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Sedimentology and kinematics of a large, retrogressive growth-fault system in Upper Carboniferous deltaic sediments, western Ireland

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ABSTRACT

Growth faulting is a common feature of many deltaic environments and is vital in determining local sediment dispersal and accumulation, and hence in controlling the resultant sedimentary facies distribution and architecture. Growth faults occur on a range of scales, from a few centimetres to hundreds of metres, with the largest growth faults frequently being under-represented in outcrops that are often smaller than the scale of feature under investigation. This paper presents data from the exceptionally large outcrops of the Cliffs of Moher, western Ireland, where a growth-fault complex affects strata up to 60 m in thickness and extends laterally for ≈ 3 km. Study of this Namurian (Upper Carboniferous) growth-fault system enables the relationship between growth faulting and sedimentation to be detailed and permits reconstruction of the kinematic history of faulting. Growth faulting was initiated with the onset of sandstone deposition on a succession of silty mudstones that overlie a thin, marine shale. The decollement horizon developed at the top of the marine shale contact for the first nine faults, by which time aggradation in the hangingwall exceeded 60 m in thickness. After this time, failure planes developed at higher stratigraphic levels and were associated with smaller scale faults. The fault complex shows a dominantly landward retrogressive movement, in which only one fault was largely active at any one time. There is no evidence of compressional features at the base of the growth faults, thus suggesting open-ended slides, and the faults display both disintegrative and non-disintegrative structure. Thin-bedded, distal mouth bar facies dominate the hangingwall stratigraphy and, in the final stages of growth-fault movement, erosion of the crests of rollover structures resulted in the highest strata being restricted to the proximity of the fault. These upper erosion surfaces on the fault scarp developed erosive chutes that were cut parallel to flow and are downlapped by the distal hangingwall strata of younger growth faults.

Keywords Deltaic, growth fault, retrogressive, Upper Carboniferous.

INTRODUCTION

The development of growth faults is a common phenomenon during delta progradation, particularly in areas with high sedimentation rates, such as at distributary mouth bars and proximal delta slopes (Rider, 1978; Coleman *et al.*, 1983; Bhattacharya & Davies, 2001, 2004). However, growth faults are also known to develop in delta-top settings (Chisholm, 1981; Elliott & Ladipo, 1981). Such synsedimentary faulting may strongly influence the dispersal of sediments in deltaic environments and can be of prime importance in controlling the resultant reservoir geometry (e.g. Busch, 1975). Understanding the kinematics of growth-fault development, and the resultant sediment architecture, are thus of key importance in hydrocarbon exploration (Coleman *et al.*, 1983), but the scale of such features often renders their study problematic. Growth faults typically measure tens to hundreds of metres in height and can disrupt strata over a length of several kilometres (Evamy *et al*., 1978). This scale of feature ensures that it is rarely possible to study an entire growth-fault system at outcrop, except for small-scale examples (e.g. Elliott & Ladipo, 1981; Bhattacharya & Davies, 2001, 2004). Although high-quality seismic data can allow fault kinematics (Cartwright *et al*., 1998) and, potentially, the three-dimensional geometry to be elucidated, they are unable to integrate this with detailed laterally extensive information on the sedimentary facies and architecture. The present paper contributes to overcoming this scale-of-observation dichotomy using evidence from seismic-scale cliff sections (up to 200 m high and nearly 8 km in length) of Upper Carboniferous deltaic strata from northern County Clare, western Ireland (Fig. 1). These sections reveal the remarkable organization and systematic development of a series of large growth faults that contrast with the apparently spatially and temporally random development reported from some other growth-fault systems (Cartwright *et al*., 1998; Bhattacharya & Davies, 2001, 2004). Although several studies have highlighted the occurrence of frequent and rapid retrogressive failure of recent slope systems (e.g. see reviews by Hampton *et al*., 1996; Locat & Lee, 2000), research documenting the longer term behaviour of growth faults is rare: the only outcrop comparable in scale to that described here is the Upper Triassic cliffs of Svalbard (Edwards, 1976), but this example is inaccessible making evaluation of facies and detailed bed geometry impossible. The County Clare sections present an outstanding and accessible example of large-scale synsedimentary growth faults and their influence upon the sedimentary facies.

The present paper aims to evaluate the interplay between growth-fault initiation, sedimentation and sediment architecture. The previous detailed analysis of small-scale growth faults in the Cretaceous of Utah (Bhattacharya & Davies, 2001, p.525) highlighted five key questions pertinent to understanding the evolution of a growth fault-controlled sedimentary system:

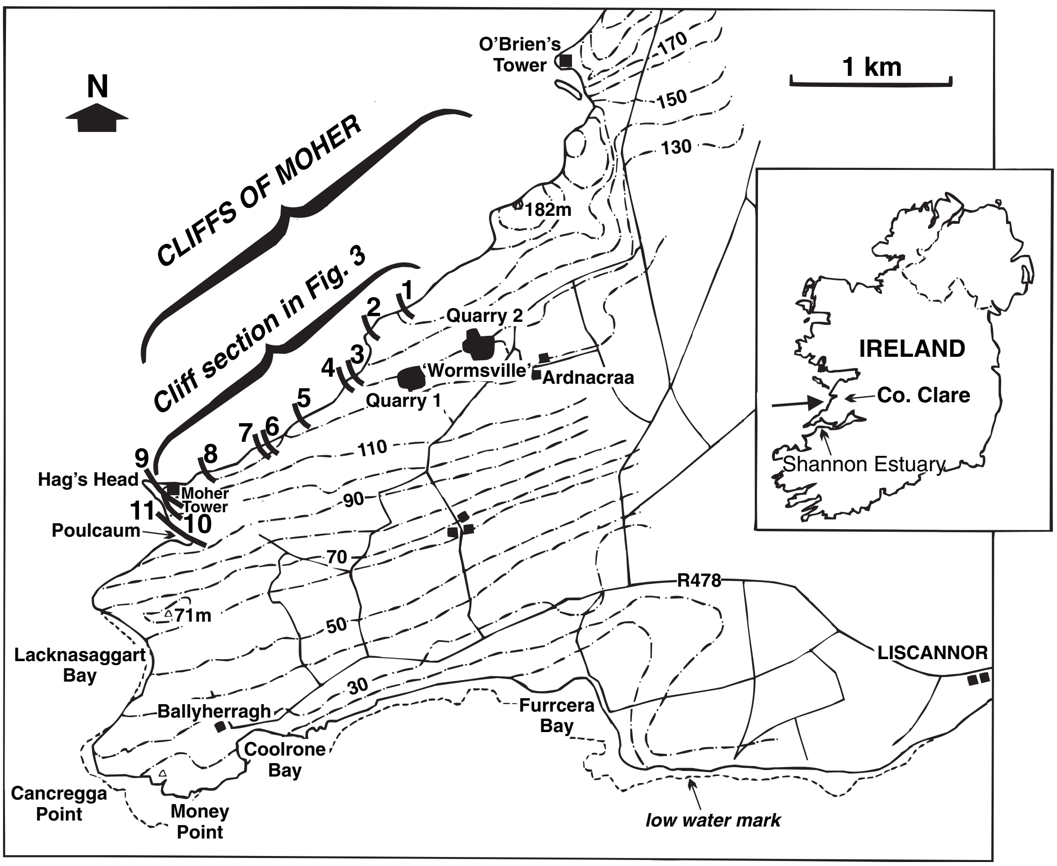


Fig. 1. Locality map of studied sections in northern County Clare, western Ireland. The locations of the 11 growth faults seen in the cliff line are depicted.

1 Are the growth faults initiated by a specific facies or depositional process?

2 Do faults initiate in a more landward position with subsequent fault nucleation occurring in a more seaward position as the delta progrades (as frequently suggested, e.g. Evamy *et al.*, 1978; Bruce, 1983), or do faults initiate in a more seaward position and migrate landwards as a retrogressive kinematic wave?

