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Enigmatic boulders and syn-sedimentary faulting in the Carboniferous Limestone of the Isle of Man

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SUMMARY: A small area of Lower Carboniferous (early Brigantian) Limestone in a coastal inlet in the south of the Isle of Man contains boulders of pale bioclastic limestone lying upon and overlain by thin undulating beds of dark calcareous mudstone. It is shown that during deposition of this facies the sea bed dipped towards a syn-sedimentary fault on the north side of the inlet where approximately 3m of normal movement occurred prior to its deposition. 50m to the south, a limebank developed above the crest of a small rollover anticline in the hanging wall of the fault. Instability of this structure led to an episode of sediment collapse. A density flow, containing blocks and boulders of pale limestone, slid northwards over black muddy sediments that were accumulating in the deeper water close to the fault. Both lithologies also show evidence of soft sediment deformation. This study shows that carbonate boulder beds and other fault-related structures can be extremely local in nature.

Poyllvaaish (which means 'bay of death' in Manx Gaelic) lies on the west-facing portion of coast half-way between Castletown and Port St Mary in the south of the Isle of Man (Figs 1a, 1b). Upper Dinantian limestones and basaltic volcanics outcrop along most of the coast and can be mapped in considerable detail in many places in the exposed zone between high and low water (*e.g.* Fig. 1c). Discrete boulder beds and isolated blocks of pale-coloured early Brigantian limestone, up to a few metres across, are found within thin, undulating beds of black muddy limestone in a small inlet (sometimes known as Ghaw Gortagh) at the northern end of the bay, near Poyllvaaish Farm, at SC 246676 (Figs 1c, 2, 5, 6).

This area attracted the interest of several Victorian geologists. For example, the earliest author, MacCullough (1819), suggested that the limestone boulders were formed as a result of weathering processes, whereas Cumming (1846) believed that the blocks were a result of disruption caused by the intrusion of dolerite dykes, three of which traverse the inlet (Figs 1c, 3, 5, 6). In 1903, Lamplugh proposed that the structures were discrete reef knolls. Most subsequent authors agreed with this idea (*e.g.* Lewis 1930), although Smith (1911) argued that the blocks were too steep-sided to be original sea-floor structures and postulated that they were weathered *roches moutonnées*. Dickson (1967) suggested that the boulder masses were the result of fault-initiated submarine rock-falls from a limestone shelf, consisting of Poyllvaaish Formation, lying to the north of the small scarp which runs along the northern side of the bay (Figs 2, 5, 6). Evidence indicating that the blocks were not in their original positions was mainly drawn from geopetal structures, which show consistent and often steep dip within the blocks but random dip between them. In their stratigraphic revision, Dickson *et al.* (1987) doubted the presence of a fault along the northern scarp but again used geopetal structures as indicators for the reorientated positions of the blocks and boulders. They also mentioned geopetal evidence for 20° of syn-sedimentary dip in the older, undisrupted pale limestones of the Poyllvaaish Formation which outcrop to the north of the bay (Figs 1, 5, 6). Dickson *et al.* (1987) proposed that the boulders were derived from the south, despite the fact that Poyllvaaish limestone is not seen to outcrop in that direction (see Figs 1b, 1c). This paper presents evidence in support of a new interpretation involving the effect of local faulting on carbonate sedimentation.

The rocks in the Poyllvaaish area have a general southerly dip and thus the oldest beds, comprising the Balladoole limestone Formation (Dickson *et al.* 1987), outcrop in the north and the youngest beds, which form part of the Scarlett Volcanic Formation, lie to the south. The inlet that forms the subject of this paper exposes the upper part of the Poyllvaaish limestone Formation and the basal part of the Close-ny-Chollagh limestone Formation (Fig. 5). These stratigraphic units are younger than the Balladoole Formation and older than the Scarlett Volcanic Formation and are approximately late Asbian and early Brigantian in age, respectively (Dickson *et al.* 1987). The main contact between the Poyllvaaish and Close-ny-Chollagh Formations occurs at a 3m high scarp on the northern side of the inlet (Figs 2, 5, 6, 7).

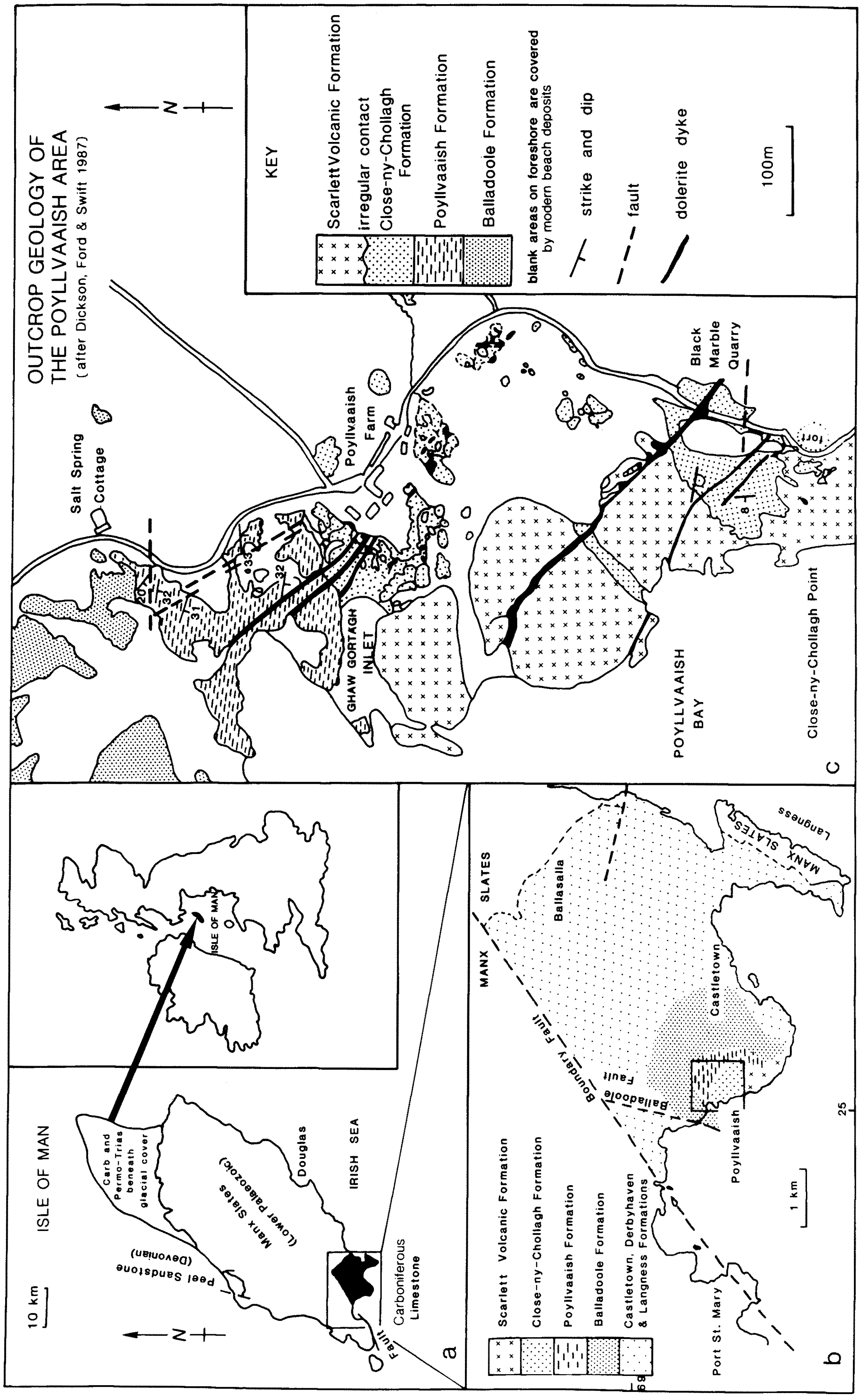

Fig. 1. Location and outcrop geology of the Poyllvaaish Bay area, Isle of Man.

