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QUARTZ-RICH CAVE SEDIMENTS IN THE BURREN, CO. CLARE, IRELAND

by

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ABSTRACT

An erosionally isolated fragment of cave passage at Poulsallagh, on the west coast of the Burren, contains a sediment sequence dominated by coarse clastics exceptionally rich in exotic (non-Carboniferous) lithologies, particularly quartz. Analysis suggests that these clasts were derived from granitic and metamorphic outcrops on the north side of Galway Bay and in Connemara, indicating transport distances of more than 50 km for some. It is deduced that these exotic sediments were reworked from till deposited by ice moving across the Burren from the north-west. Subsequent ice movement from the north-east has erased virtually all surface traces of this earlier glaciation other than a scattering of reworked erratics. The former extent of this north-westerly derived till cover is indicated by the presence of similar assemblages of exotic clasts in several other caves, including the Fergus River Cave 20 km further to the east-south-east. The age of the sediments, and the till from which they were derived, remains uncertain but they are considered to be post-Gortian (Stage 11 or 9) and pre-Holocene (Stage 1). The most parsimonious chronology would have the earlier till emplaced on the surface during Stage 4, with clasts fluvially reworked into the cave during the interstadial of Stage 3, followed by till emplacement from the north-east during Stage 2.

INTRODUCTION

Cave passages are of enormous value in reconstructing the geological and geomorphological history of an area. Not only do aspects of passage morphology provide a unique insight into the palaeohydrology of an area but those same voids represent environments in which sediment and fossils can be trapped and preserved from erosion for, in some instances, tens or even hundreds of millions of years (Simms, 1990a; Simms and Boulter *in press*). In regions which have experienced long periods of net erosion these sediment-choked voids beneath the land surface can provide the only record of parts of the geological succession long since removed by surface lowering.

Large parts of Ireland can be considered as regions of 'net erosion' for at least the last few tens of millions of years and post-Carboniferous rocks are largely absent outside of Northern Ireland. However, nearly half of the country is underlain by Carboniferous rocks (Sevastopulo, 1981) in which limestones are a major element. It is karstic voids within these that have preserved a few tantalising patches of Mesozoic and Tertiary sediment (Coxon and Coxon, 1997; Higgs and Beese, 1986; Mitchell, 1981; Simms and Boulter, *in press*). Although these ancient sediments are among the most exciting discoveries to emerge from karst voids in Ireland, many other caves and their sediments still have a fascinating story to tell despite being very much younger (Waltham *et al.*, 1996). This is particularly true for the Quaternary, extending from about 2.6 million years ago to the present. The prevailing cold climate during this time interval represents a period of particularly intense erosion. The advance of each ice sheet often destroyed, or at least severely disrupted, the evidence of earlier glacial and interglacial episodes except where these older sediments were in some way protected from erosion. However, despite the obvious value of caves in preserving some record of earlier glaciations few have been examined with this in mind (Simms, Parkes and Jones, 1991).

CAVE SEDIMENTS IN THE BURREN

The Burren, in north Co. Clare, represents one of the most spectacularly karstified regions of Ireland and, understandably, has been the site of much karst research. Many cave systems in the area have been well documented in several publications (Tratman, 1969; Self, 1981) and new discoveries are made every year. Sediments are just one of several aspects of caves, others including passage morphology, geological control and hydrology, which can be investigated to provide invaluable data on surface catchments, flow velocities within the cave and aspects of the drainage history of the system (Waltham *et al.,* 1996). However, in most Burren caves the sediments remain uninvestigated and rarely even mentioned in cave descriptions. Hamilton (1969) undertook sediment analyses from several Burren caves, with sediments briefly mentioned in several other contributions in the same volume (Tratman, 1969), but there have been few other publications on this subject. Williams and Williams (1966) examined the mollusc fauna of sediments in Ballymihil Cave, establishing the former presence in this area of woodland species, while Ailwee Cave has been the site for several investigations of cave sediments (Drew, 1974, 1975; Drew and Cohen, 1980; O'Connor, 1995). However, in general the composition of cave sediments described from the Burren has proven unremarkable, being dominated by material derived locally from the immediate catchment (Figure 1). Where large enough to be identified, clasts usually are of limestone, chert or Namurian sandstone; in a few instances the latter have been found in caves now far removed from any shale cover (e.g. Kilweelran Lower Cave on Ailwee Mountain; Self, 1981), indicating that these caves may have formed when the shale cover was much more extensive (Drew, 1989). Exotic clast lithologies (i.e. derived from beyond the Burren) have been reported from very few sites in the area. The initial descriptions of Ailwee Cave (Drew, 1974, 1975) mentioned granite cobbles up to 0.35 m in diameter in the boulder choke beyond Cascade Chamber but Drew and Cohen (1980) subsequently commented specifically on the absence of erratic (non-limestone) material in the gravels. More recently there has also been an unconfirmed report of fragments of Old Red Sandstone in Sump 2 at the far end of the cave (O'Connor 1995). Published reports of exotic clasts exist for only two other Burren caves; Formoyle East Cave, in which granite cobbles were noted (Smart 1974, 1975), and the Fergus River Cave. At the latter site up to 5% of the larger clasts were of exotic lithologies considered to originate from beyond the Burren (Patmore and Nicholson, 1965). These formed the subject of analysis by Leake (1965) who tentatively concluded that the assemblage "could have been derived from the Connemara basement and the Galway granite complex". These few tantalising records hint at a formerly much greater abundance of exotic clasts on the surface of the Burren. Hence the discovery of quartz-rich gravels in a relict cave on the west coast of the Burren merits further attention.