3 Are faults ever reactivated?

4 How is the growth faulting accommodated?

5 What kind of sedimentological and facies variations are associated with different positions in individual growth faults?

A further crucial question required for an understanding of the development of the sediment architecture is:

6 How is the interplay between sediment erosion, bypass and deposition controlled by growth-fault activity, and does this remain constant during the evolution of individual faults?

This paper aims to address these questions using the County Clare exposures as a field example.

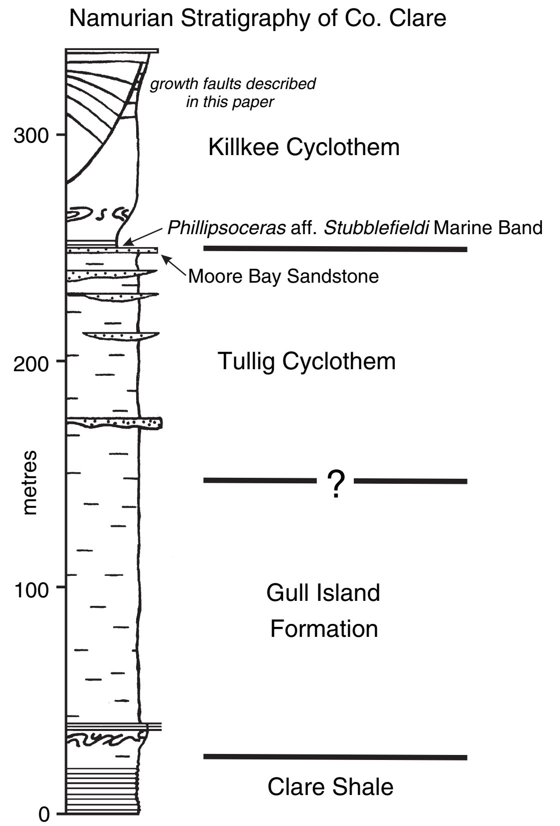


Fig. 2. Lithostratigraphic summary of the Namurian geology of north County Clare, Ireland.

GEOLOGY OF THE STUDY AREA

The coastal cliff sections of County Clare provide superb exposures of a Carboniferous basin infill that records a history typical of many NW European Carboniferous basins (Rider, 1974; Collinson *et al.*, 1991). In the Clare Basin, Dinantian ramp carbonates are overlain by a deep-water black shale (the Clare Shale Formation), which in turn is succeeded by a clastic succession of Upper Carboniferous (Namurian Series) age that records basin infill and shallowing (Fig. 2). The higher parts of the succession consist of a series of progradational, deltaic cycles (or cyclothems), up to 250 m thick, separated by condensed, transgressive sediments that include marine bands comprising thin, goniatite-bearing, black shales (Rider, 1974; Pulham, 1989; Hampson *et al.*, 1997). Delta-slope facies within these cyclothems display abundant evidence for slope collapse and soft-sediment deformation (slumps, slides and growth faults; see Martinsen, 1989) seen in the extensive series of coastal sections south of Liscannor Bay. These sites have become key localities for the study of such phenomena (Rider, 1978; Gill, 1979; Crans *et al.*, 1980; Pulham, 1989; Strachan, 2002), but the sections north of Liscannor Bay have received much less study.

The lowest deltaic cyclothems are, in ascending order, the Tullig, Kilkee and Doonlicky cycles (Fig. 2). Only the lower two cycles have extensive outcrops along the length of the County Clare coastline that allow the regional palaeogeography to be reconstructed with some confidence (e.g. Rider, 1974; Hampson *et al.*, 1997). As a result, the Tullig and Kilkee cyclothems have become key horizons in a debate concerning basin orientation during the Namurian (Wignall & Best, 2000, 2002; Martinsen & Collinson, 2002). The present study focuses on the Kilkee cyclothem sections north of Liscannor Bay (Fig. 1).

DATA AND METHODS

For this study, the northern County Clare cliff line, known as the Cliffs of Moher, was photographed from a boat, and the images were used to construct a 2 km long photomontage that formed

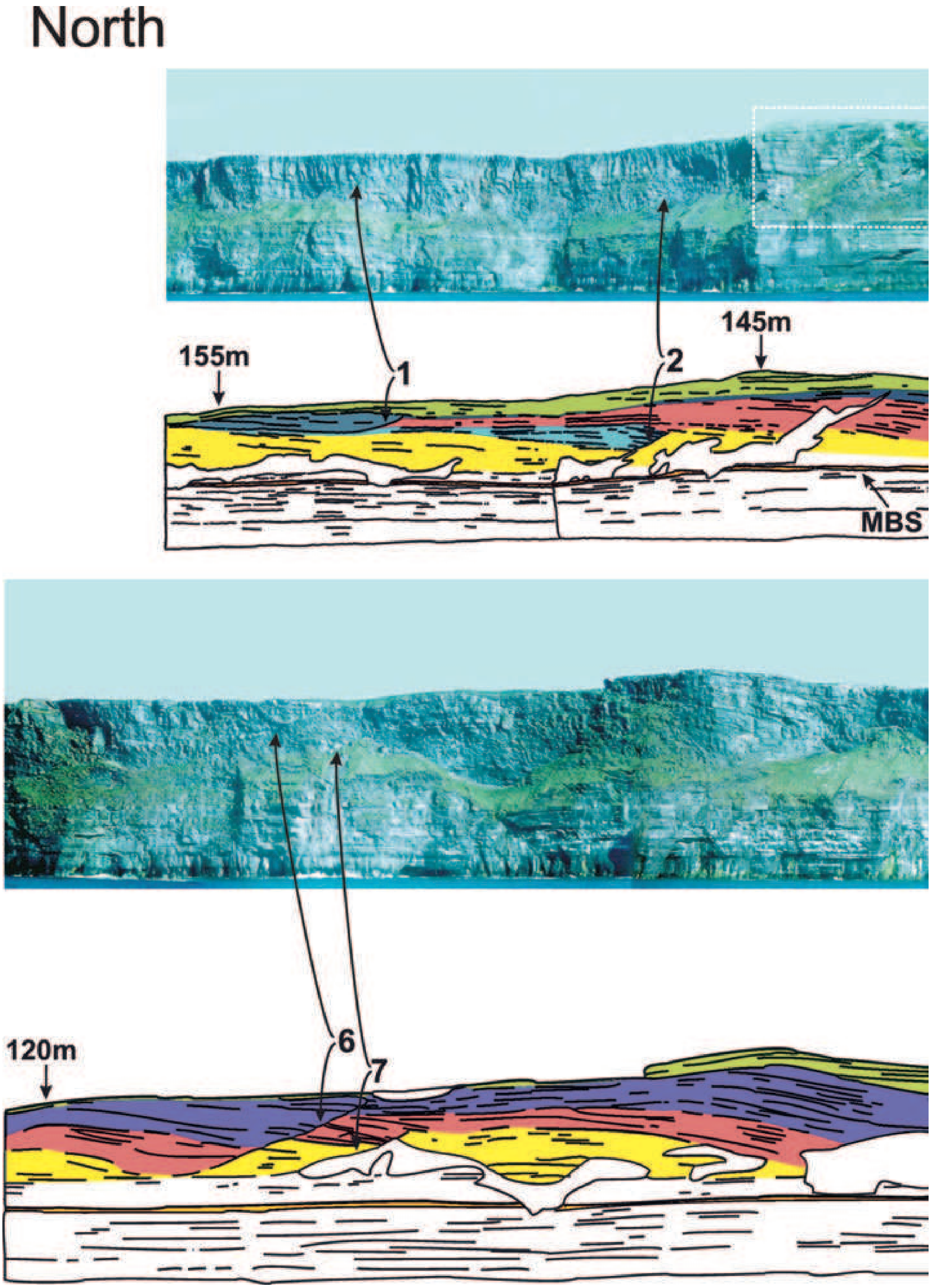


Fig. 3. Photomontage of the Cliffs of Moher section and interpretative sketch with nine growth faults indicated within the Kilkee cyclothem. The Moore Bay Sandstone (MBS) forms the topmost, undisturbed horizon of the underlying Tullig cyclothem. Coloured packages depict strata associated with individual growth faults. Strata not affected by faulting and areas covered by grass and scree slopes have not been coloured. Top photomontage also shows the location of Fig. 8.

