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A Pleistocene deposit preserved in deep karst at Coolough, County Galway, western Ireland

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GRAPHICAL ABSTRACT

Photomicrograph of a singular *Tsuga* pollen grain retrieved from sediment fill preserved in a large enclosed negative karst landform at Coolough, near Galway City in the west of Ireland. The discovery of this taxon and others suggest that the deposit dates to the Early Quaternary. The Coolough deposit hosts fluvial, lacustrine and glacial sediments from which three deglaciation events have been interpreted, along with woodland and grassland palaeoenvironments.

ABSTRACT

Buried karst features result from a complex interplay between carbonate bedrock and structural geology. The enhancement of carbonate aquifers through this interplay creates hydrogeologically-complex subsurface drainage networks and highly variable surface topographies. This paper reports on the sediment fill and fossil pollen record from a large enclosed negative karst landform at Coolough, near Galway City in the west of Ireland. It was discovered during the preliminary site investigation for the proposed N6 Galway City Ring Road. Major joint sets developed in the Carboniferous (Mississippian) limestone bedrock govern the local hydrogeology and structural evidence suggests that a local fault has controlled the east-west propagation of the deep enclosed depression. Fluvial and lacustrine palaeoenvironments are interpreted from the sediments infilling the enclosed depression, within which three discrete diamicts are identified, potentially representing distinct phases of glaciation. Pollen assemblages, which reflect palaeoenvironments of open woods and grasslands, have been correlated with other deposits in Ireland and Europe and suggest a minimum date of the Early Pleistocene for the oldest of the diamicts, and thus an upper age limit on the development of the karst depression. Fluvial disturbance to the deposit is evident and is likely to be responsible for the chronological discrepancy between the Early Pleistocene and Middle Pleistocene sediments both recorded from the deposit infill. The findings of this multidisciplinary study contribute to an understanding of Quaternary landscape evolution in western Ireland.

KEYWORDS:

carbonate geology, Carboniferous, deposit, Galway, Ireland, karst, palynology, Pleistocene, pollen, sedimentology

1 INTRODUCTION

Approximately half of the land area of Ireland is underlain by Carboniferous (Mississippian) carbonate bedrock, predominantly limestones (Sevastopulo & Wyse Jackson, 2009; Waters et al., 2011), approximately 70% of which appear to be pure enough (i.e. calcite-rich and lacking a siliceous or argillaceous component) to encourage karstification (Drew & Jones, 2000). Irish karst landscapes (Figure 1) are primarily lowland, mostly below 100 m above sea level (Drew, 2008). The 'western lowlands' region is underlain by karstified predominantly pure Mississippian limestones extending through counties Sligo, Mayo, Roscommon, Galway and Clare (Drew, 2018). Although mostly blanketed in superficial deposits (typically Quaternary in age), the region is characterised by considerable interaction between ground and surface waters, manifested through the presence of many karstic features such as losing and gaining streams, conduit networks, swallow holes, estavelles, springs and ephemeral lakes (known in Ireland as turloughs) (Drew, 2018; McCormack, Gill, Naughton, & Johnston, 2014). Karstic systems dominate drainage with groundwater flow systems feeding abundant springs along the eastern shores of Lough Corrib and Lough Mask (Coxon & Drew, 1986). These lakes function as a regional base level and were formed from scouring by Pleistocene glaciers between more resistant metasediment and granite to the west and less resistant limestone to the east (Glynn, Brown, & Rooney, 2008; McCabe, 1993). The Carboniferous limestone highlands of the Burren Plateau (Figure 1) juxtapose the western lowlands, distinct for its comparatively greater elevation, exposed bedrock and abundant conspicuous karst landforms, most notably the numerous cave systems (e.g. Aillwee Cave; Drew, 1973a). Although not as numerous or conspicuous as in the Burren, caves are also known in the western lowlands, and some have been explored and mapped (e.g. Ballyglunin Cave; Drew, 1973b. See Mullan, 2003 for a comprehensive overview).

In 2015, preliminary site investigation work including a series of boreholes and resistivity profiling, commissioned by Arup (2018) for the proposed N6 Galway City Ring Road (GCRR) project, revealed an approximately 300 m long, 100 m wide and over 110 m deep enclosed sediment-filled karst feature with steeply-inclined margins. This feature is located ~100 m west of the inactive Coolough limestone quarry near Menlo, east of the River Corrib, between Galway City and Lough Corrib (Figures 1 and 2). Karst features are abundant in the broader area; 126 such features were identified across an area of *c.*35 km^2 in the environs of Galway City during the Environmental Impact Assessment for the GCRR project. These included 79 enclosed depressions, springs, turloughs, swallow holes, superficial solution features, one cave and one small-scale estavelle (Arup, 2018). Particular examples include a series of small collapse dolines between Menlo and Galway Bay (GSI, 2007) and Ballindooley Lough (which lies approximately 1.4 km northeast of the Coolough depression), located in a large enclosed depression filled by and draining to a subsurface karst network, like a turlough (Arup, 2018). The Terryland River (Figure 2) flows from the River Corrib to discrete sinkholes in the Terryland area before discharging to Galway Bay (salt water fills the conduits during high tides causing the river to back up along a portion of its length) through an unmapped karst network (Arup, 2017; Quigley, McCabe, Hunt, & Rodgers, 2016).

Anecdotal accounts exist of similar large karst depressions elsewhere in Ireland, but they have not been subject to detailed geological investigation and documented accounts are rare in the academic literature. Notable exceptions (located in Figure 1) include a >85 m deep doline at Lisheen, County Tipperary, containing Miocene age sediment (Coxon & Coxon, 1997; Drew & Jones, 2000), a >62 m deep karst feature on Aughinish Island, County Limerick, infilled with sediment dated to the Middle Tertiary (Clark, Gutmanis, Furley, &

Jordan, 1981) and a >50 m deep karst pipe at Hollymount, County Laois hosting sediment dated to the Miocene/Lower Pliocene (Boulter, 1980; Watts, 1985).

Neogene and Paleogene sediments are rare in Ireland and most examples are found within karst dissolution features (Coxon & McCarron, 2009). Infilled karst landforms in Ireland date as far back as the Oligocene, with most pre-Quaternary deposits dating to the Pliocene (Mitchell, 1980; Simms & Coxon, 2017). For example, at Pollnahallia, situated approximately 20 km north of Coolough Quarry, a 10 m-thick organic lignite of Pliocene-Pleistocene age was discovered in a silica sand deposit located within a karstic network developed in Carboniferous limestone, beneath a cover of glacial material (Coxon, 2005; Coxon & Coxon, 1997; Coxon & Flegg, 1987). Palynology and palaeobotany remain the principal techniques used for dating Quaternary deposits through correlation to similar deposits elsewhere in Ireland, Britain or Europe which have already been assigned to a Marine Isotope Stage (MIS). However, Coxon, Mitchell, von Engelbrechten, and Vaughan, (2017) warn that 'over-simplification and mis-correlation' are major issues when attempting to date deposits biostratigraphically using these methods, particularly because of Ireland's relative remoteness in broad geographic terms.

This paper presents the findings of a sedimentological and palynological investigation of the deposit infilling the Coolough depression. The sediment in one of the boreholes extracted for the GCRR project (Arup, 2018) was investigated in order to provide a chronological and palaeoenvironmental context for the sediment infill. Karst systems can protect unconsolidated deposits from weathering and erosion; hence, they may preserve detailed terrestrial records of surface processes and palaeoenvironments. A deposit in excess of 100 m in depth is rare, and hence provides a valuable record of more recent Irish geological history.

2 GEOLOGICAL SETTING AND STUDY SITE

2.1 Bedrock geology

The Mississippian limestones of the western lowlands formed on and in a series of shelves and basins, including the extensive Galway-Roscommon Shelf and the North-West Carboniferous Basin (Barham, Murray, Joachimski, & Williams, 2012; Sevastopulo & Wyse Jackson, 2009; Somerville et al., 2009). The succession in County Galway is Tournaisian and (predominantly) Viséan in age and carbonate sedimentation was partly controlled by syn-sedimentary faulting along the NE-trending Athenry Fault and the ENE-trending Craughwell Fault (Long, McConnell, & Philcox, 2004; Morris, Somerville, & McDermot, 2003; Pracht & Somerville, 2015; Pracht et al., 2004a, 2004b). The work of Pracht and Somerville (2015) provides the most detailed and up-to-date bedrock map and assessment of the regional lithostratigraphy (Figure 3).

According to Pracht and Somerville (2015), the study area is underlain by the Asbian-aged Burren Limestone Formation, which is almost 400 m thick at its type section further southwest in the Burren region, and consists predominantly of thick-bedded to massive pale grey clean limestones with intervals of darker cherty medium-bedded limestones (Pracht et al., 2004a, 2004b; Sleeman, Pracht, & Claringbold, 1999). This unit is generally interpreted as having been deposited in a shallow subtidal shelf setting (Gallagher, MacDermot, Somerville, Pracht, & Sleeman, 2006; Pracht & Somerville, 2015) and displays distinctive palaeokarstic surfaces reflecting repeated periods of emergence due to glacioeustatic cyclicity during the Carboniferous (Gallagher et al., 2006; Pracht & Somerville, 2015; Sevastopulo & Wyse Jackson, 2009; Somerville et al., 2009) related to the onset of the Late Paleozoic Ice Age (Barham et al., 2012; Fielding, Frank, & Isbell, 2008; Wright & Vanstone, 2001). Thin non-calcareous clay or shale horizons infill the irregular palaeokarstic surfaces at the tops of the cycles and are termed ‘clay-wayboards’ or ‘palaeosols’ by various authors (e.g. Gallagher et al., 2006; Pracht & Somerville, 2015; Somerville, 1979; Walkden, 1974, 1987). Around Galway City, the uppermost lithostratigraphical subunit, the Two Mile Ditch Member (laterally equivalent to the Aillwee Member of the Burren Limestone Formation in the type area), also displays these distinctive palaeokarstic surfaces and two conspicuous clay horizons are traceable in the exposed limestone bedrock within Coolough Quarry (see Supporting Information A: Clay Horizons).

