Article:
Wignall, P.B. and Best, J.L. (2000) The Western Irish Namurian Basin reassessed. Basin Research, 12 (1). pp. 59-78. ISSN 0950-091X

Basin Research (2000) **12,** 59–78

The Western Irish Namurian Basin reassessed

P. B. Wignall and J. L. Best

School of Earth Sciences, University of Leeds, Leeds LS2 9JT, UK (p.wignall@earth.leeds.ac.uk; j.best@earth.leeds.ac.uk)

ABSTRACT

Current basin models for the Western Irish Namurian Basin (WINB) envisage an elongate trough along the line of the present-day Shannon Estuary that was infilled with clastic sediments derived from a hinterland that lay to the W or NW. This paper argues for an alternative basin configuration with source areas to the SW supplying sediment to a basin where deepest water conditions were in northern County Clare. Rapid subsidence along the present-day Shannon Estuary ponded sediment in this area throughout the early Namurian and, only with the rapid increase of sedimentation rates within the mid-Namurian (Kinderscoutian Stage), were substantial amounts of sediment able to prograde to the NE of the basin. This alternative model better explains the overwhelming predominance of NE-directed palaeocurrents in the Namurian infill, but requires fundamental revisions to most aspects of current depositional models.

Deep-water black shales (Clare Shale Formation) initially accumulated throughout the region and were progressively downlapped by an unconfined turbidite system (Ross Formation) prograding to the NE. This in turn was succeeded by an unstable, siltstone-dominated slope system (Gull Island Formation) characterized by large-scale soft-sediment deformation, which also prograded to the NE. In the northern-most basin outcrops, in northern County Clare, this early phase of basin infill was developed as a condensed succession of radiolarian-rich black shales, minor turbiditic sandstones and undisturbed siltstones. The new basin model envisages the northern exposures of County Clare to be a distal, basin floor succession whereas the traditional model considers it a relatively shallow, winnowed, basin margin succession. Later stages of basin infill consist of a series of deltaic cycles that culminate in major, erosive-based sandstone bodies (e.g. Tullig Sandstone) interpreted either as axial, deltaic feeder channels or incised valley fills genetically unrelated to the underlying deltaic facies. Within the context of the new basin model the former alternative is most likely and estimated channel depths within the Tullig Sandstone indicate that the basal erosive surface could have been generated by intrinsic fluvial scour without recourse to base-level fall. The northerly flowing Tullig channels pass down-dip into isolated channel sandbodies interbedded with wave-dominated strata that suggest the deltas of the WINB were considerably more wave-influenced than hitherto proposed. The retreat of the Tullig delta during sea-level rise saw the rapid southerly retrogradation of parasequences, as may be expected if the basin margin lay to the SW of the present-day outcrops.

INTRODUCTION

The Namurian outcrops of County Clare form part of a large outlier surrounded by Lower Carboniferous limestones (Fig. 1). They record the history of infill of the Western Irish Namurian Basin (WINB), one of a series of interlinked basins that stretched from the southern North Sea to Nova Scotia during the Late Carboniferous (Maynard *et al.*, 1997; Calder, 1998). Owing to the extensive coastal sections in County Clare, the WINB is one of the best known of these Late Carboniferous basins (Rider, 1978; Gill, 1979; Martinsen, 1989; Martinsen & Bakken, 1990; Collinson *et al.*, 1991) and the region has recently become one of the principal testing grounds in Europe for the concepts of sequence stratigraphy (Davies & Elliot, 1996; Hampson *et al.*, 1997).

Like many other Carboniferous basins in NW Europe, the Namurian clastics of the WINB rest on Visean

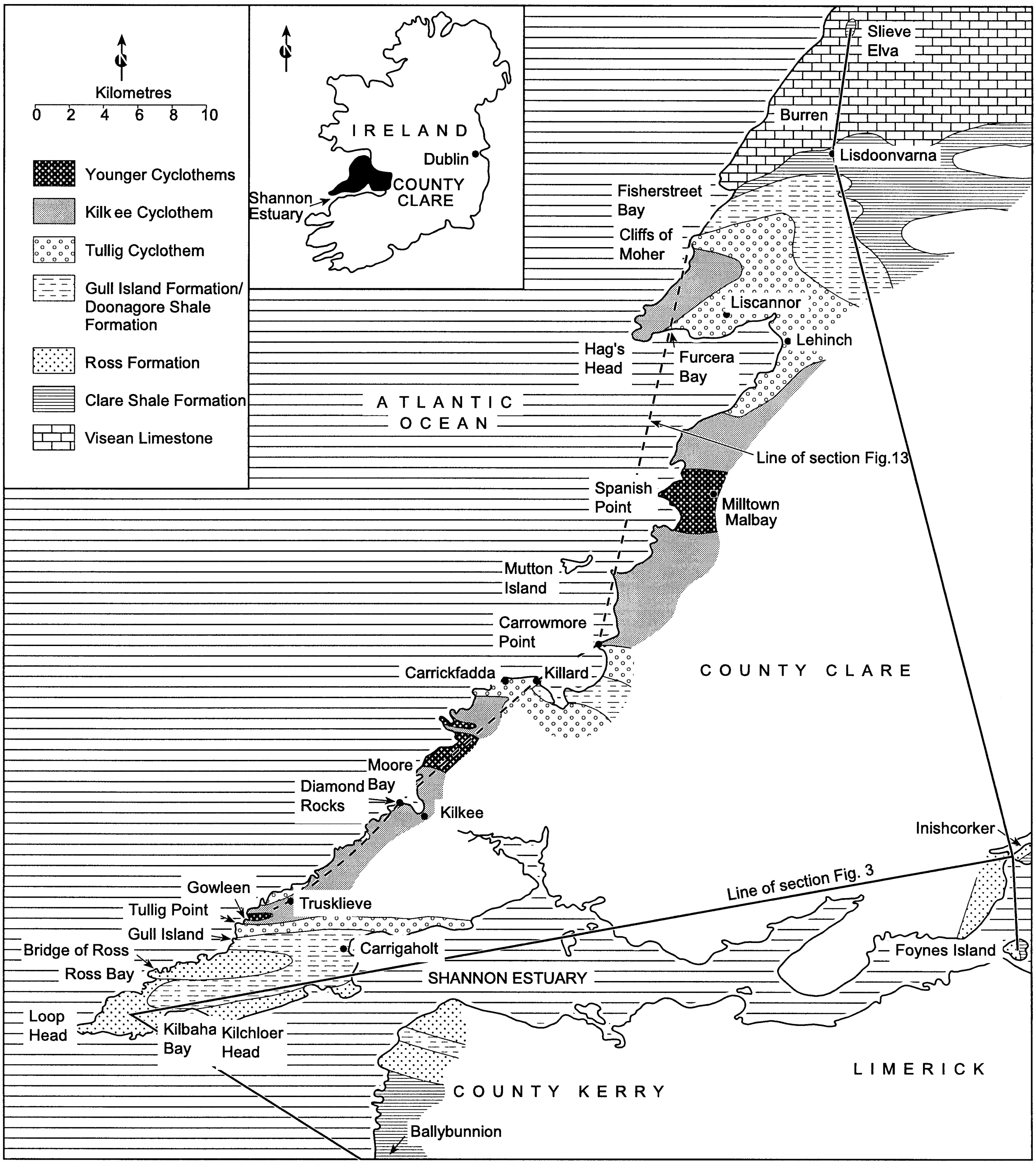

Fig. 1. Simplified geological map of western Ireland showing the principal field locations discussed in the text.

carbonates. Lateral facies changes in the uppermost Visean sediments indicate that a southerly dipping ramp was present in County Clare with the deepest water conditions occurring in the Shannon Trough, an ENE–WSW-orientated depositional axis centred on the present-day Shannon estuary (Strogen, 1988; Strogen *et al.*, 1996). Thus, the northern-most upper Visean outcrops in northern County Clare consist of bioclastic packstones (Gallagher, 1996), whereas to the south the carbonates become shalier and pass into basinal facies around Ballybunnion in County Kerry (Sevastopulo, 1981a; Fig. 1). Thickness trends in the overlying succession show that the Shannon Estuary axis was marked by the highest sediment accumulation rates in the Namurian (Hodson & Lewarne, 1961), and it has therefore been assumed that the rapidly subsiding, deep-water Shannon Trough was maintained at this time (Hodson & Lewarne, 1961; Sevastopulo, 1981b; Strogen, 1988; Collinson *et al.*, 1991). The current model for evolution of the WINB invokes a rapidly subsiding, deep-water Shannon Trough infilled by clastics derived from a hinterland to the W (Sevastopulo, 1981b; Strogen, 1988; Collinson *et al.*, 1991a). Thus, the line of the Shannon Estuary is considered to have been subsiding rapidly and continuously throughout the interval from the Courceyan Stage (Tournasian Series) to the late Namurian (Strogen, 1988).

Whilst the evidence for an Early Carboniferous Shannon Trough is convincing, the present paper proposes that, as a consequence of a prolonged interval of nondeposition on the northern margin of the basin, relatively deep-water conditions were established in this area. The subsequent progradation of a major clastic system was therefore towards the NE and this unrealized accommodation space was gradually infilled, although much sediment was trapped in the south of the basin due to the probable effects of high subsidence rates. Depositional models and sequence stratigraphic interpretations for the Namurian of County Clare thus require substantial modification. Before presenting this reasoning, it is instructive to review the history of study and development of ideas concerning the WINB.

HISTORY OF RESEARCH

The pioneering work of Hodson on the Namurian outcrops of northern County Clare (Hodson, 1954a), Foynes Island, County Kerry (Hodson, 1954b), and subsequently all the Namurian outcrops of County Clare (Hodson & Lewarne, 1961) established both the current lithostratigraphic nomenclature of the region and a detailed goniatite biostratigraphy (Fig. 2). Many of the standard European goniatite zones of the lower Namurian are encountered in the Clare Shale Formation of the Shannon Estuary and, although poorly exposed, the transition with the underlying Visean carbonates is considered to be conformable (Hodson, 1954b). In contrast, the Clare Shale rests sharply on Visean limestones in northern County Clare and no goniatites older than the Chokierian Stage are known from this area (Hodson, 1954a; Fig. 2). A 6-cm-thick bed of phosphate separates the Clare Shale from the limestones (here named the St. Brendan's Well Phosphate Bed, after a stream section 2 km east of Lisdoonvarna) and Hodson (1954a) speculated that much of the Arnsbergian and possibly the Pendleian Stage may be recorded in this highly condensed bed. From the Alportian Stage upwards, the goniatite fauna is generally restricted to thin black shales (known as marine bands) intercalated with sandstones and siltstones of the later stages of the basin fill. Although several of the marine bands of the standard goniatite zonation scheme are absent in the younger Namurian of western Ireland, sufficient bands are present to enable detailed correlation between outcrops (Fig. 2).

The most striking pattern to emerge from Hodson's studies was the dramatic southward-thickening of the Namurian succession in County Clare (Fig. 3). This is particularly apparent for the Arnsbergian strata, which attain 125 m thickness on Inishcorker (Fig. 1) whilst it is probably represented by only a few centimetres in the St. Brendan's Well Phosphate Bed. Hodson & Lewarne (1961, p. 307) therefore proposed 'that a mid-Carboniferous [i.e. Namurian] trough of sedimentation exists in County Clare and County Limerick [developed on the pre-existing Visean trough], with its axis roughly along the line of the present-day Shannon estuary.' The Clare Shale was envisaged to onlap the northern margin of this trough with the contact between the Visean limestones and phosphate bed marking a major mid-Carboniferous hiatus.

Much detailed sedimentary analysis has been undertaken in the WINB since the work of Hodson, but his model has been adopted essentially unchanged in all subsequent studies. Sevastopulo (1981b) suggested that the WINB passed eastwards into the East Leinster Basin and was flanked to the north by the Galway High and to the south-east by the Leinster High (Fig. 4). Clearly the adoption of any basin model imparts a fundamental, conceptual shibboleth on sedimentary analysis and facies interpretations, and all current facies models are intrinsically linked to Hodson's model.

In southern County Clare, the Clare Shale is overlain by the Ross Formation, a unit generally interpreted to be of turbiditic origin (Rider, 1974; Collinson *et al.*, 1991; Chapin *et al.*, 1994). Rider (1974, p. 139) reasoned that 'in order to accommodate the thick turbidite sandstone accumulation, the southern part of the area [around the Shannon Estuary] was ... originally deeper than the northern part of the area' and that the turbidites therefore flowed along a 'subsea hollow canyon'. Collinson *et al.* (1991) similarly envisaged the Ross Formation turbidite system to be laterally constrained and prograding east-north-eastwards along the axis of a narrow basin (Fig. 4), although they note palaeocurrents flowed to the NW in the lower part of the formation and to the NE in the upper part (Collinson *et al.*, 1991). The overlying Gull Island Formation also contains packages of turbiditic sandstones, but it is mostly composed of siltstones that display a spectacular range of soft sediment deformation features, including slumps, slides and growth faults (Gill, 1979; Martinsen, 1989; Martinsen & Bakken, 1990). Palaeocurrents in the lower Gull Island Formation maintain the north-eastward trend of the Ross Formation, but in the upper part of the formation Collinson *et al.* (1991) record a swing to the SE. The numerous slump horizons in the upper part of the Gull Island Formation are also interpreted to record downslope movement to the SE (Collinson *et al.*, 1991, fig. 10). Thus, the style of infill is interpreted to have changed from along-axis basin centre aggradation to oblique SE-directed progradation in the mid Gull Island Formation (Collinson *et al.*, 1991).