POL NA GRIANCHLOCH (QUARTZ PEBBLE CAVE)

Numerous short sections of relict cave passage are found along the west coast of the Burren between Doolin Point and Black Head, with most being mentioned briefly in Self (1981). Only two have received more than cursory mention in the literature. These are Poulcraveen and the Doolin 'Green Holes'. The former is truncated by glacially striated, till-draped surfaces and clearly predates the last glacial maximum (Trudgill, 1971). The latter (Jones, 1988; Simms, 1990b) are drowned cave passages which clearly relate to a period of lower sea level and probably represent parts of a strike-orientated precursor of the present

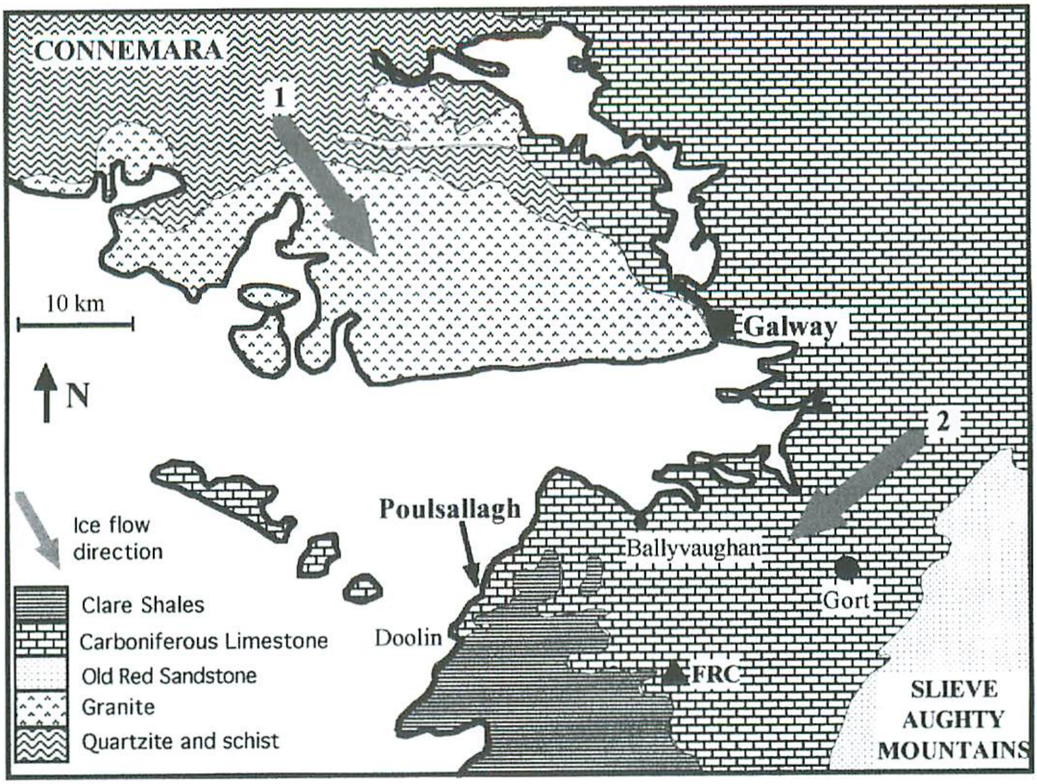

Figure 1. *General geology map for north Clare and south Galway, indicating the main locations mentioned in the text. The inferred direction of ice flow for the earlier (1) and later (2) tills is indicated. FRC : Fergus River Cave.*

Doolin River Cave (Tratman, 1969; Self, 1981). Like the latter cave, this would have formed roughly parallel to the shale margin when it lay a little further to the north; hence this cave probably also predates the last glacial maximum. Neither Poulcraveen nor the 'Green Holes' preserve any sediment.

To the north of these two sites lies the bay of Poulsallagh (Figure 2), well known to karst geomorphologists both for its exceptional development of littoral karst (Lundberg, 1977; Trudgill, 1977) and also the presence, on the north side of the bay, of a short meandering section of relict cave passage (Tratman, 1969; Self, 1981). In fact this is only one of several fragments of cave passage in the area. About 200 m to the north (Grid ref. M 0861 0200) is a largely unroofed, broad, boulder-strewn cave passage extending eastwards for about 30 m inland from the cliff top, with its floor at an altitude of approximately 12 m OD; it is the site of the detailed investigations described here and accordingly has been named Pol na Grianchloch, or Quartz Pebble Cave (site 2 on Figure 2). A fragment of the roof remains, as a conspicuous overhang, at the seaward end of the cave while at its inland end the roof is largely intact over an 8 m length (Figure 3) and preserves the sediment fill which forms the main subject of this paper. It is thought that the roof of the cave has been breached by erosion, thereby exposing the