2.2 Study site

The Coolough site is perched on a topographic high consisting of highly-jointed limestone pavement. The site comprises of a set of agricultural fields which outline the sediment-filled karst feature, from which cores (including BH03 extending to *c*.110 m depth) were extracted (Arup, 2018), and Coolough Quarry, 100 m east of the large bedrock depression (Figure 4). The limestone bedrock exposed in Coolough Quarry is heavily fractured, on a range of scales, with large-scale jointing penetrating vertically or sub-vertically through the visible outcrop. The joints predominantly trend NE-SW and NW-SE, thus defining a conjugate set. Fractures striking NW-SE are also observed in the pervasive systematic joints of the northern Burren region, south of Galway Bay (Gillespie, Walsh, Watterson, Bonson, & Manzocchi, 2001). In contrast, smaller-scale fractures show a more random pattern of orientation. The bedrock exposures also demonstrate the presence of an east-west fault damage zone within the central portion of the quarry, evident from a section of notable bedrock disturbance along the eastern quarry walls (Figure 4), and by a traceable line of disturbance which exhibits palaeokarst and demonstrates focussed groundwater flow (Figure 5) (particularly within the western quarry benches), a commonly-observed attribute of fault zones (Bense, Gleeson, Loveless, Bour, &

Scibek, 2013). Elsewhere, groundwater typically emerges above interbedded clay horizon units within the limestone; however, along this intersection it emerges above and below the clay layers (Figure 5), suggesting that structural integrity of the clay horizons has been compromised, or are thin or absent. A geophysical survey was conducted (Dolan, 2019) on the quarry floor, perpendicular to the conspicuous fault damage zone. Electrical resistivity tomography identified areas of weathered limestone and an apparent karst conduit which intersects the line of disturbance across the quarry (see Supporting Information B: Geophysics).

3 MATERIALS AND METHODS

3.1 Sediment analysis

The sediment infill from the *c*.110 m-long core BH03 (Figure 4), originally logged by BRG Ltd. (Arup, 2018), was re-examined in detail by the present authors. Units were visually defined based on overall sedimentological properties and character. Various samples were extracted from the core, including organic clays, calcareous clays, organic fragments and a sample of fine sediment (silt or sand) from a thick homogeneous unit in the upper core (*c*.36.85 m – 13.55 m depth). Further details of these analyses, including microscopy, particle size distribution and mineralogy, are presented in Dolan (2019).

3.2 Palynological analysis

Organic clay samples (each ≈2 cm^3) were extracted from core BH03 at depths of 38.6 m, 47 m, 63.8 m and 108.5 m, labelled Pol.1, Pol.2, Pol.3 and Pol.4 respectively. Sample preparation and pollen counting followed standard procedures practised at the Palaeoenvironmental Research Unit (PRU), NUI Galway (Molloy & O'Connell, 2004) and a

Leica DMLB microscope was used for counting. A *Lycopodium* spike was deemed unnecessary, as the analysis is intended for qualitative rather than quantitative purposes. A pollen sum (PS) of 1,000 pollen grains (terrestrial pollen) was achieved for each sample and percentage values are based on a total terrestrial pollen sum (TTP). Aquatic taxa and *Sphagnum* spores were counted but not included within the pollen sum, which is standard practice for lake sediment analysis (Moore, Webb, & Collison, 1991). Taxa excluded from the PS are expressed relative to the TTP. Pollen identification and nomenclature follows that of Moore et al. (1991). Pollen counts were recorded and calculations were carried out using CountPol version 3.2 (Feeser & O'Connell, 2009). Results were plotted as a series of histograms in a percentage pollen diagram following the format produced at the PRU (O'Connell, Molloy, & Jennings, 2020).

4 RESULTS

4.1 Sediment record

Core BH03 contains a varied array of sediment grain sizes, ranging from clays to gravels (Figure 6). Certain intervals of the core are occupied entirely by limestone, up to 1.65 m thick, which potentially represent matrix-supported boulders in the unconsolidated sediment. These inferred boulders, or rafts, are typically pale grey and fine- to medium-grained limestone and contain calcite veins, bioclastic debris and stylolites oriented at a high angle to the core.

Core BH03 can be subdivided into eight general (lithostratigraphic) intervals as demonstrated in Figure 6. Visual examples of each of the units is provided in Figure 7:

1) *Basal limestone (109.97 m – 104.92 m)*

The bottom 4.95 m of core BH03 is occupied mostly by continuous limestone, with a conspicuous 0.5 m thick unit of gravel (comprised principally of limestone clasts) from 107.6 m - 107.1 m and a 0.3 m thick discrete break containing organic dark brown clay which was sampled for palynological analysis. A limestone pebble extracted from the 0.5 m gap was lithologically different to the local bedrock, and also to the large inferred limestone boulders in the younger parts of the core. A small calcite-filled void exhibiting cubic purple fluorite crystals occurred at 109.4 m. This unit is succeeded by a large gap in the core (no recovery) from 104.92 m – 85.52 m.

2) *Diamict I (85.52 m – 74.97 m)*

The stratigraphically lowest diamict unit of core BH03 is characterised by dispersed angular limestone cobbles and boulders (the latter up to 1.14 m thick in the recovered core) in a poorly-sorted clay matrix containing sand and gravel. This unit is capped by a 28 cm unit of organic clay, also containing dispersed limestone gravel clasts.

3) *Laminated clays (74.97 m – 62.1 m)*

This unit consists predominantly horizontally laminated clays, with subordinate interbedded sands and silts. Organic (plant) fragments occur, along with dispersed pale grey limestone boulders (up to 74 cm length in the core). An organic clay unit between 65.68 m – 62.42 m exhibits sediment laminae oriented at a high angle to the core (almost orthogonal) in its topmost 50 cm. This interval of high-angle lamination is conspicuously discordant from the typical horizontal laminations observed above and below this layer and elsewhere in other clays of the core.

4) *Diamict II (62.1 m – 49.9 m)*

The second (middle) diamict unit in BH03 contains large limestone boulders, angular and sub-rounded cobbles and greyish gravelly clays. A suspected limestone boulder occurs between 52.46 m – 51.2 m, and displays sub-vertically orientated stylolites.

5) *Organic-rich interval (49.9 m – 36.85 m)*

This unit is dominated by clays and organic-rich clays containing plant debris and interspersed layers of sand, and occurs above the second diamict in BH03. The basal 4.7 m of the unit consists of an organic clay exhibiting traces of a blue mineral substance (possibly apatite) and also fragments of iridescent beetle elytra (rigid wing covers). Two pollen samples were extracted from this unit, at 47 m and 38.6 m.

6) *Thick sand interval (36.85 m – 13.55 m)*

The longest continuous unit in the core comprises mostly greyish brown sand with calcareous silt and exhibits some organic fragments. The particle size distribution varies without trend with depth (silt content ranges from 8.4% to 51.5%), but sand is predominant overall. At some intervals, the silty sand demonstrates faint brown laminae and centimetric banding. The mineralogy of the sand is predominantly quartz with weathered limestone fragments and minor feldspar. Recovery of this unit was poor, with a 1.4 m section of complete core loss from 16.05 m – 14.65 m.

7) *Diamict III (13.55 m – 1.2 m)*

The third and stratigraphically youngest diamict unit hosts matrix-supported angular limestone gravel and stiff sandy/silty clays with some loose clasts resulting from poor core recovery. There is a noticeable absence of large boulders in Diamict III. An angular pink (tonalitic) granite clast (≈4 cm in size) was observed within a section of sub-angular to sub-rounded grey and dark grey limestone cobbles from 3.55 m – 3.0 m depth of core. Several sections of complete core loss occur in this section and range in thickness from 0.4 m to 0.67 m.

8) *Top of core (1.2 m – 0 m)*

No sediments were recovered for the first 1.2 m of core BH03.

4.2 Palynology

A total of 44 pollen taxa were identified during the pollen counting (Figure 8). Additional slides were scanned for extra pollen types/spores not encountered during routine counting (Table 1); these types are only present in very low numbers. The most abundant pollen types recovered from all four samples include *Betula*, *Calluna*, Cyperaceae, *Ilex aquifolium*, *Isoetes lacustris*, *Pinus*, Poaceae, *Sphagnum* and *Typha latifolia*; however, counts for individual pollen types vary greatly among the four samples. Pol.4 (extracted from Unit 1 in the base of core BH03 from an interval of organic clay between large limestone boulders or rafts) contained the highest relative levels of *I. aquifolium* and *I. lacustris* and the lowest of *Sphagnum*. The percentage representation of Poaceae (42%) in Pol.3 (extracted from Unit 3) is the highest value of any pollen in this study. This Poaceae-dominant sample contained no *Isoetes* and only very low levels of *I. aquifolium* and *Sphagnum*. The two younger samples Pol.2 and Pol.1 (both extracted from Unit 5) yielded relatively similar pollen assemblages. *Sphagnum*, Poaceae, *Pinus* and *T. latifolia* dominate Pol.2 and *Pinus* dominates Pol.1, which also contains relatively high levels of Cyperaceae pollen but low levels of *I. aquifolium* and *I. lacustris* pollen.