Fig. 2. Sheet of boulder limestone overlying lower black beds close to the scarp (upper part of photograph) at the northern end of the Ghaw Gortagh inlet. The hammer is 40cm long.

1. SEDIMENTARY FACIES

Three types of lithology are recognised in the inlet:

(1) pale grey sparry micrite containing no apparent bedding planes but locally displaying faint algal laminations;

(2) pale grey bio-calcarenite present in massive beds;

(3) dark grey, thin-bedded calcilutite and calcareous shales.

These rock types will be referred to from now on simply as (1) micrite, (2) calcarenite and (3) mudstone.

Micrite and calcarenite can both occur either within one bed ("pale limestone") or as separate units in (i) thick lenticular build-ups, (ii) irregular blocks or (iii)

Fig. 3.
Dolerite dyke 1 (1m wide) separating a large block of boulder limestone on the left hand side of the photograph from lower black beds surrounding a small outcrop of Poyllvaaish Formation on the right hand side. The scarp along the northern side of the inlet can be seen in the background.

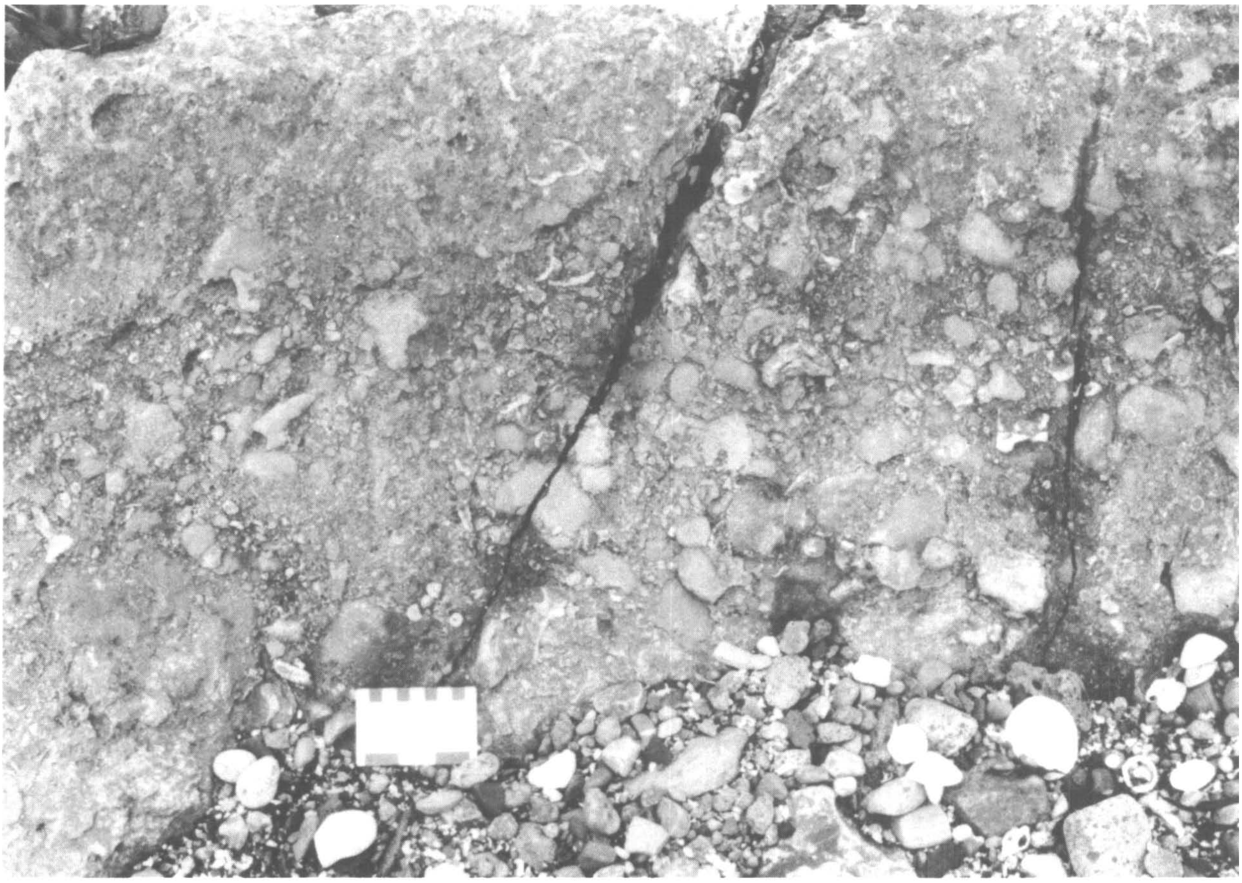

Fig. 4. Lithified talus at the base of a large block of boulder limestone. The scale card is 9cm long.

boulder beds. These rocks are generally pale grey but in some places appear faintly brown due to the effects of recrystallisation. Irregular seams, veinlets and vugs consisting of a later variety of white rhombic calcite are also quite common.

The micrite is usually fairly homogeneous in appearance except for occasional algal laminations and irregular cavities containing very coarse-grained crystals of white calcite.

The calcarenite is composed of lithified carbonate sand and shell debris. Allochems include crushed or fragmented crinoid ossicles and productid brachiopods as well as less common stick bryozoa, corals and goniatites. Algal laminations are of limited occurrence but, where present, are usually confined to finer grained zones.

Patches of lithified talus, consisting of small clasts of micrite, calcarenite and broken shells, are also found along the margins of some of the larger disrupted blocks (Fig. 4).

Geopetal fabrics can be observed in a few brachiopod shells within some of the pale limestone blocks but the apparent dip recorded is often confusing, even along one exposed face; hence, individual measurements have not been used here as definitive way-up criteria. Suffice it to say that many of the discrete blocks of pale limestone, which can be up to several metres in diameter, were upended or overturned prior to the complete or partial lithification of some of the interstitial mud.

The mudstone layers are up to 30cm thick and mostly consist of very fine-grained shell particles in a dark bituminous matrix. Black beds of pyritic shale are also present. Excluding the shell detritus, these rocks are generally unfossiliferous although a few of the lower beds contain derived crinoids and corals and phosphatised fish teeth. Some of the derived shells have been replaced by pyrite and phosphate.