In the mid-Kinderscoutian (R1b), the slope-style sedimentation of the Gull Island Formation was replaced by a repetitive succession of cyclothems, beginning with the Tullig Cyclothem. Each cycle records the progradation of a deltaic system that commonly culminates in a distributary channel sandstone (e.g. the Tullig and Kilkee

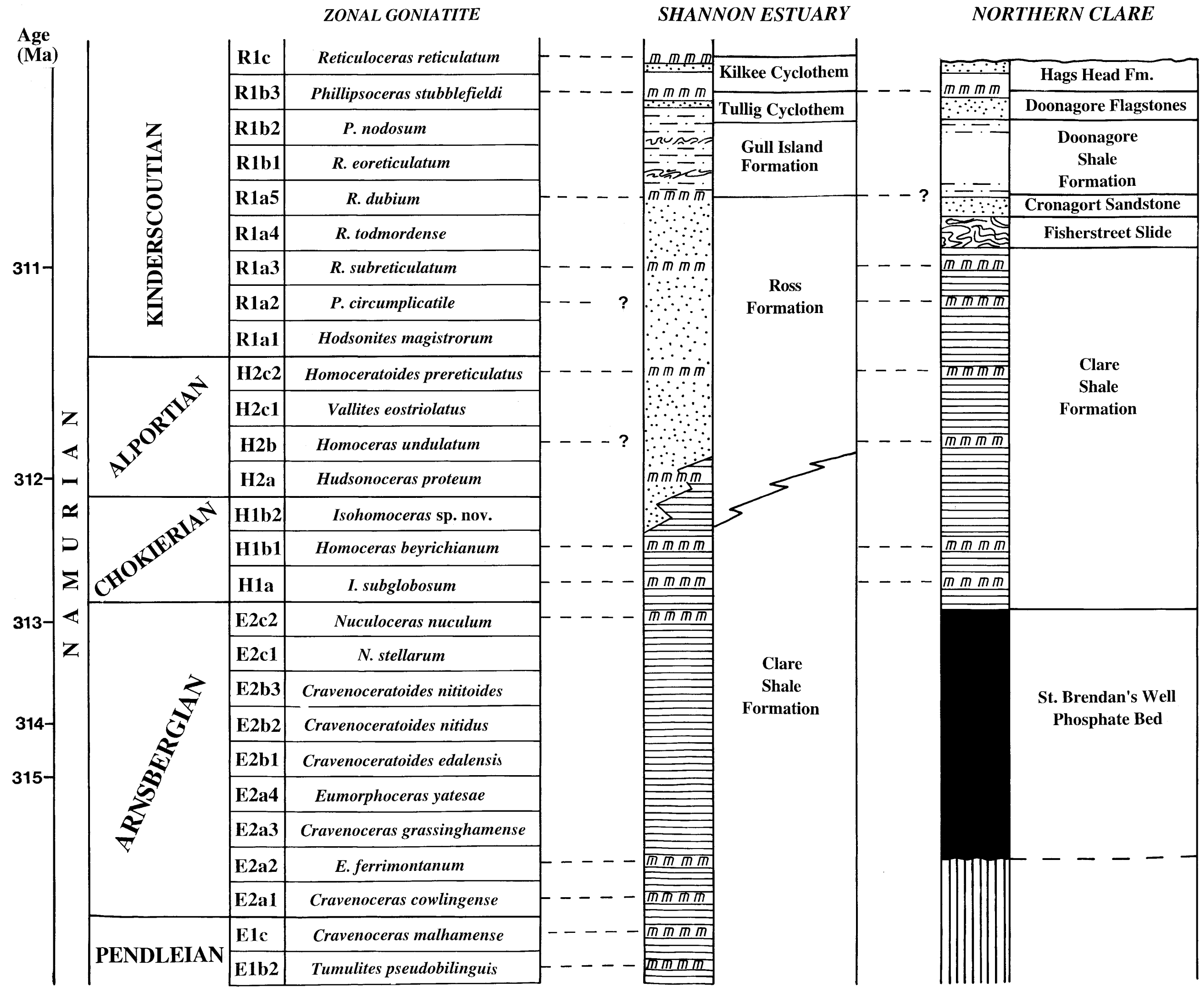

Fig. 2. Summary and comparison of the lithostratigraphy and biostratigraphy of the Namurian outcrops of northern County Clare and along the northern shores of the Shannon Estuary (after Hodson, 1954a,b; Hodson & Lewarne, 1961).

Sandstones), followed by transgression and development of marine strata (Rider, 1974; Pulham, 1989). Collinson *et al.* (1991) considered that the same SE-directed progradation persisted in the Tullig Cyclothem, the lowest of the deltaic deposits and noted (p. 236), 'Palaeocurrent directions from the main prograding sequence and from the channel sandstones suggest flows directly to the south-east.' This assertion is contradicted by all published palaeocurrent data (e.g. Rider, 1974; Pulham, 1989), which indicated predominantly northwards-directed flow. However, Pulham (1989, p. 194) postulated that, during Tullig Sandstone deposition, 'channels from the N of the basin flow[ed] towards the NE'. He resolved this apparently contradictory situation by considering the Tullig Sandstone to be a distributary of a larger birdsfoot-type delta with the distributary channels present in County Clare representing those at a high angle to the main feeder channels (e.g. figures 6 & 19 in Pulham, 1989).

The interpretation of the Tullig and younger sandstones has been revised in the light of recent sequence stratigraphic studies (Davies & Elliot, 1996; Hampson *et al.*, 1997), which suggest that the sandbodies are purely fluvial facies contained within an incised valley cut during a preceding phase of regression. The Tullig Sandstone is not present in northern County Clare, although minor, single-storey channel sandbodies do occur within the Tullig Cyclothem at Liscannor (Pulham, 1989). Rider (1969) attributed this northward transition to the subdivision of a major channel system into smaller channels, whereas in the sequence stratigraphic reinterpretation the minor channels may not be contemporaneous with the Tullig Sandstone, and the area is considered to record an interfluve setting.

In summary, the current interpretation of the development of the WINB provides a coherent story of an elongate basin that was filled by clastic sediments supplied from a hinterland to the W or NW. The SW–NE-trending coastline of County Clare is therefore considered to provide a section oblique to depositional strike, with the substantially thinner northern sections recording deposition on the basin margin. However, the present paper will argue that this view of the WINB fails to explain many aspects of the facies development and does

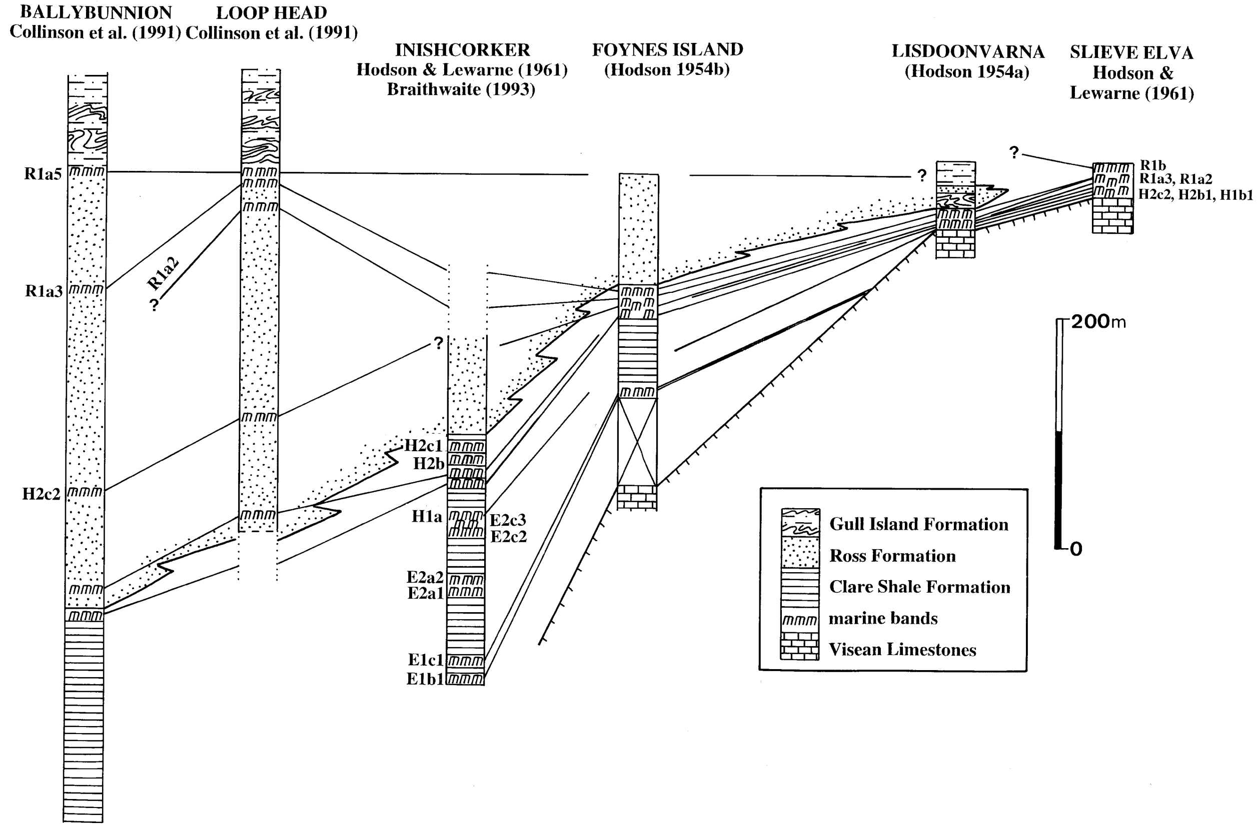

Fig. 3. Correlation of some of the principal lower Namurian outcrops in County Kerry and County Clare (based on various sources) illustrating the thinner succession in northern County Clare relative to outcrops around the Shannon Estuary. Note also the diachronous base of the Ross Formation.

not account for the majority of the flow vectors that are predominantly to the N and NE and not to the ENE to SE as required in the existing model. An alternative view of the basin history is presented below.

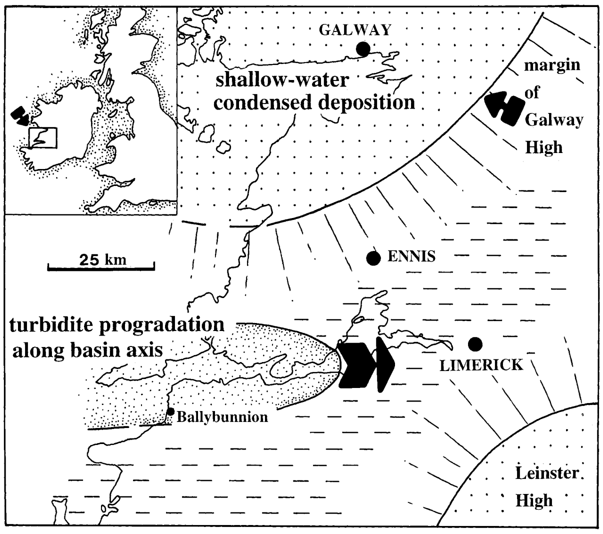

Fig. 4. Early Namurian palaeogeography of western Ireland (from Sevastopulo, 1981b) showing the proposed eastward progradation direction of the Ross Formation turbidites along the axis of the Shannon Estuary (cf. Collinson *et al.*, 1991).

A RE-EVALUATION

In the following section, evidence from sedimentary facies and palaeocurrents is used to critically evaluate Hodson's model for the WINB.

