlined below. In general, the sedimentation within the Navan Group becomes more sandy and regionally restricted northwards and westwards (e.g. Rockfield Sandstone Member in the Moathill Formation; Fig. 5).

Sedimentation began with up to 45 m thick interbedded red and polymict conglomerates, breccias, sandstone, and siltstone with pedogenetic carbonate at some horizons. The marine transgression at the base of the Navan Group is marked by bioturbated, mixed beds of sandstone or limestone and mudstone, sandstone, and rare (oolitic and skeletal) limestone of PC miospore Biozone age. This is locally (at Navan; Fig. 5) overlain by the Liscarton Formation consisting of argillaceous, peloidal, and skeletal limestone with corals and brachiopods. In *Pseudopolygnathus multistriatus* conodont biozone times (lower Ivorian), a major regression is marked by 10 m to >60 m of shallowing-upward cycles with bioturbated calcareous mudstone and peloidal wackestone and packstone capped by fenestral micrites, the Stackallan Member of the Meath Formation. Sedimentation continued with sandstone, siltstone, shale, and limestone. Timing and sedimentation patterns are broadly similar to the

Dunmore Province to the west. The youngest unit in the Navan Group, the Moathill Formation, consists of burrowed silty calcarenite, siltstone, sandstone, unfossiliferous shale, mudstone, and bryozoan rich argillaceous limestone. These sediments represent a transition to a deeper water environment in the overlying Cruicetown Group.

The Cruicetown Group begins with over 200 m of nodular bedded, crinoidal argillaceous limestone interbedded with bioclastic shale (Slane Castle Formation), which is the lateral equivalent of the Ballysteen Limestone Formation in the Dunmore Province (BA; Shepard-Thorn 1963; Somerville & Jones 1985). In most of the North Midlands Province, these argillaceous limestones are overlain by Waulsortian limestone discussed below. However, towards the northern part, where no Waulsortian was deposited, the same lithologies (Ballysteen Limestone Formation) continue to the top of the Tournaisian (Sevastopulo & Wyse Jackson 2001).

The **Kildare Province (KP)** is the northeastern extension of the Limerick Province, bounded in the east by the Leinster Massif. Undated red beds are overlain by the c. 26 m to 40 m Ferbane Formation (equiv. to LLS) consisting of interlaminated heterolithics, shale, siltstone, and fine-grained sandstone. These are overlain by up to 80 m of thick-bedded, pale-grey sandstone, limestone, calcareous siltstone, and laminated shale and sandstone of the Cloghan Formation, the upper parts of which yielded a PC miospore biozonal age and are correlated with the Ballymartin Limestone Formation (BT) of the Limerick Province (McConnell & Philcox 1994). The Feighcullen Formation (which has been used as

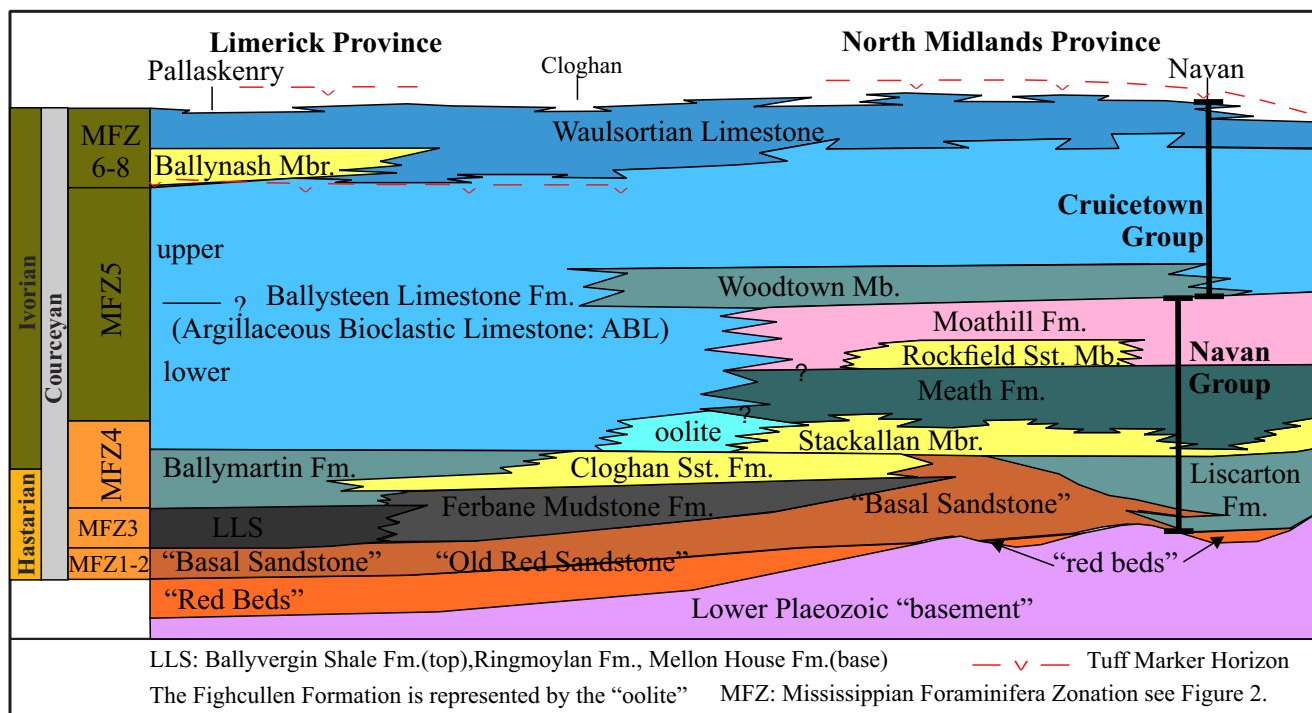


Fig. 5: Lithostratigraphic correlation of Tournaisian rocks between the North Midlands Province and the Limerick Province (modified after Gately et al. 2005).

the basal unit for the target carbonate reservoir in the Hot Lime project) consists of c. 143 m of varied shallow-water limestone, including oolites, skeletal calcarenite, and micrite with minor shale and sandstone. It is correlated with the base of the Ballysteen Limestone Formation (BA) of the Limerick Province (Sevastopulo & Wyse Jackson 2001). The Boston Hill Formation of the Kildare Province consists of >600 m of argillaceous, skeletal, laminated limestone and shale. It is equivalent to the Ballysteen Limestone Formation of the Limerick Province. These limestone units are late Tournaisian in age and correlated with similar limestone of the Malahide Formation north of Dublin near Swords.

The Limerick Province (LP) (Philcox 1984) extends from the northern margin of the South Munster Basin into the Irish Midlands (see Fig. 1). As the sea gradually transgressed northwards across the ramp, successively younger marine rocks were deposited on the “basement”. Laminated shales that directly overlie the Old Red Sandstone north of the Shannon (HD Biozone age, Hastarian) are absent further north in County Galway.

The earliest Tournaisian marine deposits in southeast Ireland (County Waterford) are shallow marine sandstone beds grading upwards into mixed sandstone/mudstone lithologies of the Castle Slate Formation with some shelly horizons during VI to HD Biozone times. These are overlain by bioclastic, partly oolitic limestone with minor shales, topped by mudstone and minor sandstone. Conodonts from the limestone are assigned to the *Polygnathus spicatus* Biozone (Hastarian; Sevastopulo & Wyse Jackson 2001; Sleeman 1977).

In the Shannon area (Figs. 1 and 5), the basal succession consists of the Lower Limestone Shales Group (LLS) and is dominated by the Mellon House Formation at its base with dark-grey, laminated siltstone, sandstone and the Ringmoylan Formation with calcareous shales, with thin bands of bioclastic limestone, topped by the Ballyvergin Shale Formation, a distinct greenish-grey non-calcareous mudstone forming a prominent regional marker horizon. The Lower Limestone Shales Group is c. 70 m thick, with a deposition centre situated near Shannon Town. The *P. inornatus* conodont Biozone (Hastarian) is recorded from the Ringmoylan Shale Formation (Somerville & Jones 1985) while a PC biozonal age was reported by Clayton et al. (1980) from the Ballyvergin Shale Formation (BV). The Lower Limestone Shales Group mark the transition from a non-marine environment to a tidally influenced marine environment. This dominantly siliciclastic succession is overlain by c. 10 m to 60 m of the Ballymartin Formation (BT) consisting of alternating thin, pale-grey, bedded, argillaceous, bioclastic limestone and dark-grey, calcareous shale in approximately equal proportions. These strata include a rich fauna that consists of brachiopods, bryozoans, crinoids, and corals of PC Biozone age (Sevastopulo & Wyse Jackson 2001). Fully marine conditions reached the northern margin of the Limerick Province during *P. multistriatus* biozone times (base Ivorian), with the deposition of c. 190 m of thick-bedded, bioclastic, argillaceous limestone and mudstone of the Ballysteen Limestone Formation (BA; Lewis 1986), on a deeper shelf or ramp (Somerville & Jones 1985; Somerville & Stroger

1992). In eastern parts of the ramp, widespread development of oolite suggests a shallower environment. The top of this unit (BA) is diachronous, being of *P. mehli* Biozone age (Ivorian) in the Shannon area and *Polygnathus cf. bishoffi* age on its northern margin near Gort (Lewis 1986).

3. South Munster Basin during the Tournaisian (MFZ1 to MFZ8)

The South Munster Basin (Fig. 1; George et al. 1976), an extensional half-graben, lies south of an important facies divide, which can be traced in a stepped configuration, following the pattern of long-lived and deep-seated basin faults, from Kenmare in the west to Cork Harbour in the south (Naylor et al. 1989). To the south of this facies divide, predominantly terrigenous sediments were deposited, whereas to the north of the divide, on the North Munster Shelf, Dinantian limestone dominates. The South Munster Basin underwent subsidence from latest Devonian times, which continued into the Tournaisian (Hastarian) with the deposition of the Kinsale Formation consisting of mudstone, siltstone, and sandstone. From latest Courceyan to Brigantian times, the deposition and subsidence of limestone on the North Munster Shelf equalled and exceeded that in the basin leading to a thicker carbonate succession on the North Munster Shelf. Within the South Munster Basin, differential subsidence led to the formation of the Bantry and Kinsale sub-basins, the Sheep's Head, and Glandore Highs (Naylor et al. 1989, 1996). Sedimentation resumed in early Ivorian times after a hiatus of non-deposition at the end of the Hastarian due to changes in subsidence rates and/or eustatic sea-level fluctuations, with the deposition of calcareous mudrock and crinoidal limestone of the Courtmacsherry Formation in the Basin centre and the Reenydonagan Formation in the Bantry sub-basin (PC Biozone age). In the Cork area in the east and the Kenmare area in the west (south of the Cork-Kenmare line), the Ballysteen Limestone Formation is overlain by Waulsortian facies. In the Cork area, the base of the Viséan is marked by the Cork Red Marble followed by the Little Island and Clashavodig Formations. Further west, black, richly pyritic, carbonaceous shales with fine-grained carbonate and nodular phosphate of the Lispatrick Formation encompass the whole of the Viséan stage in a highly condensed succession. Some of the basin faults were inverted (reverse movement) during the Variscan Orogeny, leading to local erosion and redeposition of carbonates within the basin (Sleeman & Pracht 1994; Naylor et al. 1996).