Pol.1/38.6 m	Monoletes, *Pediastrum*, *Pinus* stomata, *Selaginella* and *Succisa*
Pol.2/47 m	*Abies*, Caryophyllaceae, *Quercus*, Liguliflorae (Lactuceae), *Osmunda*, *Pinus* stomata, *Polypodium*, *Potamogeton*, *Selaginella*, and *Succisa*
Pol.3/63.8 m	*Botrychium*, *Corylus*, *Huperzia selago*, *Lycopodium*, *Polypodium* and *Selaginella*
Pol.4/108.5 m	*Filipendula*, *H. selago*, Liguliflorae, *Osmunda*, *Pediastrum*, *Pinus* stomata, *Polypodium*, and *Sucissa*

Table 1 Additional pollen and spore taxa observed in low numbers in the scanning of extra slides outside of routine counting of samples extracted from the organic clay samples from core BH03

Not part of the Holocene flora of Ireland, the pollen taxa *Tsuga* (hemlock) was identified in all four of the organic clay samples. These inaperturate pollen grains are typically large (> 50 microns), crumpled and coated with verrucae (Figure 9). These grains resemble those described by Coxon and Flegg (1987) which are compared with modern grains of *Tsuga canadensis*.

5 DISCUSSION

5.1 Karstification

5.1.1 Deep karst

The Coolough depression has been proven to a depth of 83.7 m below sea level (Figure 6). For karstification to have occurred at this depth, sea level must have been at least *c.*84 m lower than at present and the Coolough area would have been part of a flow field with a relatively steep hydraulic gradient (between Lough Corrib and the reduced sea level). Irish

Carboniferous limestones contain clear evidence of deep karst (Drew, 1990; Drew & Jones, 2000; Schuler, Duran, McCormack, & Gill, 2018), presumably formed during times of low relative sea level, associated with Pleistocene climate fluctuations (Auffret et al., 2002; Brooks & Edwards, 2006; Edwards & Craven, 2017; Edwards et al., 2017). Global water depth models provide sea level estimates of 121±5 m below present during the Last Glacial Maximum (LGM) (Fairbanks, 1989), whilst evidence from around the Irish coast supports a sea level of *c*.80 m lower than present since the LGM (Plets et al., 2015). Lowstands are also likely to have occurred earlier in the Pleistocene, some with even lower sea levels. In the western lowlands, deep caves (Drew & Jones, 2000) and offshore groundwater springs in Galway Bay (Cave & Henry, 2011; O'Connell, Daly, Henry, & Brown, 2018) attest to deep karstification during such lowstands. Today, a remnant conduit system (~65 m below sea level) drains groundwater from the Burren directly into the middle of Galway Bay (Schuler et al., 2018). Inland, evidence of karstic erosion below current sea level is also exposed at Tynagh mine, County Galway (Henry, 2014).

It is possible that the conduit(s) below Coolough Quarry may be connected to a deep and mature karst network. The River Corrib has reportedly 'disappeared' or dried up at times in the 12th and 17th centuries (Drew, 2018; O'Donovan, 1854). It is conceivable that the River Corrib was channelled into large karst conduits in the Menlo and Terryland areas around Coolough, re-activating a deep and older groundwater regime, a phenomenon also reported from Ballyglunin cave, where in 1955, the River Abbert sank into the cave (Drew, 2018).

5.1.2 Karst development

The evolution of karst is heavily influenced by existing joint patterns or will follow the trend of major faults within carbonate bedrock (Bense et al., 2013; Drew, 1973b). An extensive weathered zone under Coolough Quarry (Supporting Information B: Geophysics) aligns with a postulated east-west fault which transects the quarry and is broadly parallel to the long axis of the large depression, seemingly convergent with it. The fault damage zone is discernible on the eastern quarry face in the form of noticeably disturbed bedrock, and across the quarry towards the depression by focalised groundwater egression. The fault controls groundwater movement (further enhanced by jointing) and has evidently induced karstification along its lineament which extends far into the bedrock below Coolough Quarry and seems to have produced one or more conduits within the bedrock. This control is particularly evident with the emergence of water above and below the clay horizons exposed in the quarry in proximity to the zone of disturbance.

For a large-scale negative karst feature to form, a correspondingly large volume of bedrock must have been removed. Given the depth of the depression at Coolough and the steepness of its margins, the carbonate bedrock was most likely eroded by in-situ chemical weathering. The depression may have formed by solution from the surface downwards, as is often the case for enclosed depressions such as dolines and poljes, or by collapse into a large underlying cave or cavern, or perhaps by some combination of both. For example, the deep karst of Aughinish was produced from surface dissolution, driven by preferential weathering of dolomitised limestones associated with a fault (Clark et al., 1981). An area of particularly concentrated jointing along the already weakened lineament of the fault at Coolough, may have induced focalised, and thus enhanced, weathering in this portion of the bedrock which led to the development of a large karst pit. Alternatively, the enhanced solution may have transpired within the bedrock forming a cave or cavern along a conduit which formed along the fault. In the latter case, continued dissolution of the bedrock and enlargement of the cavity would have eventually resulted in a roof collapse and development of a pit with a steep ‘gorge-like’ profile (Figure 10), similar to the Poulaloughabo and Pollbehan collapse dolines situated above the main conduit between Gort and Kinvara adjacent to the Burren (Drew, 2018). The presence of rotated cohesive sediment packages (with high-angle laminae) in Early Pleistocene Unit 3 in BH03 suggest that a component of syn-sedimentary collapse occurred during subsequent infill of the larger depression. The presence of rotated boulders of limestone (exhibiting high-angle stylolites) could have resulted from either the top-down or conduit scenarios. However, without detailed information about the gross morphology of the Coolough pit, its classification is subjective.

5.2 Age and palaeoenvironments of the Coolough deposit

5.2.1 Palynology

The lack of warm climate species interpreted from the palynological results in BH03 suggests that the deposit is not as old as Oligocene or Miocene, and hence, is likely to be younger than *c.*5.3 Ma. Furthermore, the lack of diagnostic Neogene taxa (e.g. *Symplocus* and *Corsinipollenites*) indicates that the deposit is post-Pliocene in age, i.e. Quaternary. *Tsuga*, identified in all four of the organic clay samples, is generally considered indicative of the Neogene (Coxon & Flegg, 1987), but has also been recorded from Irish deposits dated to the Palaeocene through to the Early Pleistocene (Coxon & Coxon, 1997; Coxon & McCarron, 2009). More recent deposits in Ireland (Middle Pleistocene through to the Holocene) have not revealed *Tsuga* as part of their pollen assemblages (Coxon & McCarron, 2009; Coxon et al., 2017; Jessen, Andersen, & Farrington, 1959) and hence, the Coolough deposit is considered to be older than any of the known Irish deposits dating to the Middle Pleistocene.

The three distinct packages of diamict (I-III) (Figure 6) potentially reflect individual phases of deglaciation; however, additional drilling would be required to test their lateral continuity.

Diamicts I and II are both stratigraphically overlain by organic-rich clay units (Units 3 and 5 respectively), suggesting that the latter might be interglacial in origin and the product of recolonisation by vegetation during warm phases (Coxon & Waldren, 1995). Similar organic clays and peats elsewhere in Ireland have facilitated biostratigraphic subdivision of regional stages in Ireland for the Quaternary (Figure 11).

The relative abundance of lake quillwort (*I. lacustris*) in the lowest sample processed for palynology (Pol.4, 108.5 m) is suggestive of a lacustrine environment (see also the presence of the algae *Botryococcus*). The karst depression at Coolough may have been episodically inundated, particularly during glacial outwash and Pol.4 may reflect this. However, as the sample was recovered from an apparent void in the limestone, it is also possible that this clay was deposited by groundwater seepage through a conduit. The proximal Lough Corrib would be a likely source for this lacustrine sediment in the latter scenario.

Sample Pol.3 in Unit 3 displays a predominance of pine trees, grasses, heather, pinks/carnations, daisies and clubmosses. The pollen assemblage thus records a cool environment akin to those observed in alpine areas and it also shows limited similarity to other Pleistocene deposits in Ireland. Although the presence of coniferous trees and ericaceous vegetation is reminiscent of the assemblage described from the Pollnahallia deposit (Coxon & Coxon, 1997), several taxa identified at Pollnahallia are not observed at Coolough, such as *Alnus*, *Carya*, *Corylus*, Cupressaceae, *Salix* and Rosaceae. The Pollnahallia deposit is dated to the Upper Pliocene Epoch or Pliocene-Pleistocene boundary (*c.*2.6 Ma; Figure 11) from the presence of typical late Neogene taxa (e.g. *Sequoia*, *Taxodium*, *Nyssa* and others) (Coxon & McCarron, 2009); none of which are recorded at Coolough. A 45 cm Early or Middle Pleistocene reddish-brown silty clay, sampled from a palaeosol which accumulated over a weathered granite surface at Gowlan East, County Galway, contains thermophilous taxa such as *Tilia*, *Ulmus*, *Quercus* and *Alnus* (Coxon, 2001), which are also absent in Pol.3 from Coolough.

The Pol.3 assemblage is more comparable to the Thurnian and Baventian temperate stages in Great Britain, specifically the late phases (cooler environments) which lack floral species, contain abundant *Pinus* and are dominated by grasses and heath vegetation (Gibbard et al., 1991; West, 1961). These Early Pleistocene stages are correlated with the climatically complex interglacial Tiglian stage (specifically, substages B and C4 respectively). The Tiglian was originally determined from deposits in the Netherlands, where the most detailed and continuous records of European Early Pleistocene deposits are found (Zagwijn, 1960, 1963, 1975, 1985; Zagwijn & de Jong, 1982). The clay of Unit 3 in BH03 is thus, potentially, Early Pleistocene in age, but younger than the clays at Pollnahallia. This is significant, as a gap exists in the Irish Pleistocene biostratigraphic record for this interval, and furthermore, the lowest diamict (I) of core BH03 potentially represents an early, if not the first, Irish Quaternary glacial period (>MIS 9; Figure 11).