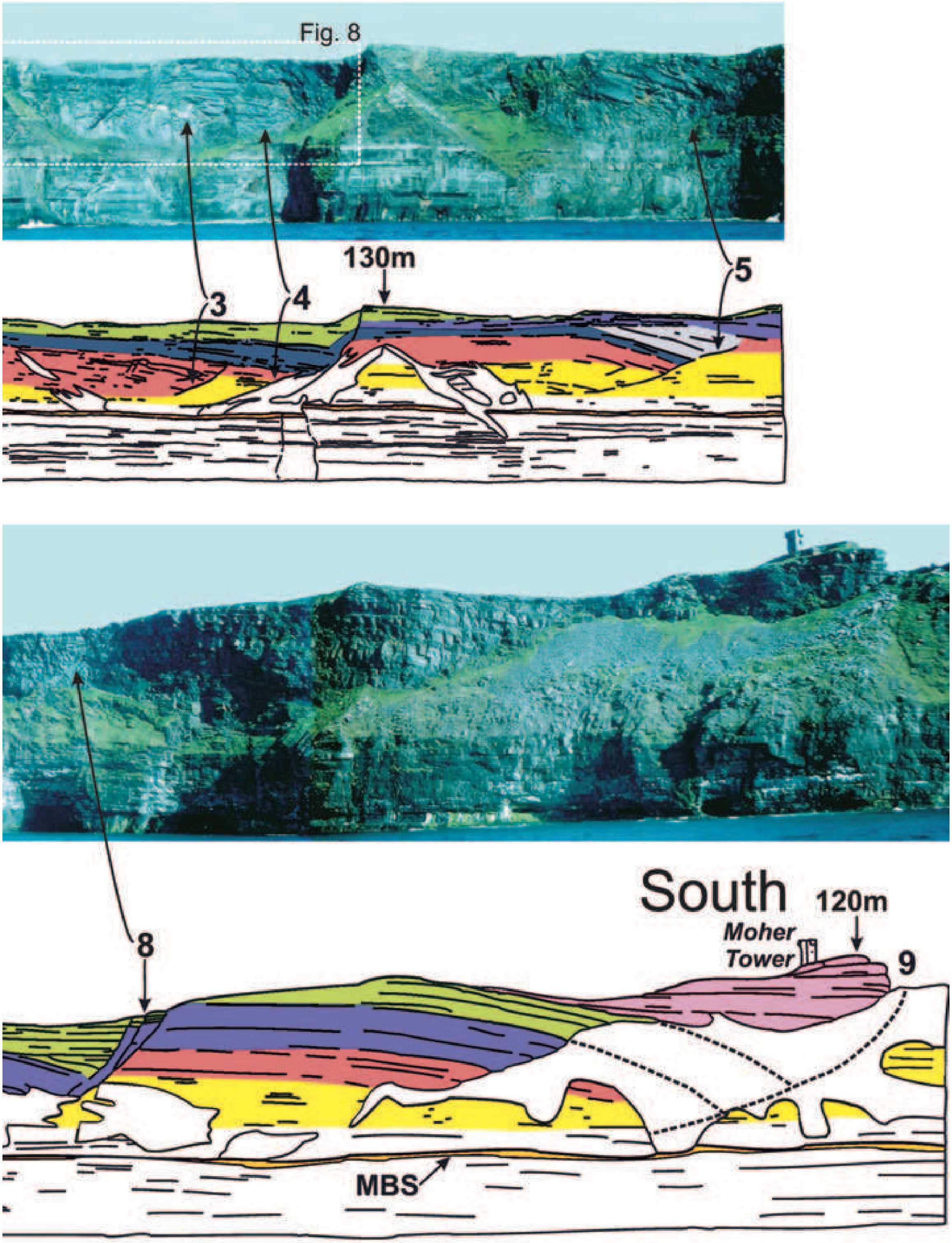


Fig. 3. Continued.

the basis for the identification of growth faults and bedding trends within this profile (Fig. 1). The course of the boat track was closest to the cliff line at the southern end of the transect and gradually became more distant towards the northern end. As a result, the scale of the photomontage decreases slightly towards the north, although this has been partially offset in software production of the photomontage that allowed rescaling of some images, together with the fact that the actual height of the cliffs can be ascertained from topographic maps of the entire cliff line. The cliff line trends NE–SW and is parallel to the palaeocurrents and dip of the faults, indicating that this is a dip cross-section. A depositional strike cross-section is provided by the cliff section on the north side of Lacknasaggart Bay, 1 km to the south of the Cliffs of Moher profile (Fig. 1), which was also photographed to enable the production of a photomontage and interpreted sketch. Another strike section is also present in the rocky promontory of Hag's Head and the adjacent cliffs beneath Moher Tower. Direct access is possible to growth fault-disturbed strata in this area, thus allowing facies and palaeocurrents to be studied and hangingwall and footwall strata to be compared. The facies in the upper part of the Cliffs of Moher section were also examined in the extensive flagstone quarries to the west of Ardnacraa (Fig. 1), an area known locally as 'Wormsville' because of the abundance of sinuous *Scolicia* traces. The 'Wormsville' quarries provided important data on erosive structures and downlap geometries that characterize the final phase of growth-fault development, in addition to allowing access to the principal facies type within the hangingwall stratigraphy. The lowermost strata of the Kilkee cyclothem are also accessible in the low cliffs between Cancregga Point and Coolrone Bay, and in cliff-top platforms immediately south and north of O'Brien's Tower (Fig. 1).

STRATIGRAPHY AND DEPOSITIONAL FACIES

The growth faults overlie the uppermost beds of the Tullig cyclothem (Fig. 2), which are seen to be undisturbed along the 8 km length of their continuous exposure from O'Brien's Tower to Lacknasaggart Bay (Fig. 1). A 2 m thick sandstone forms a distinct marker bed in the cliff (Fig. 3) and, at O'Brien's Tower, its top surface is seen to be intensely bioturbated by *Zoophycus*, indicating marine deposition. This bed, the Moore Bay Sandstone, caps the Tullig cyclothem in southern County Clare where it approaches 20 m in thickness (Wignall & Best, 2000, fig. 13), and it is the only fully marine sandstone in the entire Namurian basin fill. At the Cliffs of Moher, the Moore Bay Sandstone is sharply overlain by a 5·62 m thick succession containing two *Phillipsoceras* aff. *stubblefieldi* marine bands. The lower band is 1·57 m thick with a black mudstone at its centre that is often cemented and has common cone-in-cone diagenetic calcite. A 0·85 m thick, unfossiliferous shale with siderite concretions separates the two marine bands. The upper marine band is 3·20 m thick, but only contains common marine fossils in the basal 0·35 m.

The lower marine band marks the base of the Kilkee cyclothem, a thick, coarsening-upward succession. Above the upper marine band, grey silty shales with siderite concretions form the basal 7 m of this succession, before they are replaced by finely laminated siltstones, with minor thin beds of sandstone that are approximately 35 m thick. In the southern half of their development, from Hag's Head to Money Point, these siltstones show extensive soft-sediment deformation and flow rolls. The latter term, proposed by Gill (1979), refers to elongate rods of sandstone that are probably detached fold hinges formed during slumping. At Cancregga Point, the deformed horizon increases to over 20 m thickness where it can be resolved into three discrete slump beds separated by thin beds of undisturbed strata. Fold vergence indicators here suggest movement towards 020°. Elsewhere along the cliff line, the slumped strata are rarely more than 1 m thick.