4. Tournaisian carbonate buildups and mudmounds: Waulsortian limestone

The Waulsortian limestone consists of massive, pale-grey fine-grained, limestone, typically with stromatactis structures and micrite (“carbonate mud”). Main skeletal components are bryozoans, shell fragments, ostracods, echinoderms, foraminifers, calcareous algae/problematica, sponges,

brachiopods, bivalves, gastropods, rostroconchs, and crinoids. Based on the skeletal and non-skeletal components, Lees & Miller (1995) and Lees (2018) divided the Waulsortian facies into four “phases”, interpreted to be related to depth of deposition. Phase A was deposited in “deep” water (c. 300 m depth) and phase D (c. 90 m) within the photic zone. Not all phases need to occur. Individual mudmounds are occasionally separated by coarse-grained crinoidal limestone beds, referred to as the “off-bank” facies. These beds may mark temporary changes in the depositional environment and/or coalescence of mudmounds. The Waulsortian Limestone in Ireland is late Tournaisian (MFZ7) to early Viséan (MFZ9; e.g. Limerick Province) in age, based on very limited foraminiferal and conodont data (Sevastopulo 1982; Sevastopulo & Wyse Jackson 2001; Somerville 2003; Pracht et al. 2004, Geological Survey of Ireland 2019). Both top and bottom of the Waulsortian limestone are diachronous.

The oldest Waulsortian facies is reported from the northern margin of the South Munster Basin. Here, the succession is up to 420 m thick, with the earliest part in the *carina* conodont Biozone (base Ivorian; Sleeman et al. 1986). In the Cork Syncline around Cork Harbour, the base of the Waulsortian facies is slightly younger, within the *anchoralis* conodont Biozone. In the Shannon Trough, the base is latest *carina* Biozone (*Dollymae bouckaerti* sub-Biozone) and in the Dunmore Province foraminifera indicate a MFZ6 and MFZ7 age (Lees 2018). In the Dublin Basin, the base is con-

siderably younger than the *anchoralis* Biozone, late Ivorian to early Chadian (emend.) in age. The top of the Waulsortian facies is highly diachronous and difficult to date. In most of the shelf area, the top is of late Tournaisian age, but in the South Munster Basin the top is reported to be of early Viséan age (Sleeman & McConnell 1995) and in the southwest (Tralee Bay) the youngest ages are recorded to be Arundian (Labioux 1997).

The thickest developments of Waulsortian facies occurs in areas with high subsidence rate. In these areas, Waulsortian mudmounds amalgamate and stack to form large masses. Three main deposition centres can be distinguished (Fig. 6): the region between Cork and the Galtee Mountains, the Shannon Trough and the Dublin Basin. In the axial region of the Shannon Trough, the Waulsortian facies is estimated to be up to 1,200 m thick (Shepard-Thorn 1963). Between Cork and the Galtee Mountains thicknesses of between 350 m to 700 m are reported. In the deposition centre of the Dublin Basin, >500 m are recorded (Strogen et al. 1996). Between these areas with high subsidence, the Waulsortian facies usually thins to <200 m and approaching the zone where mudmounds become isolated (westwards and northwards) to <100 m near Gort (Lewis 1986). In the south County Galway area around Loughrea, the Waulsortian forms large mudmounds several tens of metres in thickness (Lees 1964, 1994, 2018; Lees & Miller 1985, 1995). There, it forms the typical sharp basal contact with dark grey argillaceous limestone of the underlying Ballysteen Formation. In the northern part of the shelf (e.g. Dunmore Province, Northern Province), the Waulsortian Limestone, if present, occurs as isolated lenses. Further to the north, the Waulsortian facies is absent and replaced by a distinct lithological unit (?“off-reef” facies of Philcox 2008) of thinly-bedded, light-grey, usually fine-grained, well sorted, crinoidal limestone and minor mudstone with poorly developed stromatactid cavities (?WA equivalent; Pracht & Somerville 2015), which commonly divides the argillaceous bioclastic limestone. This “off-reef” facies indicates a possible temporary deepening of the depositional environment (? = phase D of Lees & Miller 1995) and the spatial arrangement suggest fault-controlled subsidence. The cessation of growth of the Waulsortian buildups appears to be related to a relative sea-level fall resulting in increased water movement on the sea floor (Lees 2018). The northern margin of the Waulsortian facies can be traced from the northern margin of the Dublin Basin to the Dunmore Province in the west. No Waulsortian buildups occur in the Western Province (Philcox 2008; Geological Survey of Ireland 2019). A few isolated buildups are known from the Northern Province.

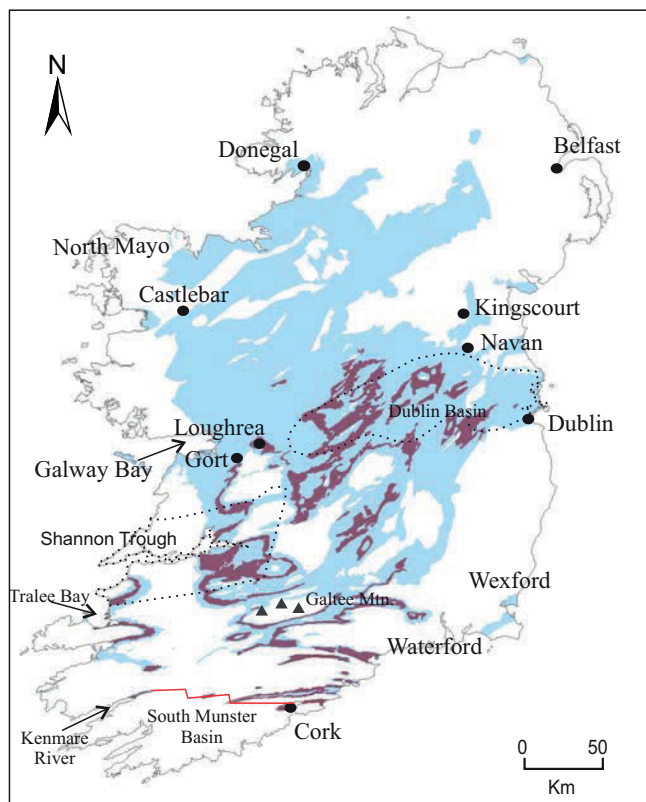


Fig. 6: Outcrop of Carboniferous Limestone (blue) and Waulsortian Limestone (magenta); modified after Sleeman et al. (2004).

5. Viséan carbonate platforms, ramps and post-Waulsortian buildups (MFZ9 to MFZ14)

During the Viséan (Fig. 7), the marine transgression increased the area of carbonate sedimentation and deep-water basins developed in areas where major subsidence occurred

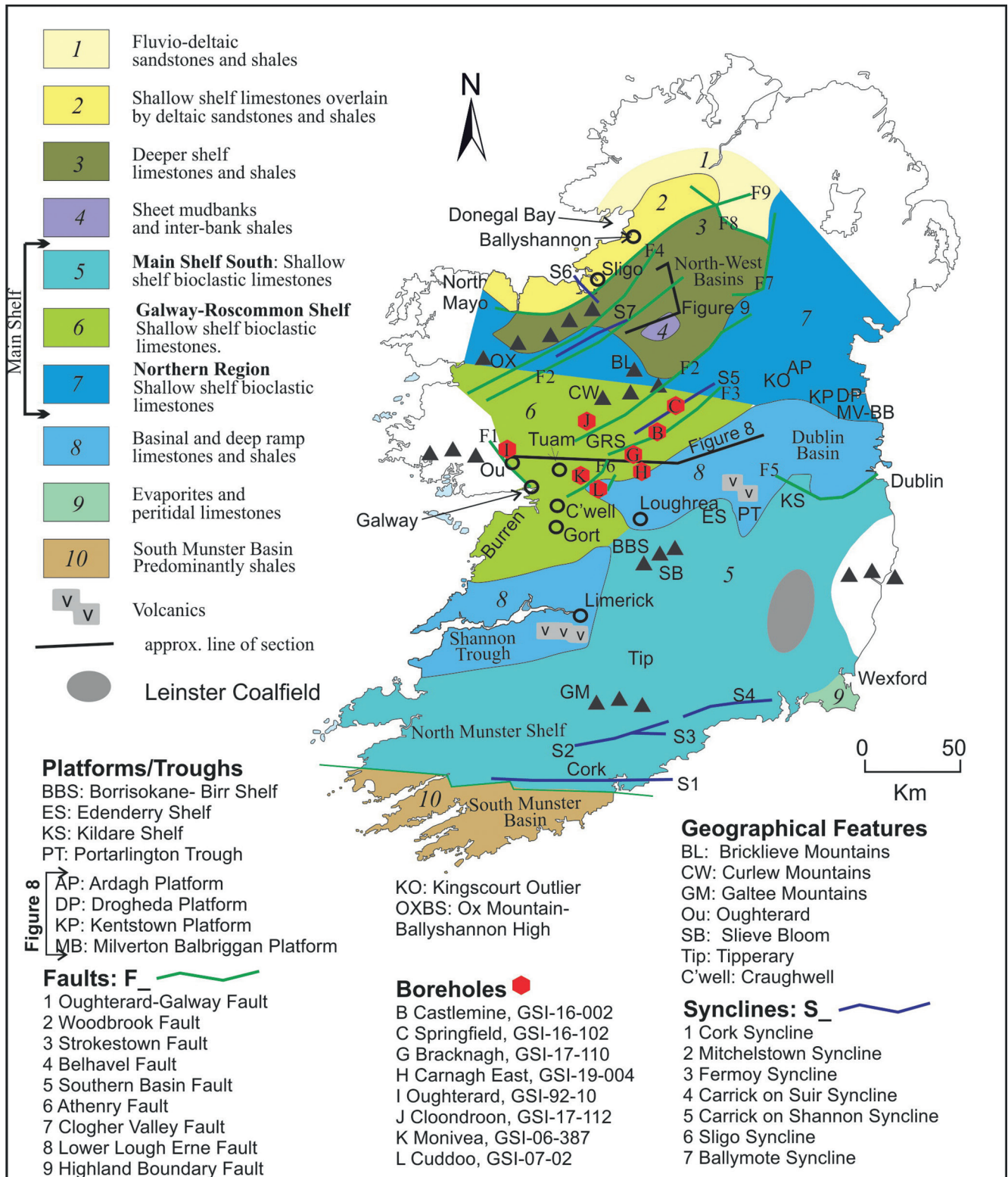


Fig. 7: Generalised Irish shelf during the Viséan with principal features as mentioned in the text.

Fault. Several siliciclastic horizons within the limestone dominated Cregg Limestone and Illaunagapul Limestone Formations indicate movement on the fault during late Tournaian to early Viséan times (Morris et al. 2003; Lees & Feely 2016). To the north, the western extension of the Woodbrook Fault separates the Oughterard succession from the Mayo succession.