The two similar pollen assemblages for samples Pol.2 and Pol.1 (from Unit 5) both indicate an open-structure wooded landscape. The presence of *Abies* and *Picea* suggest a Middle Pleistocene age, which is further supported by the sparsity of important Late Pleistocene taxa such as *Alnus* and *Ilex*. The overall assemblage (including *Abies*, *Pinus*, *Betula*, *Corylus*, *Picea*, *Juniperus* and *Ilex*) and high representation of birch and sedge pollen in these two samples is comparable to Gortian-type deposits, which are described from various locations around Ireland (Coxon & McCarron, 2009; Coxon et al., 2017; Jessen et al., 1959) and broadly correlate with MIS 7 (~190-250 ka) or MIS 9 (~280-340 ka) (Dowling, Sejrup, &

Coxon, 1998; Figure 11). Pol.1 and Pol.2 also share similarities with pollen assemblages from the Middle Pleistocene Ballyline deposit in County Kilkenny (Coxon & Flegg, 1985; Figure 11), particularly towards the top of the Ballyline deposit where the forest has waned and *Pinus*, *Picea*, Poaceae and herbaceous plants dominate. This >25 m thick, lacustrine clay is protected in a karstic depression in Viséan limestone and has been correlated with European deposits dating to MIS 11 and 13 (Coxon, 1993). The clays of Unit 5 are thus most likely to be Middle Pleistocene in age, but considering the presence of *Tsuga*, this unit is likely to be older than both the Gortian and Ballyline deposits.

5.2.2 Fluvial influence

Karst infills commonly display multiple phases of deposition, erosion and mixing of detritus of different ages through erosional disturbance or collapse events (Bosák, 2008). The Coolough deposit is no exception, and it likely to have acted as a large swallow hole connecting surface drainage with subsurface karst conduits, which were likely to be similar to the extensive networks developed in the Gort-Kinvara area in east Galway (Drew, 2018). Other large swallow holes are found across the western lowlands, e.g. Polldeelin, the Punchbowl and those in Castle Bay (Drew, 2018). Although karstic systems dominate drainage towards the western extremities of the western lowlands, evidence of former rivers on the karst landscape around Coolough are visible on satellite imagery. Meandering fields demonstrate former river channels (now in-filled with sandy unconsolidated sediment) and one such channel is exposed in cross-section where it intersects Coolough quarry (Figure 12). These former rivers may have transpired following glacial retreat during warm phases or interglacials, when water levels rose sufficiently to inundate the karstic network and forced temporary surface channels to develop on the bedrock. Riverine interactions with the karst depression at Coolough were likely to have been responsible for both erosion (during glacial outwash) and sediment deposition (as meltwaters waned). Fluvial sediments such as the sands within BH03 also suggest the periodic presence of rivers.

The significant temporal difference between the suggested Early Pleistocene deposition for Unit 3 and Middle Pleistocene deposition for Unit 5 alludes to the removal (erosion) of material during the history of the Coolough deposit. Glacial advances are likely to have infilled the Coolough depression wholly, hence the presence of three distinct diamict units indicates recurring erosion. Discrete sediment deposits may have been removed (partially or entirely) from the gorge by a sinking river which eroded the unconsolidated sediments and carried them as part of the river load into the conduit network. Through multiple glacial-interglacial phases, flowing water may have eroded sediment from the Coolough gorge on several occasions. Ultimately, unit and layer boundaries in the sediment stratigraphy of the deposit are unconformable. As karst systems are typically both polycyclic and polygenetic (Bosák, 2002), the large negative landform at Coolough may in fact be much older than the suggested minimum date (Early Pleistocene) presented in this paper.

6 CONCLUSIONS

The relatively pure carbonate bedrock near Galway City (Burren Limestone Formation) evidently consists of a variety of karst landforms and karst aquifers. At Coolough in County Galway, at least one large aquifer system played an integral role in the creation of a large enclosed karst landform. The infill from this *c.*110 m deep karst depression has been described for the first time. The enclosed depression initially formed due to enhanced groundwater flow along a pre-existing east-west fault feature in the Carboniferous limestone bedrock, which led to the enlargement of a deep-seated groundwater conduit through karstification. Progressive epigenetic dissolution and the potential expansion and unroofing of an underground cavern, along the conduit, eventually created a steep-sided, gorge-like karst landform. This was subsequently infilled by a mixture of fluvial and lacustrine sediments, along with three discrete diamicts of probable glacial origin. The Coolough sediments broadly correlate to the Early and Middle Pleistocene, based on their pollen records, suggesting formation of the karst pit prior to the onset of deposition in the early Quaternary. Similar buried deposits are likely to exist elsewhere in the wider surrounding region and across the western lowlands, particularly where the bedrock has been fractured, faulted and relatively intense karstification has transpired. Analysing such deposits allows for the reconstruction of palaeoenvironments and paleoclimates, increasing our overall understanding of the Quaternary evolution of the Irish landscape.

The results from this study also supplement our existing understanding of the geology and geomorphology of the Galway City area and of the karst nature of the Carboniferous bedrock of the western lowlands in Ireland. Finally, this paper highlights the value of adopting a broad multi-disciplinary approach in such complex geological environments.

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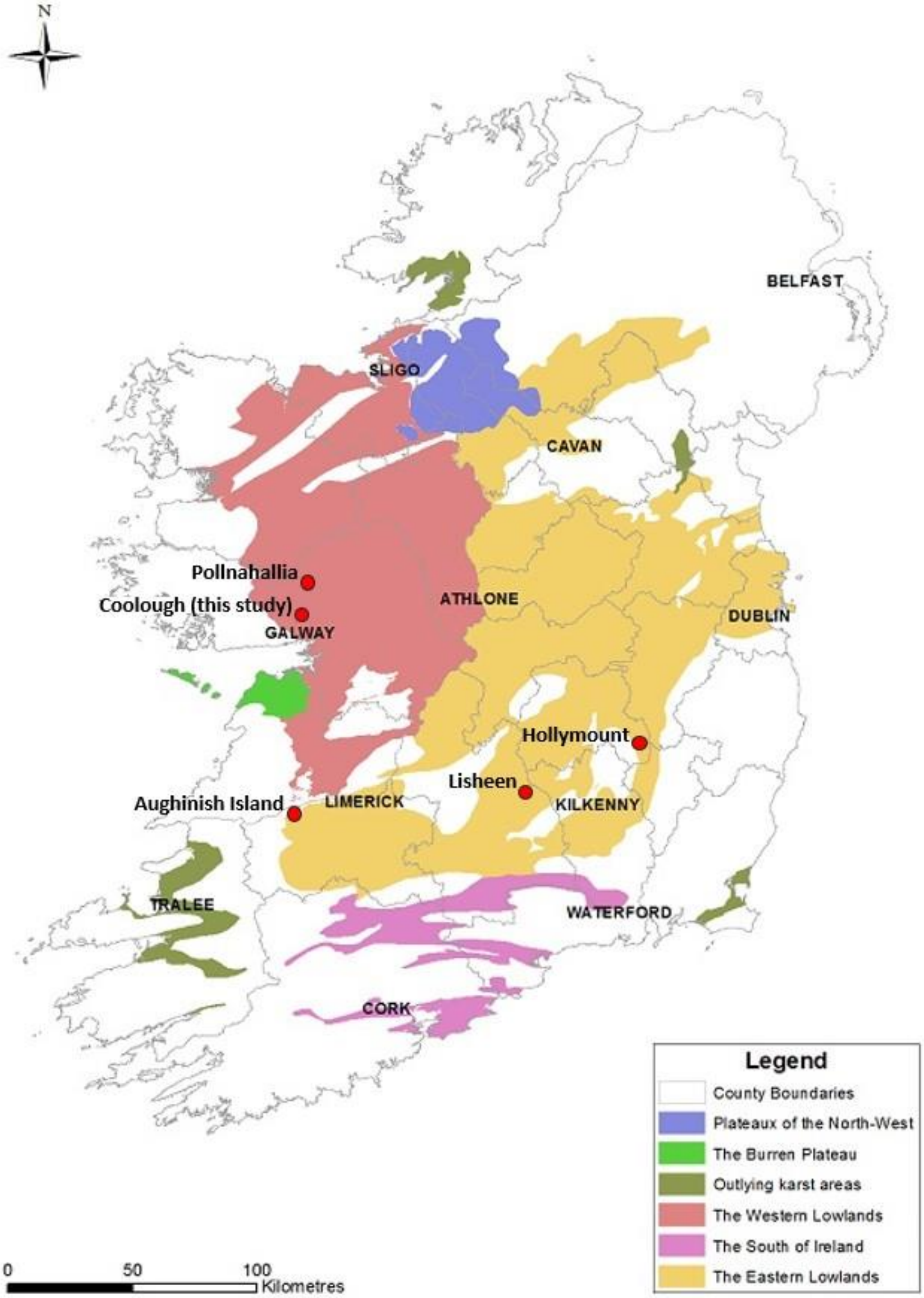

Figure 1 Karst regions of Ireland, developed principally in Mississippian limestones – adapted from Geological Survey Ireland's website. The western lowlands (in red) extends through counties Sligo, Mayo, Roscommon, Galway and Clare. Examples of large sediment-infilled karst depressions in Ireland are shown, including the Coolough landform and deposit presented in this study