Higher in the Kilkee cyclothem, thinly bedded, fine-grained sandstones dominate the succession, together with thicker (1–2 m thick) beds of sandstone displaying decimetre-scale trough cross-stratification. The thickness of these sandstone strata varies considerably, as a result of growth faulting, and locally approaches 60 m. The thin-bedded sandstones are the celebrated Liscannor Flagstones that have been, and continue to be, quarried extensively in the area between Ardnacraa and the Cliffs of Moher. The flagstones split readily into sheets between 0·015 and 0·030 m thick, and individual beds or 'flags' are typically planar-laminated in their lower half and cross-laminated by linguoid ripples in their upper part. The ripples have occasionally been modified by oscillatory currents indicating a wave influence. Palaeocurrent measurements from unidirectional linguoid ripples at 'Wormsville' indicate flow to 062°, with the crests of symmetrical wave ripples showing oscillatory flow at 048–228°.

Trace fossils are common in the Liscannor Flagstones, and the linguoid rippled horizons are often obscured by intense bioturbation. In the quarried strata at 'Wormsville', the trace fossil assemblage is dominated by *Scolicia*, whereas the flagstones in the Moher Tower section are less intensely burrowed by *Lockeia*. Rarely, the *Scolicia* traces show a gradation into *Diplichnites*, which suggests that isopods were the trace makers. Other, slightly rarer trace fossils include *Helminthoidea* (juvenile *Scolicia*?) and *Arenicolites*. This modest ichnofossil diversity suggests a brackish to freshwater basin salinity at this level of the Kilkee cyclothem (cf. Eager *et al.*, 1985).

Thicker bedded, and slightly coarser grained, sandstones are developed in the highest strata, seen in the uppermost parts of the 'Wormsville' Quarries and at the top of the Moher Tower section, where trough cross-stratification, current ripple-laminated packages and massive beds are encountered. As described below, these facies are confined to proximal hangingwall locations of growth faults.

STRUCTURAL STYLE

The structural style of the Kilkee cyclothem beds will be described in relation to three key locations shown in Fig. 1.

Cliffs of Moher and 'Wormsville' sections

Major structure

The Cliffs of Moher reveal a section in the Kilkee cyclothem that is extensively disturbed by large growth faults, ranging from 30 to 60 m in height, that dip to the NE (Fig. 3). The faults have been numbered sequentially from north to south in Fig. 3 with a total of eight faults being clearly visible. Immediately SE of the Cliffs of Moher, three additional faults are well exposed and accessible at Hags Head, together with highly contrasting hangingwall and footwall sections adjacent to the ninth fault. Fault spacing is highly variable, ranging from 30 to 250 m. No additional growth faults were seen in the cliffs that extend for 2 km to the NE of the profile, whereas many faults are clearly developed in the cliffs to the SE of the profile (described below). All the faults show a listric geometry, with fault dip angles ranging from 30° to 60° at their top terminations. All the major faults flatten out into a slip surface, or decollement horizon, at the top of the marine strata developed at the base of the Kilkee cyclothem. Several more minor faults, such as fault 1 (Fig. 3), are developed at various horizons above this level.

Rollover structures are developed in all the hangingwall sections, although the low dips produce very broad anticlines. In the 'Wormsville' quarries and adjacent headland, the axes of three broad anticlines in the footwall of fault 2 trend 108–288°, 100–280° and 110–290°, illustrating that the faults trend WNW–ESE. In the hangingwalls of faults 3 and 8, small reverse faults are associated with the rollover structures (Fig. 3). No toe-thrust structures (cf. Crans *et al.*, 1980) are seen in any of the fault blocks, suggesting that sliding was 'open-ended'. The lower part of the hangingwall strata consists of siltstone beds that do not thicken towards the faults, and thus preserve a prefaulting stratigraphy. In contrast, the upper part of the hangingwall fault blocks are dominated by thin-bedded sandstone facies, described above, that thicken dramatically towards the faults (e.g. faults 5 and 8, Fig. 3). Individual beds in the lower levels of this fault-controlled strata can be traced, commonly for several hundred metres, but higher beds become progressively less extensive. The result is that a wedge geometry is seen in the final phase of growth-fault development (e.g. the hangingwall strata of fault 6, Fig. 3). This geometry could reflect a true offlap relationship or may be produced by uplift and erosion of the hangingwall anticline before downlap by the distal hangingwall strata of younger growth faults. Investigation of these alternatives is possible in the 'Wormsville' quarries and sections at Moher Tower. This reveals that the 'offlap' is at least partially attributable to erosional truncation in the hangingwall strata.

Hangingwall erosive features

The 'Wormsville' 1 and 2 quarries (Fig. 1) allow access to hangingwall sections displaying both erosional and downlap features. In both quarries, the dip of the flagstone strata on the main quarry floor is 8–9° to the SW, which is 5–6° steeper than the regional dip, which is to the south. This increased dip is attributed to rotational steepening towards a growth fault in a hangingwall setting. The highest levels of strata seen in both quarries are horizontal, and the resultant angular discordance with the underlying beds is displayed as a conformable downlap relationship (Fig. 4A) that passes downflow, to the NNE, on to an erosion surface (Fig. 4B). The erosion surface is characterized by several elongate, incised structures (Fig. 4B), ≈ 10 m in width, orientated NNE–SSW and thus parallel to the other palaeoflow indicators. These features, here termed chutes, are infilled by massive or planar-bedded sandstone beds that thicken into the chutes and pass into laterally extensive 'wings'. Such chutes are also visible in the cliff section directly below Moher Tower, developed in the hangingwall of fault 9, and large-scale erosion is also plainly visible in the hangingwall of fault 8 and visible in cliff-top sections just north of Hag's Head (Fig. 4C, see Fig. 3 for location) and is clearly a common feature of late-stage growth-fault development.

The fault surfaces show evidence of both disintegrative and non-disintegrative movement (*sensu* Booth *et al.*, 1993). The surface of fault 8 (Fig. 4D, see Fig. 3 for location) shows a complex arrangement of sandstone blocks set within a siltstone matrix adjacent to the fault surfaces. This clearly shows the disintegrative nature of some of the fault surfaces that were able to brecciate the adjacent sediments as a result of the strain developed within the fault zones. Other faults, however, display a shear with no associated brecciation (e.g. fault 9, see Fig. 4E and discussion below).

Hag's Head sections

The cliff profile to the south side of Hag's Head (Fig. 5) provides a series of valuable exposures parallel to, and at 90° to, those described above. A major growth fault is exposed in the northern end of the extensive outcrops, where it is seen to be sharply defined and to have a dip of 50° NE (Fig. 4E). No disintegrative brecciation features are present on this fault, but large ball-and-pillow structures are present in the hangingwall adjacent to the fault (Fig. 4F). Rotation of strata in the hangingwall of this fault is seen at the most south-western end of the Cliffs of Moher profile (fault 9, Fig. 3) and indicates a fault height of around 60 m. Late-stage, hangingwall strata are dominated by trough and ripple-laminated sandstone beds with flow vectors primarily to the NE (Fig. 5B). Several broad, erosive surfaces, mantled by mudstone or siltstone, are also developed in the Hag's Head exposure (Fig. 6). These differ from the erosive chutes, described above, because of their larger size, often dewatered lower contact and the fine-grained drape that overlies and fills the erosive surface. These features are interpreted as minor fault scarps caused by sliding in the hangingwall strata and may be subsidiary growth faults comparable in size to growth fault 1 (Fig. 3). Importantly, bed truncation in these fault scarps is caused by sliding, in contrast to the chutes where it is produced by erosion.