The Tubber Formation of the Burren region (Gallagher et al. 2006; Pracht et al. 2004) is approximately laterally equivalent to the Oakport, Ballymore and Croghan Limestone Formations on the Galway-Roscommon Shelf as far north as the Carrick on Shannon Syncline, and, at the western margin, to the Cregg, Oldchapel, Illaunagapul, Ardnasillagh and Corranellstrum Formations. On the Galway-Roscommon Shelf, the base of the Viséan succession is marked by a well-bedded to massive, pale-grey, fine- to medium-grained shallow-water limestone with occasional intervals of dark, fine-grained, argillaceous limestone beds of the Oakport Limestone Formation and Cregg Formation on the western shelf margin. In the Boyle borehole, near the southeastern margin of the Curlew Mountains, the base of the Viséan has been confirmed near the base of the Oakport Limestone Formation with the first appearance of the foraminifer *E. simplex*. At the western shelf margin, the Oldchapel Formation consists of argillaceous fine-grained calcarenites and calcilitites with bird's eye textures and peloids, which contain minor calcareous shale. They are Chadian (MFZ9) to early Arundian (MFZ10) in age (Pracht & Somerville 2015). The presence of the key foraminifers *Eoparastaffella simplex*, *Pseudolituotubella*, *Brunsia*, *Pseudoammodiscus*, and *Eostaffella* represent an assemblage characteristic of Zone MFZ9 (as well as the algae *Koninckopora* sp. with monolaminar wall and abundant *Luteotubulus*). However, the presence of archaetid foraminifers (*Uralodiscus* and *Paraarchaediscus* @ *involutus* stage) in the upper part of the unit confirms an early Arundian (MFZ10) age. The presence of the rugose coral *Siphonodendron martini*, *Dorlodotia briarti* along with *Palaeosmia murchisoni* confirm an early Arundian age.

The more argillaceous parts of the Oakport Limestone Formation show bioturbation, chert nodules and occasional fenestral fabrics with pedogenic structures (e.g. rootlets) and oncoids. Large solitary rugose corals (*Palaeosmia murchisoni*), cerioid tabulate colonies (*Michelinia megastoma*), and fasciculate rugose coral colonies (*Siphonodendron martini* and *Dorlodotia briarti*) occur in the upper part of the formation. Brachiopods, bryozoans, and crinoids are the other main macrofaunal elements of the formation. Cyanophytes in some samples suggest an intertidal depositional environment. The presence of well-rounded and sorted bioclasts and peloids in medium-grained grainstone attest to turbulent high-energy environments. The trend to open shelf sedimentation persists throughout the unit. However, there are also distinct black non-calcareous mudstone beds occurring locally indicating sedimentation in quieter carbonate starved water. The Oakport Limestone Formation is c. 150 m thick in the Castlemine borehole (also at Gatestown) but thins rapidly northwards towards the North West Basins to <50 m. In some areas towards the southeast, the unit is lo-

cally c. 300 m thick, which is attributed to fault-controlled subsidence.

Furthest to the east, in boreholes GSI-17-110 (Bracknagh) and GSI-19-004 (Carnagh East) the Oakport Limestone Formation is unusually argillaceous, but contains oolitic beds with similar microfauna to the Tober Colleen Formation in the Dublin Basin (Morris et al. 2003; Fig. 8). In borehole GSI-19-004, a highly cyclic unit with millimetre thick couplets of calcareous mudstone and limestone straddling the Chadian/Arundian boundary exists. The lower part of this unit is similar to the Tober Colleen Formation of the Dublin Basin.

In the central, northern, and eastern parts of the Galway-Roscommon Shelf, the Oakport Limestone Formation is overlain by the Ballymore Limestone Formation which consists of 30 m to >200 m of fine- to medium-grained, well bedded and bioturbated argillaceous cherty limestone alternating with coarse-grained bioclastic limestone with shale interbeds. In thin section, the limestone is a moderately to poorly sorted, fine- to coarse-grained, skeletal wackestone and grainstone, and argillaceous intraclastic skeletal wackestone/packstone in which crinoids, foraminifers (especially archaetidiscids), brachiopods, colonial rugose corals, ooids, bryozoan, dasycladacean algae (monolaminar and bilaminar *Koninckopora* and *Kamaena*), and rare red algae (aoujgaliids) occur. Sponge spicules are also locally common. Micritised ooids occur but are rare.

The lateral equivalent at the western shelf margin are the Illaunagapul and Ardnasillagh Formations (Fig. 8). The Illaunagapul Formation is a siliciclastic-rich, c. 84 m-thick unit. The Illaunagapul and Ballymore Limestone Formations are Arundian (MFZ10–11; Conil & Lees unpubl.) in age, whereas the Ardnasillagh Formation is mostly late Arundian (MFZ11) but their top beds are earliest Holkerian (MFZ12). The Arundian age is based on the presence of the key foraminifers *Uralodiscus rotundus* and *U. settlensis*, *Globoendothyra*, *Glomodiscus*, *Paraarchaediscus* @ *involutus* stage, and *Forschia*, as well as the dasyclad alga *Koninckopora tenuiramosa*, rare *Nanopora*, and *Saccaminopsis*. The early Holkerian (MFZ12) age is based on the appearance of *P. @ concavus* stage. The Arundian (MFZ10–11) to early Holkerian (MFZ12) age is confirmed by the presence of the coral species *S. sociale*, *Siphonodendron martini*, and *Siphonophyllia garwoodi*, the latter two indicating a possible early Holkerian age. *Clisiophyllum multiseptatum*, *Siphonophyllia caninoides*, and *Michelinia megastoma* are reported from 6 m above the base of the Ballymore Limestone Formation in Keellogues quarry (location of Boyle borehole; Fig. 1) by Kelly & Somerville (1992), Pracht & Somerville (2015), Geological Survey of Ireland (2019), Somerville (unpublished reports to GSI). Main skeletal components are crinoids, large solitary rugose corals, tabulate coral colonies, brachiopods, bryozoans, and locally common gastropods (Ill-aunagapul Formation).

The sediments of the Ballymore Limestone Formation were deposited in a variety of depositional environments, from shallow-water, high-energy open shelf (upper and middle unit) to moderately deep water with moderate to low wa-

ter energy setting (mid- to outer open shelf: lower unit). The well-sorted crinoidal grainstone formed in a high-energy, shallow-water shelf setting, but the argillaceous skeletal wackestone with sponge spicules suggest a lower energy, deeper water setting in which foraminifers are scarce and, as at Castlemine, calcareous algae are absent. The biota in the grainstone is moderately rich and diverse implying shallow-water turbulent conditions within the photic zone. Overall, a deepening towards the west and southwest can be demonstrated, also in addition to a southeastward deepening within the fault-block (see below). There is a marked increase of mud content westward and southwestward.

In the northern parts of the Main Shelf (Galway-Roscommon Shelf), the Ballymore Limestone Formation is overlain by c. 140 m of dark-grey, fine- to medium-grained argillaceous, commonly nodular, bioclastic limestone, thin bedded pale-grey bioclastic limestone, and black calcareous mudstone of the Croghan Limestone Formation, which is of Holkerian (MFZ12) to early Asbian (MFZ13) age (Geological Survey of Ireland 2019; see also Morris et al. 2003). At the western shelf margin (see Fig. 8), the lateral equivalents are the Holkerian (MFZ12) *Aughnanure Oolite* and (Holkerian to Asbian) *Corranellistrum* Formation. The c. 30 m thick *Aughnanure Oolite* consists of oolitic bioclastic calcarenite with local concentrations of crinoid and shell debris. Cross-lamination and low-angle cross-bedding occur on several scales. The 100–120 m thick *Corranellistrum* Formation consists of medium-grey, clean, fine- to medium-grained, bioclastic calcarenite in medium to thick beds. The macrofauna mainly consists of brachiopods and corals.

In the northernmost part of the Galway-Roscommon shelf, the base of the Croghan Limestone Formation is of latest Arundian age, based on the presence (c. 7 m above base) of the key foraminifers: *Uralodiscus rotundus*, *U. settlensis*, *Glomodiscus*, *Paraarchaediscus @ involutus* stage, *Paraarchaediscus @ concavus* stage *Forschia* (typical of Zones MFZ10–11), as well as the dasyclad algae *Koninckopora tenuiramosa*. However, above this horizon the presence of common *Paraarchaediscus @ concavus* stage is typical for the Holkerian (MFZ12). The appearance of *Valvulinella* at 25.3 m below the top suggests an Asbian age for the upper unit. The coral *Solenodendron hibernicum* appears in the lower part, succeeded by *Solenodendron furcatum* in the upper part; the latter is a small coral species, diagnostic of the Asbian to Brigantian (Nudds 2013; Somerville et al. 2009) and forms part of a phylogeny that evolved from the larger older species *S. hibernicum*, which is commonly recorded in Ireland around the Holkerian-Asbian boundary (Clarke 1966; Nudds 2013).

The various lithofacies in the Croghan Limestone Formation indicate deposition in environments that range from deeper marine, open shelf, below the photic zone, to very shallow high-energy intertidal environment. A general trend emerges in which the lower part of the formation represents a shallow marine environment with low to high water energy levels in an inner shelf/protected lagoonal environment. This is followed by a more open marine environment with common green algae. The main, middle part of the formation is

represented by sediments deposited in (very) shallow-water and high-energy levels in the intertidal zone of an inner shelf. In the upper Croghan Limestone Formation a deepening of the water occurred (Geological Survey of Ireland 2019).

In the northwest Main Shelf area (GSI-17-112, Cloondroon borehole), a c. 1 m thick calcareous sandstone bed with some bioclasts occurs, which is possibly a distal tongue of the Mullaghmore Sandstone Formation. South of the Lower Palaeozoic Slieve Dart Inlier, the formation becomes considerably more argillaceous and contains beds of mudstone.

Near the northern margin of the Main Shelf with the North West Basins, the succession is followed by the Asbian *Bricklieve Limestone Formation*, which consists typically of medium- to thick-bedded, grey, cherty, bioclastic limestone, with a coral-rich fauna and very minor mudstone near the base (Caldwell & Charlesworth 1962). In the Springfield borehole, the base of the formation is upper Viséan (Asbian, MFZ13–14) in age, based on the presence of the diagnostic rugose coral *Solenodendron furcatum*. At its type locality in the Bricklieve Mountains, County Sligo, the age of the Bricklieve Limestone Formation is early Asbian (MFZ13) to late Asbian (MFZ14) (MacDermot et al. 1996; Morris et al. 2003; Cózar et al. 2005; Aretz et al. 2010; Somerville et al. 2009; Somerville & Waters 2011).