Clare Shale Formation

Both the basal and the top contacts of the Clare Shale are highly diachronous. At Ballybunnion in County Kerry, the base is approximately basal Pendleian in age and the top is of mid-Chokerian age (H1b1), whereas in northern County Clare the base is of lower Chokerian age (H1a) and the top of mid-Kinderscoutian age (Fig. 2). Much of the development of the Clare Shales in the north of the basin is therefore laterally equivalent to the turbiditic sandstones of the Ross Formation in the south (Fig. 3). The St. Brendan's Well Phosphate Bed occurs at the base of the formation in northerly outcrops, and several thinner phosphatic pebble beds occur in the overlying few metres of the Clare Shale (O'Brien, 1953; Hodson & Lewarne, 1961). Thin-section analysis reveals the presence of rounded phosphatic clasts up to a few centimetres in diameter. Clast types are highly variable and include oncoid-like morphologies and phosphatized limestone pebbles in which vestiges of original bioclasts are preserved (Fig. 5a). The fossil content includes

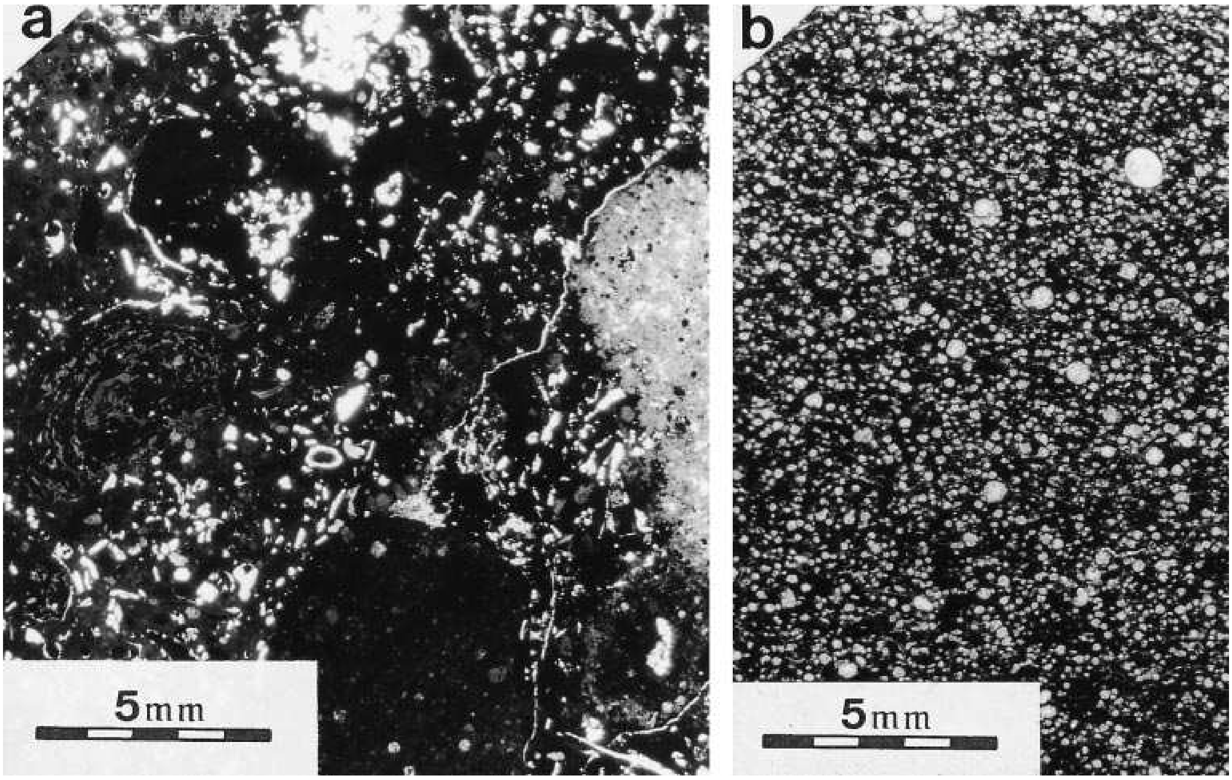

Fig. 5. (a) Photomicrograph of the St. Brendan's Well Phosphate Bed from the type locality near Lisdoonvarna. A phosphatic oncoid occurs left of centre and a pale, phosphatic concretion occurs at the right-hand edge. The groundmass consists of apatite pellets, apatite microspar and abundant pyrite crystals. (b) Photomicrograph of an organic-rich radiolarite from the R1a3 marine band at Fisherstreet Bay. This sample is from the core of a concretion which displays an uncompacted fabric: abundant spheres of radiolaria are infilled and replaced with calcite.

common fish teeth and bones, conodonts and rare goniatites and crinoids. At some locations, the top surface of the St. Brendan's Well Phosphate Bed is characterized by burrows of *Rhizocorallium* and *Diplocraterion*.

Across its outcrop, the Clare Shale consists of alternations of dark grey shales interbedded with thinner horizons of laminated, organic-rich shales, commonly with large carbonate concretions (Braithwaite, 1993). Other than the very fine laminations, no sedimentary structures indicating tractional currents (such as winnowing and concentration of bioclasts) are found. In the condensed northerly outcrops, the organic-rich shales are more fossiliferous and often contain abundant radiolaria (Fig. 5b). The macrofauna consists of goniatites and an impoverished fauna of benthic bivalves (*Caneyella, Posidoniella, Dunbarella*) and rare gastropods and crinoids. The pyrite content of the sediments is high as is the degree of iron pyritization (Braithwaite, 1995).

Clearly the Clare Shale records tranquil, anoxic to dysoxic deposition over the entire WINB during the early Namurian. The thin northern development has been interpreted as a record of condensed, shallower-water deposition on a basin margin that was 'sufficiently elevated to have been starved of ... sand' and where 'slight agitation may have been able to keep fines in suspension and prevent significant deposition' (Collinson *et al.*, 1991, pp. 236–7). However, there is no sedimentary evidence for such agitation and the radiolarian-rich horizons are more typical of deep-water, sediment-starved locations (e.g. Holdsworth, 1966). The condensation of the northern Clare Shale sections therefore more likely reflects sedimentation in a distal, sediment-starved location rather than winnowing on a basin margin. In sequence stratigraphic terms, the Clare Shale condensation is probably a product of unrealized accommodation space rather than a lack of accommodation space. The fact that the northern Clare Shale is stratigraphically the most complete in the region (for example, the H2b and R1a2 marine bands are only found in the northern outcrops) further suggests that this is a deep-water condensed section rather than a shallow-water winnowed section.

The significance of the phosphatic levels at the base of the Clare Shale is enigmatic. The faunal and trace fossil content, together with the evidence for rounding and abrasion of the phosphatic clasts, suggests that they accumulated in considerably shallower and better oxygenated waters than the remainder of the Clare Shale. Phosphate deposition coincides with a major change of depositional style and possibly a phase of basin reorganization whose significance is discussed further below.

Ross Formation

The thickest development ($\sim$400 m) of the Ross

Formation and its best exposures occur in north-eastern County Kerry and south-western County Clare (Fig. 3), particularly around the Loop Head Peninsula where a range of turbiditic facies are well exposed (Collinson *et al.*, 1991; Chapin *et al.*, 1994). Sheet-like sandstones, ranging from a few centimetres to several metres in thickness, interbedded with thin silty mudstones and shales, are the principal facies. Incised, lenticular, channellized sandbodies up to 10 m thick also occur, and have been interpreted as feeder channels from a mid-fan location (Chapin *et al.*, 1994; their fig. 14). One such accessible channel is seen above the Ross Slide at the Bridge of Ross (Fig. 6) and shows an erosive relief of 1 m. The infill of this channel consists of trough cross-bedded sandstones showing some dewatering, mud-clast conglomerates and debris flows together with well rippled sandstones with occasional dune-scale cross-stratification. Palaeocurrents from these channel sandstones show mean flow to the NE (Fig. 7). Published palaeocurrent data from sole marks and ripples in the Ross Formation also indicate a predominantly north-easterly flow direction that occasionally veered to the E and NW (Rider, 1974; Collinson *et al.*, 1991; Chapin *et al.*, 1994). Megaflute scours, ranging from several metres to 20 m in width and up to 3.5 m deep (Collinson *et al.*, 1991; Chapin *et al.*, 1994; Elliott, 2000), are also present at several levels and again record flow to the NE.

Previous workers have assumed that the Ross Formation is restricted to the area around Loop Head and that the topmost few metres of the Clare Shale in northern County Clare represent time-equivalent strata (Rider, 1974; Gill, 1979; Collinson *et al.*, 1991). However, there is no biostratigraphic support for this assumption and it is noteworthy that the Clare Shale sections throughout County Clare are overlain by a thin succession of turbiditic sandstones (Hodson & Lewarne, 1961), typical of the Ross Formation facies. In the southern outcrops, the *Reticuloceras dubium* Marine Band (R1a5) marks the top of the Ross Formation and the *R. paucicrenulatum* Marine Band (R1a3) occurs some distance beneath it (Collinson *et al.*, 1991; Fig. 3). However, at Fisherstreet Bay in northern Clare the highest marine band in the Clare Shale is the R1a3 horizon (Hodson & Lewarne, 1961), and this is directly overlain by the Fisherstreet Slide (cf. Gill, 1979) and the Cronagort Sandstone. Above this level a marked grain size reduction to siltstone marks the base of the Doonagore Shale Formation (Figs 2 and 3). A similar fining-up occurs in southern County Clare at the top of the Ross Formation, where it marks the start of the siltstone-dominated Gull Island Formation. Therefore, on lithostratigraphic grounds the uppermost Ross Formation in southern County Clare may be equated with the Fisherstreet Slide and Cronagort Sandstones in the north (Fig. 2). Biostratigraphic proof of this correlation would be obtained if the R1a5 marine band was found in the base of the Doonagore Shale, but unfortunately the only outcrop of this level occurs in the inaccessible cliff sections to the south of Fisherstreet Bay.

The uppermost 100 m of the Ross Formation is marked by the presence of several slump horizons, of which the 6 m-thick Ross Slide (which should more correctly be termed a slump), exposed in a kilometre-length outcrop at the Bridge of Ross, is the most extensive. Internal deformation is highly variable and ranges from tightly folded siltstones to coherent glide blocks of sandstone. Gill (1979) interpreted a south-eastwards movement direction for this horizon whereas Collinson *et al.* (1991) suggested displacement to the NE. Slickensides on the sole of the Ross Slide are orientated SW–NE, which, together with some imbricate thrusts and overturning of beds, are in accord with movement to the NE (Fig. 7). A similar dichotomy exists in the interpretation of movement direction for the Fisherstreet Slide, a major slump developed around the same stratigraphic level as the Ross

Fig. 6. Photograph of erosive margin (arrowed) of a turbidite channel overlying the Ross Slide at the Bridge of Ross (cf. Fig. 1). The main cliff face is 5 m high and approximately 1 m of erosive relief is seen; flow is out of the outcrop (mean flow = 056°).

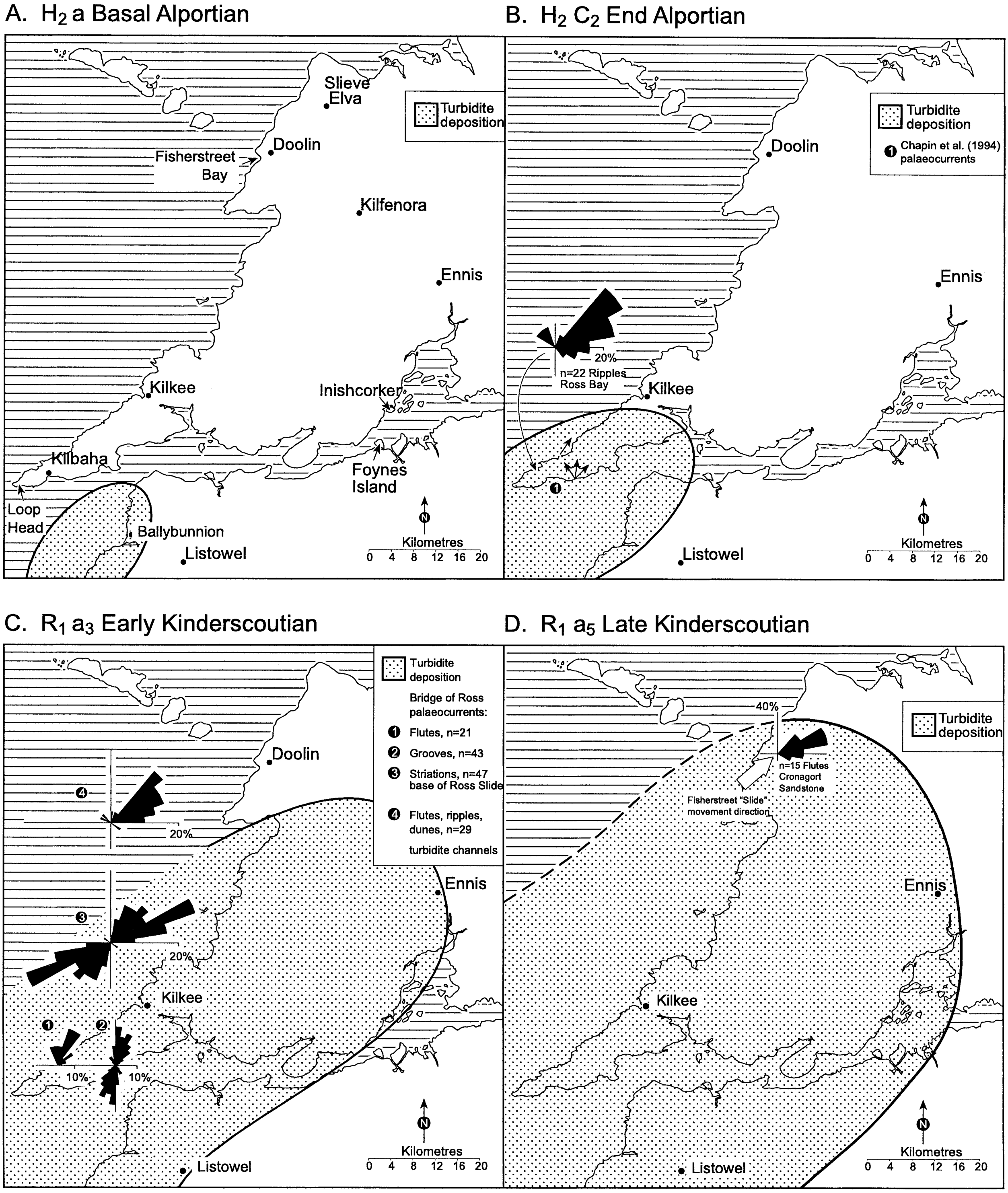

Fig. 7. Evolving palaeogeography of the WINB from earliest Alportian to mid Kinderscoutian times showing north-eastwards progradation of Ross Formation turbidites. Palaeocurrent vectors from the turbidites and interpreted movement directions of slumps consistently indicate a downslope direction to the north-east.