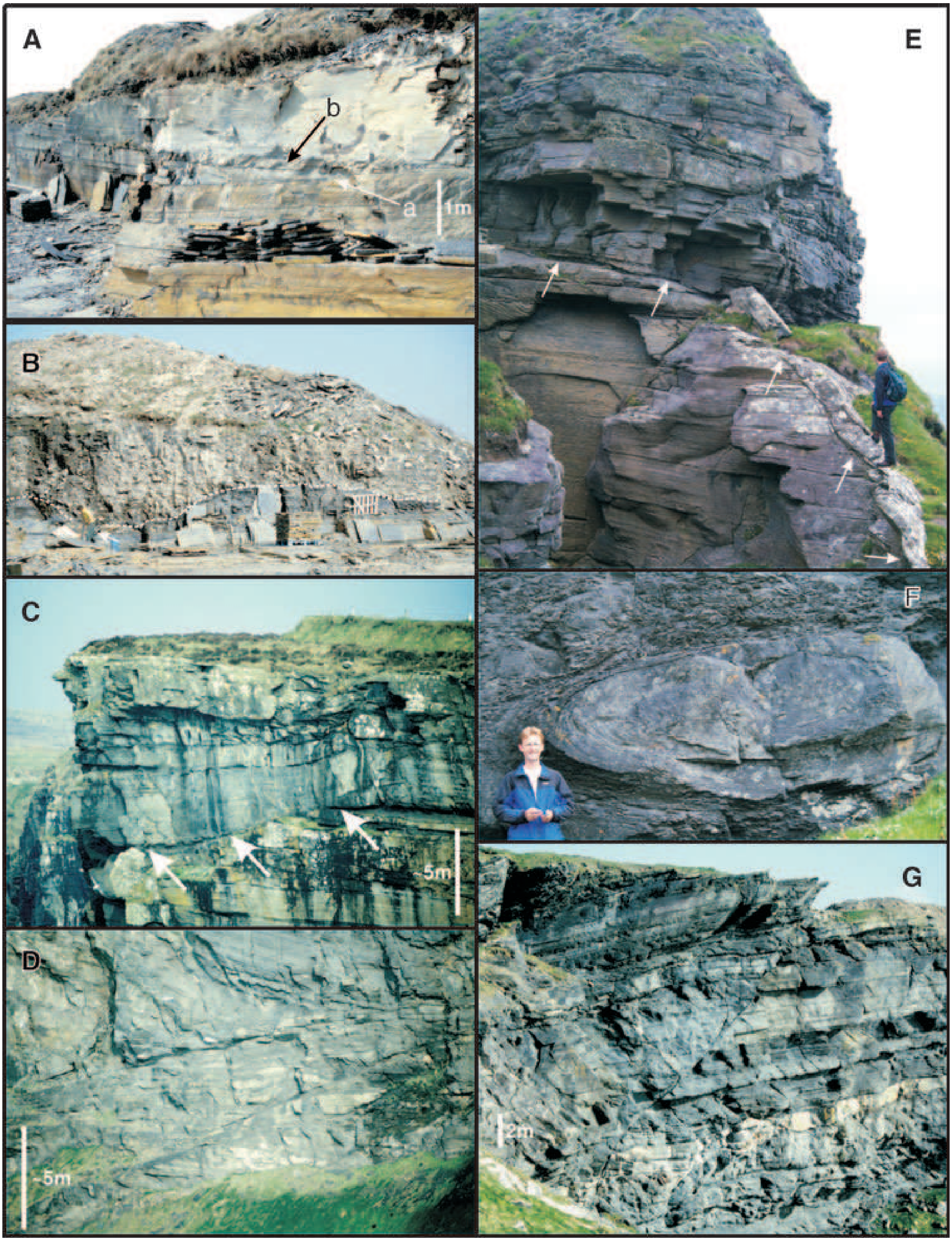
The footwall stratigraphy of growth fault 9 is finer grained than that seen in the adjacent hangingwall and is dominated by planar-laminated coarse siltstones (Fig. 5B). Several minor growth faults are present in this stratigraphy and include an example of a conjugate fault with a throw to the SW, with the result that a horst structure is present (Fig. 4G). A thin sandstone bed, developed in the footwall adjacent to fault 9, thickens to the SW and displays a broad anticlinal structure. Both these features suggest that a further large growth fault (fault 11) is present, but not visible, in the large coastal embayment at the southern end of the Hag's Head cliffs with bed thickening and rotation occurring as the fault is approached (see Fig. 5A).

Lacknasaggart Bay

The 1 km wide cliff section on the north side of Lacknasaggart Bay again provides a section that is orthogonal to that seen in the Cliffs of Moher profile (Figs 1 and 7). Several faults are seen, with examples dipping towards both the NW and the SE (Fig. 7), suggesting that the fault surfaces have a broadly arcuate or cuspate profile in plan view.

Fig. 4. (A) Downlap surface (a) at Wormsville quarry 2 developed in flaggy sandstone facies. A thin shale bed (b) becomes asymptotic as it approaches surface a. This geometry is interpreted as the product of rotation of hangingwall strata resulting from growth-fault movement, followed by subsequent downlap of strata prograding from a more landward-developed growth fault. (B) Erosive chute at 'Wormsville' quarry 1; chute trends 036–216°; person (arrowed) for scale. This face is immediately north of, and orthogonal to, the face in (A). (C) Large erosive-based chute seen in the hangingwall strata of growth fault 8, Cliffs of Moher. (D) Closely spaced faults of growth fault 8 showing some disintegration of sandstone beds in proximity to the faults. (E) Top termination of growth fault 9 (marked with arrows) in the Hags Head section. (F) Large sandstone ball in the hangingwall strata of growth fault 9 seen in the Cliffs of Moher, below Moher Tower. (G) Cliff section immediately south of Moher Tower (section 3 in Fig. 5) showing growth fault 10. Displacement along the fault declines upwards to near zero at the top of the cliff. The white sandstone bed in the lower part of the footwall stratigraphy is offset by a small conjugate fault.

The decollement horizon at Lacknasaggart Bay is over 30 m above the top of the Moore Bay Sandstone (Fig. 7), considerably higher than that seen in the Cliffs of Moher. This level of slip is marked by several soft-sediment deformation features, including slumps and a major water-escape feature or diapir (Fig. 7) indicated by the upward deflection of a thin sandstone bed (Fig. 7). As