Main components of the Bricklieve Limestone Formation at Springfield are intraclasts, hexactinellid sponge spicules, fenestellid bryozoans, calcispheres, crinoids, trilobites, and colonial rugose corals (*Solenodendron*), with rare foraminifers and an absence of calcareous algae. A similar microfacies was recorded in the lower part of the formation at Kesh Corann in the Bricklieve Mountains (Somerville et al. 2009; Fig. 14). Higher strata in the formation, exposed further north (County Sligo), contain thick *Siphonodendron* biostromes (Caldwell & Charlesworth 1962; Dixon 1972; MacDermot et al. 1996; Somerville et al. 2009; Aretz et al. 2010; Somerville & Waters 2011) which can form regionally extensive bio-events.

The Bricklieve Limestone Formation was deposited in an open shelf setting. The skeletal wackestone with abundant sponge spicules, fenestellid bryozoan sheets, and trilobites formed in a moderately shallow-water, low-energy shelf. However, the presence of intraclasts in the facies suggests periodic turbulence, possibly storm-induced.

In the southern parts of the Galway-Roscommon Shelf, apart from a few outliers in the northeast (Lecarrow, Toberdan) the Croghan Formation is overlain by pale-grey and thickly bedded to massive bioclastic limestone of the Asbian-aged (MFZ13–14) *Burren Limestone Formation*. This formation crops out extensively in its type area, the “Burren” in County Clare (Gallagher 1996; Gallagher et al. 2006; Pracht & Somerville 2015).

On the Galway-Roscommon Shelf, the age is based on the presence of the key foraminifers: *Paraarchaediscus @ angulatus* stage, *Nodosoarchaediscus*, *Koskinotextularia*, *Lituotubella*, the red alga *Ungdarella*, and the algae/problematicum *Kamaena*, *Salebra sibirica*, and *Diplosphaerina*. A late Asbian (MFZ14) age is indicted in some boreholes

north and northeast of Galway city by the presence of bilaminar palaeotextulariids, *Pseudoendothyra*, *Neoarchaediscus*, *Cribrostomum lecomptei*, *Koskinotextularia cribriformis*, and *Palaeotextularia longiseptata*. This assemblage is typical of the microfossils recorded in the late Asbian Terraced Member of the Burren Formation in the type section in County Clare (Gallagher et al. 2006). Similarly, microfossils recorded from a sample taken from the upper bench in the working quarry, Lecarrow No.1 include abundant *Saccaminopsis fusilinaeformis*, *Neoarchaediscus* sp., and *Nodosarchaediscus* sp. of latest Asbian to early Brigantian age (MFZ14–15; Aretz et al. 2010). The heterocoral *Hexaphyllia* is locally abundant in boreholes north of Galway City. *Lithostrotion* sp. colonies have been found in several road cuts along the Tuam-Gort motorway.

In the central part of the northern Galway- Roscommon Shelf, up to 170 m of the formation have been drilled and intervals of dark-grey, argillaceous, bioclastic limestone and some black mudstone occur locally as does mudbank facies with fine-grained light-grey limestone. Mudbank facies in the Burren Limestone Formation has not been reported from the Burren region to the south, but is known from similar aged limestone in localities in County Cork (Gallagher et al. 2006).

Most of the limestone in the Burren Limestone Formation is composed of fine-, medium-, and coarse-grained, clean skeletal packstone and grainstone, with abundant bioclasts. The bioclasts are brachiopods, brachiopod spines, bryozoans, bivalves, crinoids, foraminifers, ostracods, calcispheres, green and red algae, and microproblematica (*Eotuberitina* and *Diplosphaerina*). The foraminiferal assemblage is usually rich and diverse. Calcareous green algae (*Koninkopora tenuiramosa*, *K. inflata*, *Kamaena*) are abundant in some boreholes (e.g. GSI-16-103, Curraghmore). However, red algae (aoujgaliids, *Stacheia*) occur in most samples, indicating, overall, a shallow-water shelf facies. The problematicum *Draffania biloba* and *Eotuberitina* are recorded in some boreholes north of Galway City (e.g. Keekil, Angliham) together with the heterocoral *Hexaphyllia*. Some samples contain unusually rich and diverse algal and problematicum assemblages.

The mudbank facies consists of fine-grained wackestone and packstone with peloidal and grumulous mud fabrics. Geopetal cavities occur, with radial fibrous calcite cements present. In the Keekil borehole, fenestellid sheets of ten line cavities, along with fistuliporid and trepostome bryozoans. Crinoids are common elements but dasyclad algae are absent, red algae (aoujgaliids) are rare, and foraminifers are very sparse (to absent, Toberdan). At Keekil, the sponge spicules are common and the problematicum *Draffania biloba* and the heterocoral *Hexaphyllia* is recorded.

The Burren Limestone Formation is dominated by cyclothem sequences (from shallow subtidal to slight deepening to shallowing followed by emergence) of platform carbonates during the later part of the Asbian and Brigantian (Gallagher 1996). However, more argillaceous lithologies also occur. The presence of peloidal geopetal sediment in cavities in the Keekil borehole suggests a mound flank facies in a

deeper shelf setting. This is supported by the occurrence of trilobites and sponge spicules in some boreholes, which may suggest a middle to outer, lower energy platform facies.

In the Burren region, the early Viséan succession is characterised by medium-grey, crinoidal calcarenites with peloidal, oolitic horizons and shaly units of the Tubber Formation overlain by the Burren Limestone Formation. This is followed by the Slievenaglasha Formation which shows similar cyclic (without emergence horizons) crinoidal and intraclastic limestone of Brigantian age. In the Burren, the succession is capped by a palaeokarst surface (Gallagher et al. 2006; Pracht et al. 2004).

The most northerly area, north of a line from Clew Bay via the Curlew Mountains to the Longford Down Inlier, is referred to as the **Northern Region** (Sevastopulo & Wyse Jackson 2001). The Viséan sequence in the area is complex and only the Sligo-Ballymote Syncline and Donegal are very briefly summarised. Successions in the northeast (Armagh, Clogher Valley Benburb, Fintona Block, Kesh-Omagh, Newtownsteward, Lisnaskea, and Cavan-Monaghan) are not discussed.

Between the southeastern flank of the **Ox Mountains-Ballshannon High** and the **Ballymote Syncline** (Fig. 7), the earliest Carboniferous rocks are the Moy Sandstone Formation consisting of conglomerate, red, green, and grey sandstone up to 140 m thick overlain by the Dargan Limestone Formation with crinoidal, oolitic, and argillaceous limestone, c. 60 m thick. In the Castlebar area, the Moy Sandstone Formation is overlain by shallow-water limestone containing siliciclastic material of the Lough Akeel Oolite and Castlebar River Limestone Formation.

In the **Sligo Syncline** (Oswald 1955), the Ballyshannon Formation consists of pale grey, crinoidal shallow-water limestone (Lower Viséan to Arundian) and rests on a metamorphic basement or on a thin mixed Tournaisian succession of pebbly sandstone, argillaceous micrite, skeletal calcarenite, and oolite (Twigspark Formation; MacDermot et al. 1996). Along the coasts of **Donegal Bay** and in **North Mayo**, the lower Viséan succession evolves from fluvial conglomerate and sandstone to marginal marine sandstone, shale, and shaly limestone (early Viséan Moyny Limestone Formation in North Mayo; Shalwy Formation in Donegal). Overlying, fully marine, argillaceous limestone and shales of the Rinn Point Formation are lateral equivalents to parts of the Ballyshannon Limestone Formation further east. This succession records a marine transgression (Graham 1996; Graham et al. 2014). In Clew Bay, a PU miospore biozone age has been retrieved from the non-marine Capnagower Formation. The Muckross Head Formation shows a gradual increase in siliciclastic input resulting in the deposition of pebbly (non)- calcareous sandstone, oolitic, sandy limestone, micrite, and mudstone.

In the **Sligo Syncline**, the shallow-water limestone is overlain by the Bundoran Shale Formation: dark fossiliferous shales, silty in the upper part. The fossil assemblage consists of crinoids, echinoids, brachiopods, bryozoans, and corals. Siliciclastic sand of the Mullaghmore Sandstone Formation of deltaic origin spread from the north-northwest and

the **Drogheda Platform**, the **Kentstown Platform**, and, north of the early Palaeozoic Longford-Down inlier, the **Ardagh Platform** (Fig. 9, for location see Fig. 7). The stratigraphy on the various platforms is simplified and summarised in Fig. 9. Some of the main differences between the platforms are in the onset of sedimentation, erosion events, tilting of blocks, subsidence, and uplift history.

The succession on the **Milverton/Balbriggan Platform** is named Milverton Group (Nolan 1986; Pickard et al. 1994; Strogen et al. 1996). The base of the Milverton Group is represented by the McGuinness Formation of late Courceyan age overlain by the late Courceyan to Chadian Lane Formation. This is topped by an angular unconformity due to temporary relative sea-level fall, followed by erosion. Above this unconformity and cut by another is a local unit, the Smugglers Cave Formation. The succeeding Holmpatrick Formation consisting of well-bedded bioclastic limestone with oolites near the base. The limestone of the Holmpatrick Formation is the result of a marine transgression at the beginning of the Arundian. The Holkerian and Asbian Mullaghfin Formation is very thin on this platform (Pickard et al. 1994). Shallow-water carbonate mudbanks were developed along the platform margin at different times. The **Drogheda Platform** is located on the northern side of the Milverton/Balbriggan Platform and developed as an asymmetric graben (Rees 1992). The lower Viséan (Chadian) shallow-water carbonates of the Yellowbatter and Tullyallen Formations are overlain by the dark basinal limestone of the Mornington Member of the Lucan Formation. This change in lithology is subsidence-related caused by movement on the northern boundary fault that continued into early Arundian times. To the south, up the ramp, the shallow-water limestone of the Crufty Formation was deposited. With the Platin Formation, the shallow-water sedimentation prograded northwards through most of the Arundian and Holkerian times. In Asbian times, the shallow-water, high-energy carbonates of the Clonlusk Formation were deposited with locally developed carbonate mud-mounds. In Brigantian times, the basinal limestone and shales of the Loughshinny and Donore Formations transgressed over the platform margin and the platform became progressively drowned. On the **Kentstown Platform** (McConnell et al. 2001; Pickard et al. 1994), the <200 m-thick Navan Group of Courceyan age is preserved locally. Uplift of the platform and erosion, which removed most of the Courceyan sequence, continued until late Chadian time. Above the unconformity, a similar succession as on the Drogheda Platform was deposited (McConnell et al. 2001). The **Ardagh Platform** (Strogen et al. 1996) occupies the northern half of the Kingscourt Outlier. The Viséan is represented by the >850 m thick Milverton Group, which rests on a thin Courceyan succession (Cruicetown Group) in the southern part of the platform, but directly on Lower Palaeozoic rocks further north. The Milverton Group on the Ardagh Platform includes the early Viséan Crufty Formation, the early Viséan to Holkerian Holmpatrick and Platin Formations, and the Asbian Mullaghfin Formation, which are similar to their equivalents on the Drogheda and Kentstown platforms. The overlying Brigantian Deer Park Formation

consists of shallow-water crinoidal calcarenites and thinly bedded argillaceous limestone (Strogen et al. 1996). Pendleian and Arnsbergian sediments onlap these rocks above an erosion horizon.