2. DOLERITE INTRUSIONS

The inlet is traversed by three NW-SE trending dolerite dykes, each about 1m wide and dipping approximately 70° to the south-west (Fig. 3). They are thought to be of early Tertiary age. Beds to the south of each dyke appear to have been downthrown by a few decimetres and it therefore seems likely that the dykes occupy minor normal faults (Fig. 6). For ease of discussion, these have been numbered 1, 2 and 3 from north to south across the inlet.

3. LOCAL STRATIGRAPHY

3.1. Poyllvaaish Formation

The scarp on the northern side of the inlet (Location H) is composed of massive beds of calcarenite with an approximate dip of 30° to the south (Fig. 5). These rocks

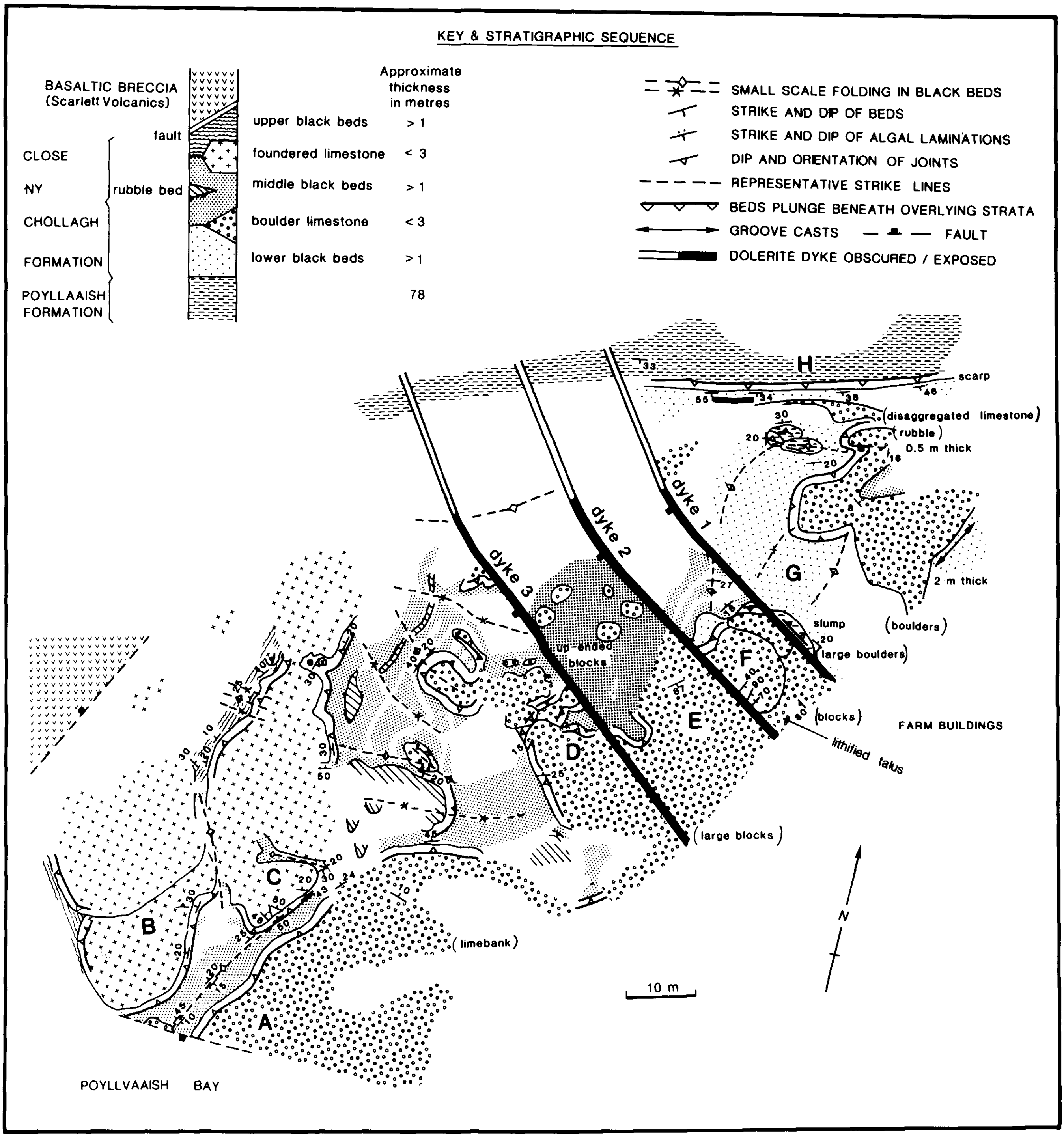

Fig. 5. Detailed geological map of the Ghaw Gortagh inlet area, Poyllvaaish, Isle of Man. Areas without symbols are concealed by modern beach deposits.

comprise the highest exposed part of the Poyllvaaish Formation and are overstepped unconformably by the basal part of the Close-ny-Chollagh Formation (Fig. 7). To the south of the scarp only two outcrops of Poyllvaaish limestone have been located and these are completely surrounded by Close-ny-Chollagh beds (Fig. 5). These inliers occur at a level approximately 3m below the highest beds of the Poyllvaaish limestone exposed to the north of the scarp (Figs 5, 6), even though the limestones are apparently similar. This suggests that the Poyllvaaish Formation was down-faulted prior to deposition of the Close-ny-Chollagh Formation, with the scarp face representing the exhumed fault plane (Figs 2, 7).

3.2. Lower black beds

In the northern corner of the inlet, dark calcareous mudstone, belonging to the basal part of the Close-ny-Chollagh Formation and known here as the 'lower black beds' (Fig. 5), overlies an erosional surface on the