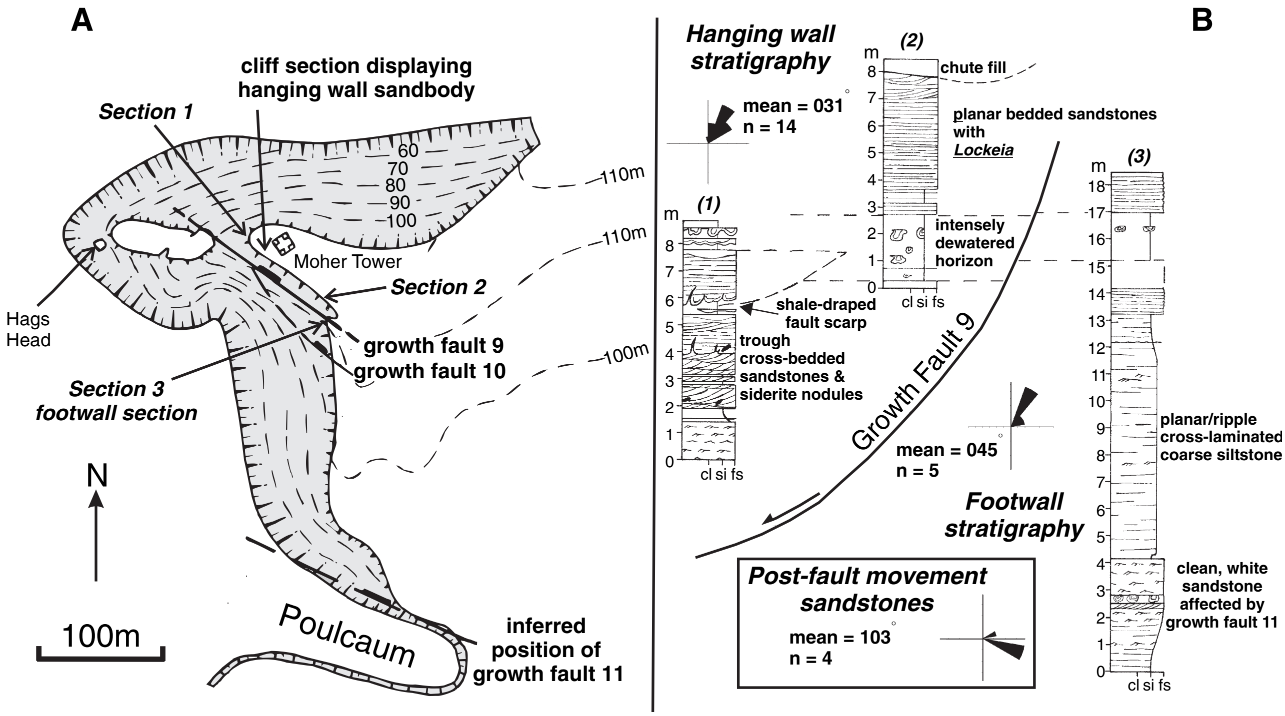


Fig. 5. (A) Detailed location map of the Moher Tower–Hag's Head section showing location of growth faults 9–11. (B) Correlation panel of footwall and hangingwall sections either side of growth fault 9 showing the development of coarser, cross-bedded strata in the hangingwall.

Fig. 6. Photograph of cliff seen on the south side of Hag's Head showing shale-draped fault scarp (dotted line) associated with a minor growth fault within the footwall of growth fault 9. Two other minor faults are arrowed and labelled 'f'.

noted above, this horizon is also intensely affected by slumping south of Lacknasaggart Bay.

KINEMATIC RESTORATION

With the exception of the Moore Bay Sandstone, which underlies the fault-affected succession, no bed can be traced the full length of the Cliffs of Moher profile. However, bedding is well displayed in the growth fault-affected Liscannor Flagstone facies, and the outcrop is sufficiently good that many bedding surfaces can be traced for tens to hundreds of metres. The most prominent and visible of these bedding surfaces have been sketched in Figs 3 and 8, and it is these that have enabled the order of fault development and sediment geometry to be ascertained. For

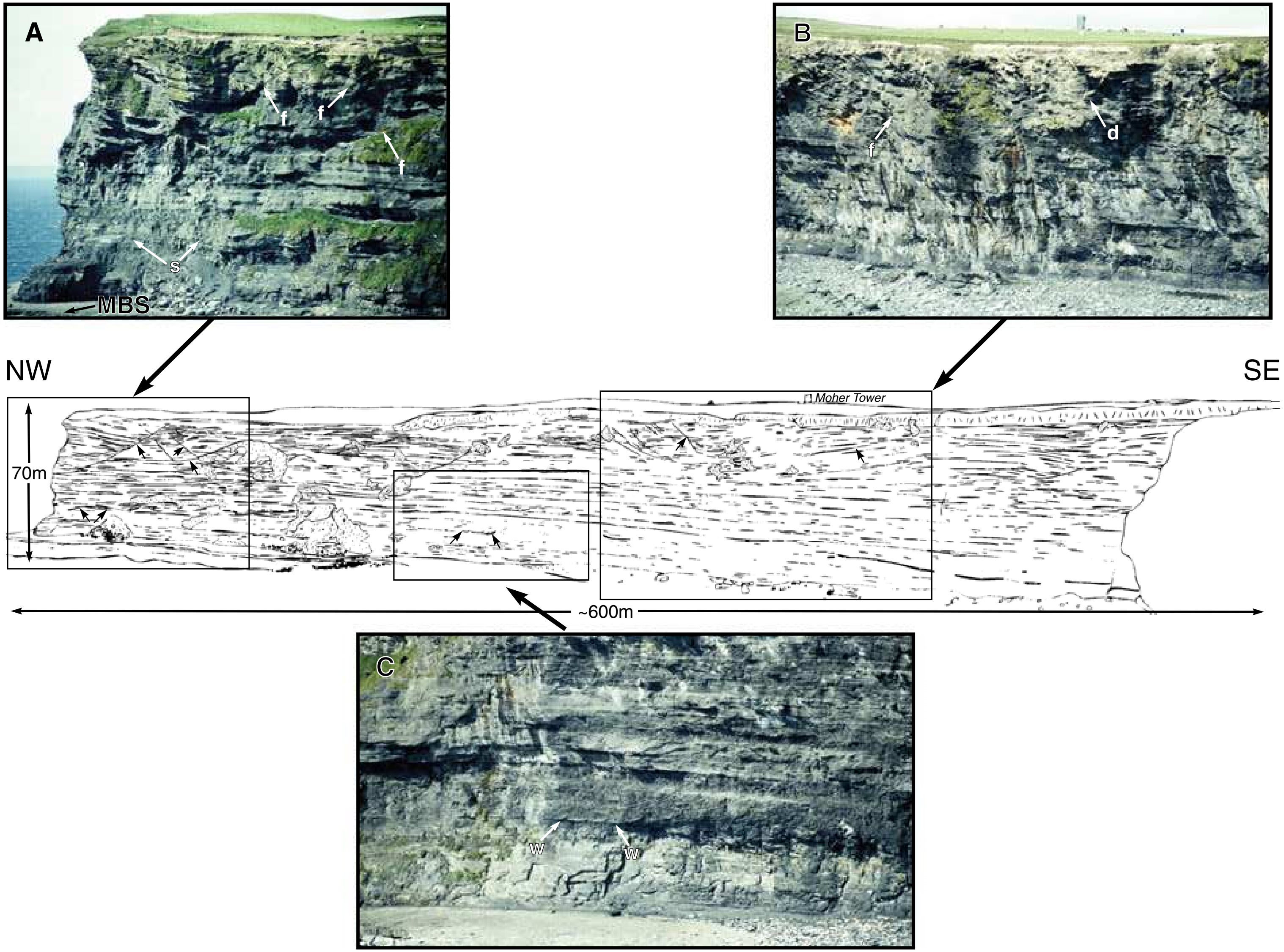


Fig. 7. Interpretative sketch and photographs of the cliff line on the north of Lacknasaggart Bay (see Fig. 1 for location). (A) and (B) Several faults (f) define broad, scoop-shaped features interpreted as recording sections normal to growth-fault movement. Label 'd' points to the dip of the bedding in one of these broad, scoop-shaped features. A horizon of slumping (s) and the Moore Bay Sandstone (MBS) are also labelled in (A). (C) A horizon of slumping and diapiric activity. A thin sandstone bed (w) has broken into large rafts that are upturned and partially imbricated. This feature is interpreted as being on the flanks of a diapiric structure.