To the **north of the Galtee Mountains**, the Viséan succession contains increasingly more oolitic, very shallow, marine limestone and lacks mudbank facies. In the northeastern parts of the southern shelf, early Viséan basinal limestone, shales, and volcanic rocks are overlain by shallow-water limestone of Arundian age. A short temporary deepening represented by the Lagganstown Formation is followed by renewed shallow-water facies of the Hore Abbey Formation in the Asbian (Archer et al. 1996). Further east, the region was a shallow-water carbonate shelf with periodic emergence in the Asbian (Archer et al. 1996; McConnell & Philcox 1994; Tietsch-Tyler & Sleeman 1994). To the west of the **Leinster Coalfield**, the Waulsortian limestone is followed by cherty, crinoidal packstone of the Crosspatrick Formation (late Tournaisian to early Viséan), dark fine-grained, peloidal, and oolitic limestone of the Aghmacart Formation (early Viséan) and coral bearing limestone, shale, cross-bedded oolite, and fenestral micrite of the Durrow Formation (Arundian to Holkerian). The oolites are overlain by the Ballyadams Formation consisting of skeletal limestone rich in corals and brachiopods (Holkerian to Asbian) and cyclic carbonate sedimentation (Asbian to Brigantian). The Clogrennan Formation is a dark, cherty unit and forms the top of the succession. To the east of the Leinster Coalfield, Waulsortian limestone is absent and the Ballysteen Limestone Formation is overlain by c. 250 m thick Milford Formation of pale grey, crinoidal limestone, dark, fine-grained, peloidal grainstone, and skeletal limestone. In the **Wexford area** to the south (Fig. 7), the Ballysteen Limestone Formation is overlain by >500 m of Wexford Formation with fine-grained, shallow-water micrite, dolomite, and limestone breccia with evaporites (Tietsch-Tyler & Sleeman 1994). At the southern margin of the Dublin Basin, the **Kildare Shelf** and the **Edenderry Shelf** are separated by the **Portarlington Trough** (McConnell & Philcox 1994). On the Kildare Shelf, the Waulsortian limestone is overlain by late Tournaisian to Arundian Allenwood Formation consisting of peloidal and oolitic grainstone, peloidal mudstone, mudstone, and peloidal grainstone (Emo 1986), as well as the Edenderry Oolite Member with cross-stratified and oolitic grainstone on the Edenderry Shelf. The **Borrisokane-Birr Shelf**, to the west of Slieve Bloom, has 500 to 600 m of early Viséan shallow-water limestone of the Terryglass Formation deposited over the dark-grey, fine-grained, deeper water limestone of the Oldcourt Cherty Limestone Formation or directly on Waulsortian limestone. These beds are of Chadian age and include pale grey, cross-bedded, well-sorted, oolitic, and peloidal grainstone. They are overlain by dark-grey, peritidal limestone of the Lismaline Micrite Formation, also Chadian in age. In north **Tipperary**, the Slevoir Formation consists of dark-grey, well-bedded, fine-grained limestone and shale. It marks the return to normal open marine conditions in the Arundian (similar to the Ballymore Limestone Formation on the Galway-Roscommon Shelf). This is topped by Arundian

to Holkerian Borrisokane Formation of massive to thickly bedded crinoidal algal packstone and grainstone (Gatley et al. 2005).

In the **Mitchelstown Syncline**, the Waulsortian Limestone is overlain by the Johnstown Red Marble Formation (Cork Red Marble of the **Cork Syncline**) of Lower Viséan and possibly Arundian age. It consists of c. 80 m of (oolitic) limestone and red limestone breccia (Sleeman & Pracht 1994). The succeeding unit (**Cork Syncline: Little Island Formation; Mitchelstown and Carrick-on-Suir Synclines: Rathronan Formation**) consists of carbonate mudbank facies, which in turn is overlain by Asbian shallowing-upward carbonate cycles. Some cycles are bounded by palaeokarst and/or palaeosol surfaces as seen in the Clashavodig Formation in the Cork Syncline overlying the Little Island Formation. In the Mallow area and western part of the Mitchelstown Syncline, the Waulsortian facies reaches into the early Viséan and is overlain by the Copstown Limestone Formation with dark, fine-grained, skeletal limestone (Arundian to early Asbian; in the Mitchelstown and Carrick-on-Suir Synclines: Kilsheelan Formation) and overlain by the Asbian Hazelwood Formation with fine-grained mudbank limestone (in the Mitchelstown and Carrick-on-Suir Synclines: Rathronan Formation). This mudbank limestone is overlain by the Ballyclough Limestone Formation, which consists of stacked shallowing-upwards cycles with evidence of emergence at their tops. In the western part of the Carrick-on-Suir Syncline a thick oolite unit, the Ballyglasheen Formation, is the lateral equivalent to the Rathronan Formation and has been mapped by Keeley (1983). The youngest rocks west of Mallow are Brigantian limestone beds of the Liscarroll Formation (Gallagher & Somerville 1997) consisting of crinoidal and coral-rich limestone overlain by dark, cherty limestone.

6. Mississippian Basins

The Mississippian marine transgression in Ireland (and Britain) occurred during N–S to NNW–SSE extension, which resulted in the formation of basins, such as the Shannon Trough, Dublin Basin, and Lough Allen Basin. The initial phase of extension occurred during the Tournaisian to early Viséan and continued during the late Viséan after a relatively quiet time (Worthington & Walsh 2011).

The Shannon Trough in the west of Ireland and the Dublin Basin in the east of Ireland are separated by a narrow corridor of shallow shelf deposits. Sediment thicknesses for the Dinantian sequences in the Shannon Trough and Dublin Basin is with c. 2,000 m to 2,500 m in both basins similar, suggesting similar subsidence rates. However, the basin histories differ markedly. While the Shannon Trough remained a ramp system throughout the Dinantian (Somerville & Strogon 1992), the Dublin Basin evolved from a ramp in the Tournaisian into a horst and graben configuration in the early Viséan. In the Viséan, the cumulative subsidence in the Dublin Basin exceeded that in the Shannon Trough (Pickard et al. 1994; Strogon et al. 1996).

The South Munster Basin has a distinct Devonian–Carboniferous history and contains a dominantly terrigenous succession and for this reason, has been discussed above.

6.1 Shannon Trough

The Shannon Trough was initiated in the Courceyan by transtensional movement on basement faults at its margin (Strogon 1988; Sleeman & Pracht 1999). The basin is a half-graben and fault bounded at its southern side but presents a gentle ramp up to the northwest (Somerville & Strogon 1992). It extends offshore westwards as far as the Porcupine Basin. The line of highest subsidence of the basin probably ran along the Shannon Estuary in the late Viséan.

Ramp sedimentation in the Shannon Trough occurred throughout the Dinantian, without the break-up seen in the Dublin Basin (see below). However, basement fault involvement on its southern margin is attested by the distribution and migration patterns of volcanic centres in the Chadian to Arundian (Strogon 1988).

The Tournaisian succession has been described above as part of the Limerick Province. In northwest County Limerick, the Viséan succession is mostly continuous and is used here to demonstrate the evolution of the Limerick Ramp as a whole. The Waulsortian facies is conformably overlain by c. 460 m of Chadian to Arundian (MFZ9 to MFZ11), dark, generally unfossiliferous mudstone with thin beds of fine-grained, argillaceous limestone, assigned to the Rathkeale Formation (Shepard-Thorn 1963). The formation has been interpreted by Somerville & Strogon (1992) as ranging from distal ramp to basinal facies. The Rathkeale Formation is overlain by the 307 m thick Durnish Formation. This formation consists of uniform black argillaceous and cherty bioclastic limestone, which is of Asbian age (*Solenodendron furcatum*), near its top. The overlying c. 50–77 m thick Shanagolden Formation consists of black mudstone and well-bedded, chert-free limestone with a distinct coral fauna. Based on corals, foraminifers, and conodonts, the formation is of Asbian age (Sleeman & Pracht 1999). It represents carbonate deposition on the middle to outer part of the Limerick Ramp in gradually deepening water (Sleeman & Pracht 1999). The Asbian to Early Brigantian Parsonage Formation (Sleeman & Pracht 1999) consists of pale to dark-grey, generally unfossiliferous limestone and calcareous mudstone. The limestone contains distinct, dark and pale “striped limestone”, which is interpreted as replaced evaporite (MacDermot & Sevastopulo 1972). The youngest Viséan limestone (mid- to late Brigantian age) consists of deep-water limestone and shales (c. 6 to 24 m thick) of the Corgrig Lodge Formation. They are conformably overlain by the Namurian Clare Shale Formation. Variations from this general lithostratigraphy occur across the Shannon Basin, e.g. in the East Clare Syncline, the Fergus Estuary, south of Limerick City, north County Kerry and Tralee Bay, although they can readily be correlated with the standard northwest Limerick succession.

6.2 Dublin Basin

During the Courceyan, sedimentation in the Dublin Basin occurred on a ramp. Following the break-up of the ramp by extensional faulting in Chadian time, sedimentation differentiated into shallow-water platform and deep-water basin. The shallow-water platforms, which bound the Dublin Basin in the northeastern part, have been discussed as part of the shelf stratigraphy (Fig. 9). The boundaries between sub-basins are generally poorly known. Progradation of sedimentation from the platforms into the basinal parts, across platform-bounding faults, occurred locally (Sevastopulo & Wyse Jackson 2001). Westwards, the northern margin of the Dublin Basin is the structural contact with the Longford-Down Inlier, including large east–west and east–northeast trending faults (see Fig. 12).

In the Dublin region, the basin was bounded to the north by the Balbriggan Shelf, to the south by the Kildare Shelf. Basinal facies of the Fingal Group (Nolan 1989) are well-exposed along the coast of north County Dublin. Here, the oldest Viséan rocks are mudrock with a cleavage fabric and minor limestone of the Tober Colleen Formation. The formation is 50 to 250 m thick and contains boulder beds interpreted as debris flows. Along the coast, the overlying c. 270 m thick Rush Conglomerate Formation consists of graded quartz- and limestone conglomerates, thin limestone beds, sandstone, and shales. The formation is early Viséan to earliest Arundian in age and time-equivalent to the Smuggler Cave Formation on the Milverton Platform (Fig. 9; Sevastopulo & Wyse Jackson 2001). While the Tober Colleen Formation is interpreted to represent deep-water basinal muds, the Rush Formation is interpreted as turbidites and sediment flow deposits generated by extensional faulting along the margin of a shallow-water shelf to the east (Nolan 1986, 1989). The overlying Lucan Formation consists of argillaceous, cherty, spiculitic limestone and shale with horizons of interbedded, graded, skeletal, and oolitic limestone. The Lucan Formation was deposited in relatively deep water, the oolitic limestone as distal turbidites. The Lucan Formation is 300 to 800 m thick and is Arundian to Asbian in age. In the northeastern part of the basin, the Lucan Formation is overlain by the Naul Formation comprising >100 m of grey, graded, skeletal limestone and calcisiltite. The overlying 100 to 150 m thick Loughshinny Formation is of Brigantian age and consists of coarse limestone breccias, graded limestone, argillaceous limestone, and dark shales. The northern margin of the basin can be traced westwards to the Walterstown Fault (Pickard et al. 1994), which controlled the western margin of the Balbriggan-Kentstown platforms (s. a.). Here, as in the Drogheda and Ardagh platforms, the Loughshinny Formation oversteps the basin margin northwards (Fig. 9; Sevastopulo & Wyse Jackson 2001).

