Carbon isotopes, ammonites and earthquakes: Key Triassic-Jurassic boundary events in the coastal sections of south-east County Antrim, Northern Ireland, UK

Andrew J. Jeram[a,*], Michael, J. Simms[b], Stephen P. Hesselbo[c] and Robert Raine[d]

[a] 17 Balfour Avenue, Whitehead, County Antrim, BT38 9RD, U.K.

e-mail: andyjmail@btinternet.com

[b] National Museums Northern Ireland, Cultra, Holywood, BT18 0EU, U.K.

e-mail: michael.simms@nmni.com

[c] Camborne School of Mines and Environment and Sustainability Institute, University of Exeter, Penryn Campus, Penryn, Cornwall TR10 9FE, U.K.

[d] Geological Survey of Northern Ireland, Dundonald House, Belfast BT4 3SB, U.K.

Key Words: Rhaetian, Hettangian, mass extinction, large igneous province, carbon isotopes, seismites, correlation, Triassic-Jurassic boundary, $p\mathrm{CO}_2$

ABSTRACT

A continuous succession of marine and marginal-marine sediments of Rhaetian (Late Triassic) and Hettangian (Early Jurassic) age is present in the Larne Basin in Northern Ireland. These strata cover a period in Earth's history that included the emplacement of the Central Atlantic Magmatic Province (CAMP), the End Triassic mass Extinction (ETE), the Triassic–Jurassic boundary (TJB) and major perturbations in the global carbon cycle. The Waterloo Bay section in the Larne Basin offers a well exposed record of sediments that span this interval, and it has previously been proposed as a candidate GSSP for the base of the Jurassic. A high-resolution $\delta^{13}C_{org}$ and organic carbon record for this locality is presented here, with these new data tied to previous stratigraphic descriptions, ammonite biostratigraphy, atmospheric carbon dioxide concentration ($p\mathrm{CO}_2$) reconstructions, and nearby borehole sections that do not suffer from the thermal alteration that has affected the Waterloo Bay section. Several new exposures, unaffected by thermal metamorphism, are described that could provide future palynological and micropalaentological studies across this important boundary interval. Correlation is established between the well-studied sections in North

Somerset and the likely position of the TJB in the Larne Basin is discussed. Records of soft sediment deformation, synsedimentary fault movement, relative sea-level change and their likely causes are discussed.

1. Introduction

The Triassic–Jurassic transition coincides with the onset of Pangaean break-up and development of the Central Atlantic Magmatic Province (CAMP) in the main rift zone (Rhul et al., 2020 and references therein). The volcanism generated ~2–4 x 10^6 km^3 of flood basalts (McHone, 2003) and huge volumes of CO_2, SO_2 and other gases (Svensen et al., 2007; Korte et al., 2009, 2019; Bond and Wignall, 2014; Heimdal et al., 2018, 2019) over a period of ~500–600 ka, with a particularly intense early pulse concentrated in just 60 ka (Blackburn et al., 2013; Korte et al., 2019).

The CAMP volcanism had a global impact on ocean–atmosphere chemistry and probably influenced both the climate and biosphere, and also the End Triassic mass extinction (ETE) (Whiteside et al., 2010; Pálfy and Kocsis, 2014). There is evidence for major biotic turnover in the latest Triassic (Bond and Wignall, 2014; McElwain et al., 1999, 2009; Wignall and Atkinson, 2020), but questions remain about the timing, duration and causes of diversity loss (Lucas and Tanner, 2015; Onoue et al., 2016) and there is still room for scepticism (e.g. Smith and McGowan, 2007; Lucas and Tanner, 2008, 2015; Fox et al., 2020).

Linking abiotic events to biotic change requires a precise temporal framework based upon accurate, reliable and precise stratigraphic correlation. Biostratigraphy, traditionally considered a primary correlation tool in the Phanerozoic, can prove challenging when the biota is of low-diversity, sparse and in flux (as in the wake of a mass extinction). Across the Triassic–Jurassic Boundary (TJB) interval, in particular where there is an absence (as in the UK) of key boundary marker ammonoids such as *Psiloceras spelae* Guex, carbon isotope stratigraphy has increasingly come to the fore as a correlation tool (Korte et al., 2019; Ruhl et al., 2020).

One of the first high-resolution carbon isotope records to be documented through the TJB interval was from St Audrie's Bay, North Somerset in south-west Britain (Hesselbo et al., 2002). Considered to preserve the most complete marine succession through this interval in the U.K., this section was proposed as a candidate for the base-Hettangian GSSP (Warrington et al., 1994, 2008). Even now it remains a widely used reference section because the position of the 'initial' and 'main' negative Carbon Isotope Excursions (CIEs) have been established relative to magnetostratigraphic, cyclostratigraphic and biostratigraphic records from the same section and hence can be correlated more readily with many TJB marine successions than can the TJB GSSP (Global Stratotype Section and Point) at Kujoch, Austria (Hillebrandt et al., 2013). However, this view is not universally held and Fox et al. (2020) have recently cast doubt on the nature of the C-isotope signal at St Audrie's Bay, North Somerset (and by inference other UK curves), attributing it to the biotic effects of sea-level change, rather than reflecting exogenous sources of carbon.

Regardless of the cause of isotope excursions, correlation of carbon isotope curves also has its issues. Sedimentation rates and the relative contributions of terrestrial and marine organic matter may vary both within and between sections (Schobben et al., 2019). Even at St Audrie's Bay several different positions have been proposed for the TJB, based upon various interpretations of the isotope profiles from the Austrian GSSP and sections in the Americas (Guex et al., 2004; Thibodeau et al., 2016, Yager et al., 2017; Wignall and Atkinson, 2020). Without clear consensus, global correlation of the TJB remains in doubt, as does the reliability of the CAMP/ETE stratigraphic framework which has depended heavily upon the St Audrie's Bay stratigraphic record. A near identical carbon isotope curve to that at St Audrie's Bay has been recorded from Doniford Bay (Clémence et al., 2010), just 2 km to the west, but few other carbon isotope data from this interval have been published from the UK except for the Mochras borehole in North Wales (Storm et al., 2020) and the Carnduff-2 borehole within the study area of this paper (Boomer et al., 2020).