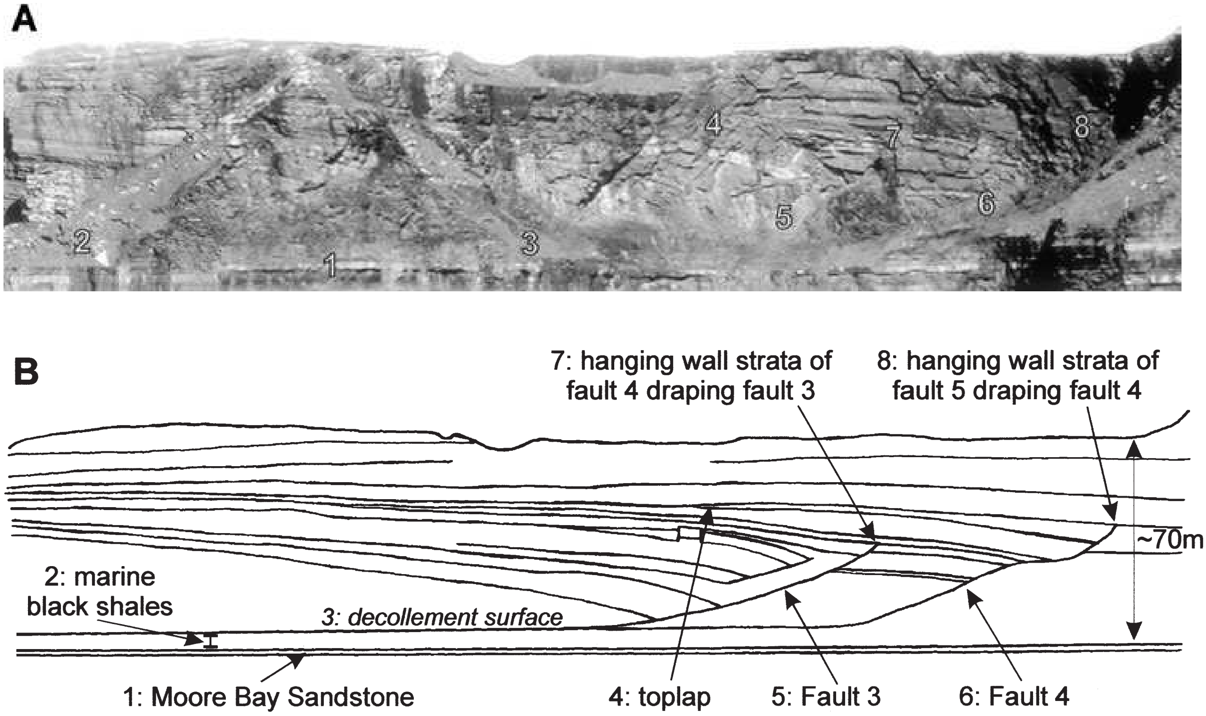


Fig. 8. Detail of the stratal geometry associated with growth faults 3 and 4 in the Cliffs of Moher section (see location in Fig. 3).

example, the upper part of the hangingwall stratigraphy of fault 4 clearly post-dates movement on fault 3 because the distal hangingwall strata of fault 4 overlie the top termination of fault 3 (Fig. 8). The same relationship is demonstrable for faults 5 and 4. The relationship is more difficult to determine for the two southernmost faults, faults 8 and 9, because the faults reach the top of the cliff line. However, it is clear that movement on fault 8 must post-date the movement of faults 6 and 7 because these are overlain by a distinct bed of sandstone (the topmost sliver of green-coloured strata in Fig. 3) that can be traced southwards until it terminates against fault 8 (Fig. 3). Overall, it is clear that the cliff profile shows a systematic and dominantly retrogressive development of growth faulting from NE to SW (Fig. 9). The only clear exception is growth fault 1, the smallest in the section, which cuts the distal hangingwall sediments of faults 3 and 4, but probably moved before fault 5. Additionally, growth faults 6 and 7 are closely spaced, and their relative movement is difficult to discern; they may have been contemporaneously active.

All the major faults sole out at the horizon that marks the sharp transition from marine to non-marine shales. Consequently, the thickness of stratigraphy cut by faults became progressively greater as the fault package developed (Fig. 9). For example, at its onset, fault 2 affected 40 m of strata whereas fault 8 affected around 60 m of strata, this difference being a record of the amount of aggradation in the footwall settings during the evolution of this part of the growth-fault system. Sandstone deposition appears to have dominated both footwall and hangingwall deposition once the growth-fault system was initiated, whereas siltstones were accumulating before movement. Modest accumulation of sandstone in footwall sections occurred during most fault activity, and it is postulated that this increased loading on the failure plane was able to initiate the landward-stepping faults.

The amount of hangingwall aggradation varies considerably from fault to fault (e.g. 25 m for fault 2, over 35 m for fault 8). However, hangingwall thicknesses have clearly been affected by erosional truncation of the rollover structures. The hangingwall strata of fault 1 are overlain by undisturbed beds that can be traced south-westwards, for nearly a kilometre, before terminating against fault 8. Thus, the development of this fault, in an unusual downdip location, appears to have caused a broad zone of updip erosion and sediment bypass.

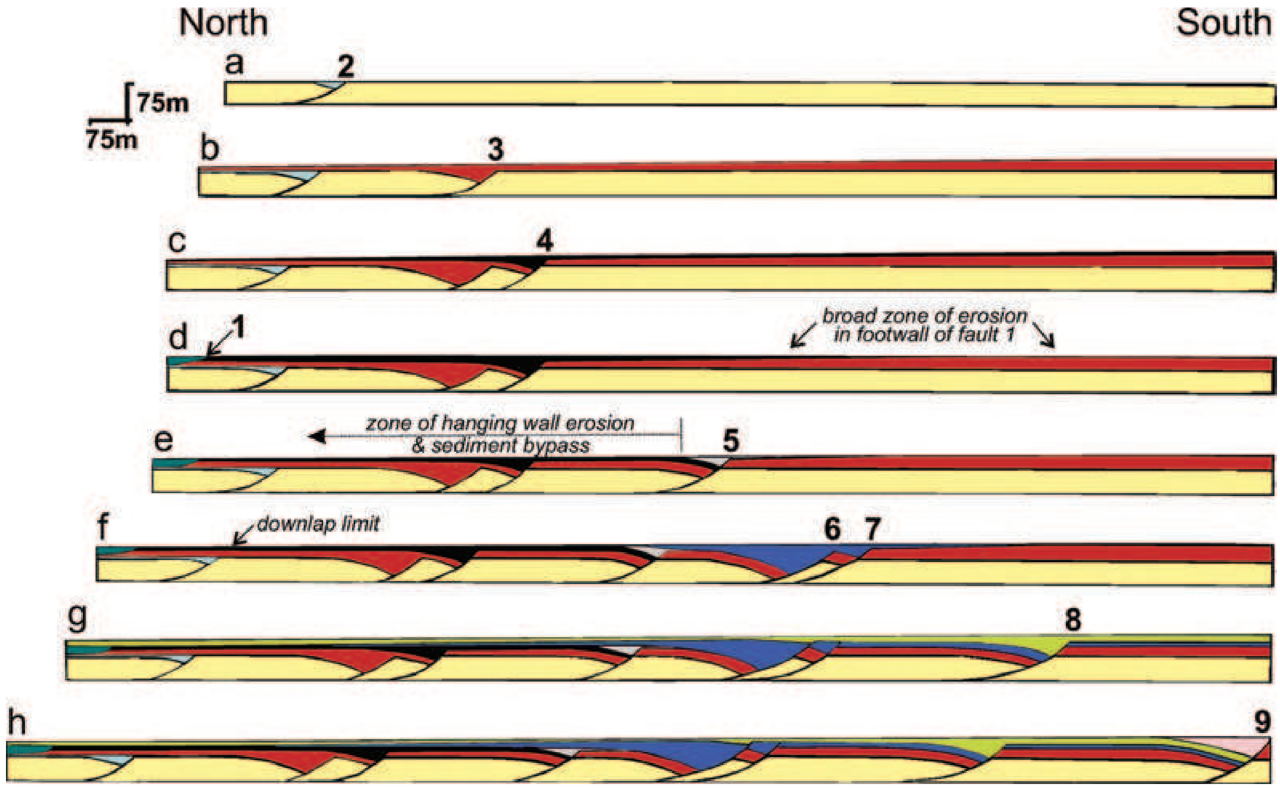


Fig. 9. Reconstruction of the kinematic history of the Cliffs of Moher growth-fault system.