In the Navan area, the top of the Waulsortian facies is marked by a disconformity which cuts southeastwards through c. 600 m of Tournaian rocks into Lower Palaeozoic basement (Ashton et al. 1992; Philcox 1989). Above the disconformity, the c. 50 m thick Boulder Conglomerate Member of the Lucan Formation consists of conglomeratic debris

flow deposits including Waulsortian facies boulders up to 8 m in size. The conglomerates are overlain by Viséan turbiditic limestones of the Lucan Formation, indicating tectonic activity on east–northeast trending and southerly dipping faults during deposition (Sevastopulo & Wyse Jackson 2001).

The basin margin in the south approximately coincides with the present fault contact (Blackrock-Newcastle Fault) between Carboniferous rocks and the Leinster Granite with its Lower Palaeozoic envelope (see Fig. 12). Tectonic activity along this margin occurred during the Arundian and later in the Asbian. Intrabasinal faults were also active (Nolan 1989; Sevastopulo & Wyse Jackson 2001).

In the central part of the eastern half of the Dublin Basin, as seen in the Athboy borehole, the Tober Colleen Formation is overlain by the Lucan Formation followed by the Naul Formation with a combined total thickness of >1,125 m of Viséan basinal limestone and shale (Strogen et al. 1990). Towards the west, the basin orientation changes to a northeast–southwest trend based on surface mapping of basinal facies and little is known about the basin margin. The most western record of the Tober Colleen Formation is in the Carnagh East (GSI-19-004) borehole, on the west side of Lough Ree. Here, the formation consists of a laminated and cyclic grainstone to mudstone. Main skeletal components are shell fragments, foraminifers, calcispheres, sponge spicules, brachiopods, brachiopod spines, echinoderms, crinoids, ostracods, trilobites, bivalves, sponge spicules, and some silicified bioclasts. Based on foraminifers, the formation is Lower Viséan (Chadian – MFZ9 to late Arundian – MFZ11) in age (Geological Survey of Ireland 2019).

In the southwestern part of the Dublin Basin (around Loughrea and Craughwell), a basinal limestone succession has been drilled. It has been assigned to the Lucan Formation, as described further east (Pracht & Somerville 2015). Lithologically, the formation is very similar but lacks oolitic horizons. Main skeletal components are crinoids, corals (solitary corals and *Michelinia*), gastropods, sponge spicules, and calcispheres. The foraminiferal assemblage is generally small and dominated by a similar suite of taxa between boreholes. Richer and more diverse foraminiferal and dasyclad algal (*Nanopora*) assemblages occur in some thin grainstone beds, probably derived from a nearby shelf and transported into the basin. Neomorphosed fabrics and bioturbation in fine-grained wackestone and mudstone are common. Pyrite, authigenic quartz, feldspar, and muscovite flakes occur in various levels and quantities. Muscovite is typical of the Lucan Formation.

In this southwestern part of the basin, a similar Arundian to Asbian age has been retrieved for the Lucan Formation, based on a sparse foraminiferal and algal assemblages. New borehole data from the Geological Survey of Ireland (Pracht & Somerville 2015; Geological Survey of Ireland 2019 and unpublished data) indicate that the basin margin on this western end is at least partially fault-controlled during the late Tournaian and possibly in the early Viséan. In places, the change from very thick (>400 m) shelf limestone facies to very thick (>700 m) basinal facies over very short dis-

tances (<2 km) suggests fault control of a palaeo-slope, but further research is required. Boreholes GSI-07-01, Cuddoo, and GSI-06-387, Monivea, show that the Lucan Formation interdigitates with the shelf limestones of the Tubber Formation during the Holverian and Asbian (Pracht & Somerville 2015). A vertical offset between these two boreholes of c. 300 to 450 m on the Athenry Fault (downthrow to the west) is probably the result of late Carboniferous Variscan deformation.

6.3 Lough Allen Basin

The Lough Allen Basin (Figs. 10 and 11) is a northeast-southwest-trending Carboniferous graben structure with a >2.9 km thick Dinantian succession (Worthington & Walsh 2011). It is bounded in the north and east by the Lower Lough Erne and Clogher Valley faults, in the south by the Woodbrook/Curlew Fault and in the west by the Belhavel Fault and Ox Mountain Fault. The Lough Allen Basin is part of the Northwest Basins which includes the Donegal Basin (Kelly in press).

The Northwest Basins started to develop during the Tournaisian in the hanging wall of extensional faults parallel to the southeastern margin of the Ox Mountains. In the Tournaisian, the eastern part of the basin remained stable (Macnean and Dowra High) while deposition centres developed in the southwest and west (Drumkeeran-Big Dog-Slisgarrow-Kilcoo Cross). Differential subsidence in and around the Lough Allen Basin continued in the Arundian (Philcox et al. 1992; Worthington & Walsh 2011). The Dinantian succession of the Lough Allen Basin has been divided into a Tournaisian “Basal Clastic” succession, a Viséan Tyrone Group and an Asbian to Namurian Leitrim Group.

The “Basal Clastic” succession generally consists of a basal sandstone, overlain by evaporitic, silty and sandy mudstone which are topped by an upper sandstone. In the Sligo Syncline, Kilcoo and Big Dog boreholes, the “Basal Clastics” are overlain by the “Twigspark Beds” consisting of sandstone, shale, and sandy limestone. In the Slisgarrow 1 and Drumkeeran South 1 boreholes the Kilbryan Limestone Formation rests directly on the “Basal Clastics”. The Kilbryan Limestone Formation consists of calcareous shales and argillaceous carbonates (Philcox et al. 1992).

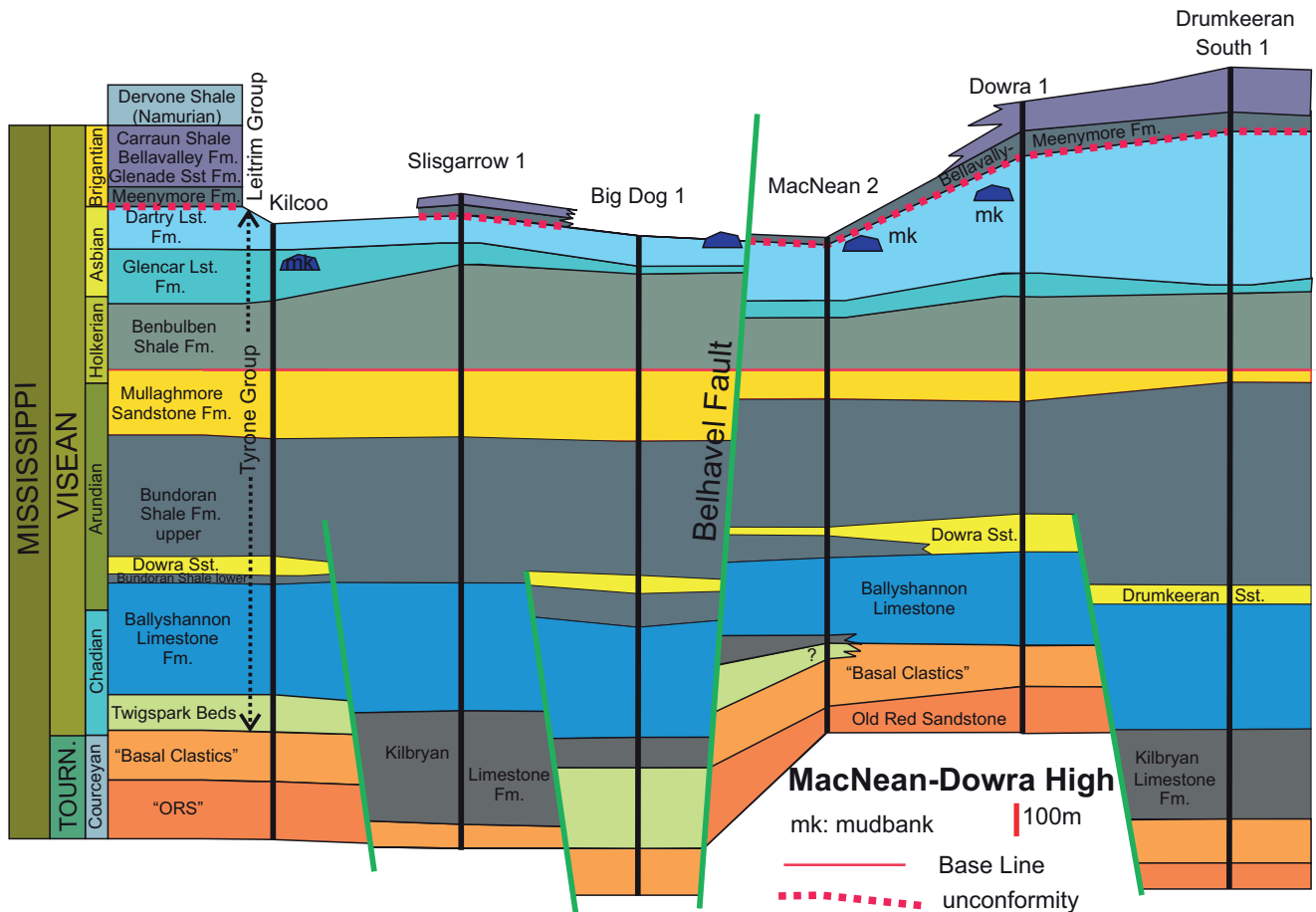


Fig. 10: Schematic cross section through the Dinantian succession of the Lough Allen Basin. Based on exploration wells; modified after Sevastopulo & Wyse Jackson (2001); Worthington & Walsh (2011); J. Kelly unpubl.