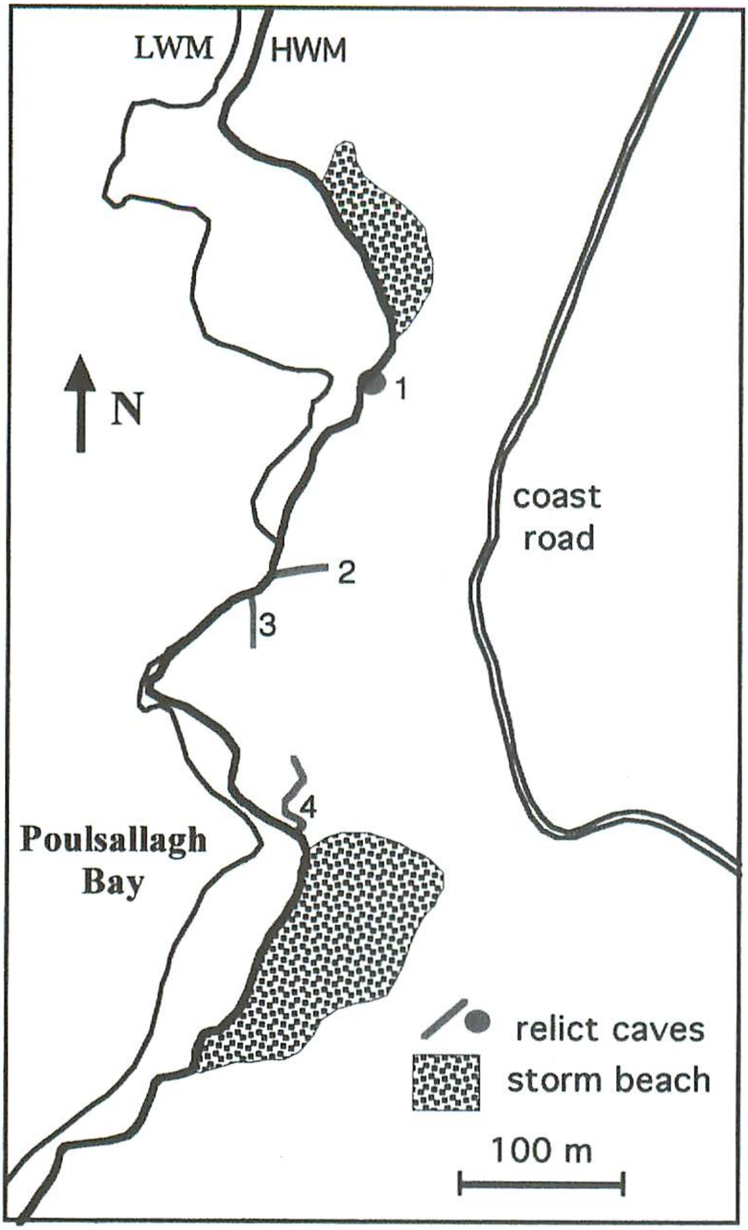

Figure 2. *Locality map for cave sites at Poulsallagh Bay. 1 : un-named choked passage; 2 : Pol na Grianchloch (Quartz Pebble Cave); 3 : unentered section of passage on cliff top; 4 : Poulsallagh.*

sediment fill, a little further to the east where a level grassed area interrupts the limestone pavement. Trudgill (1971) mentioned a 25 metre long section of cave passage on the cliff top to the north of Poulsallagh, which appears to correspond to this site, and it has been confirmed as corresponding to site S1a in the UBSS cave inventory of the Burren (G. Mullan, *pers. comm.*).

Two other nearby sites require mention here. A large opening is visible in the cliff just to the south west of the seaward end of Pol na Grianchloch and presumably represents a north-south orientated continuation of it. However, the cliff below falls sheer into the sea and there are no records of this cave (site 3 on Figure 2) having been entered. Another cave passage, truncated by erosion, is exposed at the foot of the cliff about 200 m to the north-east of Pol na Grianchloch (site 1 on Figure 2). This passage, some 4 m wide and 2 m high, is completely choked with angular to subrounded limestone blocks, the largest more than 2 m across. A few small quartz and granite pebbles are also present in the silt and clay matrix.

Geomorphology

Small-scale karren features preserved in places on the walls of Pol na Grianchloch demonstrate that it formed entirely through karstic dissolution rather than marine erosion, although the latter agent has subsequently destroyed or enlarged parts of the original passage. At its seaward (western) end the passage, or what remains of it, has a rounded canyon shape, about 4 m high and perhaps 3 m wide (Figure 3). Indistinct scalloping on the walls indicates flow to the west. In the roofed section to the east the passage is largely sediment filled but the upper metre or so has a rounded morphology indicating development under phreatic conditions (Ford and Williams, 1989). Subhorizontal notches and ledges are developed on the walls in the roofed section of passage, curving upwards at an angle of about 20° at its western end. The upward curve of these wall notches in the direction of flow is clear evidence that the passage formed by paragenesis within the phreatic zone, a mechanism whereby dissolutional enlargement of the passage is confined to the roof and walls above a sediment floor (Lauritzen and Lundberg, 2000), which in this case appears to have been undulating. Similar features are seen even more strikingly in the meandering canyon passage on the north side of Poulsallagh Bay, where the roof profile is subparallel to the undulating wall notches, clear evidence for a paragenetic origin despite previous claims that the passage is a typical vadose canyon (Tratman, 1969). The disequilibrium between these fragments of relict paragenetic passage and the current hydrological situation in this area suggests that they are significantly pre-Holocene in age.

Sediments

This stretch of coast is subject to severe winter storms which have entirely removed any sediments from the unroofed section of Pol na Grianchloch and destroyed virtually the entire north wall (Figure 3). However, sediments have survived in the roofed section, filling the passage completely at its eastern extremity. The possibility that these sediments were actually emplaced within the cave by marine processes can be dismissed since similar quartz-rich sediments were found during the course of this investigation in Lysacht's Cave in Oughtdarra (Self, 1981), 1.6 km to the east-north-east of Poulsallagh, and were also described from the Fergus River Cave (Leake, 1965), 20 km to the east-south-east.

Two sections were measured in the roofed section; one on the face at the eastern end of the passage, where the sediment fill is to the roof, and a second section on the south side of the passage about 2.5 metres further west (Figure 3). Each of the sedimentary units is subhorizontal, with no evidence of eastward dips comparable with those of the paragenetic notches preserved at the western end of the roofed section of passage.

Section 1

(iii) Up to 0.70 m - Matrix-supported angular to subrounded limestone clasts up to several cm across in a matrix of grey-brown clay. Subordinate quartz pebbles, fine-grained pink granite clasts and fragments of flowstone. Locally at base may be 2-3 cm of fine, better-sorted limestone gravel.

(ii) 0.04-0.10 m - Brown clay with scattered matrix-supported limestone fragments and quartz pebbles. In places deformed and with highly irregular contact with overlying bed.

(i) 0.15 m (seen) - Poorly-sorted mix of mostly rounded, but a few angular, limestone clasts, quartz pebbles and a few brown sandstone clasts.

Section 2

4. Up to 0.40 m - Diamictite, of angular to subrounded limestone clasts in a matrix of grey-brown clay, passing down into coarse, poorly-sorted, muddy gravel with limestone and quartz pebbles up to several cm in diameter. Thin clay lenses, some laminated, are locally developed in the lower part of the unit.

3. 0.18 m - Brown, plastic, structureless clay with scattered small matrix-supported limestone and quartz pebbles.

2. 0.10 m - Well-washed and well-sorted quartz pebble gravel. Numerous laminated brown mud flakes up to two cm thick and several cm in length, often orientated at high angles to the bedding.

1. 0.25 m (seen) - Coarse, fairly loose, quartzitic sand. Coarsely laminated with indistinct cross-beds dipping to the west.