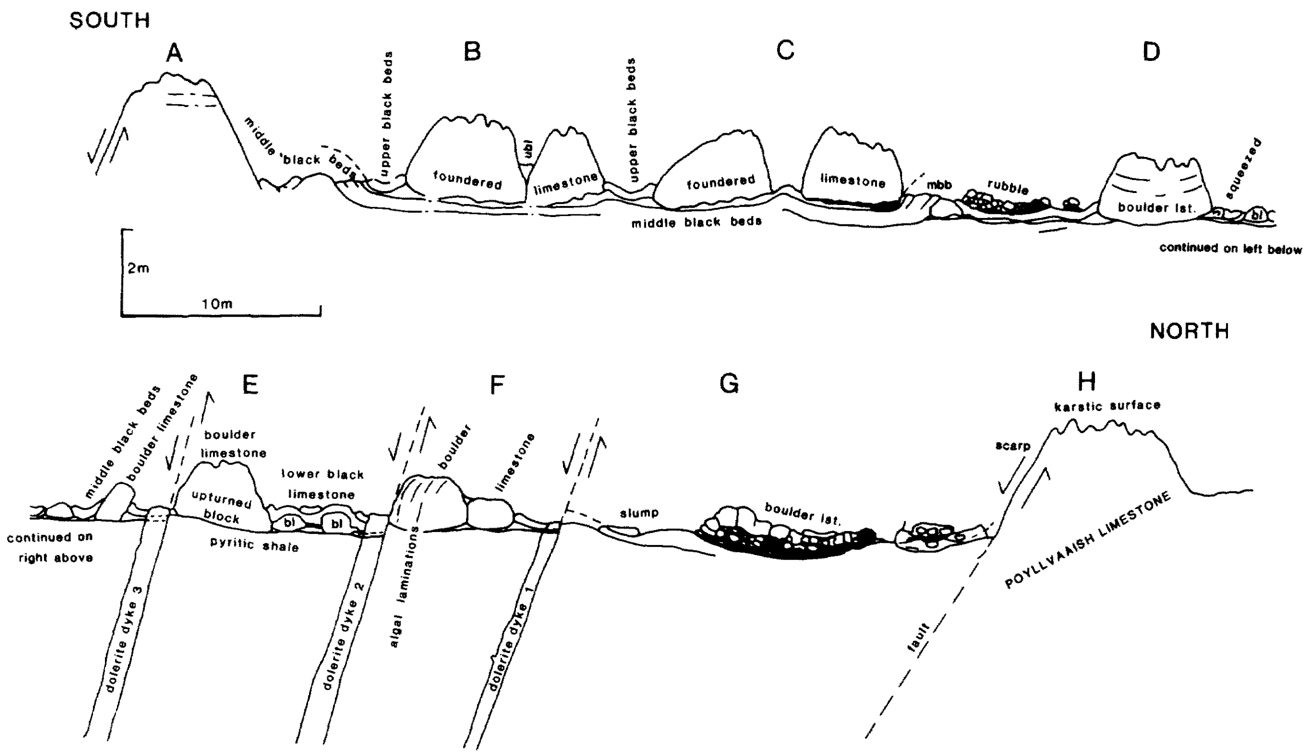

Fig. 6. Detailed profile south-north across the Ghaw Gortagh inlet. Letters refer to localities on Fig. 5.

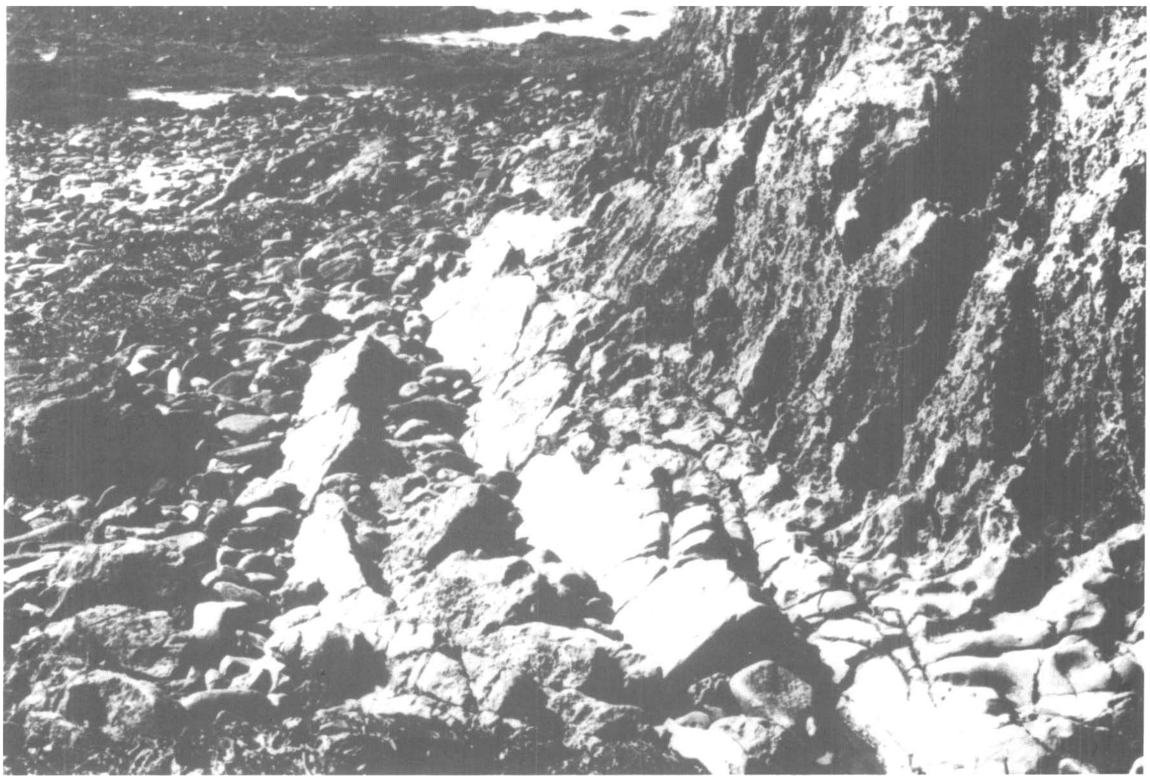

Fig. 7. Lower black beds (30cm thick), steepened by compaction against the underlying Poyllvaaish Formation which here forms the scarp at the northern end of the inlet.