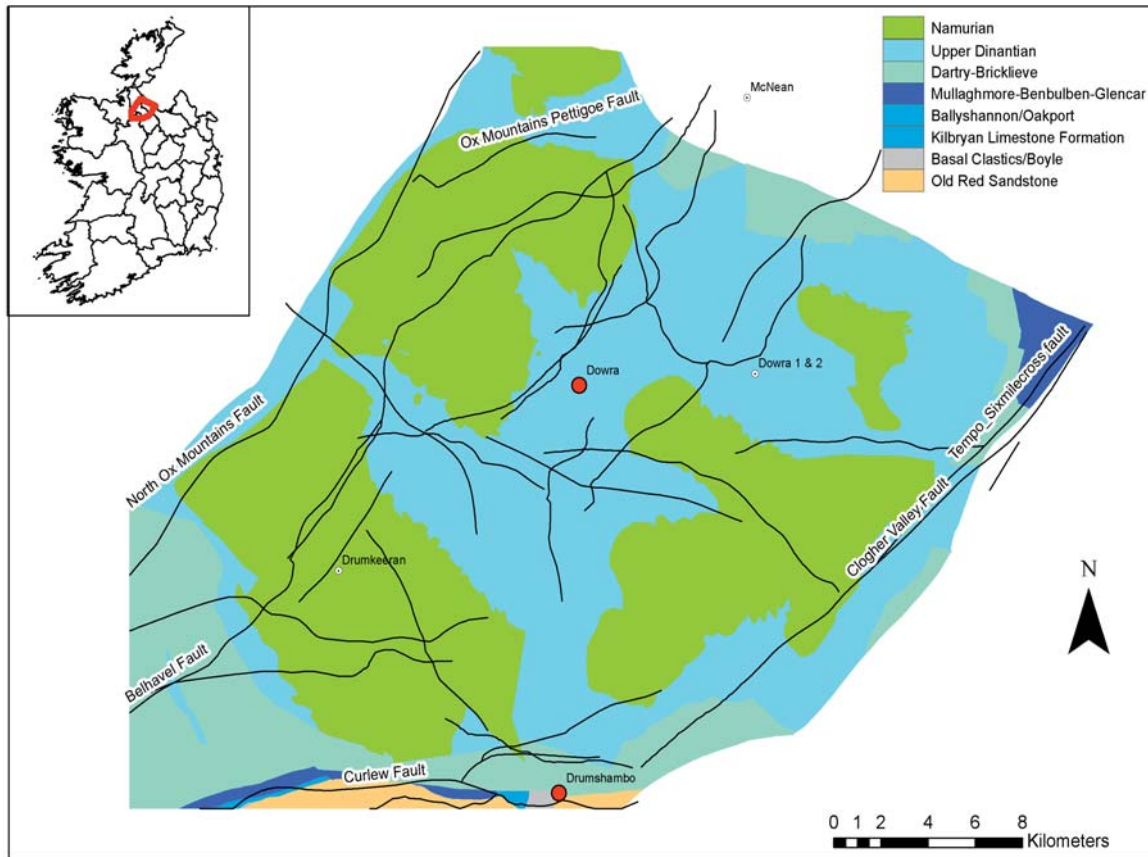


Fig. 11: Geological map of the Lough Allen pilot area with the simplified stratigraphy and drillholes used for 3D modelling. Drillholes are shown as white circles with black dots. Inset: Location of the study area.

In the **Lough Allen Basin**, the Kilbryan Limestone Formation, or, where absent, the “Basal Clastics”, is overlain by the Ballyshannon Limestone Formation. The thick-bedded to massive crinoidal packstone typical of the Ballyshannon Limestone Formation outside the basin are replaced by dark argillaceous crinoidal limestone with subordinate mudstone, interpreted as a deeper water facies by [Philcox et al. \(1992\)](#) and [Sheridan \(1972\)](#). The Ballyshannon Limestone Formation is of Chadian to Arundian age and c. 300 m thick (Slisgarrow1 borehole). It is overlain by 450 to 650 m of laminated unfossiliferous calcareous shales, mudstone, and minor evaporites of the Bundoran Shale Formation (Arundian), interbedded with two sandstone members, the Dowra and Drumkeeran Sandstone members. This sudden change to mud-rich sediments is associated with uplift in the north, which caused a massive input of mud into the sea, and led to a southward progradation of the fluvio-deltaic system of the Mullaghmore Sandstone Formation (Arundian to Holverian age based on TS miospore biozone age by [Higgs 1984](#)).

The Mullaghmore Sandstone is >200 m thick in the northwest of the basin (e.g. Big Dog 1 borehole) but thins southwards to less than 50 m (Drumkeeran South 1 borehole). These fluvio-deltaic sandstones are overlain by the

Holverian to lower Asbian aged Benbulben Shale Formation comprising calcareous shales and argillaceous, fine-grained calcarenites/calcsiltites. They are 170 to 365 m thick and become more limestone-rich in the Lough Allen Basin than in the Sligo Syncline. Main biota are crinoids, brachiopods, solitary corals with large caniniids, and bryozoans. In areas where the Mullaghmore Sandstone Formation is not recognisable (e.g. Ballymote Syncline to the south), the shales (Bundoran and Benbulben shales) are grouped together as the Lisgorman Shale Formation ([MacDermot et al. 1996](#)). This shale unit consists of up to 275 m of grey calcareous shales interbedded with very fine-grained limestone beds. On the shelf to the south, the Ballymore Limestone and Croghan Limestone Formations are the lateral equivalent, comprising c. 310 m of crinoidal calcarenites and dark nodular limestone with various amounts of shale.

In middle to late Holverian times, the deltas retreated northward, and sedimentation became dominated by carbonates. The Glencar Limestone Formation consists of a mixed transitional argillaceous limestone and shale facies, followed by the Asbian dark, fine-grained, cherty limestone of the Dartry and Bricklieve Limestone Formations. Mudbank facies within the Dartry Limestone Formation developed over

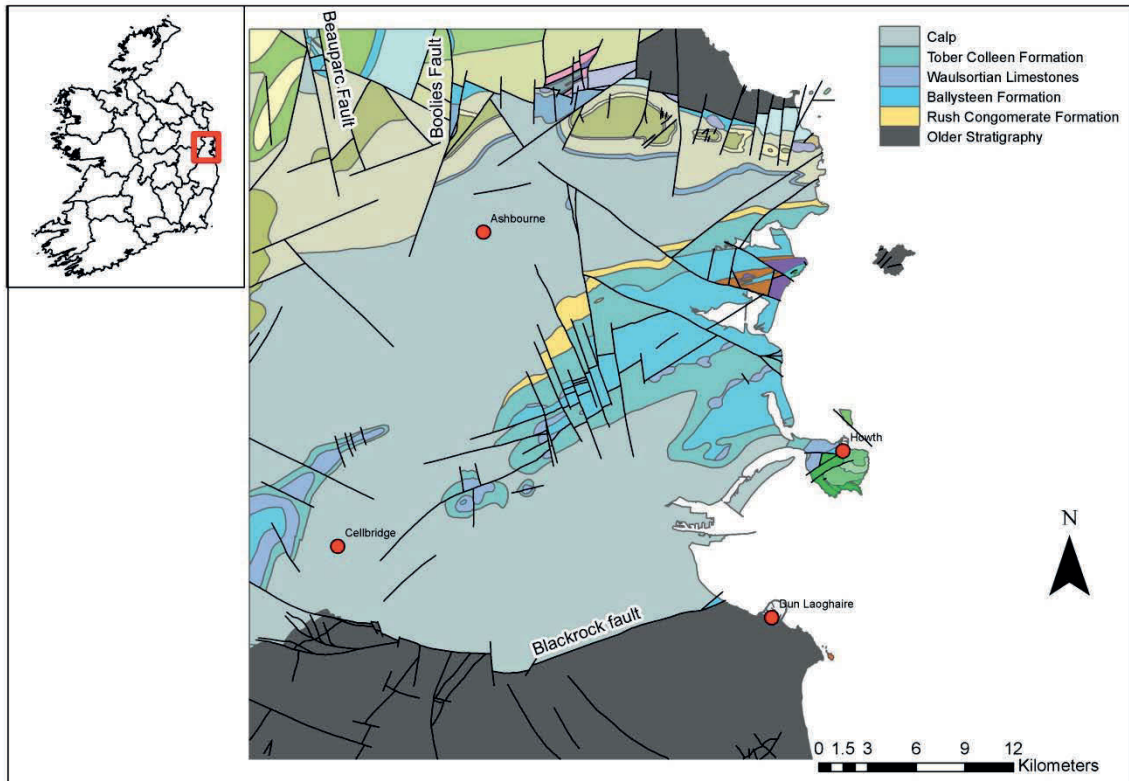


Fig. 12: Location map of the Dublin pilot area with the stratigraphy that will be used for 3D modelling. The legend has been simplified to show only the reservoir relevant stratigraphy. Inset: location of the study area within Ireland.

the Dowra-Macnean High and along the northern and southern margins of the basin (MacDermot et al. 1996). Variations in thickness within the basin have been attributed to facies changes (Philcox et al. 1992) and local tectonic control of subsidence during the Asbian (Kelly 1996; Legg et al. 1998).

The Leitrim Group (Brigantian–Namurian; Cózar et al. 2005) marks a major facies change in the Lough Allen Basin. A disconformity at the base of the group is the result of a sea-level fall. The Meenymore Formation consists largely of unfossiliferous shales with few bioclastic horizons interbedded with evaporites and fine-grained, laminated limestone, interpreted as stromatolites. The Meenymore Formation is overlain by the Glenade Sandstone Formation composed of brown, thick-bedded medium-grained quartzose sandstone. Based on palynological data, a fluvial and lagoonal environment with short-lived, anoxic marine incursions near the base is deduced by Smith (1996). The sandstone is overlain by alternating fossiliferous shales, micrites, laminated limestone with evaporites and sandstone of the Ballavally Formation, followed by dark-grey shales and mudstone with limestone units of the Carraun Shale Formation. The formation contains goniatites with a P1b/P1c to P2c Biozone age (Sevastopulo & Wyse Jackson 2001). Dinantian rocks further north (Armagh- Cookstown area, Dungannon area, and north of Slieve Gullion) reflect a similar pattern of fluctuating sea levels with local variations and are not further discussed.

7. Geothermal potential of Dinantian successions in Ireland

Carbonate rocks are the most common low-enthalpy geothermal aquifers on a global scale (Goldscheider et al. 2010). Ireland has a recognised potential for low-to-medium temperature deep geothermal energy resources which may be suitable for large scale or district heating in residential or industrial settings (Blake et al. 2020).

Ireland has a complex basement geology, created and modified by several phases of the Caledonian tectonic cycle. The resulting structural template was reactivated during Carboniferous extension to form sedimentary basins and shelves that were variable through time, resulting in complex carbonate stratigraphy. Bounding faults provided fluid pathways for mineralisation (e.g. Navan mines) and karstification, and subsequently accommodated Variscan compression and brittle fracturing. Thus, the fault pattern defines zones of both karstic and brittle fracture high-permeability pathways for geothermal/hydrothermal fluids in these carbonate basins.

The faulted southern margin of the Dinantian Dublin Basin has been explored for geothermal energy potential at Newcastle, County Dublin. The Blackrock-Newcastle Fault (BNF) is a normal fault that bounds the southern side of the Dublin Basin, with synsedimentary and subsequent throw of at least 1,500 m. Viséan argillaceous limestone covers lower

strata of the basin fill that include carbonate grainstone, Waulsortian mudmounds and basal siliciclastic rocks. Two boreholes were drilled to a depth of 1,400 m in the sedimentary succession just north of the fault by GT Energy in 2008. A temperature of 46.2 °C was measured at the bottom of one borehole with an estimated geothermal gradient of c. 32 °Ckm⁻¹, suggesting that the fractured carbonates and porous sandstone in the lower part of the Carboniferous sedimentary sequence close to the fault have potential to deliver heat through a geothermal well doublet. Recent magnetotelluric modelling (Vozar et al. 2020) has imaged a dextral shear zone with the BNF as a highly fractured and partly conductive zone filled with saline waters.