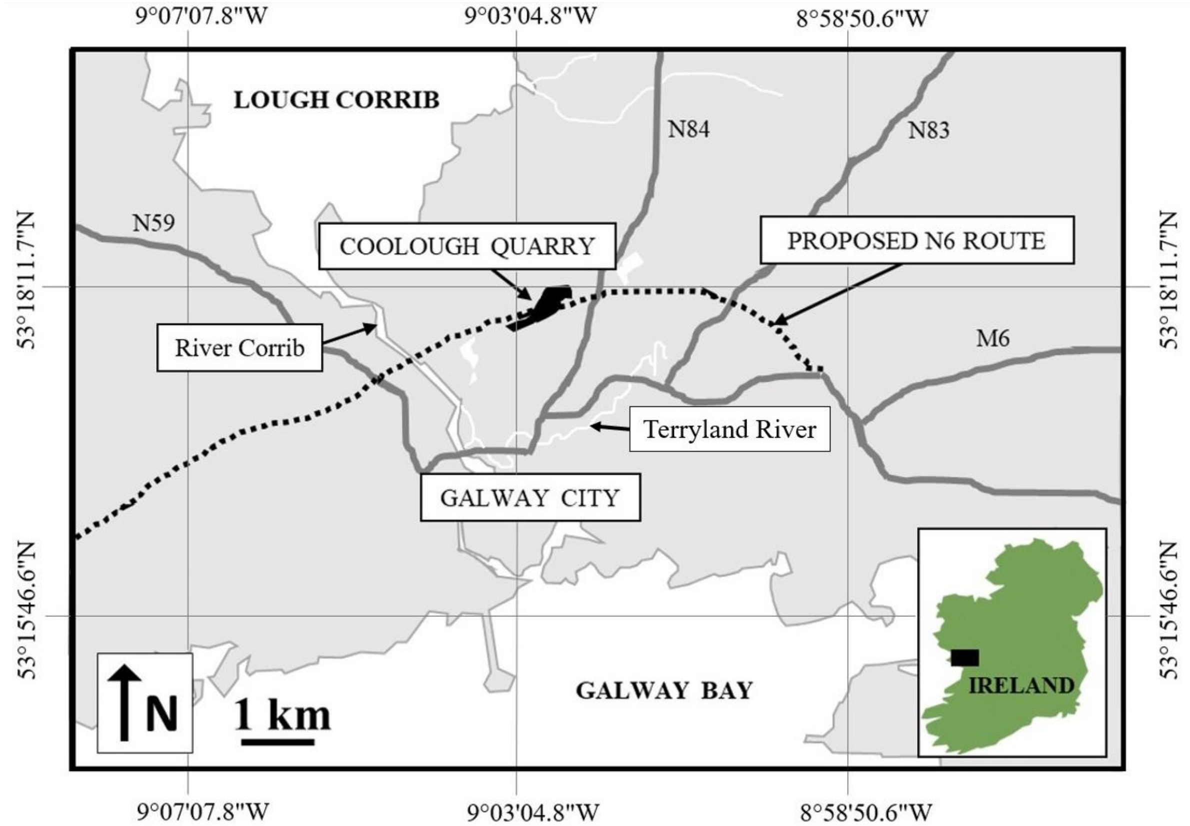

Figure 2 Geographical location of Coolough Quarry, between Galway City and Lough Corrib in County Galway, Ireland. Currently operating major roads are shown in solid grey. The proposed route of the new N6 Galway City Ring Road is delineated in dotted black. Inset map (bottom left) shows location of study area in western Ireland

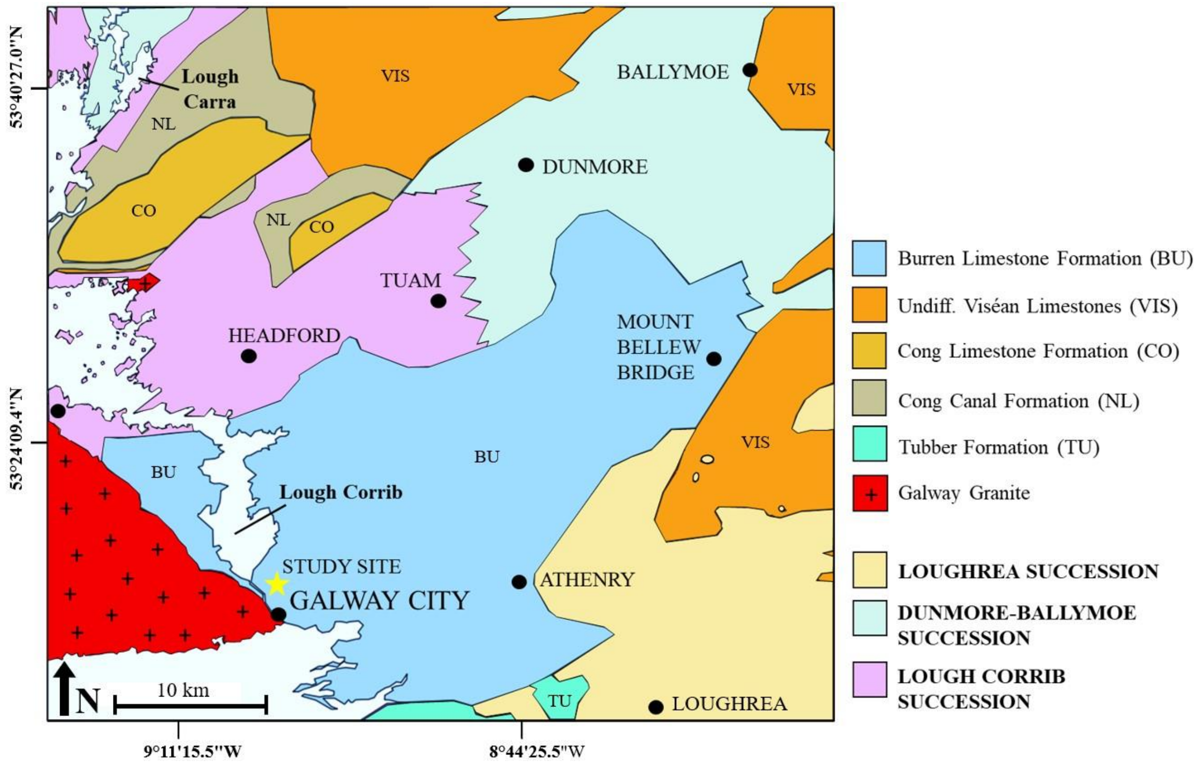

Figure 3 Geological bedrock map of north-west County Galway and south County Mayo adapted from Pracht and Somerville (2015). Three unified stratigraphic successions consist of Mississippian bedrock formations (representing the Courceyan sub-stage through to the Asbian). Undifferentiated Viséan Limestones (VIS), the Burren Limestone Formation (BU) and Tubber Formation (TU) each span across more than one succession and are presented independently of successions on this map. The Coolough depression is located on the map (study site)

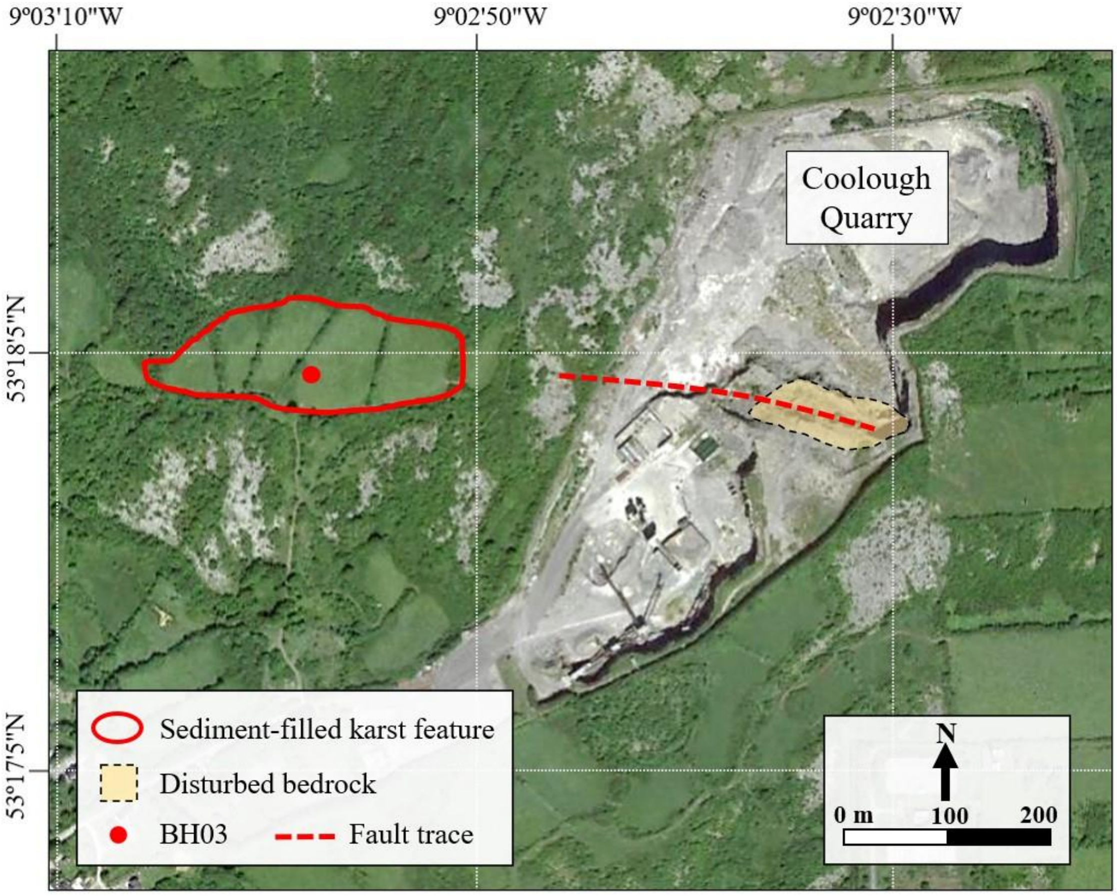

Figure 4 The Coolough study site which comprises the sediment-filled karst feature (outlined in red) and Coolough Quarry. Core BH03, used in this study, was extracted by Arup (2018) from the location marked by a red dot within the karst deposit. The trace of an apparent fault is demonstrated by a dashed red line and an area of observed notable topographic disturbance is highlighted. Aerial image source: Google Maps (2020)