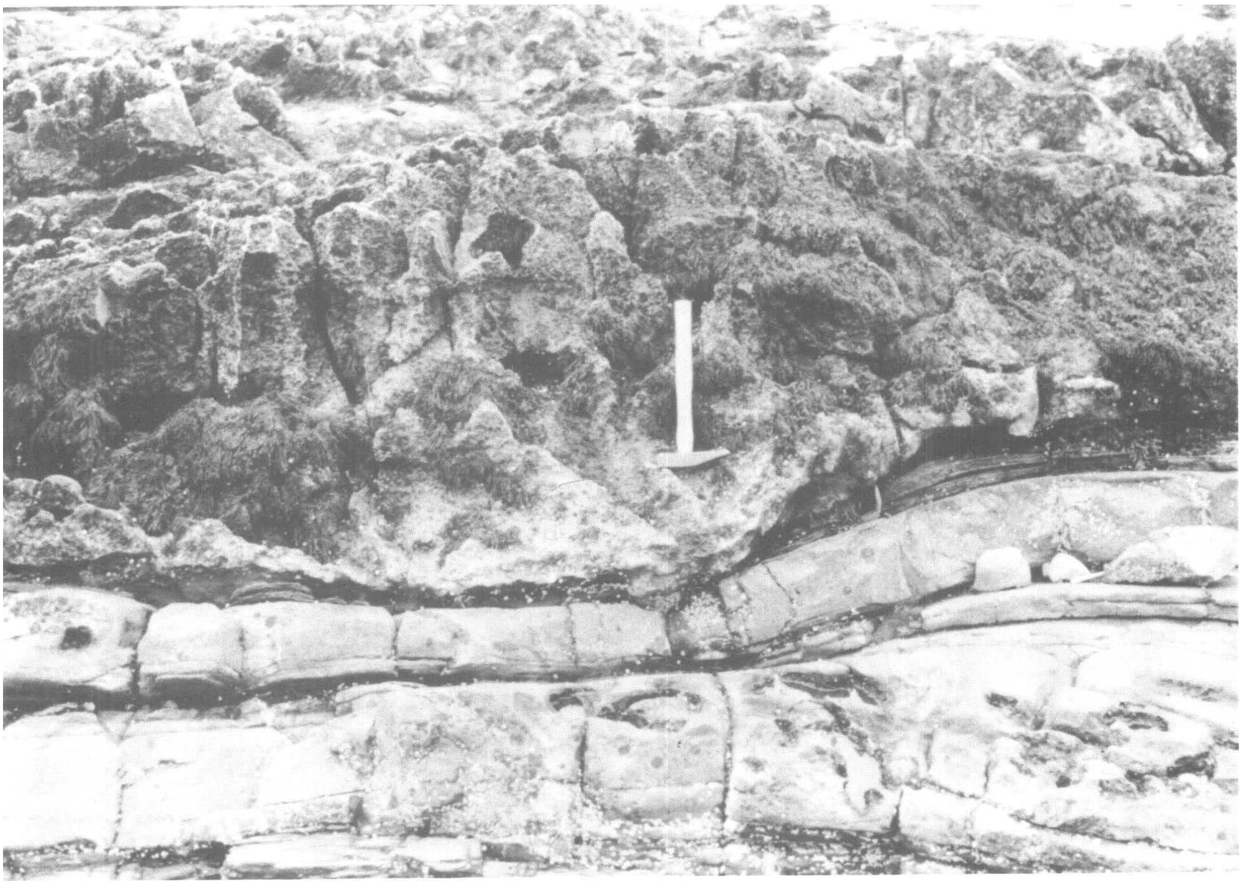

Fig. 8. Boulder limestone overlying lower black beds. The hammer is 40cm long.

Poyllvaaish Formation at the bottom of the scarp (Figs 6, 7). Locally these beds have a maximum dip of 55°, apparently as a result of compactional over-steepening along the unconformity. In places the mudstone contains pyritised brachiopods and goniatites and phosphatised crinoids and fish teeth. The latter have been identified as *Cladodus* sp. and *Helodus turgidus* (Agassiz).

Several metres to the south of the scarp, a small outcrop of Poyllvaaish limestone forms a small fractured dome which is completely surrounded by lower black beds. Black shale, also belonging to the lower black beds, has infilled some of the fractures within the inlier.

25m further away from the scarp, a similar outcrop of Poyllvaaish limestone is truncated on its south-western side by dolerite dyke 1 (Location G, Figs 3, 5, 6). However, the northern edge of the inlier is overlain by a lobe of dark calcilutite, approximately 1m long, which represents a thickened member of the lower black beds. This appears to have moved northwards over the top of the Poyllvaaish limestone prior to its lithification and therefore represents a slump structure (Fig. 6). Small syn-sedimentary joints occur within the slumped mass itself which have been infilled with darker mud of slightly younger age.

The lower black beds become paler and more calcareous towards the southern end of the inlet.

3.3. Boulder limestone

A thin pyritic shale in most places marks the top of the lower black beds and is overlain by the main boulder bed, a discontinuous horizon known here as the 'boulder limestone' (Figs 5, 6, 8). This consists of pale-coloured, bioclastic calcarenite and micrite. Boulder limestone can be traced from near the northern scarp, where it consists of an irregular sheet of boulders, approximately 0.5m thick (Figs 2, 9), for a distance of 100m to the south side of the inlet (Location A), where a prominent knoll of the same rock type accounts for at least 3m of stratigraphic thickness. This knoll displays a few horizontal bedding planes and some fine-grained and faintly graded layers which show no evidence of disturbance. The morphology of this structure suggests that it represents a discrete carbonate build-up; the non-genetic term 'limebank' (*e.g.* Miller & Grayson 1982) is used here.

For a few tens of metres north and west of the limebank, lower black beds plunge beneath large blocks of boulder limestone (Fig. 10), whereas the 'middle black beds', which directly overlie the lower black beds in the middle of the inlet, lap up to and over the blocks (Fig. 6).

3.3.1. Lateral changes in boulder limestone

Close to the scarp, the most northerly outcrop of

Fig. 9. Part of the sheet of boulder limestone shown in Fig. 2. Here the bed is 0.5m thick.

boulder limestone consists of small, matrix-supported clasts of pale crinoidal calcarenite within a 35cm thick bed of mudstone at the top of the lower black beds (Fig. 11). The clasts display diffuse boundaries and in some parts consist only of isolated crinoid ossicles where the pale limestone has completely disaggregated. Therefore, here it appears that the boulder limestone was deposited within soft mud (of the lower black beds) as a partially lithified breccia.

A few metres south of this outcrop a much thicker sheet of boulder limestone, some 25m long, is exposed (Fig. 2). At its northern end it is 0.5m thick and consists of irregular cobble-sized clasts (Fig. 9). The thickness rapidly increases to 2m towards the south where larger boulders form the upper part of the bed. Stylolitic contacts occur between most of the clasts within the sheet.

In the north-eastern corner of the inlet (Location G), groove casts are preserved on the upper surface of the lower black beds immediately beside the boulder limestone (Fig. 5). The grooves strike in an 028° direction.

South of dolerite dyke 1 (Location F), blocks of boulder limestone, a few metres across, preserve algal laminations that are orientated vertically or dip steeply to the SE (Fig. 6). The outlines of small, rounded to sub-angular intra-clasts are seen near the edge of some of these blocks (Fig. 4).

South of dolerite dyke 3 (Location D), the largest block of boulder limestone contains algal laminations that dip gently in towards the middle of the block; thus its structure is saucer-shaped (Figs 5, 6). The western edge of this block overlies a thin lower black bed (equivalent in age to the pyritic shale further north) containing derived *Michelinia* sp. coralla. This bed in turn appears to have squeezed out over slightly smaller blocks of boulder limestone during emplacement of the larger body.

A few metres NW of the saucer-shaped block (Location D), large up-ended pieces of boulder limestone resembling gravestones can be seen sticking out of over-steepened middle black beds (Fig. 12). These structures are quite enigmatic as regards their formation and preservation.

Most of the exposed part of the limebank at the southern end of inlet (Location A) occurs at the same stratigraphic level as the boulder limestone (see Fig. 5). The base of the structure is not seen but it appears that the lower black beds wedge out towards it. Therefore, the limebank probably lies directly on top of Poyllvaaish limestone. Several metres further south, the limebank forms a 1 to 2m high, E-W trending scarp which marks the northern edge of the main part of Poyllvaaish Bay (Fig. 1). The surface of the scarp is overstepped at its base by middle black beds but in places the scarp also shows evidence of fault movement with downthrow to the south (Fig. 6).

3.4. Middle black beds and rubble bed

The 'middle black beds' tend to abut, overstep and bury

Fig. 10. Large block of boulder limestone underlain by lower black beds. The hammer is 40cm long.

Fig. 11. Diffuse clasts of boulder limestone within lower black beds close to the scarp at the northern end of the inlet. The scale card is 9cm long.