Slide, on the southern side of Fisherstreet Bay in northern County Clare. Gill (1979) noted that kinematic indicators (fold axis overturning, displacement along thrusts) indicate movement predominantly to the NE, but he interpreted these structures to have formed on the northern flanks of a major slump that moved south-eastwards. It is noteworthy that both flutes and current ripples present in the overlying Cronagort Sandstones also record flow to the NE (Fig. 7).

A consensus exists in the literature that the Ross Formation, and its lateral equivalents in northern Clare, records the initial stage of infill of the WINB by a turbidite system. However, the configuration of the basin at this time is debatable. Having adopted Hodson's model for basin configuration, subsequent authors have favoured deposition in a laterally confined, narrow trough coincident with the line of the present-day Shannon Estuary which runs E–W (Gill, 1979; Sevastopulo, 1981b; Martinsen, 1989; Collinson *et al.*, 1991; Fig. 4). However, as noted above, most palaeocurrent indices for turbidites and turbidite feeder channels (Fig. 6) indicate flow to the NE, including those on the supposed northern margin of the basin. Equally puzzling is that the turbidites from the lowest part of the Ross Formation at Loop Head record flow to the NW (Collinson *et al.*, 1991, p. 234; Chapin *et al.*, 1994, fig. 5B), a direction that is difficult to reconcile with a turbidite system prograding to the E along a narrow trough. This contradiction is revealed in Collinson *et al.*'s (1991, p. 236) observation that the deep basin axis was

> 'elongated ENE–WSW [strictly speaking this should be E–W] along the Shannon Estuary as previously suggested by Hodson & Lewarne (1961). The northern outcrops then record deposition on a shallower, north-western margin of the basin, sufficiently elevated to have been starved of a gravity-controlled supply of sand from the south-west.'

As Collinson *et al.* (1991) amply documented, outcrops of the Ross Formation in SW County Clare predominantly record NE-flowing palaeocurrents. Thus, flow direction was towards the supposedly marginal northern outcrops in northern County Clare and not along the Shannon Estuary. Consideration of the spatiotemporal evolution of the early Namurian turbidite system offers an alternative depositional model (Fig. 7).

The turbidite sandstones overlying the Clare Shales have an extensive, but poorly exposed, inland outcrop (Hodson & Lewarne, 1961; Hodson, 1978). Turbidites were initially restricted to the Ballybunnion area (Fig. 7A), but then rapidly prograded into south-western County Clare by the end of the Alportian (Fig. 7B). Significantly, subsequent progradation was *not* along the axis of the Shannon Estuary as claimed previously (e.g. Collinson *et al.*, 1991, p. 236) but was to the NE in the direction of Ennis (Fig. 7C). Thus, turbidites are first developed around Ennis in the R1a3 Zone whilst Clare Shale deposition persisted at this time at Foynes Island in the upper Shannon Estuary (Figs 3 and 7C). Turbidite deposition reached its maximal extent in the mid-Kinderscoutian, with the Cronagort Sandstone section at Fisherstreet Bay representing its most northerly development (Fig. 7D). No turbidites are developed to the north of Fisherstreet, and the outlier at Slieve Elva shows condensed black shale deposition of the Clare Shale persisting to the top of the section which is of R1b age (Hodson & Lewarne, 1961).

The palaeogeographical development of the Ross Formation thus indicates that a north-easterly prograding turbidite system downlapped onto condensed black shales of the northern County Clare outcrop. At its peak extent (Fig. 7D), turbidite deposition covered most of County Clare whilst deep-water anoxic facies persisted in the northern-most part of the basin. The W to E component of progradation was slow: turbidites are first developed at Ballybunnion immediately above the H1b1 Zone, but they do not appear at Listowel, 14 km to the east, until R1a times (Hodson, 1978). In the same interval the Ross Formation prograded over 50 km to the NE (Fig. 7). It can therefore be concluded that the Ross Formation is elongated along a NE–SW axis that is at a high angle to the trend of the Shannon Estuary. Obviously, the presence of a north-easterly prograding turbidite system also accords with the predominance of the north-easterly flow vectors in the Ross Formation.

Gull Island Formation

In southern County Clare, the Ross Formation is overlain by 550 m of siltstones and sandstones of the Gull Island Formation. The sandstones are laterally persistent sheets, generally less than 1 m thick, that often display both fluted bases and current rippled tops. They occur in packages up to 15 m thick and form between 25 and 50% of the thickness of the Gull Island Formation. Both sandstones and siltstones in the Gull Island Formation have been deformed at numerous levels, and locally up to 75% of the formation has been affected by such soft-sediment deformation (Rider, 1978; Gill, 1979; Martinsen, 1989; Martinsen & Bakken, 1990). In northern County Clare, the Gull Island Formation is equivalent to the Doonagore Shale Formation, a unit that can be viewed, but not accessed, in the cliff sections between Fisherstreet Bay and the Cliffs of Moher (Fig. 8). The formation appears to be composed of approximately 100 m of undisturbed siltstones with a single, 7- to 8-m-thick, lenticular sandstone body developed near the middle of the formation, of similar geometry to the feeder channels seen in the Ross Formation at the Bridge of Ross and near Kilbaha (cf. Chapin *et al.*, 1994).

Reported transport directions of the turbidites and slumps in the Gull Island Formation are generally regarded to have been ESE to SE (Gill, 1979; Collinson *et al.*, 1991), although it has been suggested that there was a systematic upward change of turbidite flow directions from NE to SE (Collinson *et al.*, 1991, p. 235, fig. 10). This proposal has been tested at White Strand, near Killard, where the upper half of the Gull Island Formation is exposed in an accessible foreshore outcrop. The typical range of facies is developed here, with packages of turbiditic sandstones being interbedded with undisturbed siltstones (Fig. 9). Palaeocurrents measured from linguoid ripples on the top surfaces of the sandstones show a consistent north-easterly flow direction (Fig. 9). Significantly, flow vectors to the S and SE are also recorded at White Strand, but these are confined to thin sandstones located immediately above two major slumps in the lower part of the section. These deviations in palaeocurrent trends may be expected if slump emplacement created sufficient seafloor topography to

Fig. 8. Photograph of cliff section to the north of O'Brien's tower, Cliffs of Moher, showing the presence of a turbidite channel within the Doonagore Shale Formation near the base of the cliff. The upper half of the cliff consists of the Tullig Cyclothem with shales of the Kilkee Cyclothem forming the topmost few metres. The cliff is approximately 180 m high.

deflect or reflect smaller turbidity currents. Therefore, the evidence from White Strand suggests flow to the NE, with the topography associated with slump and slide movement perhaps responsible for local variability of flow directions.

As with the slumps in the top of the Ross Formation, the movement direction of the Gull Island slumps is also contentious. Gill (1979) and Collinson *et al.* (1991, p. 235) stated that movement was towards the ESE–SE, although their figures also show displacement to the NE. Evidence from growth faults in the upper Gull Island Formation also clearly suggests a predominance of more northerly dipping slopes. For instance, the beautifully exposed growth fault at the Point of Relief (Martinsen & Bakken, 1990) downthrows to the W–NW.

The currently prevailing depositional model for the Gull Island Formation envisages the south-easterly progradation of a slope, with higher subsidence and sedimentation rates in southern County Clare generating instability and slope failure (Martinsen, 1989; Collinson *et al.*, 1991, fig. 11C). The striking lack of soft sediment deformation in the Doonagore Shale is attributed to the much lower sedimentation rates on the northern margin of the basin with the result that the slope in this region showed no signs of instability (Collinson *et al.*, 1991, p. 236). Clearly the abundant evidence for slumping in southern County Clare makes this slope model an attractive one, but the downslope direction, to the SE, appears unlikely given the dominance of north-easterly flowing turbidity currents. This latter evidence rather suggests that the slope prograded and dipped to the NE (Fig. 10) and evidence for movement direction within the slumps would clearly merit further study. In the reinterpretation of the basin model in the current synthesis, the lack of slumping within the Doonagore Shale of northern County Clare may be simply attributable to its deposition in a basin floor location.

Tullig Cyclothem

As noted above, the upward transition from the slope facies of the Gull Island Formation into the Tullig Cyclothem marks the onset of a repetitive succession of prograding deltaic cycles. The base of this transition is gradational and often arbitrarily drawn at the top of the last major deformation horizon in the Gull Island Formation (Pulham, 1989; Collinson *et al.*, 1991), although major growth faults continue to occur in the lower part of the Tullig Cyclothem (Pulham, 1989). As with the underlying Gull Island Formation, these record downslope failure in a range of generally northerly directions, including examples down-faulting to the NW (Fig. 11). The lowest part of the cyclothem records a gradual coarsening-upward succession from silty mudstone to thinly bedded oscillatory and current rippled sandstones which are locally capped by lenticular sandstone bodies displaying trough cross-bedding. This is the first of several small-scale, coarsening-up cycles (parasequences) identified by Rider (1974) and Pulham (1989), who interpreted them as the record of progradation by deltaic distributaries. The abundance of wave ripples in the upper parts of the parasequences records a diversity of oscillation directions including NW–SE, W–E and NE–SW (Rider, 1969; Pulham, 1989). The principal wave oscillation is from NW to SE, which Pulham (1989) interpreted to indicate wave approach primarily from the SE, although it could equally well be from the NW.

The Tullig parasequences are erosively overlain by a major sandstone body, the Tullig Sandstone, interpreted to be either a major fluviodeltaic distributary (Rider, 1978; Pulham, 1989) or truly fluvial facies within an incised valley (Hampson *et al.*, 1997). Unlike the minor sandstones capping the parasequences, the Tullig Sandstone rests on a marked erosion surface (Fig. 12a), and internally comprises up to six individual storeys that are up to 10 m thick (Pulham, 1989; Williams & Soek, 1993). The base of each channel storey is often erosional and characterized by abundant intraformational mudclasts and wood debris. Thin shales in the lower channel storeys at Trusklieve yield the conchostracan *Hemicyclo-*

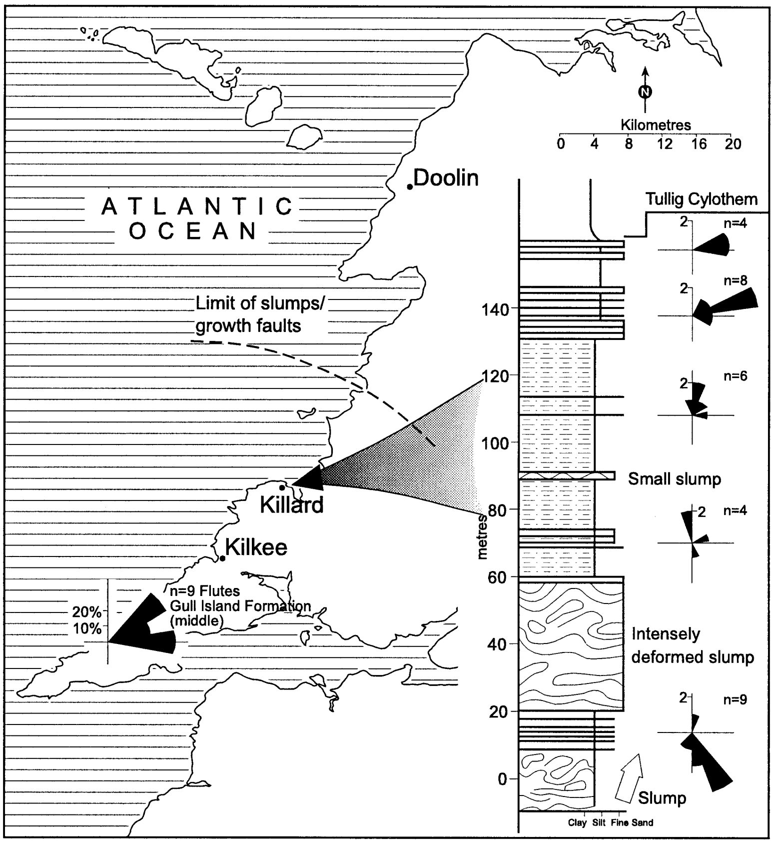

Fig. 9. Palaeogeographical summary of the limit of soft-sediment deformation in the Gull Island Formation together with a sedimentary log and palaeocurrents (mostly derived from linguoid ripples capping thin turbidites) from the upper part of the Gull Island Formation near White Strand, Killard.

leaia, supporting the freshwater origin of these sediments. These sandstones have been interpreted to represent deposition in low-sinuosity channels (Pulham, 1989; Williams & Soek, 1993). Internally, the individual storeys are composed primarily of a series of stacked unidirectional, sinuous dunes (Fig. 12b). These northerly dipping cross-sets may be both asymptotic with the lower erosion surface or in places swept-out, which, together with a humpback shape to the dune profile, indicates transitional flow conditions to upper-stage plane beds, which are also present at this locality. The height of individual dune cross-sets measured at Trusklieve and Killard (Fig. 1) ranges from several decimetres to 1 m and may be used to estimate the palaeoflow depth. Allowing