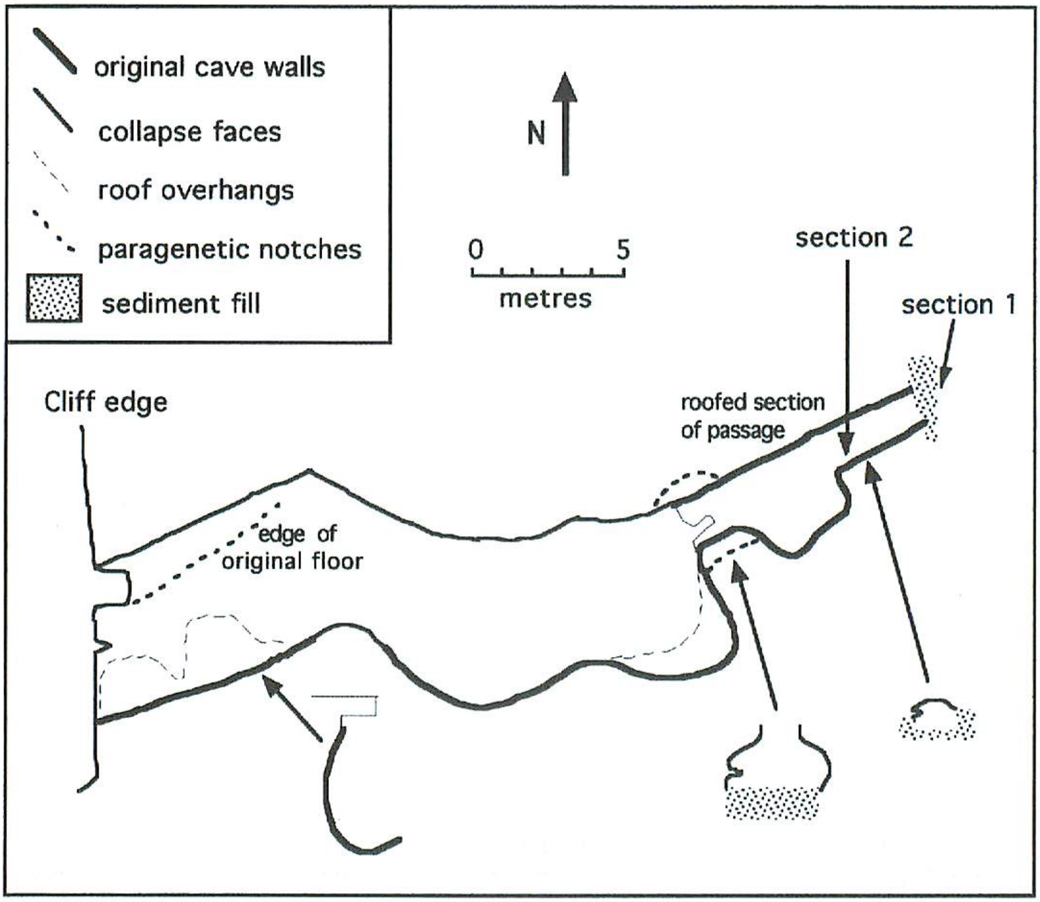

Figure 3. *Plan survey of Pol na Grianchloch (Quartz Pebble Cave) showing passage sections, viewed from the east, and location of sediment sections 1 and 2. Surveyed to BCRA Grade 5.*

Sediment analysis and interpretation

The sediments exposed in section 1 show considerable evidence of post-depositional disturbance and contamination. The predominance of angular, matrix-supported, limestone clasts in bed (iii) suggests contamination of earlier quartz-rich sediments by limestone-rich diamictite introduced from above during the last glacial maximum, while the clay unit of bed (ii) has been deformed and thickened in places by intrusion of the overlying sediments. These effects suggest that the section of passage east of the present limit of the cave was unroofed during the last glacial maximum, allowing the injection of diamictite into the passage. Because of this disturbance the sediments of section 1 have not been investigated in any further detail. However, the sediments of section 2 appear to have experienced little such disturbance, except towards the top of bed 4, and hence form the subject of the following analyses and interpretation.

Grain Size

500g (dry weight) samples from each of beds 1, 2 and 4 were wet sieved, dried, weighed and then the data plotted as bar charts (Figure 4). Bed 3 was excluded on account of its clay-dominated lithology.

Bed 1 is a poorly sorted, indistinctly cross-bedded sand, such as are fairly typical of fluvial sands. Grain size and cross-beds suggest deposition in a vadose environment by water flowing westwards at velocities of 0.2-0.3 ms-1, as deduced from the Hjulström Curve (Boggs 1987). The particularly poor sorting suggests a fairly short transport distance by this mechanism.

Bed 2 again is poorly sorted but shows a bimodal clast size distribution, with peaks of very fine and very coarse clasts. The conspicuous peak in the <0.15 mm fraction in fact reflects the nature of some of the larger clasts, which are actually ripped-up flakes of laminated mud derived from the erosion and transport, over a short distance, of pre-existing cave sediments. Intact, these mud intraclasts are of similar dimensions to some of those forming the >4 mm fraction, often being several centimetres across. The much coarser nature of the obdurate clasts in bed 2, the largest of which are more than 30 mm across, and the presence of these large flakes of laminated clay, intact deposits of which resist entrainment more effectively than significantly coarser sediments (Boggs, 1987), suggests that flow velocities exceeded 1 ms-1 during deposition of bed 2.

Bed 3 is a diamictite, a matrix-supported conglomerate with only scattered pebbles of limestone and quartz in a matrix of structureless brown clay. The absence of any laminations in the clay suggests emplacement as a mud slurry, perhaps into a water-filled passage, during a single short-lived event.

Bed 4, like beds 1 and 2, is again rather poorly sorted though with a stronger skew towards clasts >4 mm. It probably represents conditions similar to those prevailing during deposition of bed 2, with flow velocities exceeding 1 ms-1 during deposition, though the grain size distribution towards the top of the unit has been significantly influenced by the injection of a more recent diamictite from above. The secondary peak in the <0.15 mm fraction can also be attributed, at least in part, to the presence of thin clay lenses in bed 4. These clay lenses indicate periods of low flow between the high energy events which emplaced the coarse gravels.