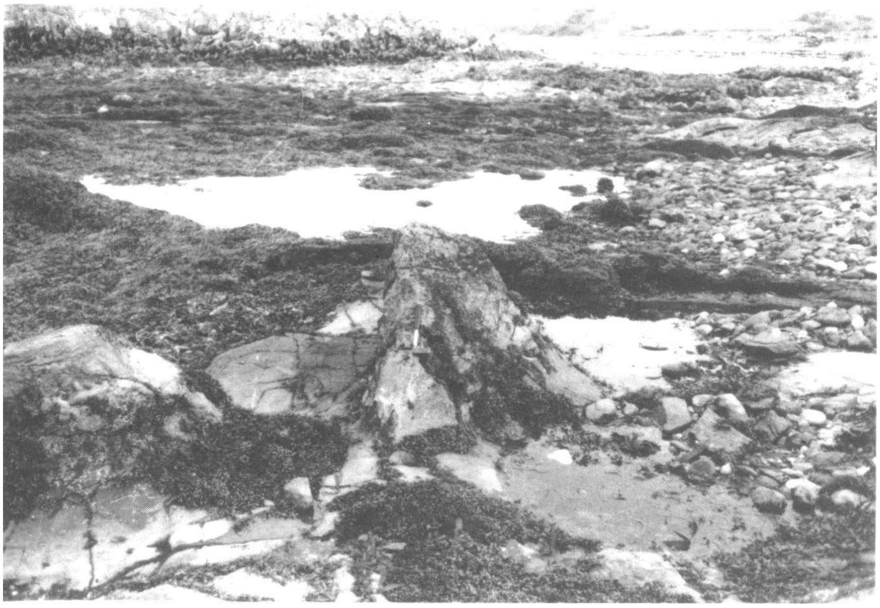

Fig. 12.
Up-ended pieces of boulder limestone surrounded and overlain by middle black beds. The hammer is 30cm long.

blocks of older boulder limestone (Figs 12, 13). They are similar in appearance to the lower black beds in that they consist of thin-bedded dark mudstone but they are generally more calcareous. In some places small anticlines have developed in the middle black beds, probably where they overlie older blocks of boulder limestone.

A second boulder bed, known as the 'rubble bed', occurs just north of the limebank within the middle black beds (Figs 5, 13). This is 0.5m thick and only outcrops over a small area.

3.5. Foundered limestone

To the west of the limebank (Locations B, C), the middle black beds are directly overlain by several mound-like bodies, approximately 2m thick, consisting of homogeneous micrite, which are collectively known as 'foundered limestone' (Figs 5, 6, 14). They are finer grained and less fossiliferous than the boulder limestone and appear to represent carbonate mudmounds or algal bioherms. Cavities containing very coarse-grained sparry calcite occur throughout the foundered limestone.

Most of the foundered limestone appears to have pressed down into the middle black beds leading to pronounced steepening, folding and thinning of the underlying beds at the edges of and beneath the mounds (Fig. 14). In places the base of the limestone displays lobate protuberances indicative of soft-sediment loading (Fig. 16). Syn-sedimentary joints, sometimes infilled with later mudstone, also run across parts of the mounds. Foundered limestone typically occurs on either side of, rather than directly above, small anticlines in the middle black beds (Figs 6, 14) which are themselves thought to overlie blocks of boulder limestone.

Larger bodies of foundered limestone overlying more homogeneous and flat-lying middle black beds are also exposed in the adjacent bay a short distance south of the study area (Fig. 1c).

3.6. Upper black beds

The mudstones comprising the 'upper black beds' (Fig. 5) either lie directly on top of the middle black beds or onlap intervening foundered limestone.

3.7. Scarlett Volcanic Formation

A down-faulted outlier of basaltic breccia, which belongs to the lower part of the Scarlett Volcanic Formation, occurs in the SW corner of the inlet (Fig. 5). This consists of thick lava flows containing many angular pieces of broken limestone.

3.8. Stratigraphic sequence south of Poyllvaaish Farm

500m south of the inlet, near the Black Marble Quarry (Fig. 1c), beds of Scarlett Volcanic Formation directly overlie the upper black beds of the Close-ny-Chollagh Formation.

The Black Marble Quarry itself exposes beds of mudstone with N-S strike and a shallow westerly dip. These contain compressed goniatites, posidonid bivalve shells, trace fossils such as *Chondrites,* and some plant remains. Nodules of pyrite and horizontal stylolites, with associated vertical calcite veins, are also present. 46m of these black beds were drilled beneath the quarry floor without pale limestone being encountered (Dickson 1967).

4. SYN-SEDIMENTARY DEFORMATION STRUCTURES

Throughout the Poyllvaaish area evidence is seen of sediment having behaved both in a lithified and an unconsolidated manner during deposition. For example, the widespread occurrence of boulder beds in

Fig. 13. Rubble bed (left hand side) within middle black beds which themselves overlie large blocks of boulder limestone (*e.g.* upper right hand side). The hammer is 40cm long.

Fig. 14. Mounds of foundered limestone overlying middle black beds which are themselves younger than the limebank visible in the lower left hand corner of the photograph. Note deformed black beds on the right.
The hammer is 40cm long.

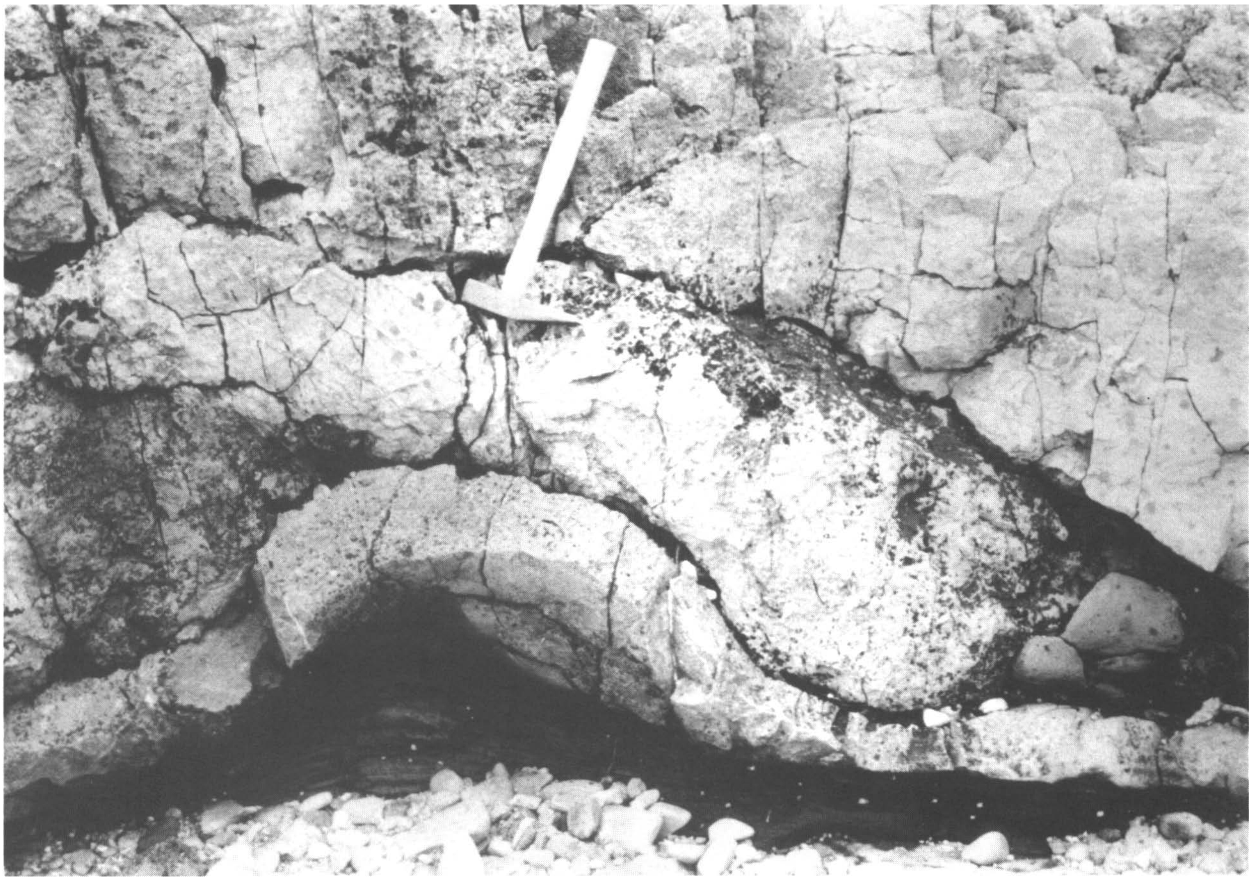

Fig. 15. Evidence of the effects of loading at the base of a sheet of boulder limestone. The hammer is 40cm long.