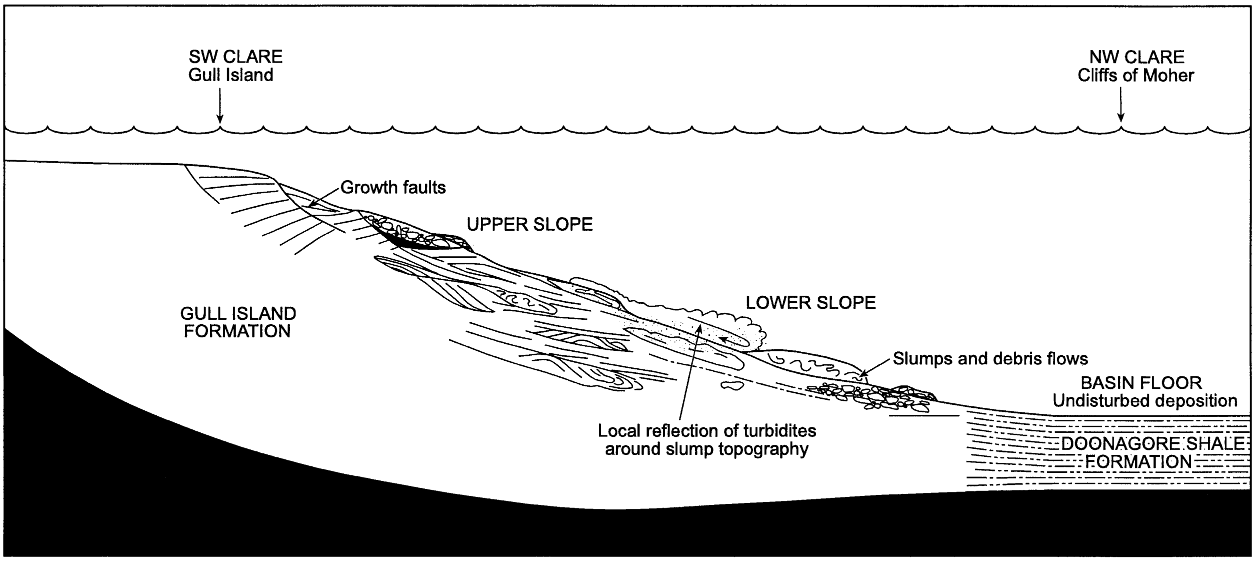

Fig. 10. Depositional model for the Gull Island Formation. The lower slope is dominated by slumps and turbidites whilst up-slope growth faults become the dominant style of deformation (cf. Rider, 1978). Note that the vertical scale is much exaggerated for clarity.

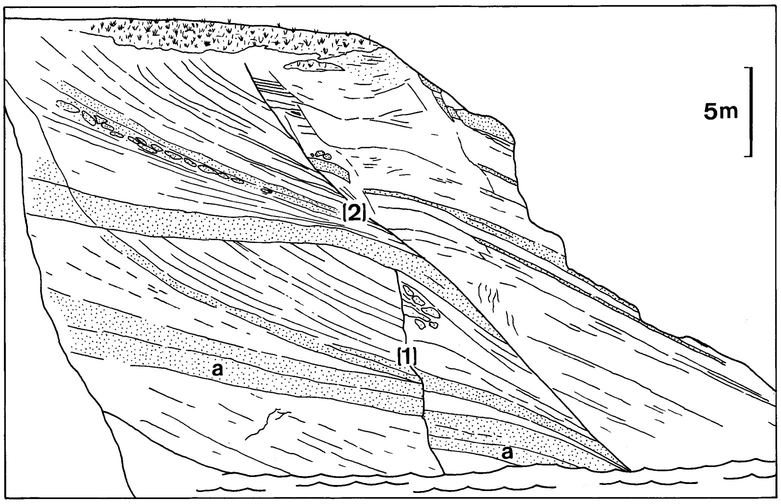

Fig. 11. Field sketch of two growth faults, (1) and (2), in the lower Tullig Cyclothem at Carrickfadda (Grid Ref. 933 676). Throw on (1) is less than 2 m (note offset of bed a), whereas it is not possible to trace beds across (2) implying a throw in excess of 25 m. Further faults are probably present but not seen to the left of the cliff. Hangingwall deposition is characterized by large foresets prograding to the right (NNW).

for erosion of the dune (since stoss sides are rarely preserved) by assuming set thickness is often only a maximum of 50% of the original bedform height (LeClair *et al.*, 1997), and accepting that equilibrium dune height is approximately 0.25–0.40 of the flow depth (Jackson, 1976; Bennett & Best, 1996), yields maximum flow depths of between 5 and 8 m, in good accord with estimates of flow depth from preserved channel dimensions (2–5 m). This

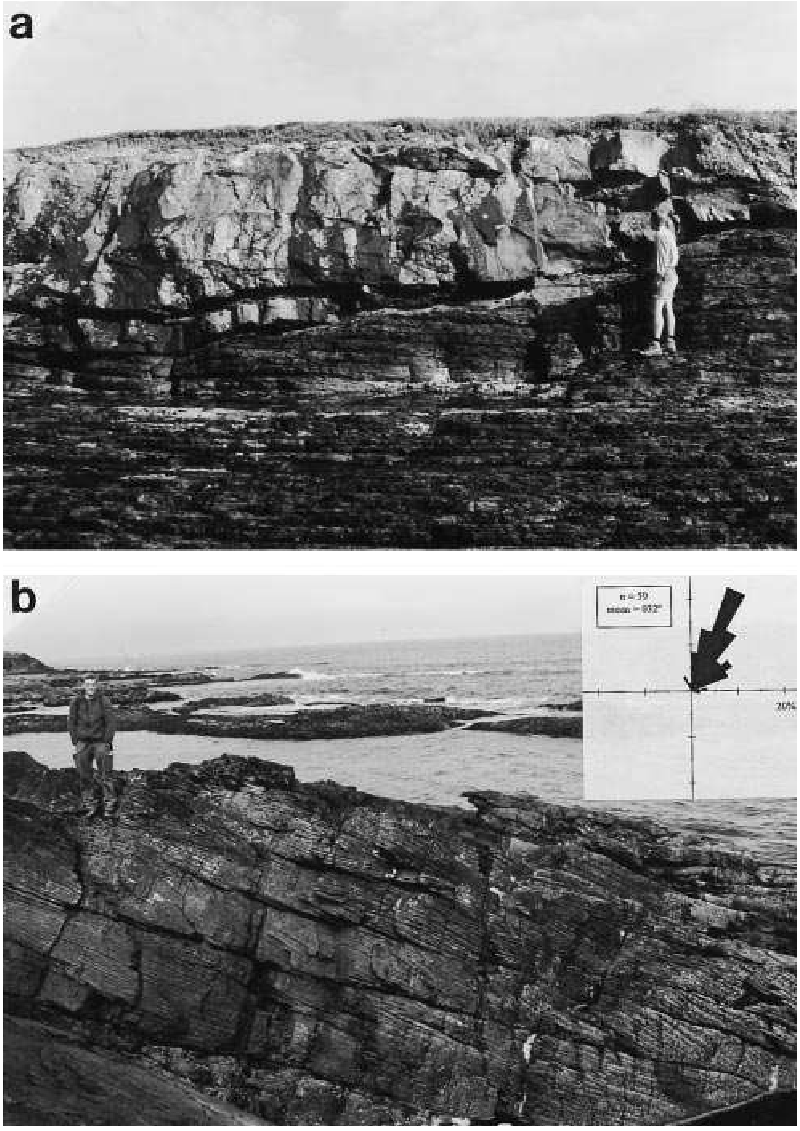

Fig. 12. (a) Basal contact of the Tullig Sandstone at Carrowmore Point showing 3 m of erosive relief. The sediments underlying the Tullig Sandstone consist of thin-bedded alternations of siltstones, siderite bands and wave-rippled sandstones. (b) Stacked dune cross-sets within the Tullig Sandstone at Killard (inset shows palaeocurrent rose measured at this outcrop). Warren Crundall for scale.

has considerable implications for the origin of the base-Tullig Sandstone erosion surface. Locally this surface removes up to 8 m of strata and regionally it may cut out up to perhaps 30 m of underlying sediments. This significant erosion surface has been interpreted as a sequence boundary generated by base-level fall and incision of fluvial valley systems (Hampson *et al.*, 1997). However, given that flow depths may have been up to 8 m, and intrinsic channel scour may be up to five times the mean channel depth (Best & Ashworth, 1997), possible autocyclic scour depths may have reached up to 40 m, or within the range of relief at the base of the Tullig Sandstone. This suggests that the erosive relief on this basal surface could record purely intrinsic channel scour associated with progradation of a fluvial system into the WINB. The alternative, in which it is due to base-level fall, is not supported by the nature of the underlying and laterally equivalent facies.

The sediments underlying the Tullig Sandstone in southern County Clare show a range of sedimentary characteristics, from oscillatory, wave-ripples with reversing current directions at Trusklieve, to thinly interbedded sandstones and siltstones with a moderately diverse trace fossil assemblage (including *Asterichnus*, *Limulicubichnus* and *Arenicolites*) indicative of brackish conditions at Killard. These facies and a thin bed of plant debris-rich shale immediately beneath the Tullig Sandstone at Killard are probably interdistributary bay facies (Pulham, 1989). These underlying sediments are thus within the depth range that may be expected to have been removed by autocyclic fluvial scour into the underlying sediments.

The regional palaeogeography of the Tullig Cyclothem is also contentious, particularly in the northernmost outcrops. Sections in the upper Tullig Cyclothem on the northern side of Liscannor Bay (Fig. 1) consist of wave-dominated sediments with common rootlet horizons and incised, small channels with northerly palaeocurrents. This finer-grained development of the Tullig Cyclothem has been interpreted to be the distal fringe of a delta top, possibly where the main distributary channels have divided to produce a series of smaller channels (Rider, 1969), or a delta top environment lateral to the main delta channel (Pulham, 1989). In the sequence stratigraphic reinterpretation of Hampson *et al.* (1997), the area is regarded as a nondepositional interfluve setting during Tullig Sandstone deposition. Deciding between these alternatives hinges on the recognition of the laterally equivalent facies of the Tullig Sandstone in northern County Clare. Palaeocurrents within the Tullig Sandstone indicate northward flow (Pulham, 1989) but the major channel system clearly did not reach the northern region of County Clare. The minor, individual channels interbedded within wave-dominated delta top facies at Liscannor also show northward flow vectors. Stratigraphically, they occur at the same level within the Tullig Cyclothem and can be interpreted to be the down-dip development of the Tullig Sandstone (in accord with Rider, 1974). There is no evidence for interfluve development with well-developed palaeosols in the Liscannor outcrops as predicted by the sequence stratigraphic model.

It is also likely that the Tullig delta may have been shaped by wave action to a larger extent than has been assumed in previous palaeoenvironmental interpretations. Thus, the delta morphology may have been more lobate than the commonly applied fluvially dominated Mississippian analogue. The large axial fluvial channels of such wave-influenced deltas would be expected to bifurcate down-dip into a greater number of smaller, shallower channels – a transition that is seen in the SW to NE transect of the County Clare coastal sections. Implicit in this reinterpretation of the Tullig Cyclothem is that the northern County Clare development of the Tullig Cyclothem records relatively distal facies compared with those seen in the south of the county.

Tullig–Kilkee Transition

The Tullig Sandstone is capped by a thin layer of bioturbated sandstone overlain by a few decimetres of dark, shaly mudstone that yields pyritized shells of protobranch bivalves and articulate brachiopods (productids and chonetids). This is the first of three marine bands that mark the transition to the Kilkee Cyclothem. The upper two marine bands consist of thin beds of dark grey and black shales that yield orthocone nautiloids, *Dunbarella*, *Caneyella,* crinoids and, most importantly, the R1b3 goniatite *Phillipsoceras* aff. *stubblefieldi*. The middle marine band has been taken to mark the base of the Kilkee Cyclothem.

At the Cliffs of Moher in the north of the WINB, all three marine bands occur within 3 m of strata separated by unfossiliferous shales, but to the south the marine bands are separated by nearly 100 m of strata which record the development of two substantial coarsening-up units. At Moore Bay, Kilkee (Fig. 13) the lower coarsening-up unit contains a 30-m-thick sandbody in its upper part that is penetrated by several mud diapirs (Gill, 1979). This unit, herein designated the Moore Bay Sandstone, contains a few metre-scale, trough cross-bedded horizons, but mostly displays broad, low-amplitude swaley cross-stratification, upper-stage plane beds and wave-reworked horizons. Such storm- and wave-generated features characterize the Moore Bay Sandstone at all outcrops (Fig. 13). Near the top of this unit at Trusklieve, escape traces are common along with *Planolites* bioturbation within thin, silty shale beds and rare shelly lenses that yield fragmentary brachiopods.