Although the largest clast observed in the analysed samples has a maximum dimension of only 33 mm, this is by no means the maximum clast size observed at this site. Tabular sandstone clasts up to 90 mm across have been observed in bed 4, with quartz pebbles up to

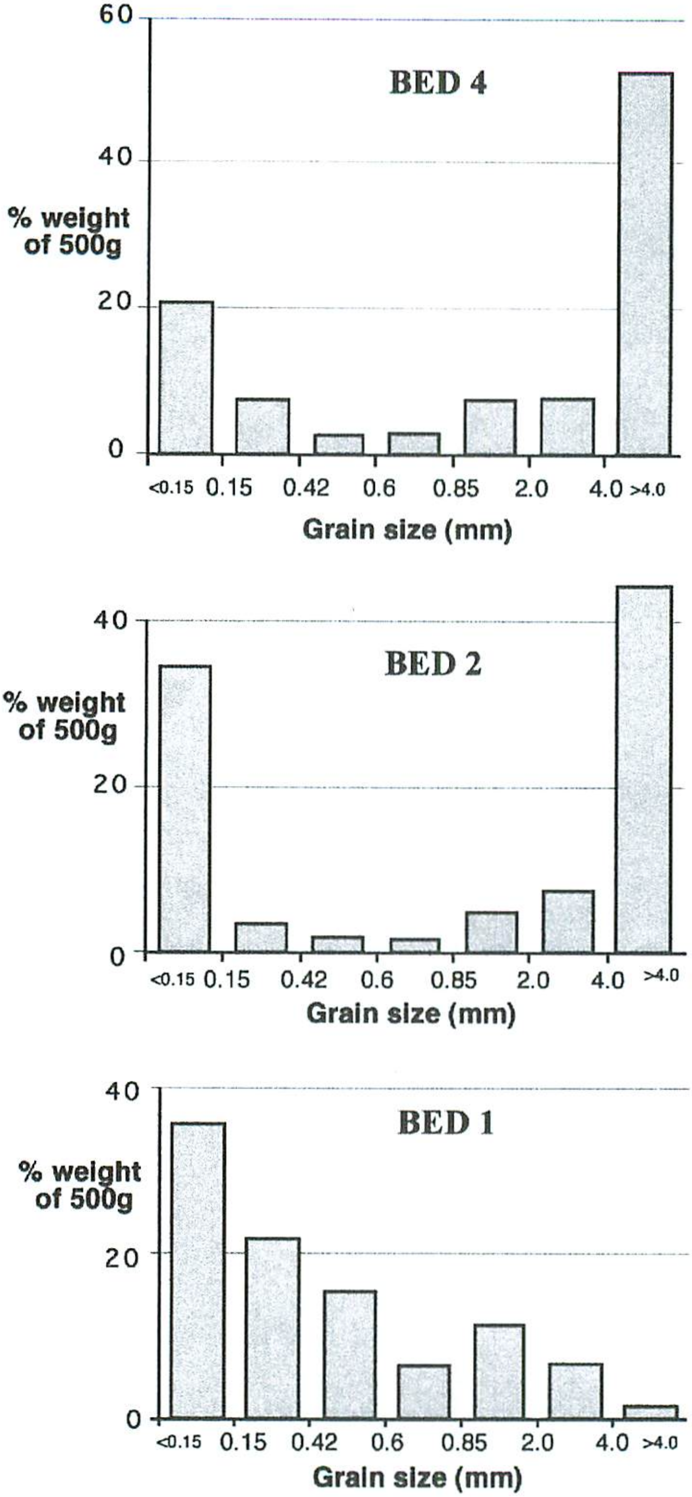

Figure 4. *Sediment weight histograms for beds 1, 2 and 4 of section 2.*

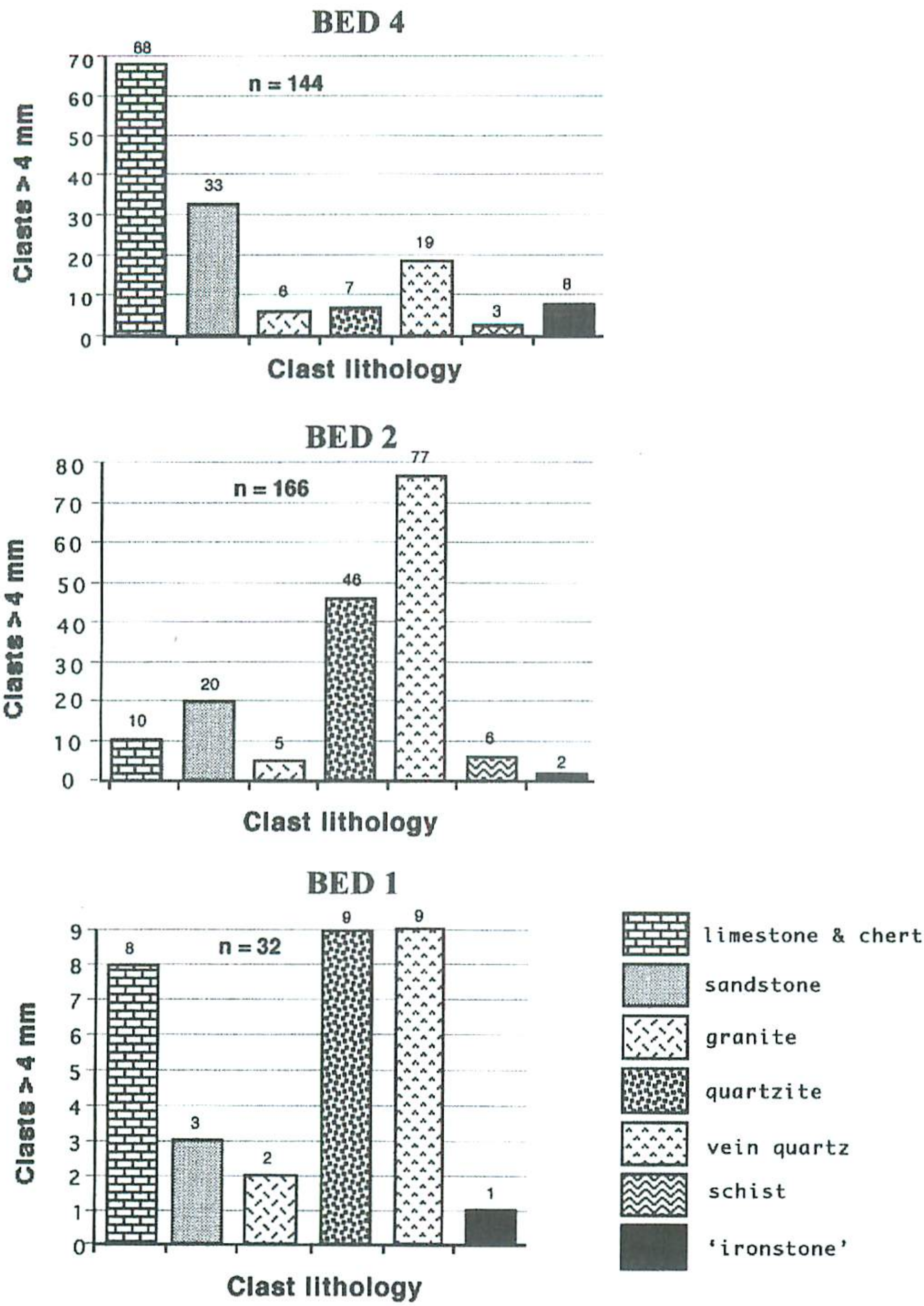

Figure 5. *Lithology histograms for beds 1, 2 and 4 of section 2.*

80 mm across collected loose on the floor of the cave. In addition, a well-rounded granite boulder 0.55 m in diameter can be seen on the south side of the passage just inside the roofed section. Such large clasts testify to, at times, very rapid and turbulent flow through this cave passage.