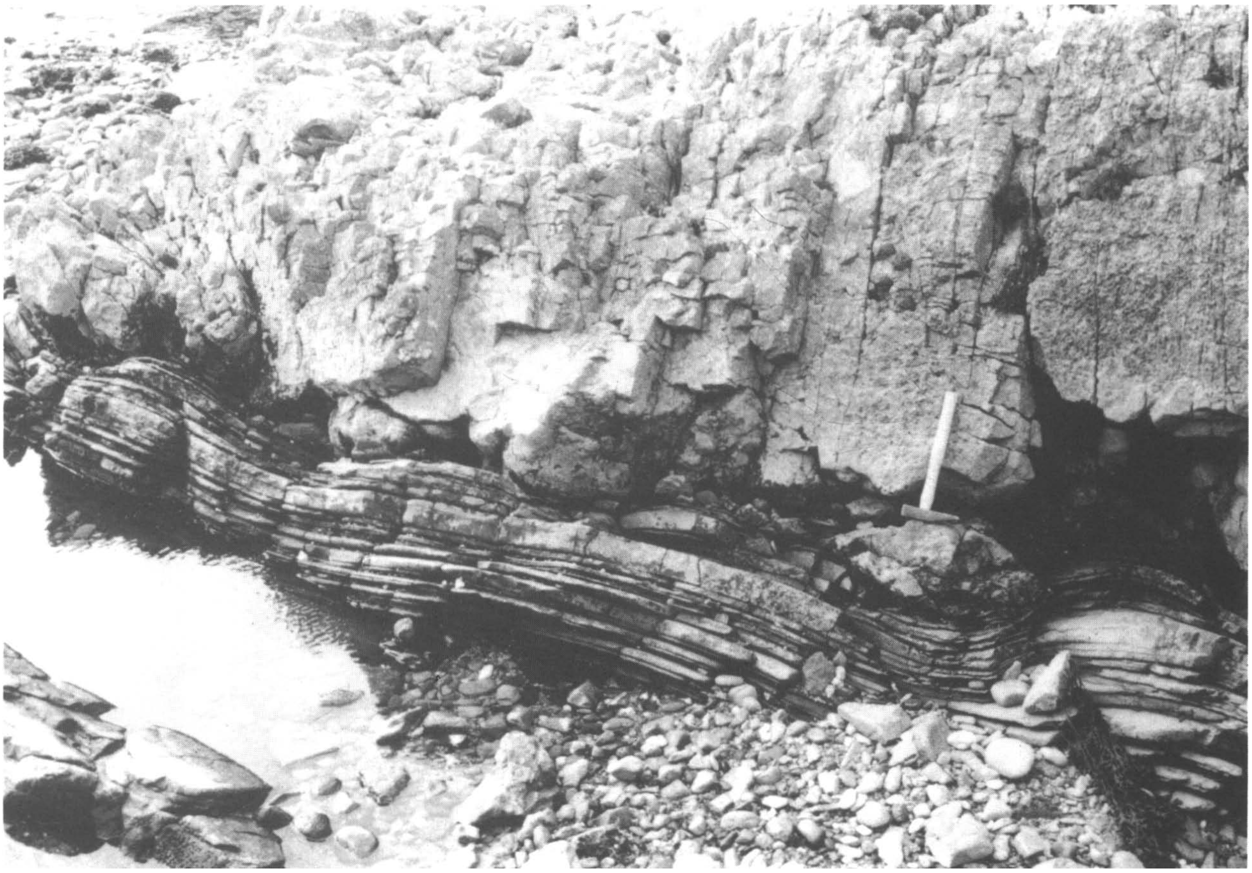

Fig. 16. Load casts at the base of the mound of foundered limestone shown in the foreground of Fig. 14. The hammer is 40cm long.