The upper coarsening-up unit, sandwiched between the upper and lower beds of the R1b3 Marine Band, displays the greatest southward-thickening trend. The 2 m of shaly strata at the Cliffs of Moher thickens to 16 m at Kilkee and then to over 60 m at Tullig Point where a thick sandstone is developed in its upper part. This

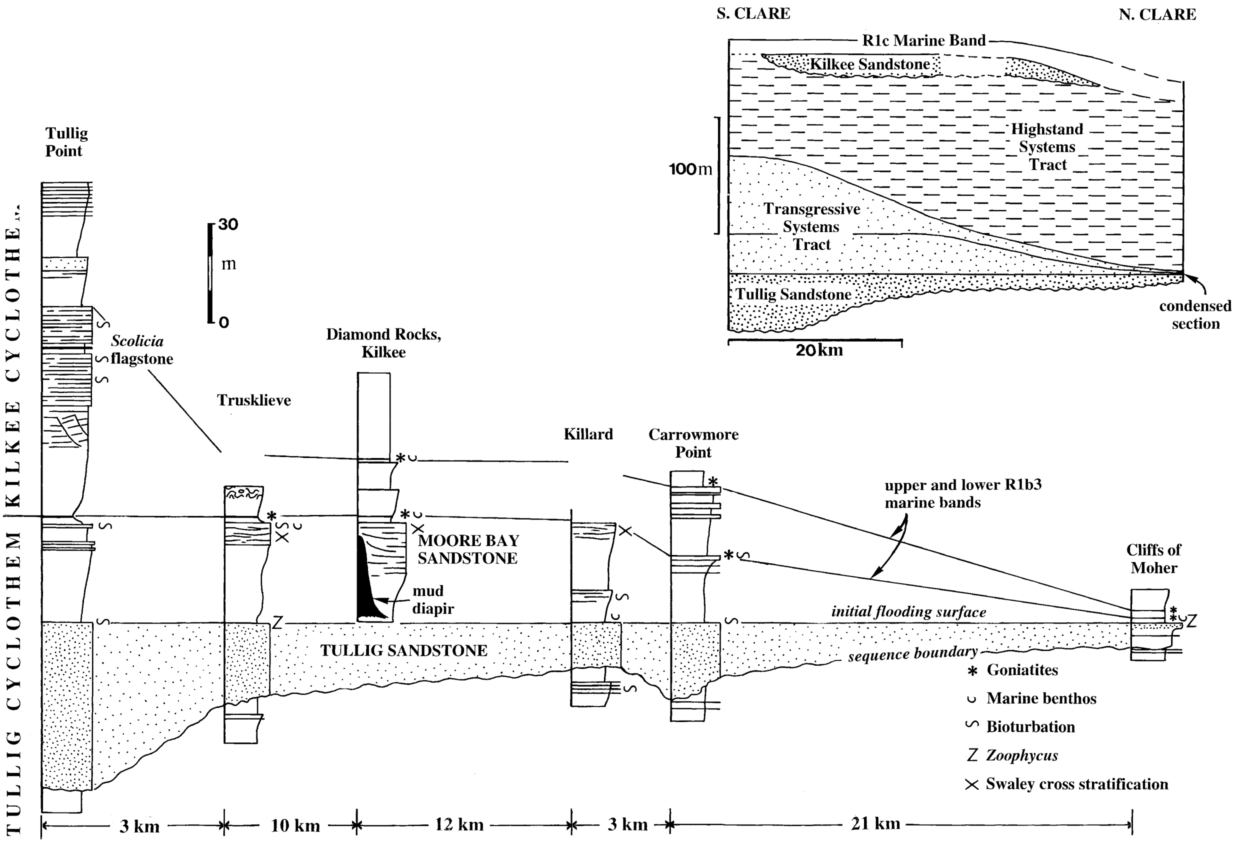

Fig. 13. Correlation of the Tullig to Kilkee Cyclothem transition in County Clare showing the rapid southward thickening of strata between the initial flooding surface that caps the Tullig Sandstone and the upper R1b3 Marine Band. The inset figure shows the thickness variations of the interval between the base of the Tullig Sandstone and the top of the Kilkee Cyclothem. This reveals the retrogradational nature of the strata in the main figure and the subsequent progradation of the higher levels of the Kilkee Cyclothem which are consequently interpreted to be a transgressive and highstand systems tract, respectively.

oscillatory-rippled sandstone displays well-developed flaggy partings and bedding planes covered in the sinuous traces of *Scolicia*. Further coarsening-up cycles are developed higher in the Kilkee Cyclothem but the absence of marker fossils makes study of their lateral thickness distribution problematic. The next fauna occurs in the *Reticuloceras* aff. *reticulatum* Marine Band that marks the base of the succeeding Doonlicky Cyclothem (Fig. 13).

The sequence stratigraphic interpretation of the Tullig–Kilkee transition offers several insights into the nature of the WINB. The occurrence of marine facies above the fluvial facies of the Tullig Sandstone indicates marine transgression and an increase of marine influence within the basin. Davies & Elliot (1996) have appropriately designated the strata between the lowest (initial) flooding surface and uppermost (maximum) flooding surface a transgressive systems tract. Such tracts are generally characterized by the retrogradation of their component parasequences towards the hinterland, a feature displayed to perfection by this example (Fig. 13). Retrogradation is, by definition, marked by the retreat of sedimentation towards the basin margin and by the spread of relatively sediment-starved conditions in more basinal locations. Thus, in this County Clare example, the dramatic condensation in the two parasequences shown at the Cliffs of Moher suggests that this was a relatively deep basinal location, whereas the greatly expanded section at Tullig Point indicates that the basin margin lay to the south. It is worthy of note that the sandstone facies developed within the transgressive systems tract display a predominance of oscillatory and combined flow-generated sedimentary structures which, together with their fossil content, indicates wave and storm-influenced marine deposition.

Kilkee Cyclothem

The Kilkee Cyclothem displays a similar hierarchical internal stratigraphy to the Tullig Cyclothem, with small-scale coarsening-up cycles (parasequences) and an overall coarsening-up trend culminating in the development of a major, erosive-based, multistorey sandbody (Rider, 1974; Pulham, 1989; Hampson *et al.*, 1997; Fig. 13) called the Kilkee Sandstone. Palaeocurrents from the Kilkee Sandstone predominantly indicate flow to the SE (Rider, 1974; Pulham, 1989; Hampson *et al.*, 1997), rather than the north-easterly dominant flow direction for the underlying WINB infill. This palaeocurrent trend implies that the SW–NE line of the coastal sections cuts orthogonally across the trend of the sandstone body (Fig. 13). Thus, the Kilkee sandstone is not present at Gowleen, the most southerly section in the County Clare outcrops, where the upper part of the Kilkee Cyclothem consists of several small-scale coarsening-up cycles. The uppermost of these cycles, developed immediately beneath the *R.* aff. *reticulatum* Marine Band, shows large, north-westerly prograding foresets developed in a 5-m-thick sandstone. In the northerly sections, the uppermost portion of the Hags Head Formation (the lateral equivalent of the Kilkee Cyclothem) has been removed by erosion and it is therefore difficult to constrain the precise horizon of the Kilkee Sandstone. However, the sections between Kilkee and Spanish Point indicate that the Kilkee Sandstone thins to the north and rapidly cuts-up section (Rider, 1974; Pulham, 1989).

Both Rider (1974) and Pulham (1989) interpreted the Kilkee Sandstone to be a major distributary channel whereas Hampson *et al.* (1997) suggest it is a truly fluvial facies that infills an incised valley. This latest interpretation appears reasonable, although the lack of evidence for palaeosol development in supposed interfluve settings, such as at Gowleen, is surprising. The lateral correlation of the section at Gowleen and those to the north around Kilkee deserves further field research, but the similarity of the Kilkee Sandstone to the facies of the Tullig Sandstone suggests that the basal 'sequence boundary' could be the product of intrinsic autocyclic processes.

Higher cycles

The Kilkee Cyclothem is overlain by the Doonlicky Cyclothem, which in turn is succeeded by two further, unnamed cyclothems of Marsdenian age. Outcrop sections of all three cyclothems are restricted (Fig. 1) but reveal a similar range of facies to those encountered in the lower cyclothems with soft sediment deformation being particularly common in the prodelta siltstone facies (Rider, 1969; Gill, 1979). A mature palaeosol also occurs within the Doonlicky Cyclothem at Spanish Point whilst a thick, fluvial sandstone body occurs in this unit in the cliffs south of Kilkee. This palaeosol has therefore been interpreted as an interfluve coeval with the fluvial sandbody (Davies & Elliot, 1996; Hampson *et al.*, 1997) which, although an attractive possibility, awaits verification through detailed correlation of the Doonlicky strata. Published palaeocurrent vectors for the Doonlicky and younger cycles (Pulham, 1989) indicate a range of flow directions from the NE to SE, while the sense of displacement on numerous synsedimentary faults indicates palaeoslopes that dipped to the NE and locally to the E (Rider, 1978).

A NEW MODEL FOR THE WESTERN IRISH NAMURIAN BASIN

The foregoing discussion of facies and palaeoslope indicators from the Namurian of western Ireland suggests that the currently accepted configuration of the WINB and aspects of the depositional facies models require considerable reinterpretation. The current synthesis suggests that, for much of the Namurian, a major clastic depositional system prograded from the SW of County Clare towards a deep-water, sediment-starved basin centre located in the NE of the county (Fig. 14). This reinterpretation fundamentally alters two aspects of Hodson's original model. Firstly, the infill is primarily thought to record NE-directed progradation rather than basinal aggradation with sediment sourced from the W or NW. Second, the Namurian outcrops of northern County Clare are interpreted to be relatively distal, deeper-water facies and not relatively shallow, basin-margin facies.

In the current reinterpretation, we argue that the transition from carbonate deposition in the late Visean to black shale deposition in the early Namurian coincided with substantial deepening over the Galway High as sedimentation in this area ceased. As noted, the 6-cm-thick St. Brendan's Well Phosphate Bed records both shallow-water (abraded phosphate clasts, oncolites and trace fossils) and deep-water (abundant syngenetic pyrite) conditions in its prolonged depositional history. Published radiometric dates for the Carboniferous vary considerably, but it is clear that 7–9 Myr of geological history occurred between cessation of Visean Limestone deposition and the onset of Clare Shale deposition. Even modest subsidence rates of 0.05 mm yr^{-1} would be sufficient to generate 350 m of water depth in this time. Gallagher's (1996) study of Visean carbonates in northern County Clare suggests subsidence rates may have exceeded this immediately before shutdown of carbonate productivity in the Brigantian stage.

During the earliest Namurian (Arnsbergian Stage), black shale deposition was restricted to the Shannon Estuary region but gradually began to expand northwards as the previous basin high began to deepen in the absence of any sediment deposition (Fig. 14A). By the early Chokierian, black shale deposition extended throughout the WINB and conditions were probably uniformly deep. Turbidite progradation from the SW began in the basal Alportian and gradually expanded to the NE (Fig. 7). The dramatic thinning of the Ross Formation to the NE (Fig. 3) is therefore interpreted as a proximal-to-distal trend. Isostatic loading in the western reaches of the Shannon Estuary may have caused much of the clastic supply to be trapped in the SW of the basin and thus contributed to continuing starvation of the less-rapidly subsiding northern part of the basin (Fig. 14B). Sedimentation rates increased substantially during deposition of the Gull Island Formation in southern County Clare. Thus, the 400 m maximum thickness of the Ross Formation accumulated during nine goniatite zones, whereas the 550 m maximum thickness of the Gull Island Formation was developed in only 2–3 goniatite zones. Much of the sediment supply to this prograding slope system was again trapped in the SW of the basin, although