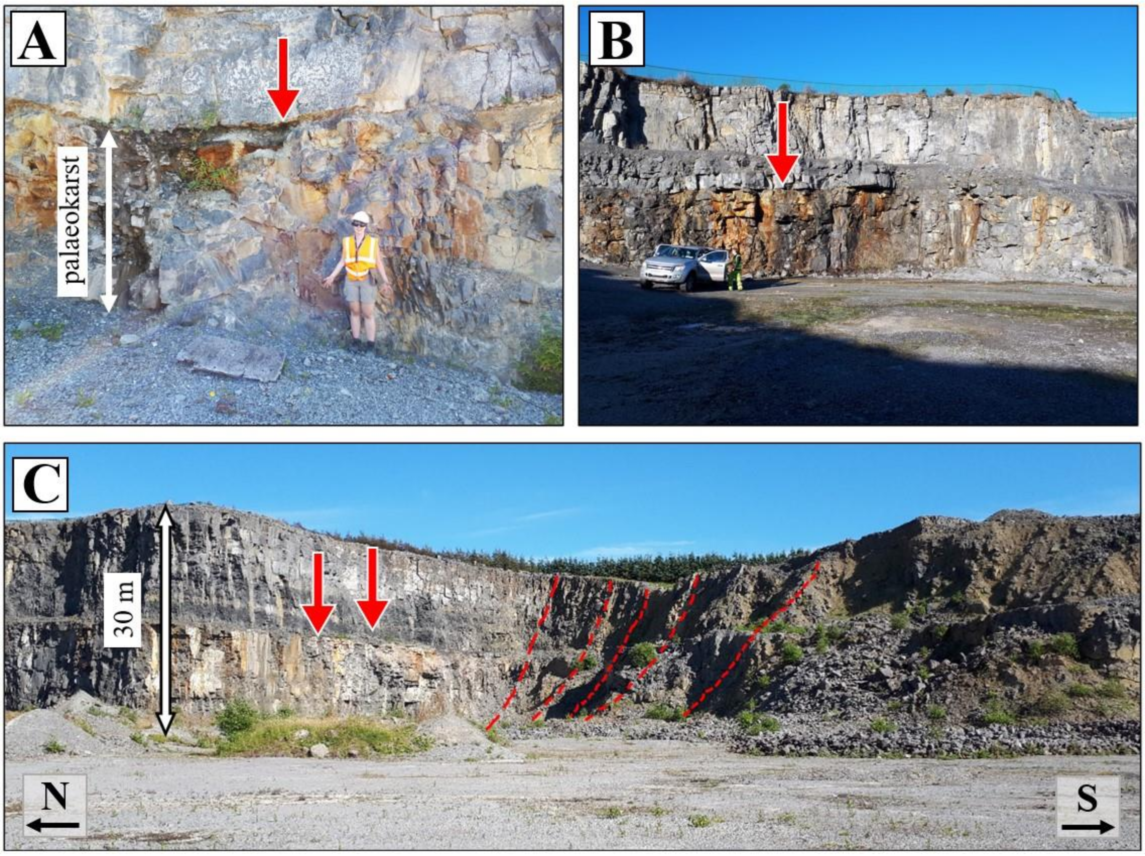

Figure 5 Photographs from Coolough Quarry – red arrows point to exposed clay horizons within the limestone bedrock. (A) Palaeokarst in a western quarry bench, below the undulating surface of a clay horizon and along the proposed fault trend (geologist for scale). (B) Focalised egression of groundwater and conspicuous iron staining (vehicle for scale). (C) Notable bedrock disturbance (see red dashed lines) in the apparent fault damage zone along the eastern quarry benches

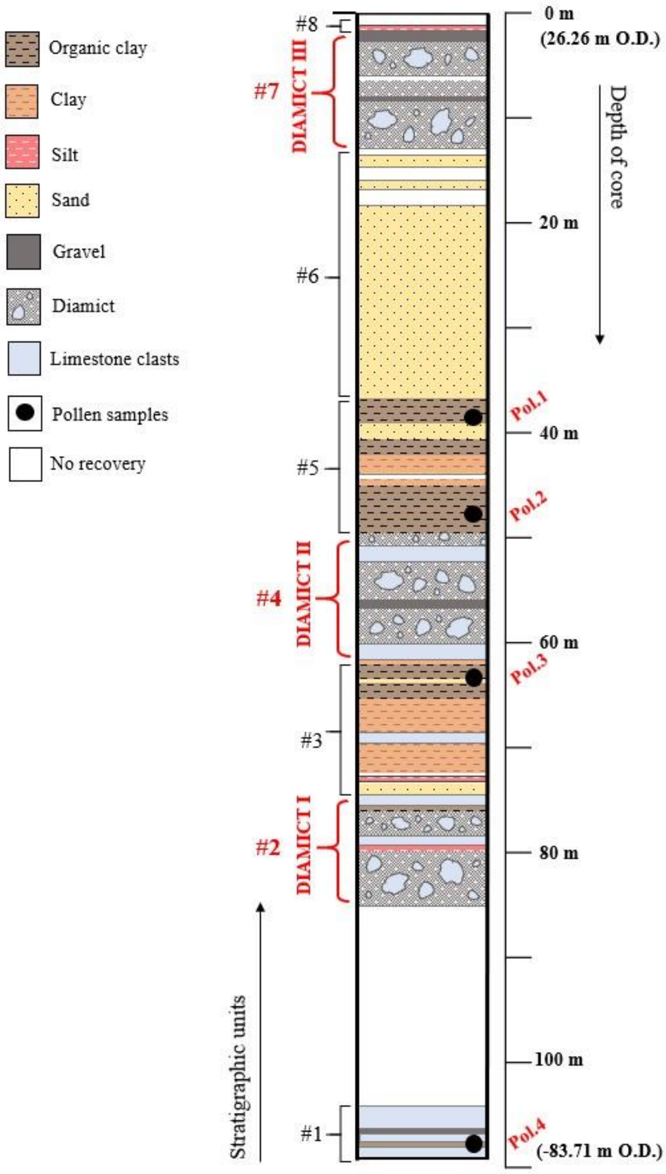

Figure 6 Stratigraphy of core BH03. The key to the sediment types is shown on the left. Black dots represent levels from which organic clay samples were extracted for a pollen analysis

Figure 7 Representative photographs of core BH03 from the first seven stratigraphic intervals. Each of the core boxes are 1 m in length

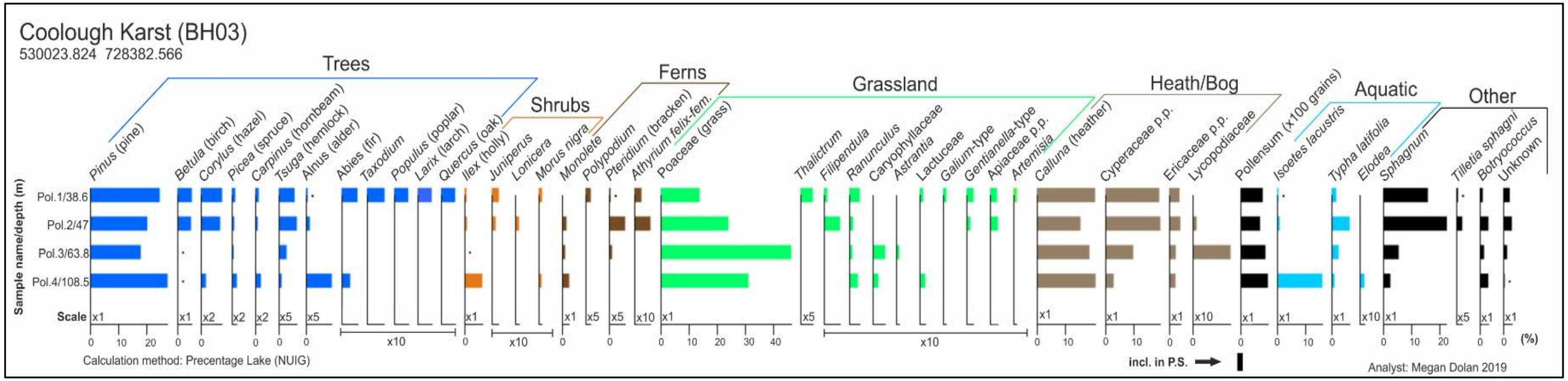

Figure 8 Pollen assemblages, as determined for each organic clay sample (extracted from core BH03) in the palynological study. Pollen sum is 1000 grains. Ecological groups are differentiated using colour coding and pollen curves are grouped accordingly; the exaggeration factor for each curve is indicated above the x-axis; small dots emphasise low values that might not otherwise be obvious

Figure 9 Tsuga pollen grain as seen in samples from Unit 3 and Unit 5 of core BH03 extracted from the Coolough deposit