Codema, the Dublin energy agency, has analysed the potential for geothermal district heating in South County Dublin as part of the HeatNet project, based on the promising geothermal conditions discovered at Newcastle. It is estimated that between 80 and 400 MW_{th} of heat could be provided by 28 geothermal doublets in the limestone reservoir of the Dublin Basin as a whole, giving carbon savings of between 80,000 and 400,000 tonnes CO₂ per annum, compared to natural gas. Currently, the Newcastle project is stopped for non-technical reasons; the present lack of legislation, planning guidelines, clear policy signal, or financial incentives make it an unattractive risk.

The Lough Allen Basin and the Dublin Basin are being studied as part of the ongoing **GeoERA HotLime project**, to help de-risk exploration for geothermal resources by constructing 3D models and modelling the temperature of the reservoirs. Publicly available hydrocarbon exploration seismic and borehole data for the **Lough Allen Basin** from the 1960s and 1970s have been used for mapping, characterisation and assessment. The potential reservoir assumed for this study was the succession between the “Basal Clastics” and the Mullaghmore Sandstone Formation (described in detail above; Fig. 10). Stratigraphical units were simplified for the purposes of 3D modelling (Fig. 11) and active Carboniferous basin-forming faults identified to produce the 3D model (Guo & Walsh 2016).

The eastern part of the **Dublin Basin** is more closely aligned with heat demand, but no seismic or deep drilling data are currently available. Again, the stratigraphy of the basin was simplified for 3D modelling purposes (Fig. 12). The target carbonate reservoir defined and characterised in this study comprises the succession above the Feighcullen Limestone Formation and below the Tober Colleen Limestone Formation; within the Dublin Basin, the Ballysteen Formation is represented by its stratigraphical equivalents, the Malahide Formation and the Boston Hill Formation (described in detail above).

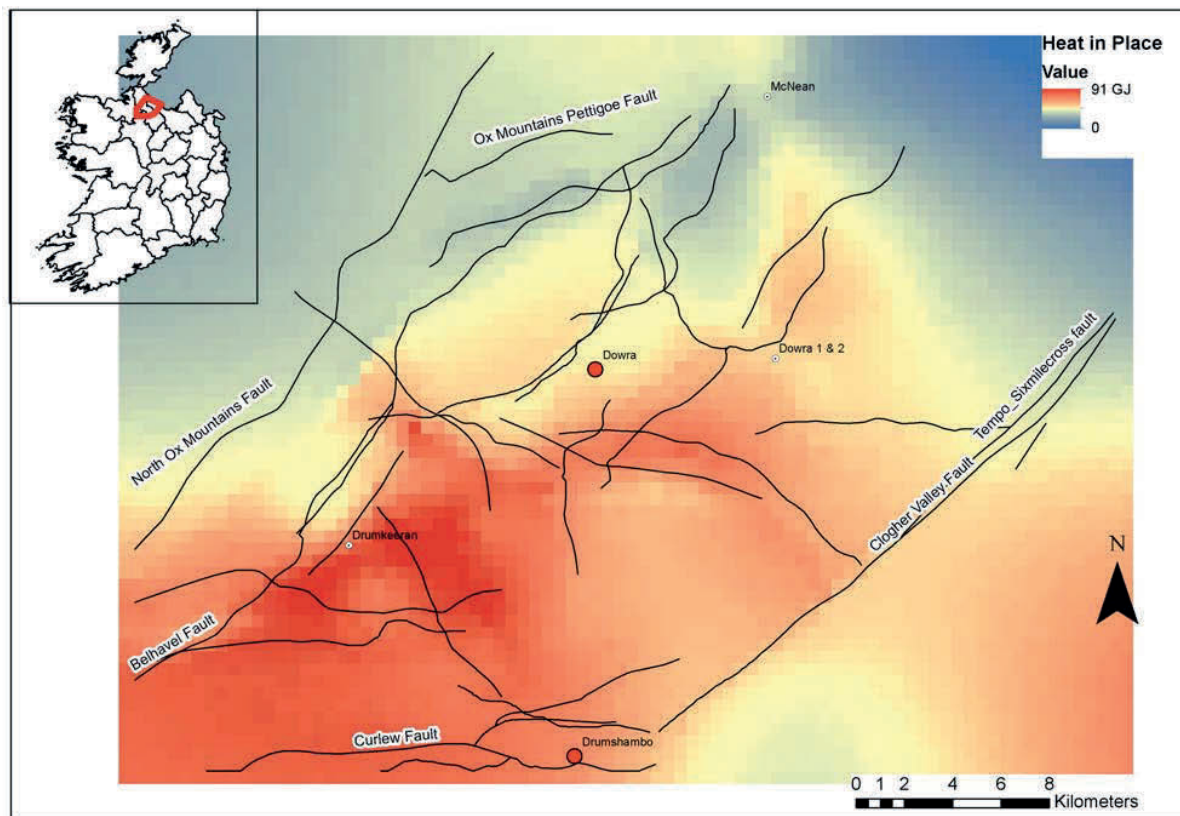


Fig 13: Map showing the variation of heat in place in the Lough Allen study area with the principal faults overlaid as black lines. The highest thermal potential is towards the southwest.

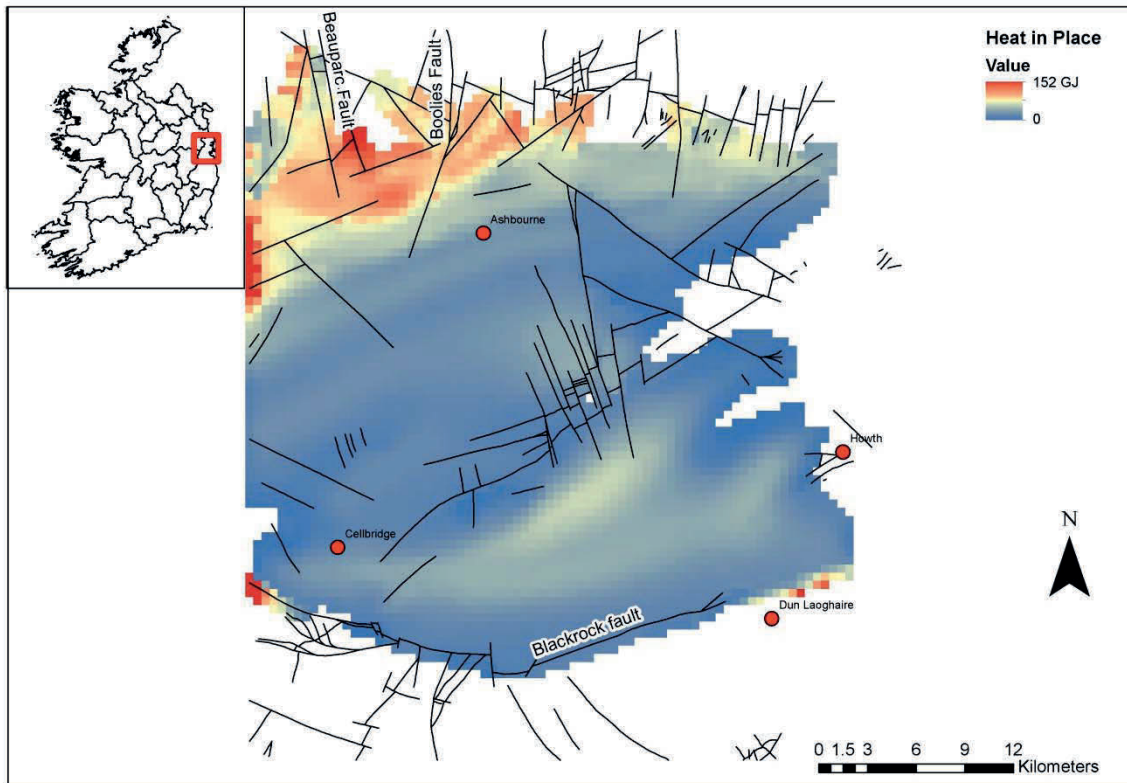


Fig. 14: Map showing the variation of heat in place in the Dublin study area with the principal faults overlaid as black lines.

To standardise outputs from all partner institutions in the HotLime project (Diepolder et al. 2020), a volumetric heat in place method (HIP) is being used (Muffler & Cataldi 1978; Garg & Combs 2011; Limberger et al. 2018) as a first step towards geothermal resource assessment:

$$\text{Heat in Place} = [(1 - \Phi)c_{\text{rpr}} + \Phi c_{\text{wpw}}] * V * (T_r - T_{\text{ref}})$$

where Φ is the porosity, c_{rpr} is the volumetric heat capacity, commonly in $\text{Jm}^{-3}\text{K}^{-1}$, of the rock at reservoir conditions and c_{wpw} is the volumetric heat capacity of the pore fluid, commonly water, at reservoir condition, V is the volume of reservoir (reservoir thickness \times areal extent), T_r is the average reservoir temperature, and T_{ref} is the reference (or surface) temperature.

HIP is particularly sensitive to porosity, which is not well constrained in the case study basins. As a first approximation, typical values from the literature have been applied for the anisotropic secondary porosity of carbonates. Similarly, there are few robust subsurface temperature data for the Irish HotLime pilot areas, so the average reservoir temperature for both the Lough Allen and Dublin Basins has been modelled simply using the geometry determined in the 3D models and a geothermal gradient of $25\text{ }^\circ\text{Ckm}^{-1}$ based upon an estimated average geothermal gradient for Ireland (Goodman et al. 2004). The surface temperature used in these models is $10\text{ }^\circ\text{C}$ (based upon an average groundwater temperature for Ireland of $9.5\text{--}10.5\text{ }^\circ\text{C}$ (Aldwell & Burdon 1986)).

The Lough Allen Basin study area shows the highest thermal potential in the southwest (Fig. 13), resulting from a combination of reservoir thickness and overall depth of the reservoir. Heat in place is weighted too heavily on these factors as there is a lack of porosity and permeability data. The Dublin Basin study area (Fig. 14) shows the highest thermal potential in the northwest of the basin, which is again related to reservoir thickness and depth, primarily.

8. Conclusions

As a first pass de-risking exercise, the results will allow identification of targets for future data generation and allow comparison to conditions in existing well-defined reservoirs. Although heat in place in the two reservoirs is low compared to other geothermal targets, both the Lough Allen Basin and the Dublin Basin reservoirs are of sufficient volume to have potential for district heating purposes.

Further development of geothermal resource estimation in Ireland will require a detailed study of the porosity, karst features, and permeability of deep carbonates in Ireland, including the variation of both parameters in relation to faults. The understanding of geothermal potential will be further improved by geophysical data and drilling surveys that characterise the overall geometry of the basins and highlight significant fault zones, particularly for the centre of the Dublin Basin. The methodology outlined in this report to determine

heat in place using existing data could also be applied to other carbonate regions of Ireland.

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