Clast lithology and shape

The lithology of the >4 mm fraction from beds 1, 2 and 4 was examined and is depicted in figure 5. Brief examination of the <4 mm fractions under low power microscope served only to confirm the results obtained from the larger fractions. Observations were also made of clast shape for the different lithologies in the >8 mm fraction from beds 2 and 4.

In Bed 1 limestone and chert clasts comprise 25% of the total, with pale brown Namurian sandstone constituting a further 9%. However, almost two-thirds (62%) of the total are of lithologies which rarely, if ever, occur *in situ* anywhere in the Burren. Of these 6% are of granite while the remainder comprises equal proportions of vein quartz and quartzite. The coarser nature of bed 2 provided a much larger dataset (166 clasts vs. 32 clasts for bed 1) but contained only one additional lithology, schist. Limestone and chert account for only 6% of the total, with Namurian sandstones a further 12%. Granite accounts for only 3% but vein quartz and quartzite comprise 74% of the total and schist a further 3%.

Bed 4 also furnished a fairly large dataset (144 clasts) but, in contrast to beds 1 and 2, clast lithology is dominated by locally derived material. Limestone and chert account for more than 47% of clasts, with Namurian sandstone a further 23% and 'ironstone' more than 5%. Exotic clasts (granite, quartz and schist) account for just under a quarter (24%) of the total.

In bed 2 the larger clasts (maximum dimension greater than about 30 mm) of locally derived lithologies (limestone, chert and sandstone) are angular to subrounded, with the sandstone clasts typically tabular in shape reflecting their original bedding. Granite clasts usually are fairly well rounded but often the felspars are badly decomposed and some clasts have begun to disintegrate into angular fragments. Most of the granite clasts are coarsely crystalline but a few have a more aplitic texture. The quartz and quartzite clasts vary from subrounded to well-rounded, with a small minority of angular clasts; the vein quartz in particular is sometimes found as very smooth, highly rounded pebbles indicating a polycyclic history. The schist and schistose quartz clasts typically are subrounded and often have a tabular shape, reflecting the schistose fabric of the rock. In bed 4 the locally derived material varies from angular to subrounded. The few chert clasts are conspicuously angular while the sandstone clasts typically are subrounded and tabular in shape. The vein quartz pebbles are rounded to subrounded but some have been broken before emplacement into the sediment, perhaps as a result of ice pressure during transport.

Origin of the various lithologies

The striking feature of the sediments within this cave is the great abundance, sometimes exceeding 75% of the total, of quartz and quartzite pebbles in the lower units and the virtual absence of limestone except in the upper units. The Burren is located in a geologically diverse region, in which a broad range of sedimentary, igneous and metamorphic rocks all crop out within a 50 km radius of this site (Figure 1). However, the Burren itself is composed entirely of Carboniferous sediments, dominated by hard, compact limestone in which chert bands are common at certain levels; these are the source of the limestone and chert clasts in the cave sediments. Mineral veins cutting through the limestones of the Burren and the Gort lowlands are common but the vast majority are of calcite. Fluorite, galena and other metal sulphides form only a minor component of this mineralisation and quartz is subordinate even to these (O'Raghallaigh *et al.*, 1997). Above the limestone lies a succession of dark shales and sandstones which crop out extensively just a few km to the south of the area and also on Knockauns Mountain and Slieve Elva, less than 5 km to the east of this site. This perhaps is the source of the tabular sandstone clasts and probably also the occasional fragments of 'ironstone', thought to represent fragments of limonitic concretions. The limestone is underlain by mudstones, sandstones and conglomerates of the Old Red Sandstone, of Devonian age. Their nearest outcrop is in the Slieve Aughty Mountains, some 40 km to the east of Pol na Grianchloch (Figure 1). It is possible that the quartz pebbles have been reworked from some of these Old Red Sandstone conglomerates but there is no conclusive evidence to support this.

A much greater range of lithologies lie to the north of the Burren. The north coast of Galway Bay, 20 km north of Pol na Grianchloch, is dominated by the outcrop of the Galway Granite (Figure 1), which in fact comprises several distinct granite bodies. There can be little doubt that this represents the source of the granite clasts in the cave sediments. Still further north and north-west, beyond the Galway Granite, lies a complex series of, mostly, metamorphic rocks up to 750 million years old (Morris *et al.*, 1995). Fractured and deformed schist and quartzite, cut by innumerable quartz veins, are common lithologies in the region (Figure 1) and probably represent the source of much of the exotic material which dominate the cave sediments, despite these outcrops lying at least 40 km to the north of Pol na Grianchloch.

By comparison, the sediments noted by Leake (1965) from the Fergus River Cave include fine and coarse granites, pure quartzite, muscovite-bearing quartzite, pieces of quartz, and a clayey sandstone. He concluded that the Fergus River Cave "assemblage could have been derived from the Connemara basement and the Galway granite complex" but that it was "impossible to identify any fragments with certainty as coming from the area, or to rule out completely other sources of supply". Nonetheless, he noted "the similarity of the migmatitic granites to those found in Connemara; the similarity of the quartzite fragments to the main quartzite, which is usually rich in muscovite, in Connemara and the resemblance of the igneous granites to the various facies of the Galway granite. The piece of migmatite intruded into the hornblende schist is particularly helpful and the porphyry dyke fragments are also useful as pointers to this diagnosis. The pieces of sandstone could have been derived from the Silurian sandstones which are now exposed in north-east Connemara." Patmore and Nicholson (1965) stated that these erratics were found throughout the cave and formed between 0.5 and 5.0% of the 5-50 mm size range, while Wilkins *et al.* (1972) commented on the presence of exotic cobbles up to 150 mm across in Acoustic Passage, more than 500 m in from the entrance. Both the size and lithological diversity of the material in the Fergus River Cave is reminiscent of that in Pol na Grianchloch though the latter site has a much greater abundance of exotic clasts. This may reflect the effects of prolonged fluvial modification of the original deposit in the Fergus River Cave, which is still a major active flood conduit, while Pol na Grianchloch has been hydrologically inactive since emplacement of these sediments.