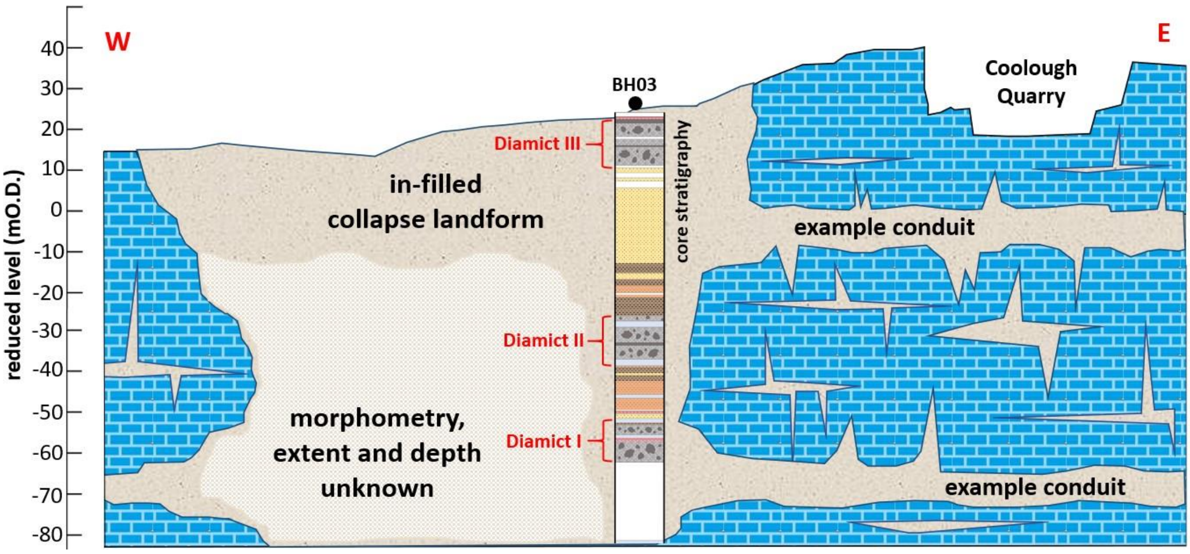

Figure 10 Conceptual model of the Coolough infilled karst landform. Conduits presented are examples only; the size and shape of conduits, and the nature of any conduit network is unknown. The size and morphology of the inferred former cave/cavern is also unknown. The karst depression boundary has not yet been mapped out below -10 m O.D. The schematic is adapted from Arup (2018); Figure 1.0 Section with Plotted Data, Appendix B Lackagh Tunnel Design Details

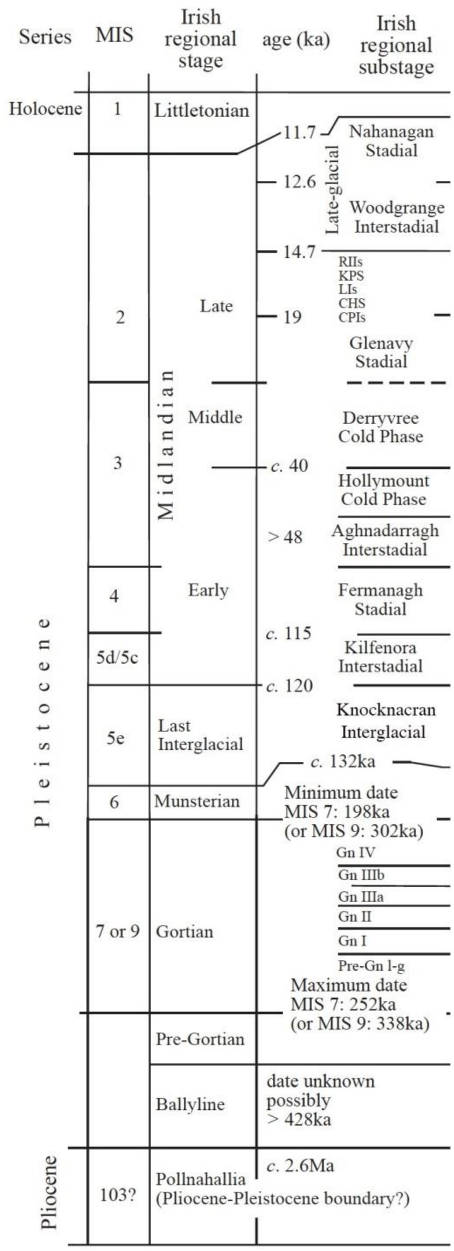

Figure 11 Subdivisions of the Quaternary with Irish Regional Stages and corresponding Marine Isotope Stages (MIS), after Coxon and McCarron (2009), Coxon et al. (2017)

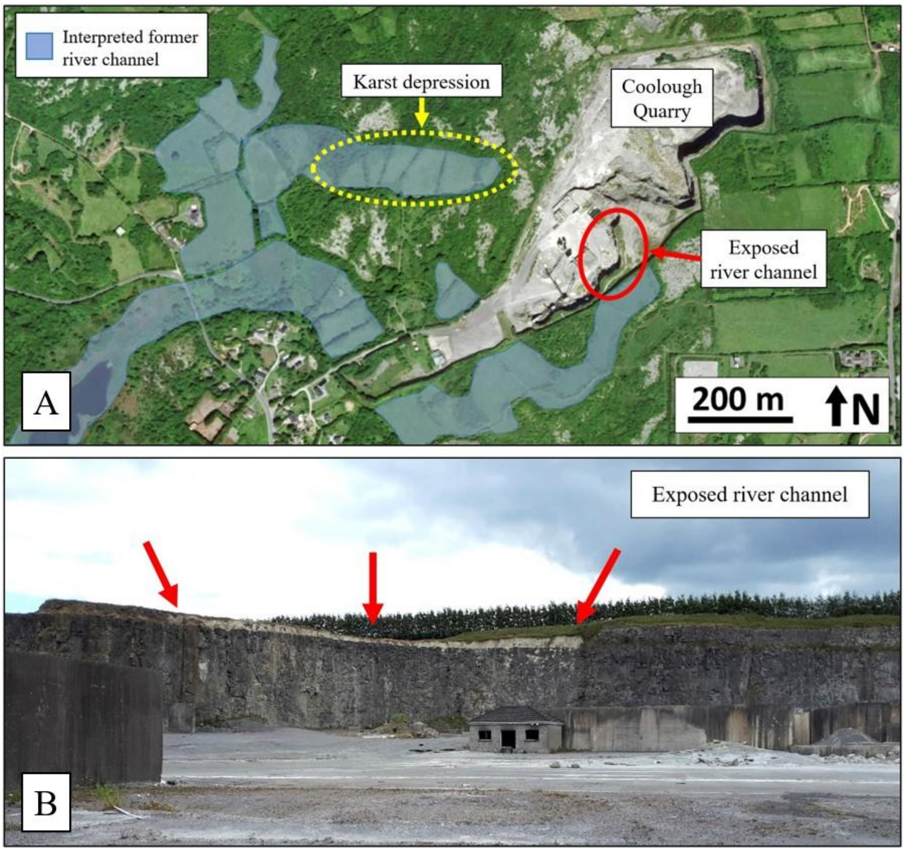

Figure 12 Evidence of rivers on the karst landscape around Coolough Quarry. (A) Meandering fields (in blue) demonstrate the path of former river channels (now in-filled with sandy unconsolidated sediment). (B) Exposed cross-section of former river channel where it intersects Coolough quarry

SUPPORTING INFORMATION A: CLAY HORIZONS

The two discrete but conspicuous clay-rich bands around Coolough Quarry have an average thickness of 25 cm (Figure A1). The undulating bedding surface of the limestone units which precede the clay wayboards suggest that the limestone was subjected to weathering prior to the accumulation of clay on the corroded surface. The stratigraphically lower clay horizon is a mostly non-calcareous, dark grey shale-like clay (Figure A2). The clay is argillaceous and produces a black dusty material when touched. The contact with limestone units above and below consists of a weathered orange crust (iron) whilst the clay itself exhibits pyrite stringers in typically elongate, irregular shapes < 10 cm in length (Figure A3). The top 8 cm is dark grey to black, organic rich, exhibits coalified plant matter and is calcareous to weakly calcareous. The presence of carbonised plant material in the lower clay wayboard indicates a terrestrial origin.

The stratigraphically higher clay horizon is a calcareous, medium dark grey shaley clay unit which varies in thickness and is highly weathered. The unit base is quite fissile in places. This clay unit is argillaceous. In-situ, flattened brachiopod fossils are found within this unit (Figure A4) and their presence indicates a marine depositional environment.

A comprehensive geochemical analysis of the clay wayboards is presented by Dolan (2019).