The growth faults seen in the section at Lacknasaggart Bay are developed at a higher level in the Kilkee cyclothem, with the slip horizon being roughly 30–35 m above the main decollement surface in the Cliffs of Moher. It therefore seems likely that these faults post-date those seen to the NE, and that the total south-westward backstepping pattern was at least 3 km in extent.

DISCUSSION

The Cliffs of Moher and associated sections reveal many features typical of those reported from other growth faults (Rider, 1978). Thus, the principal failure plane occurs at the point of inversion of the density profile, in this case the shale–silty shale transition near the base of the Kilkee cyclothem. To the south of Moher Tower, this level is extensively slumped and shows diapiric structures, suggesting that the sediments were originally water rich and highly mobile, thus further steepening the inverted density profile. The steepness of the profile increased greatly with the initial appearance of sandstones within the Kilkee cyclothem, and this loading appears to have initiated the growth faulting and its subsequent retrogressive development. The organic content of the sediments near the failure horizon may also have aided failure by release of gas during organic matter remineralization, a factor that can reduce sediment stability (Booth *et al.*, 1993; Coleman *et al.*, 1993; Hampton *et al.*, 1996; Nisbet & Piper, 1998). The focusing of subsequent sandstone deposition in proximal hangingwall locations is another feature common to many growth-fault systems, thus increasing loading (Busch, 1975).

In some respects, the Cliffs of Moher growth faults are atypical in that they record an end-member in the style and rate of fault movement on sedimentary slopes. This can range from large-scale, single-event, slope collapse features, often associated with slide movement (e.g. Nemec *et al.*, 1988), to growth faults that show intermittent movement with the resultant accommodation in the hangingwall often infilled by Gilbert delta-style foresets (e.g. Bhattacharya & Davies, 2001). No such foresets are seen here, suggesting small increments of movement, but examples are known from other growth faults in the Namurian strata of County Clare (e.g. Rider, 1978; Wignall & Best, 2000, fig. 11).

Perhaps the most unusual aspect of the Cliffs of Moher section, apart from the scale of the exposure, is the clear record that it provides of the retrogressive landward collapse of a slope system. Some workers have postulated that growth-fault systems should step seawards in response to progradation (Evamy *et al.*, 1978; Bruce, 1983), whereas seismic and outcrop studies have tended to reveal a random pattern of fault movement (Rider, 1978; Cartwright *et al.*, 1998; Bhattacharya & Davies, 2001, 2004). Retrogressive movement of slides has commonly been observed in modern settings (Hampton *et al.*, 1996), but this has not been documented over the longer timescales involved in the case study detailed here. The apparently unique aspect of the Cliffs of Moher growth-fault system may stem from the large scale of the exposure, which allows the relationship between faults to be evaluated with unusual precision, rather than inferred from seismic profiles or from smaller outcrops. A further factor may be the extreme weakness of the failure horizon in the present study, in which it appears that only a few metres of sand aggradation in the footwall were required to initiate faulting.

DEPOSITIONAL MODEL

The Kilkee cyclothem outcrops of northern County Clare provide a valuable insight into how the interaction of growth-fault activity and delta development controls sandstone geometry (Fig. 9). Mouth bar sandstones are prevalent among the facies identified in the deltaic facies of the Namurian basin infill of the region (Rider, 1974; Pulham, 1989), and the Liscannor Flagstones, superbly exposed at 'Wormsville' and in the section near Hag's Head, appear likely to have formed in such an environment. Thus, they display repeated alternation of phases of sheet sandstone deposition followed by periods of non-deposition that are required to allow intense bed-top bioturbation and sometimes wave rippling. These features suggest higher discharges from the mouth of a distributary during floods, followed by more quiescent conditions when waves and animals reworked the sediment. Bioturbation is not present in the latest stages of hangingwall infill, when thicker beds of sandstone, often displaying trough cross-stratification, are developed. More continuous distributary discharge is inferred at these levels, possibly associated with a more proximal mouth bar setting, with more continuous flows perhaps being concentrated into these topographically low areas.

Sandstone geometry within most hangingwalls consists of a series of offlapping wedges that records the progressive restriction of deposition to the vicinity of the fault during the history of movement. This geometry has probably arisen as a result of two factors. First, increasing rotation of the hangingwall stratigraphy during fault development may have focused deposition closer to the fault. Secondly, at the termination of growth-fault development, the crest of the hangingwall anticline often became a zone of erosion and sediment bypass as erosive chutes were developed orthogonal to the faults (Fig. 4B and C). The 'offlap' geometry is thus at least partially the result of erosional truncation, with the erosional surface downlapped by the distal hangingwall strata of the next growth fault that developed in a more landward location (Fig. 10).

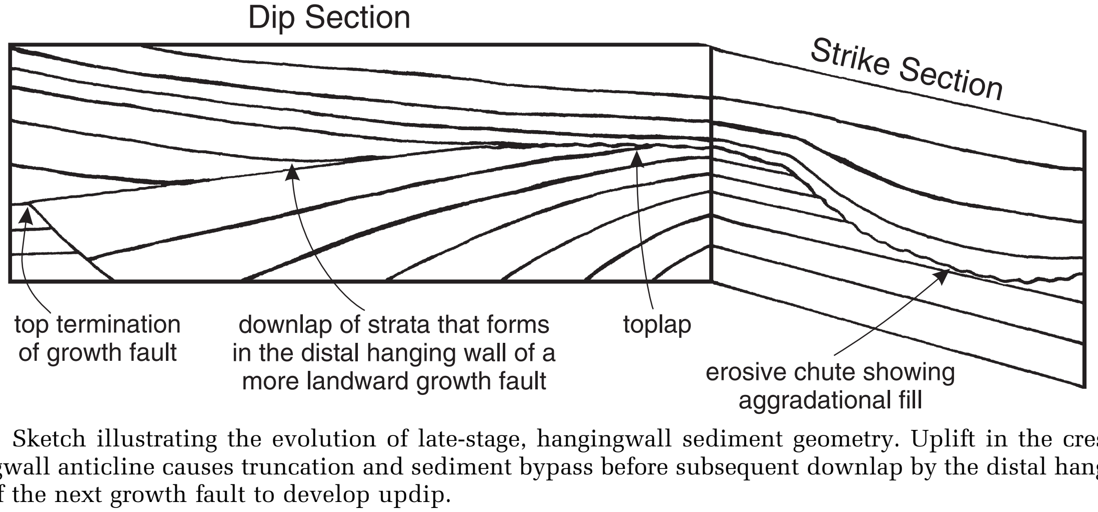


Fig. 10. Sketch illustrating the evolution of late-stage, hangingwall sediment geometry. Uplift in the crest of the hangingwall anticline causes truncation and sediment bypass before subsequent downlap by the distal hangingwall strata of the next growth fault to develop updip.

CONCLUSIONS

In relation to the questions posed at the beginning of the paper, the County Clare sections provide the following answers:

1 The growth-fault system initiated with the onset of sandstone deposition on a succession of siltstones that overlay a thin, marine shale. The slip horizon developed at the shale/siltstone contact for eight of the first nine faults, by which time aggradation in the hangingwall exceeded 60 m in thickness. After this time, failure planes developed at higher stratigraphic levels and were associated with smaller scale faults.

2 The faults sequentially show a progressive landward retrogressive movement.

3 In this large growth-fault system, fault reactivation was not important and, for most of the sequence, only one major fault was active at any one time.

4 As far as can be determined, unrestricted downslope movement accommodated growth faulting, as no compressional features are present at the base of the growth faults.

5 and 6 Thin-bedded sandstones of distal mouth bar facies dominate the hangingwall stratigraphy. In the latter stages of fault movement, erosion of the crests of rollover structures resulted in the highest preserved hangingwall strata occurring only in close proximity to the fault. Erosion surfaces show chutes cut parallel to flow that are downlapped by the distal hangingwall strata of younger growth faults.

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