GLACIAL TILLS IN THE NORTH AND WEST BURREN

Patches of till, sometimes forming distinct drumlins, are a common feature of the Burren. They underlie many of the grassland areas on the limestone outcrop as well as forming the low islands and peninsulas along the north coast. Till is well exposed along the course of the Caher River and also at many places along the coast, such as at Ballyvaughan, Fanore (Croot and Sims, 1996), Poulcraveen (Trudgill, 1971) and on the south side of Poulsallagh Bay (Warren, 1993). At several of these sites, as well as others in the Burren (Farrington, 1965), glacial striae beneath the till cover show a consistent NE-SW orientation (Figure 1), recording the movement of ice from the north-east during the most recent glaciation in this region (McCabe, 1987).

Exotic clasts do occur in these tills but invariably constitute only a very minor element of the total, being greatly subordinate to locally derived material. Warren (1993) commented that they do not generally show in counts of 200-400 clasts while Farrington (1965) noted an extensive exposure of till near Kilfenora in which all the clasts appeared to be of limestone, with similar results at most of the other sites he visited. Similarly, at Poulsallagh and Poulcraveen only locally derived lithologies (limestone, shale and Namurian sandstone) have been seen *in situ* in till exposures, although at both sites the adjacent beach contains occasional, but conspicuous, cobbles and pebbles of granite, quartzite and schist, presumably reworked from the till exposed behind. Further north, low till cliffs exposed on the shore at Ballyvaughan again are dominated by limestone clasts but also contain occasional angular fragments of granite and rare quartz pebbles, with granite erratics up to a metre or more across fairly common on the shore here. Still further to the north, on the north coast of Galway Bay, McCabe and Dardis (1989) noted the predominance of limestone clasts (70%) in the massive diamict facies of a drumlin at Salt Hill. Surprisingly only 10% of the clasts were of granite despite the site's location on the Galway Granite outcrop. Brief examination of many other exposures of till on the Burren have failed to identify any in which exotic lithologies, necessarily derived from beyond the Burren, form more than a very minor component. Certainly none have been encountered which have a range or distribution of lithologies in any way comparable with beds 1 and 2 of the sedimentary sequence recorded in Pol na Grianchloch.

DISCUSSION

The geomorphology of the cave fragments at Poulsallagh are significantly different from most described from the Burren. Firstly, Poulsallagh Cave and the other cave fragments nearby, clearly formed in a phreatic environment through the process of paragenesis despite earlier interpretations of this passage as a vadose canyon. This does not necessarily mean that the regional piezometric surface was significantly higher than it is now since many of the active caves in the Burren today contain phreatic sections perched, on chert or shale bands, many metres above sea level (Drew, 1989). However, whatever the precise hydrological situation of the Poulsallagh caves, the position of the coast at the time that they were hydrogically active must have been significantly further west than it is today to maintain the phreatic environment in which the passages developed. Their present situation, truncated both by glaciation and marine erosion, suggests that they significantly predate the last glacial maximum.

Primary sediments in paragenetic phreatic environments typically are fine-grained, clay to sand-grade, rather than the coarse gravel, pebble and even boulder-grade sediments now found in Pol na Grianchloch. Coarse-grained sediments such as these may be transported through phreatic passages under pipe-full, or sliding bed, conditions producing poorly-sorted or chaotic gravels (Ford and Williams, 1989). This mechanism may account for the presence of the 0.55 m diameter granite boulder mentioned earlier, but the associated sliding bed facies, if it is present at all, must lie beneath the present sediment floor of the roofed section. The presence of several discrete sedimentary units in the upper part of the succession is evidence for more normal fluvial processes during at least the later stages of infill. The four sedimentary units visible in the roofed section of the cave are all subhorizontal, with a cross-cutting relationship to the eastward-dipping paragenetic notches at the western end of the roofed section. This lack of conformity between the sediments and original paragenetic morphology suggests that an earlier sediment fill was present during paragenetic cave development but subsequently this was flushed out, or at least greatly modified, prior to emplacement of the sediments which now fill the passage.

Analysis of clast lithologies in Pol na Grianchloch (Figure 5) indicate that a significant proportion of the material ultimately was derived from outcrops lying 40 km or more to the north or north-west (Figure 1), with the remainder being of local derivation and having travelled no more than a few km at most. The distance involved and the nature of the intervening topography, which today includes at least 10 km of open sea, together with the large size of some of the clasts, precludes transportation by water and hence the material must have been transported across Galway Bay by an ice sheet, to be deposited on the Burren as a quartz-rich till at some time during the Pleistocene. If there was a significant time lapse between arrival of this till in the area and its fluvial reworking and emplacement in the cave, then any limestone component may have been reduced still further by leaching. It is possible that the initial period of hydrological activity in this cave system had already long ceased by this time and that sections of passage further upstream, to the east, had been breached by glacial erosion. This would have allowed ready access by glacial meltwater, flushing out the original fine sediments prior to emplacement of the coarser sediments which it now contains.

As already stated, glacial striations throughout the north and west Burren have a consistent orientation indicating the final ice movement from the north-east (Farrington, 1965; McCabe, 1987). This produced rounding of north-facing slopes and extensive plucking of the limestone beds on south-facing scarps, as is demonstrated spectacularly by comparing the smoothed north scarp of the Burren around Black Head with the plucked south-facing crags of Oughtdarra. On a smaller scale this glacial plucking and rounding is responsible for the present appearance of Poulsallagh Bay, with plucked crags on the north side and more rounded, and conspicuously striated, limestone on the south side. Significantly it indicates that the basic shape of the bay was already in existence prior to the last glacial advance, which was also responsible for the till deposits now exposed on the south side of the bay.