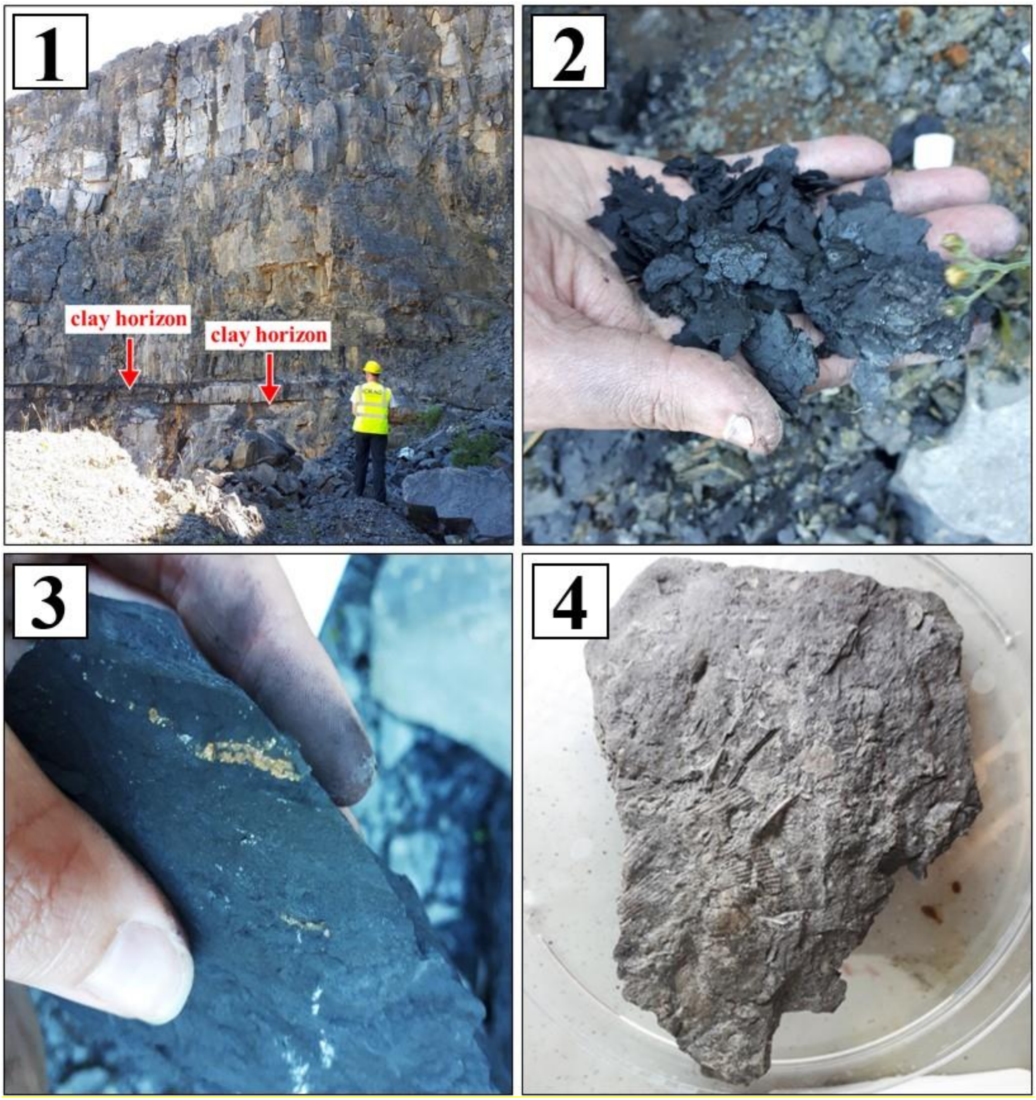

Figure A 1) Two clay horizons as seen in the exposed bedrock of Coolough Quarry, 2) flaky clay sediment extracted from one of the clay horizons, 3) pyrite stringer in clay horizon sample and 4) brachiopod with attached spines in clay horizon sample

SUPPORTING INFORMATION B: GEOPHYSICS

An ERT study was designed to investigate potential bedrock resistivity anomalies in the subsurface beneath the floor of Coolough Quarry. The ERT surveys (Line A and Line B) were oriented approximately perpendicular to the putative fault trace referred to in Section 2.2 and adjacent to the karst depression (Figure B). Full details of the methodology and inversion technique is provided in Dolan (2019).

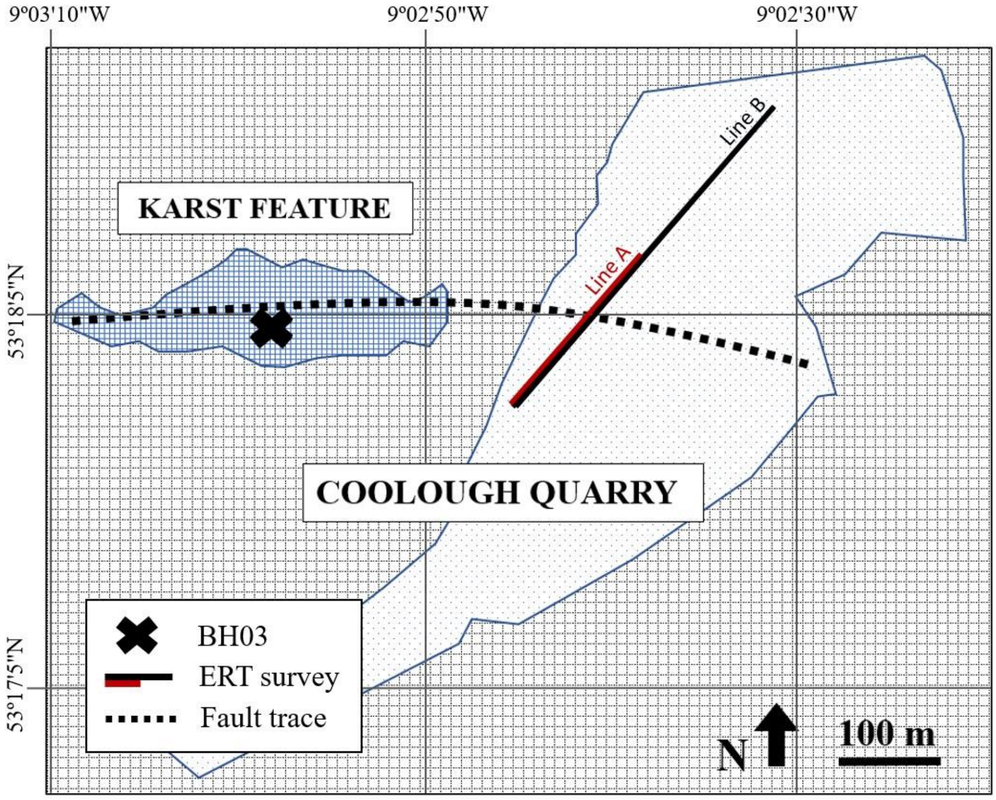

Figure B Map of study site showing the karst feature delineated by Arup (2018), the collar location of borehole BH03, Coolough Quarry, the apparent trace of a fault damage zone and the extent of the electrical resistivity tomography survey line

Modelled resistivities for Line A and Line B are shown in Figure C. Zone (i) is a large area of relatively low resistivity (measurements between 3357-6325 Ωm), approximately 65 m wide, which intersects the postulated large E-W fault line that crosscuts Coolough Quarry and seemingly connects to the buried bedrock depression further to the west of the quarry. This well-defined area of lower resistivity is likely to define the lateral extent of the damage zone associated with the fault. The major karst depression west of Coolough Quarry probably formed along the western continuation of this bedrock fracture. Additionally, the deeper portion of the ERT profile, zone (ii), which has resistivity values similar to zone (i), may represent an extensive weathered zone deep under Coolough Quarry. The interpreted fault damage zone seemingly prevails through the vertical extent of the profile between 240-305 m on Line B. As zone (ii) appears to be larger than zone (i), it could potentially represent a more heavily karstified area, possibly a conduit in the bedrock at a depth below -30.0 m O.D. elevation. Zone (y) is approximately 70 m wide and displays the lowest true resistivity values within the ERT surveys (as low as 632 Ωm). Zone (y) demonstrates that intense karstification is not confined to the immediate vicinity of the fault trace.

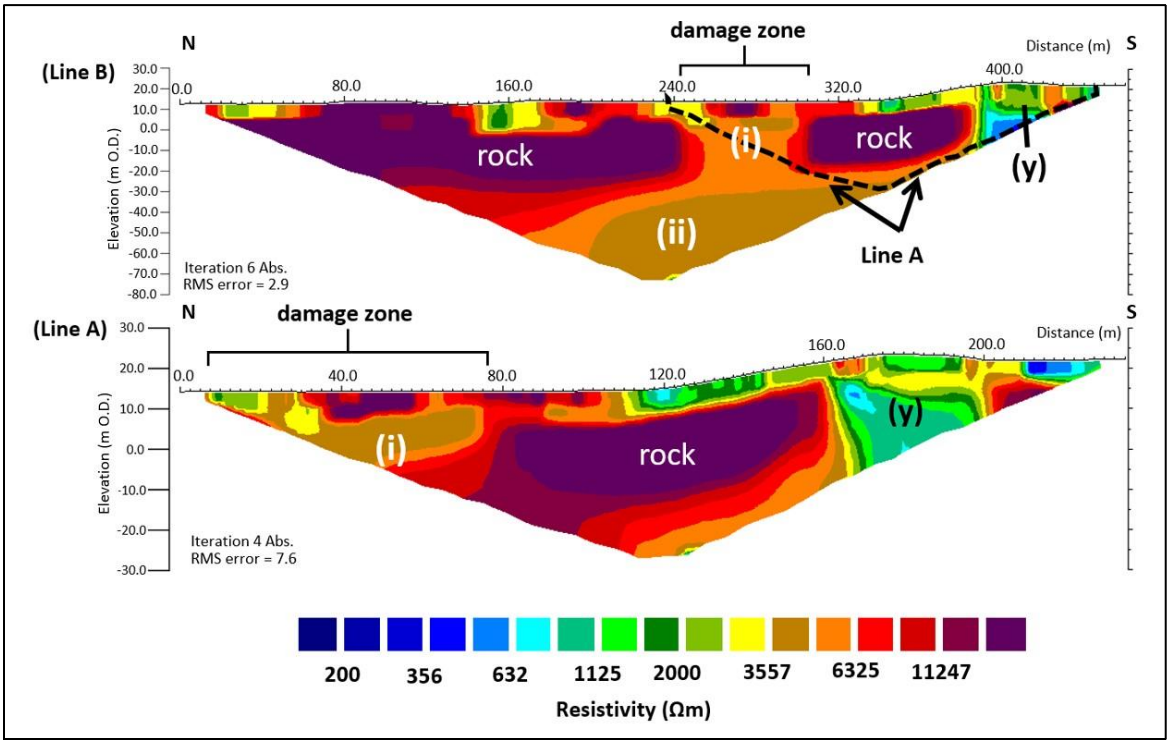

Figure C Electrical resistivity tomography data from Coolough Quarry, Galway. Modelled resistivities for the Wenner-Schlumberger configuration on the 480 m survey (Line B) and the 240 m survey (Line A) within the quarry. A dashed black line indicates where the survey extent of Line A overlaps Line B. Adopted from Dolan (2019)