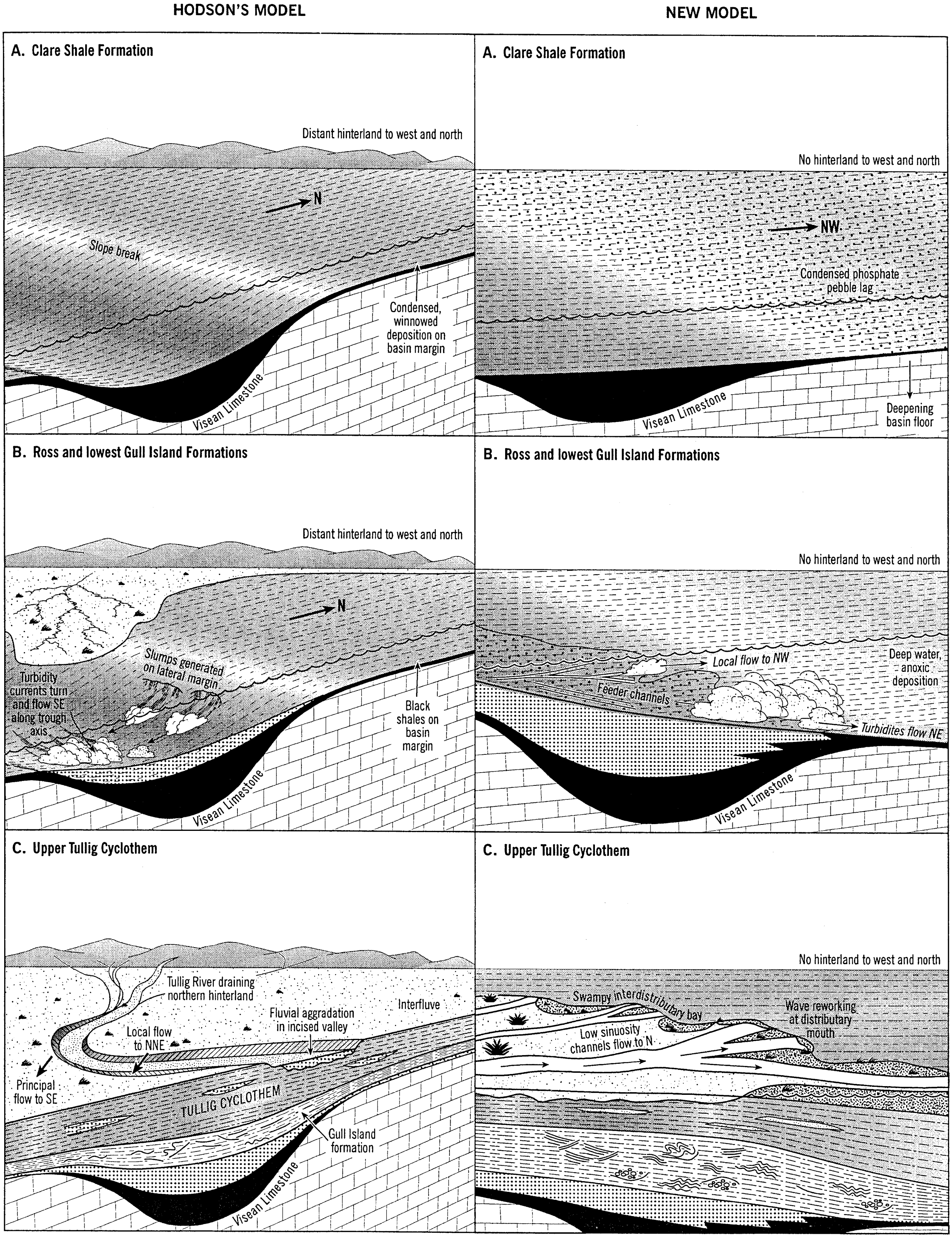

Fig. 14. Comparison of stages of infill of the WINB with the geometry originally proposed by Hodson, and adopted in all subsequent studies, and the new basin geometry proposed here.

substantially more sediment (the siltstones of the Doonagore Shale Formation) reached northern County Clare (Fig. 10). This sedimentation marks the gradual infilling of the unrealized accommodation space in the northern part of the WINB and, by late in the Tullig Cyclothem (mid-Kinderscoutian), the presence of rootlet horizons indicates that base level was reached at least transiently in this area (Fig. 14C).

By the mid-Kinderscoutian, the differences in relative thickness between strata in the southern and northern sections of County Clare had essentially ceased. This suggests extremely high sedimentation rates during this interval (approaching 1 km Myr^{-1}) which were able to outpace the high rates of subsidence in the Shannon Estuary, thus allowing progradation and infill to base level in northern County Clare. The greater range of palaeocurrents above the Tullig Cyclothem (from NNW to SE) may reflect reduced depositional gradients and a more variable direction of sediment supply.

IMPACT ON EXISTING BASIN AND FACIES MODELS

The Chokierian to early Kinderscoutian progradation of the Ross Formation turbidite system is interpreted as the record of a north-easterly prograding turbidite fan that downlapped onto condensed, basinal black shales (Fig. 14B). Thus, the persistence of black shale deposition until the mid-Kinderscoutian in northernmost County Clare reflects the persistence of deep-water, probably euxinic, depositional conditions in this distal location. In the alternative viewpoint of Collinson *et al.* (1991), these conditions occur on a shallow-water basin margin, an unusual location for such low-energy, stagnant conditions (Fig. 14B). The north-westerly palaeocurrent vectors of the lower Ross Formation are also difficult to reconcile with the Hodson model: these indicate flow back upslope towards the postulated hinterland.

Interpretation of the Gull Island Formation also requires substantial modification in the revised model. Whilst agreeing with the slope interpretation of Rider (1978), Martinsen (1989) and Collinson *et al.* (1991), the revised model suggests that the slope faced consistently to the NE rather than the SE (Fig. 14C). This better explains the predominance of movement indicators to the NE and also the undisturbed nature of the Doonagore Shale Formation siltstones. Although they lack evidence for slope failure, Collinson *et al.* (1991) interpreted this unit as a slope facies. With the exception of a single channellized sandstone unit (Fig. 8), the absence of sandstones in this unit is also puzzling considering the importance of sandstones in the slope facies of the Gull Island Formation. However, in the revised WINB model proposed here, the Doonagore Shale is interpreted to have accumulated on a distal basin floor – a setting that may be unlikely to show evidence for slope failure (Fig. 10). The lack of sandstone in the Doonagore Shale, as compared to the presence of turbiditic sandstones in the underlying Cronagort Sandstone, may record the effects of relative sea-level rise associated with the R1a5 Marine Band. The combination of base-level rise at a time of rapid sediment flux may have caused rapid aggradation of the slope setting in southern County Clare, a factor that may also explain the prevalence of slope failure in the southern outcrops.

The interpretation of the Tullig Cyclothem depositional system also requires considerable reassessment, although the overall deltaic epithet of Rider (1974) and Pulham (1989) seems undoubtedly correct. One of the principal modifications concerns the orientation of the system. Palaeocurrent vectors are overwhelmingly to the N and NE in the Tullig Cyclothem, implying that this was the axial drainage direction. Pulham (1989) and Collinson *et al.* (1991) suggested that the outcrops of County Clare record the northern-flowing distributaries of a deltaic system that possessed an overall flow trend to the E or SE. However, for the distributaries to show a northerly flow would require branching at an angle of 90–120° to the main deltaic system: given the dearth of palaeocurrent evidence for any south-easterly flow, plus the fact that the channels of the Tullig Sandstone in the south of County Clare are taken to represent the major axial feeder channels, this seems a somewhat unlikely scenario.

The sequence stratigraphic interpretation of the Tullig Sandstone as an incised valley fill is also open to question. Although the unit clearly rests on an erosive surface with considerable relief, no demonstrable interfluve facies have been located. Hodson's basin model predicts that the Tullig Sandstone in northern County Clare should lie in an interfluve setting (Fig. 14C), but no mature palaeosols are known from the area. Similarly, the Kilkee Sandstone, whilst more obviously occupying an incised valley (Hampson *et al.*, 1997), also lacks correlative interfluve surfaces. Mature palaeosols are known from higher in the Namurian succession (e.g. Doonlicky Cyclothem), but these probably record the later stages of basin history when subsidence rates had declined and infill was closer to completion.

In the present reinterpretation, the Tullig and Kilkee Sandstones simply record the rapid progradation of the deltaic fluvial feeder channels. The erosive bases of these sandbody complexes may be generated through intrinsic fluvial scour and need not necessarily imply a relative sea-level fall as has been recently proposed (e.g. Hampson *et al.*, 1997). In the more basinal sections of northern County Clare, the lateral correlatives of the fluvial sandbodies consist of minor distributary channel sandbodies and extensive wave-reworked sandbodies (Fig. 14C), representing the more distal fringes of the wave-influenced delta and marginal shoreline settings.

Subsidence rates and tectonic controls

As with most Carboniferous basins in the British Isles, the underlying tectonic control on subsidence patterns in the WINB has been attributed to reactivated features in the Caledonide basement, particularly the Iapetus Suture (Haszeldine, 1988; Strogen, 1988). The location and orientation of this terrane boundary has been the subject of conflicting suggestions. Several authors suggest that the boundary underlies the Shannon Estuary and passes eastwards into the Silvermines–Navan lineament, a NE–SW-trending fault system running through central Ireland (Haszeldine, 1988; Gawthorpe *et al.*, 1989; Collinson *et al.*, 1991). Strogen *et al.* (1996) retained the E–W orientation but placed the suture over 20 km to the S along a line parallel with the N coast of the Dingle Peninsula. The best constraint of the location of the Iapetus Suture comes from the regional magnetic survey of Morris & Max (1995) which distinguished between a low magnetic terrane to the S of the suture and a higher magnetic terrane to the N. These data indicate that the Iapetus Suture has a NE–SW trend which, in the region of central County Clare, is displaced 60 km dextrally along the Aran–Waterford line (Fig. 15). The Silvermines–Navan lineament appears to coincide with the line of the suture to the E of this strike-slip feature but, significantly for the present reinterpretation of the WINB, the western development of the Iapetus Suture trends at a high angle to the Shannon Estuary and not parallel to it as others have suggested. It is perhaps not coincidental that the progradation of the Ross Formation (Fig. 7) appears to be closely related to the position of the Iapetus Suture indicated by the data of Morris & Max (1995; Fig. 15).

Classification of the type of basin recorded in the Namurian of County Clare is hindered by the limited outcrop of Namurian strata which records only a remnant of the original basin fill. Subsidence clearly outpaced sedimentation during deposition of the Clare Shale Formation but the subsequent phase of infill was more rapid (approximately 0.5–1.0 km Myr^{-1}). To the west of the WINB, evidence from offshore indicates that Upper Carboniferous deposition persisted into the Westphalian and onshore maturity profiles suggest that between 2 and 4 km of strata has been stripped off the Namurian outcrops (Croker, 1995; Goodhue & Clayton, 1999). Thus, the entire Namurian–Westphalian interval may have been marked by high subsidence rates. Comparison with basin evolution elsewhere in the region provides further clues as to the regional tectonic context of the western Irish basin.

REGIONAL CARBONIFEROUS BASIN DEVELOPMENT

The crucial stage in the Carboniferous basin history of western Ireland is the sudden shut-down of carbonate productivity in the Brigantian in shallow ramp settings. Although the prolonged lack of sedimentation (other than a few centimetres of phosphatic clasts) following this event is sufficient to explain the subsequent establishment of deep water (several 100 m?) conditions, the reason for the cessation of shallow-water carbonate productivity is enigmatic. Comparison of the tectonic history of adjacent Carboniferous basins may provide a solution.

In the major Carboniferous intermontane basin of Nova Scotia, the mid-Carboniferous is marked by a transition from purely extensional to a briefly transpressive regime before the establishment of transtensional conditions (Calder, 1998). The mid-Carboniferous transition in the basins of northern England also shows a similar tectono-sedimentary history, with Brigantian (latest Visean) inversion followed by rapid subsidence and basin formation (Gawthorpe, 1987; Fraser & Gawthorpe, 1990). Thus, the break-up of extensive carbonate platforms (e.g. the Bowland and Central Pennine Highs) in the late Brigantian–Pendleian interval generated deep-water black shale deposition on sites formerly characterized by shallow-marine carbonate deposition (Gawthorpe, 1987; Leeder & McMahon, 1988). The similarity with the depositional history of northern County Clare is striking, as is the subsequent progradation of a turbidite system (the Pendle Grit) into the basin (Sims, 1989). Similarly, in the southern North Sea, accelerated subsidence in the early Namurian created several narrow, deep, anoxic basins (Leeder & Hardman, 1990).

Thus, the proposed mid-Carboniferous change in basin geometry in western Ireland coincides with contemporary

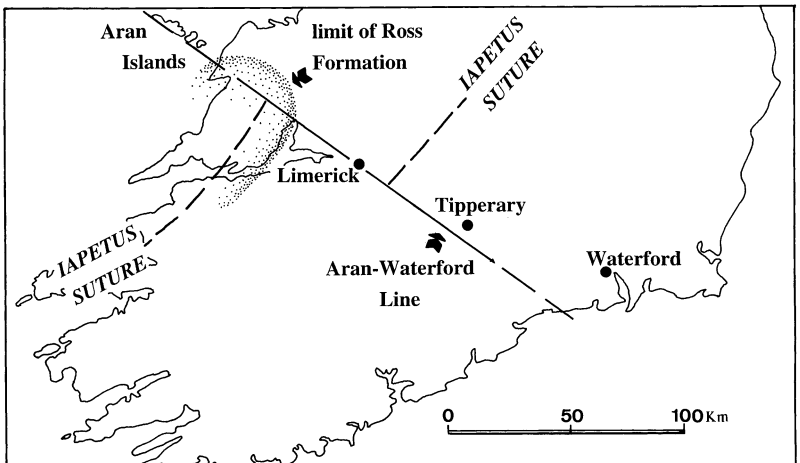

Fig. 15. Interpreted location of the Iapetus Suture in southern Ireland (after Morris & Max, 1995). For comparison, the distribution of turbidite facies of the Ross Formation is shown (cf. Fig. 7). Note the progradation direction of the turbidite system parallels the line of the Iapetus Suture in County Clare.

changes in most other basins of the region, and points to a significant tectonic event at this time on the southern margins of the Euramerican continent. It has been postulated that the onset of Rheic Ocean subduction and Variscan deformation to the SW of Ireland may have occurred around this time (cf. Fraser & Gawthorpe, 1990; Maynard *et al*., 1997). This is supported by the contemporaneous development of foreland basin-style deposition and deformation in SW England (G. Lloyd, personal communication). Therefore, the high subsidence rates of the WINB noted above may point to the influence of flexurally induced subsidence, and their onset may have been sufficiently rapid to drown the carbonates of the Galway High.