These north-easterly derived tills are dominated by Carboniferous Limestone with only rare erratics of granite and other exotic lithologies (Farrington, 1965; Warren, 1993; Croot and Sims, 1996). Farrington considered the occasional presence of the latter as evidence of an older till deposited by ice moving directly from the north-west, though the rarity and essentially random distribution of these surface erratics has always prevented conclusive demonstration of this (Warren, 1993). To the east of the Burren at Boleyneendorish, the type site for the Gortian Interglacial, near the town of Gort, Jessen *et al.* (1959) described a succession in which they recognised two distinct tills above the Gortian interglacial sediments. They considered that whereas stone orientations in the upper till indicated a NE-SW ice flow, those in the lower till indicated ice movement from WNW to ESE. They did not record any additional evidence, such as striae, to support this west-north-west origin for the lower till, though it would be consistent with transport of material to the Burren from Connemara. Farrington (1965) concluded that the far-travelled erratics scattered across the Burren were relics from this earlier glaciation, subsequently reworked by the ice flow from the north-east.

The overwhelming dominance of exotic lithologies, derived from north or north-west of the Burren, in the cave sediments of Pol na Grianchloch suggests that they were derived from a till much richer in far-travelled erratics than that now found on the surface of the Burren. These exotic clasts were then fluvially reworked and emplaced in the cave passage before the later ice advance from the north-east largely removed any surface manifestation of the earlier till. Purely in the context of this site it is impossible to date this fluvial reworking event, other than to suggest that it predates the last ice advance from the north-east. However, if the two tills described by Jessen *et al.* (1959) at Boleyneendorish represent the same two glacial events for which we find evidence at Poulsallagh, then we can perhaps deduce a possible maximum age limit for the quartz-rich gravels in Pol na Grianchloch. The age of the Gortian deposits which underlie the lower till remain somewhat enigmatic, though Coxon (1996) has suggested that they may equate with Oxygen Isotope Stages 9 or 11, indicating a maximum age of 352 ka (Stage 10) or 302 ka (Stage 8) for the overlying 'lower till'. However, there is no age constraint on the boundary between the upper and lower tills, or on the age of the 'upper till', other than it must be pre-Holocene, with Ireland considered to have been ice-free by about 14 ka (McCabe 1987). The most parsimonious solution would be that both tills postdate the interglacial of Stage 5e, with the lower till, originating from the north-west, emplaced during Stage 4 and the upper till, originating from the north-east, during the glacial maximum of Stage 2. Since the quartz-rich cave sediments were reworked from a till considered here to correlate with the lower till at Boleyneendorish then they must be younger than it, though not necessarily much younger, but also older than the till originating from the north-east. This suggests that they may have been emplaced during the interstadial of Stage 3, since during the glacial maximum of Stage 2 the underground conduits would have been effectively sealed by permafrost (Waltham *et al.,* 1996). However, this chronology is only a tentative suggestion and further evidence is required to constrain it.

The presence of a similar assemblages of exotic lithoclasts as far afield as the Fergus River Cave, 20 km to the east-south-east of Poulsallagh, suggests that this Connemara-derived till was once widespread across the Burren but that surface manifestations of it have been virtually obliterated by subsequent ice advance(s). On the surface of the Burren today only a few of these exotic clasts have survived as relicts of this earlier till, either as isolated erratics on the bare limestone pavements or incorporated into later till deposits. However, these erratics are widely scattered with no clearly discernible distribution pattern and with large granite boulders disproportionately represented. They offer, at best, a very distorted picture of the composition, and hence source, of this earlier till. By contrast, the cave sediments reworked from this till have been protected from the later ice advance which largely erased direct evidence of this till on the surface. Although these cave sediments too may provide a distorted picture of the original till composition, they provide a much richer source of lithological information from which to deduce the origin of the clasts and hence the direction of ice movement which emplaced this earlier till.

Postulated sequence of events

1. Development of Pol na Grianchloch and associated caves by paragenesis, probably with deposition of fine sediment.

2. Movement of post-Gortian (possibly Stage 4) ice sheet south eastwards from Connemara, across Galway Bay and into the Burren. Widespread deposition of till rich in quartzose lithoclasts.

3. ? Breaching and rejuvenation of Pol na Grianchloch passage by glacial erosion and meltwater activity. Original paragenetic fill of fine sediment fill flushed out.

4. Reworking of quartzose till by fluvial action during post-Gortian interglacial/interstadial (possibly interstadial of Stage 3) and emplacement in caves.

5. Coastal retreat and creation of Poulsallagh Bay, probably by invasion of dry valley formed at some time prior to this.

6. Ice advance from north-east, largely removing surface evidence of the earlier ice advance and till. Breaching of Pol na Grianchloch and injection of limestone-rich diamictite into upper sediment units. Glacial modification of Poulsallagh Bay and widespread deposition of limestone-rich till.

7. Coastal retreat and surface lowering destroys seaward end of Pol na Grianchloch and removes much of sediment fill, causing passage collapse

CONCLUSION

Coarse sediments rich in granitic and quartzose lithoclasts are preserved in a relict cave fragment at Poulsallagh, on the west coast of the Burren. The sediments are interpreted as having been fluvially reworked from till, but their lithological composition is quite distinct from any till found on the surface of the Burren today and indicates derivation from Connemara and the north shore of Galway Bay. Similar assemblages of exotic lithoclasts are known from other caves in this area as far afield as the Fergus River Cave, 20 km to the east-south-east. These occurrences testify to the widespread distribution of this Connemara-derived till and indicate transport distances, for some material, of more than 50 km. This provides strong evidence for an ice advance from the north-west prior to that, from the north-east, which deposited the limestone-rich till now found on the surface of the Burren. These observations are consistent with different ice flow directions inferred from stone orientations recorded from two distinct till units near Gort, to the east of the Burren. The age of the two tills, and of the cave sediments reworked from the earlier till, cannot be precisely constrained on the present evidence, though both must be post-Gortian (Stage 11 or 9) and pre-Holocene (Stage 1). The most parsimonious chronology would place the earlier till as Stage 4, the younger till as Stage 2, and emplacement of the cave sediments during the interstadial of Stage 3.

The preservation of these exotic sediments in several widely separated caves demonstrates, once again, the importance of caves as a source of information for reconstructing Pleistocene events.

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