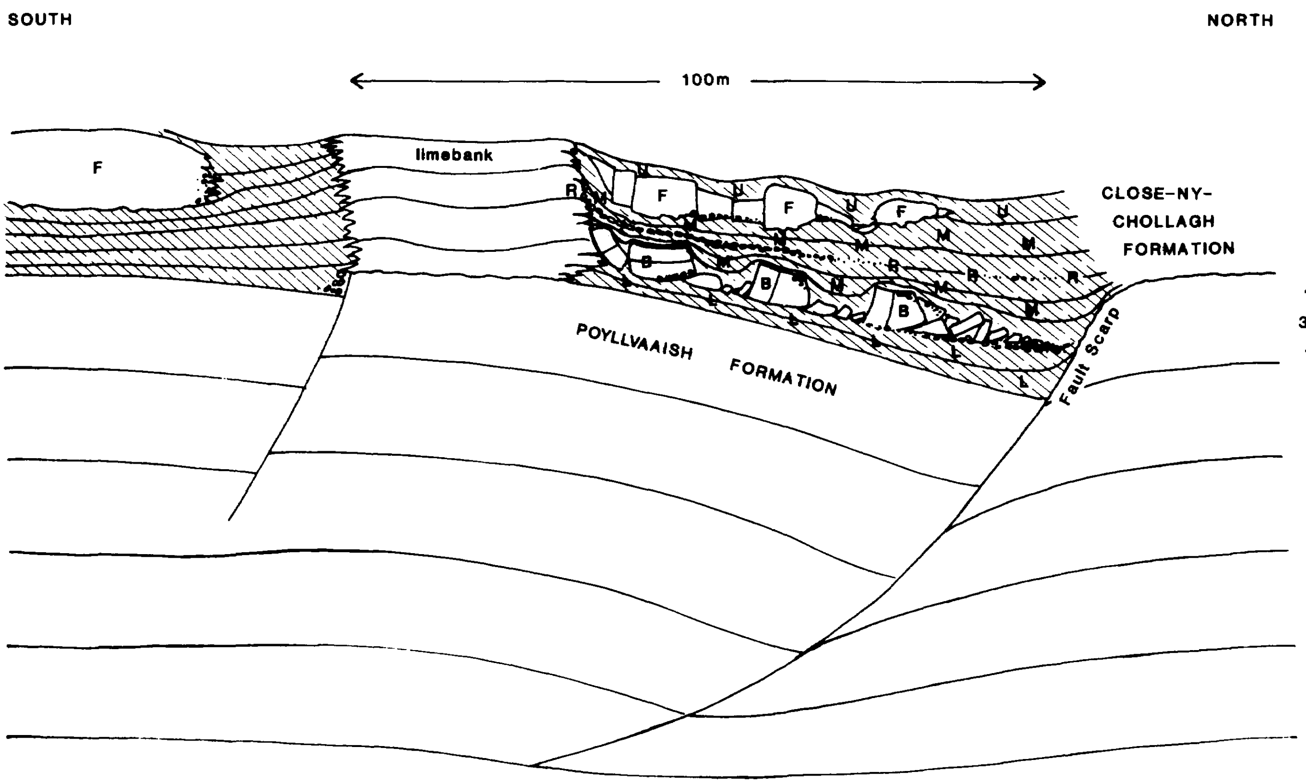

Fig. 17. Idealised cross-section through study area, after deposition of the Close-ny-Chollagh Formation, showing interpreted half-graben structure.
Key: B = boulder limestone; F = foundered limestone; L = lower black beds; M = middle black beds; U = upper black beds; R = rubble bed.

the inlet implies that most of this pale limestone was lithified prior to movement (Figs 2, 9, 10, 12, 13). Yet these same boulders often appear to have pressed down into the underlying mudstones in a ductile manner also leading to the development of small syn-sedimentary anticlines in the mudstone around the sides of the boulders (Figs 8, 10, 14, 15). Load casts and proto-ball-and-pillow structures of pale limestone can be observed at the base of some of the bodies of foundered limestone (Fig. 16). Furthermore, the algal laminations in some of the blocks of boulder limestone have been folded in a manner indicative of soft sediment deformation whilst at the same time displaying an overall steep to vertical dip, contrary to the surrounding beds, suggesting that the whole block was overturned *en masse*. Elsewhere, clasts of boulder limestone showing diffuse boundaries have become incorporated with mudstone of the lower black beds (Fig. 11), apparently as a result of the former flowing into the latter. In contrast, groove casts and syn-sedimentary joints infilled with later shale are found on the upper surface of a few of the more calcareous mudstone beds indicating that, in some places at least, the argillaceous sediment had itself become partially lithified at the sea-water interface.

An explanation for these apparently contradictory observations is that during sedimentation a short period of high stress caused much of the limestone to deform in a brittle manner whereas a prolonged phase of gentle stress resulted in ductile behaviour. Evidence of these two effects is generally more commonly seen in pale limestone and mudstone, respectively.

5. DISCUSSION

The most unusual feature of the geology of Poyllvaaish Bay is the presence of blocks and cobbles of pale limestone within beds of black calcareous mudstone. Most of these belong to a single discontinuous stratigraphic horizon known as the boulder limestone. The size of the clasts and thickness of the bed increase away from a fault scarp on the northern side of the inlet towards a limebank on the southern side. The overall thickness of the black beds probably decreases in a southerly direction which is also matched by a lessening in the amount of organic material and pyrite and an increase in the shallow-water fossil content. Furthermore, roughly south-dipping algal laminations and groove casts indicate that the boulders may have moved northwards by back-rotation and sliding of limestone mega-clasts derived from the limebank. Therefore it is proposed that an important episode of gravitational collapse during carbonate sedimentation allowed boulders to travel rapidly towards the fault scarp. The decrease in the size of the clasts away from the limebank implies that they were carried in a turbidity current. Several points arise from this model. Firstly, a difference in height must have been present between the lower black beds and the limebank thus allowing collapse and movement to occur. Presumably also the sea floor at this time, which is represented by the upper surface of the lower black beds, had slight northerly dip. Secondly, something must have triggered the break-up — either tectonism, inherent instability or a combination of both. Thirdly, rather unstable structures appear to have been preserved intact, suggesting that subsequent sedimentation was relatively rapid. In a general sense it would seem that the inlet exposes a small asymmetric trough or micro-basin bordered on its northern and southern sides by a syn-sedimentary fault and a limebank, respectively. In fact, the southern edge of the limebank is also delineated by a (smaller) syn-sedimentary fault (Fig. 6).

The model used to explain all these observations and inferences is shown in Figure 17. It is proposed here that at the start of Close-ny-Chollagh times a 3m high E-W trending fault scarp was created in the Poyllvaaish limestone at the northern end of the present day inlet as a result of extensional movement. 100m further south a synthetic normal fault was also formed at the same time or soon after to accommodate rollover in the hanging wall of the main fault (Fig. 17). Thus a northerly-dipping half-graben had developed between the two faults. Subsequently a limebank developed in the shallow water on the upthrown side of the half-graben. To the south of the synthetic fault only deeper water sediments were deposited and to the north of the main fault the older Poyllvaaish limestone may have either become subaerially exposed or buried beneath more shallow water carbonates. Within the trough, in the deeper part of the half-graben between the limebank and the main fault, carbonate deposition was restricted from the open sea to the south and thus black muds were mainly deposited. This sediment probably accumulated most thickly in the axis of the trough beside the fault scarp thus leading to its gradual infill. However, the limebank itself was inherently unstable and, possibly as a result of renewed fault movement, the northern margin began to break up thus initiating a mass flow which deposited the boulder limestone within the trough. As the trough began to fill up, a second episode of collapse deposited the rubble limestone, although this was of much more limited extent (Fig. 17). Later, probably as a result of a more general sea-level rise, the biohermal masses of foundered limestone developed beside the old limebank. These became slightly contorted due to differential compaction of the underlying sediments.

Finally the area was blanketed by the Scarlett Volcanics which may have played a part in the remarkable preservation of these unusual sedimentary features.

On a regional scale it is possible that in Close-ny-Chollagh times the northern part of the Poyllvaaish Bay represented the faulted margin of a larger basin (see Ziegler 1982) in which were deposited carbonate muds and shales such as are present in the Black Marble Quarry, 500m to the south-east of the inlet (Fig. 1c).

6. CONCLUSIONS

Stratigraphic relationships indicate that a small half-graben, only 100m wide, rapidly developed at the end of Poyllvaaish (early Brigantian) times. A normal fault, with downthrow to the south, produced a submarine scarp, a few metres high, in an area of previously shallow water carbonates. Due to rollover on the southern side of the fault, the seabed was tilted northwards towards the fault and a synthetic normal fault developed to the south, thus forming a half-graben. On the up-tilted side of the half-graben a small limebank began to build out northwards over black muds that were accumulating on the gently sloping seabed. Either because the pale limestone began to prograde over a steepening and more muddy seafloor, thereby inducing natural instability, or because of renewed tectonism, blocks and boulders of partially consolidated limestone moved downslope towards the fault scarp due to collapse of the northern edge of the limebank. A second, less important collapse event is also recorded. Rubble and boulder beds close to the fault scarp grade into large blocks, and finally unbroken limebank limestone, with increasing distance southwards. Some time later, pale algal-bound bioherms developed within the trough itself, which was by then mostly filled with black mud. These began to founder on the incompetent muds beneath the mounds thus leading to their folding and over-steepening of the latter. Finally, widespread basaltic volcanism engulfed the area and probably helped in the preservation of this unusual sedimentary microcosm.

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