The post-Namurian development of the WINB can only be a matter of conjecture given the erosion of rocks of this age. However, a thick succession of younger Carboniferous sediments occurs in the basins of northern England and they display an intriguing change in sediment provenance in the immediate post-Namurian interval. Much of the Namurian infill of the region was derived from terranes to the north-east, but in the Westphalian the principal sediment supply switched to the west (Rippon, 1996). The Sr–Nd signature of the new source material suggests a young crustal source probably associated with a developing orogenic front (Glover *et al*., 1996). It may be that the same (Variscan?) source that began to infill the WINB in the Namurian reached the adjacent basins of northern England later in the Carboniferous.

FURTHER WORK

That it is possible to reinterpret many current ideas concerning the WINB highlights the need for considerable further work on many aspects of the geology of the region. The nature of the transition between the Visean limestones and the Namurian Clare Shale is especially intriguing. The Gull Island Formation also records a fascinating phase of basin infill of which more could be deciphered from the array of soft-sediment deformation structures: existing interpretations of movement directions are highly conflicting. The possibility that the slumps created obstacles to the flow of turbidity currents is worth consideration. Depositional models for the deltaic phase of infill also require further analysis since, although fluviodeltaic facies are considered to dominate these successions (Rider, 1974; Pulham, 1989), this somewhat neglects the abundance of wave-formed structures. Some sandbodies (e.g. the Moore Bay Sandstone) appear to be entirely the product of shelf depositional processes. Finally, provenance analysis of the Namurian sediments of County Clare would be of considerable value in determining the source terrain of the WINB infill and perhaps, indirectly, ascertaining the regional tectonic significance of the mid-Carboniferous basin rearrangement.

ACKNOWLEDGMENTS

We thank Karen Braithwaite for discussions concerning the County Clare stratigraphy over the past few years, Lorna Strachan, Kath Osborn and Alice Graham for their insights on the Ross and Fisherstreet slides, James Maynard and Mike Leeder for their constructive thoughts on an earlier version of the manuscript and finally reviewers Andy Pulham, John Graham and Trevor Elliot for their detailed and critical reviews.

REFERENCES

Bennett, S.J. & Best, J.L. (1996) Mean flow and turbulence structure over fixed ripples and the ripple-dune transition. In: *Coherent Flow Structures in Open Channels* (Ed. by P.J. Ashworth, S.J. Bennett, J.L. Best & S.J. Mclelland), pp. 281–304. Wiley and Sons, Chichester.

Best, J.L. & Ashworth, P.J. (1997) Scour in large braided rivers and the recognition of sequence stratigraphic boundaries. *Nature*, **387**, 275–277.

Braithwaite, K. (1993) The stratigraphy of a section spanning the mid-Carboniferous at Inishcorker, County Clare, Ireland. *Ann. Soc. Geol. Belg*., **116**, 209–221.

Braithwaite, K. (1995) *Stratigraphy of the mid–Carboniferous boundary*. Unpubl. PhD Thesis, University of Leeds, Leeds, UK.

Calder, J.H. (1998) The Carboniferous evolution of Nova Scotia. In: *Lyell: the Past Is the Key to the Present* (Ed. by D.J. Blundell & A.C. Scott), *Spec. Publ. Geol. Soc. Lond*., **143**, 261–302.

Chapin, M., Davies, P., Gibson, J.L. & Pettingill, H.S. (1994) Reservoir architecture of turbidite sheet sandstones in laterally extensive outcrops, Ross Formation, western Ireland. In: *Submarine Fans and Turbidite Systems*, pp. 53–68. GCSSEPM Foundation 15th Ann. Res. Conference.

Collinson, J.D., Martinsen, O., Bakken, B. & Kloster, A. (1991) Early fill of the Western Irish Namurian Basin: a complex relationship between turbidites and deltas. *Basin Res*., **3**, 223–242.

Croker, P.F. (1995) The Clare Basin: a geological and geophysical outline. In: *The Petroleum Geology of Ireland's Offshore Basins* (Ed. by P.F. Croker, & P.M. Shannon), *Spec. Publ. Geol. Soc. Lond*., **93**, 327–339.

Davies, S.J. & Elliott, T. (1996) Spectral gamma ray characterisation of high resolution sequence stratigraphy: examples from Upper Carboniferous fluvio-deltaic systems, County Clare, Ireland. In: *High Resolution Sequence Stratigraphy: Innovations and Applications* (Ed. by J.A. Howell & J.F. Aitken), *Spec. Publ. Geol. Soc. Lond*., **104**, 25–35.

Elliott, T. (2000) Megaflute erosion surfaces and the initiation of turbidite channels. *Geology*, **28**, 119–122.

Fraser, A.J. & Gawthorpe, R.L. (1990) Tectono-stratigraphic development and hydrocarbon habitat of the Carboniferous of northern England. In: *Tectonic Events Responsible for Britain's Oil and Gas Reserves* (Ed. by R. F. P. Hardman & J. Brooks), *Spec. Publ. Geol. Soc. Lond*., **55**, 49–86.

Gallagher, S.J. (1996). The stratigraphy and cyclicity of the late Dinantian platform carbonates in parts of southern and western Ireland. In: *Recent Advances in Lower Carboniferous Geology* (Ed. by P. Strogen, I. D. Somerville & G. Ll. Jones), *Spec. Publ. Geol. Soc. Lond*., **107**, 239–251.

GAWTHORPE, R.L. (1987) Tectono-sedimentary evolution of the Bowland Basin, N. England, during the Dinantian. *J. Geol. Soc. Lond.*, **144**, 59–71.

GAWTHORPE, R.L., GUTTERIDGE, P. & LEEDER, M.R. (1989) Devonian and Dinantian basin evolution in northern England and North Wales. In: *The Role of Tectonics in Devonian and Carboniferous Sedimentation in the British Isles* (Ed. by R. S. Arthurton & S. C. Nolan), *Yorkshire Geol. Soc. Occ. Publ.*, **6**, 1–23.

GILL, W.D. (1979) Syndepositional sliding and slumping in the West Clare Namurian Basin, Ireland. *Spec. Pap. Geol. Surv. Ireland*, **4**.

GLOVER, B.W., LENG, M.J. & CHISHOLM, J.I. (1996) A second major fluvial sourceland for the Silesian Pennine Basin of northern England. *J. Geol. Soc. Lond.*, **153**, 901–906.

GOODHUE, R. & CLAYTON, G. (1999) Organic maturation levels, thermal history and hydrocarbon source rock potential of the Namurian rocks of the Clare Basin, Ireland. *Mar. Petrol. Geol.*, **16**, 667–675.

HAMPSON, G.J., ELLIOTT, T. & DAVIES, S.J. (1997) The application of sequence stratigraphy to Upper Carboniferous fluvio-deltaic strata of the onshore UK and Ireland: implications for the southern North Sea. *J. Geol. Soc. Lond.*, **154**, 719–733.

HASZELDINE, R.S. (1988) Crustal lineaments in the British Isles: their relationship to Carboniferous Basins. In: *Sedimentation in a Synorogenic Basin Complex. The Upper Carboniferous of Northwest Europe* (Ed. by B.M. BESLY & G. KELLING), 53–68. Blackie, Glasgow.

HODSON, F. (1954a) The beds above the Carboniferous Limestone in northwest County Clare, Eire. *Q. J. Geol. Soc. Lond.*, **109**, 259–283.

HODSON, F. (1954b) The Carboniferous rocks of Foynes Island, County Limerick. *Geol. Mag.*, **91**, 153–160.

HODSON, F. (1978) Namurian of Ireland. In: *A Correlation of Silesian Rocks in the British Isles* (Ed. by W. H. C. Ramsbottom, *et al.*), *Spec. Report Geol. Soc. Lond.*, **10**, 35–43.

HODSON, F. & LEWARNE, G.C. (1961) A mid-Carboniferous (Namurian) basin in parts of the counties of Limerick and Clare, Ireland. *Q. J. Geol. Soc. Lond.*, **117**, 307–333.

HOLDSWORTH, B.K. (1966) A preliminary study of the palaeontology and palaeoenvironment of some Namurian Limestone 'bullions'. *Mercian Geologist*, **1**, 315–337.

JACKSON, R.G. (1976) Sedimentological and fluid-dynamic implications of the turbulence bursting phenomenon in geophysical flows. *J. Fluid Mech.*, **77**, 531–560.

LECLAIR, S.F., BRIDGE, J.S. & WANG, F. (1997) Preservation of cross-sets due to migration of subaqueous dunes over aggrading and non-aggrading beds; comparison of experimental data with theory. *Geoscience Can.*, **24**, 55–66.

LEEDER, M.R. & HARDMAN, M. (1990) Carboniferous geology of the Southern North Sea Basin and controls on hydrocarbon prospectivity. In: *Tectonic Events Responsible for Britain's Oil and Gas Reserves* (Ed. by R. F. P. Hardman & J. Brooks), *Spec. Publ. Geol. Soc. Lond.*, **55**, 87–105.

LEEDER, M.R. & MCMAHON, A.H. (1988) Upper Carboniferous (Silesian) basin subsidence in northern Britain. In: *Sedimentation in a Synorogenic Basin Complex. The Upper Carboniferous of Northwest Europe* (Ed. by B. M. BESLY & G. KELLING), 43–52. Blackie, Glasgow.

MARTINSEN, O.J. (1989) Styles of syndepositional deformation on a Namurian (Carboniferous) delta slope, Western Irish Namurian Basin, Ireland. In: *Deltas – Sites and Traps of Fossil Fuels* (Ed. by M. H. Whateley & K. T. Pickering), *Spec. Publ. Geol. Soc. Lond.*, **41**, 167–177.

MARTINSEN, O.J. & BAKKEN, B. (1990) Extensional and compressional zones in slumps and slides – examples from the Namurian of County Clare, Ireland. *J. Geol. Soc. Lond.*, **147**, 153–164.

MAYNARD, J.R., HOFMAN, W., DUNAY, R.E., BENTHAM, P.N., DEAN, K.P. & WATSON, I. (1997) The Carboniferous of western Europe: the development of a petroleum system. *Petrol. Geosci.*, **3**, 97–115.

MORRIS, P. & MAX, M.D. (1995) Magnetic crustal character in Central Ireland. *Geol. J.*, **30**, 49–67.

O'BRIEN, M.V. (1953) Phosphatic horizons in the Upper Carboniferous of Ireland. In: *Compte Rendu 19th Int. Geol. Congr.*, pp. 135–143. Algeria.

PULHAM, A.J. (1989) Controls on internal structure and architecture of sandstone bodies within Upper Carboniferous fluvially-dominated deltas, County Clare, western Ireland. In: *Deltas – Sites and Traps of Fossil Fuels* (Ed. by M. H. Whateley & K. T. Pickering), *Spec. Publ. Geol. Soc. Lond.*, **41**, 179–203.

RIDER, M.H. (1969) *Sedimentological studies in the West Clare Namurian, Ireland and the Mississippi River delta*. Unpubl. PhD Thesis, Imperial College, London.

RIDER, M.H. (1974) The Namurian of West County Clare. *Proc. R. Irish Acad.*, **74B**, 125–142.

RIDER, M.H. (1978) Growth faults in the Carboniferous of Western Ireland. *Bull. Am. Ass. Petrol. Geol.*, **62**, 2191–2213.

RIPPON, J.H. (1996) Sand body orientation, palaeoslope analysis and basin-fill implications in the Westphalian A-C of Great Britain. *J. Geol. Soc. Lond.*, **153**, 881–900.

SEVASTOPULO, G.D. (1981a) Lower Carboniferous. In: *A Geology of Ireland* (Ed. by C.H. HOLLAND), pp. 147–172. Scottish Academic Press, Edinburgh.

SEVASTOPULO, G.D. (1981b) Upper Carboniferous. In: *A Geology of Ireland* (Ed. by C.H. HOLLAND), pp. 173–188. Scottish Academic Press, Edinburgh.

SIMS, A.P. (1989) Bed and sand-body architectures in the Pendle Formation of north-west England. *Brit. Sed. Res. Group Field Guide, University of Leeds*, pp. 9-1–9-26.

STROGEN, P. (1988) The Carboniferous lithostratigraphy of southeast County Limerick, Ireland, and the origin of the Shannon Trough. *Geol. J.*, **23**, 121–137.

STROGEN, P., SOMERVILLE, I.D., PICKARD, N.A.H., JONES, G.Ll. & FLEMING, M. (1996) Controls on ramp, platform and basinal sedimentation in the Dinantian of the Dublin Basin and Shannon Trough, Ireland. In: *Recent Advances in Lower Carboniferous Geology* (Ed. by P. Strogen, I. D. Somerville & G. Ll. Jones), *Spec. Publ. Geol. Soc. Lond.*, **107**, 263–279.

WILLIAMS, H. & SOEK, H.F. (1993) Predicting reservoir sandbody orientation from dipmeter data: the use of sedimentary dip profiles from outcrop studies. In: *The Geological Modelling of Hydrocarbon Reservoirs and Outcrop Analogues* (Ed. by S. D. Flint & I. D. Bryant), *Spec. Publ. Int. Ass. Sedimentol.*, **15**, 143–156.

Received 20 August 1999; accepted 16 February 2000