In eastern Co. Antrim the uppermost Triassic (Lilstock Formation) and succeeding early Hettangian (Waterloo Mudstone Formation) succession is substantially thicker than in North Somerset (Simms and Jeram, 2007). This paper examines events recorded through this interval at several exposures on the East Antrim coast, with particular emphasis on relative sea level change, depositional environments, tectonic activity and ammonite biostratigraphy. Carbon-isotope data compiled for the Waterloo Bay section can be compared with other curves from the nearby Carnduff-2 Borehole (Boomer et al. 2020a) as well as sections in North Somerset and further afield. The stratigraphy at Waterloo Bay has been described in detail previously (Simms and Jeram, 2007) but several other coastal exposures (The Gobbins, Cloghan Point, Cloughfin Port) are described here for the first time.

2. Geological Context of the Larne Basin and Previous Research

The Larne Basin is a NE–SW trending half-graben formed by tensional reactivation of pre-existing Caledonian structures during the Permian (Anderson et al., 1995; Raine et al., 2020), bounded by the Southern Uplands Fault Zone to the south and the Highland Boundary Fault Zone to the north. The localities described here all lie towards the southern side of the basin and together provide a transect across from the centre towards the margin (Fig. 1). Cloghan Point and Cloughfin Port are located above the geophysical trace of the Southern Uplands Fault Zone, along which associated faults may have been active during deposition of the Penarth Group. Waterloo Bay lay closer to a depocentre and The Gobbins occupied an intermediate position.

Basalts of the Antrim Lava Group (Paleocene) conceal much of the basin (Fig. 1), but coastal outcrops expose a succession from the Mercia Mudstone Group (Late Triassic), through the Penarth Group (Rhaetian) and into the Lias Group (Early Jurassic). The Lias Group of the Larne Basin extends no higher than the Turneri Zone, early Sinemurian (Ivimey-Cook, 1975, Boomer et al., 2020) and is succeeded unconformably by the Late Cretaceous Hibernian Greensands Formation (Manning et al., 1970; Griffith and Wilson, 1982). Although Mesozoic rocks of the Larne Basin were, in general, little-affected by Paleocene volcanism, much of the Waterloo Bay section has been thermally altered, presumably due to a buried igneous intrusion.

The Rhaetian–Hettangian succession of southeast County Antrim was first investigated more than 150 years ago (Portlock, 1843; Tate, 1867). Drilling of the Larne-1 Borehole (Manning and Wilson, 1975; Fig. 1, inset) prompted Ivimey-Cook (1975) to review the Rhaetian and Hettangian of southeast Antrim, but poor core recovery hindered correlation with surface exposures. Reid and Bancroft (1986) established Larne as the type locality for the ammonite *Caloceras intermedium* (Portlock), figured type material of *Psiloceras sampsoni* (Portlock) from the Lough Foyle Basin and mentioned *Psiloceras erugatum* (Phillips) at Larne and Islandmagee. Simms (2003, 2007) described the Lilstock Formation (Cotham Member) seismites at Larne and Cloghan Point, both in Co. Antrim and correlated them with other sites across the UK, including St. Audrie's Bay. Waterloo Bay was designated the type section for the Waterloo Mudstone Formation (Mitchell, 2004) and proposed as a candidate GSSP for the base of the Hettangian Stage (Simms and Jeram 2007) which saw publication of the first detailed log and ammonite biostratigraphy of the boundary succession (Simms and Jeram, 2007). Stomatal abundance in plant cuticle from the sections described here has been used to assess atmospheric CO_2 concentrations (Steinthorsdottir et al., 2011), changes in the marine benthos have also been investigated (Atkinson et al., 2019, Opazo and Page, 2021) and new borehole material (Carnduff-1 and Carnduff-2) have been described and analysed (Boomer et al., 2020).

3. Lithostratigraphy of the Triassic–Jurassic Transition in SE County Antrim

Based on new information both from exposures and published work on the new boreholes (Boomer et al. 2020) the position of some lithostratigraphic boundaries indicated here differs from those identified previously (Simms 2003, 2007; Simms and Jeram, 2007). The lithostratigraphic terminology developed in south-west Britain (Warrington et al. 1980) has been applied to the Northern Ireland succession (Raine et al. 2020, 2021) but correlation is not always straightforward, particularly for the Lilstock Formation, due to facies differences and a lack of biostratigraphic markers between south-west Britain and Northern Ireland. Hence the use of common terminology in Northern Ireland and south-west Britain does not imply exact chronostratigraphic equivalence.

3.1 *Mercia Mudstone Group*

The lithostratigraphy of the Mercia Mudstone Group in Northern Ireland was defined largely from boreholes (Wilson and Manning, 1978, Mitchell, 2004). The Collin Glen Formation at the top of the group, considered equivalent to the Blue Anchor Formation of England (Warrington et al., 1980), comprises up to 10 m of pale green silty mudstone directly below the Penarth Group. At Waterloo Bay (Fig. 2) the upper ~50 m of the normally red Mercia Mudstone Group comprise pale green sediments, probably due to the effects of thermal alteration, making location of the lower boundary of the Collin Glen Formation difficult at this location. Marine palynomorphs recovered from the Carnduff-1 borehole (Boomer et al., 2020) suggest a Rhaetian age for the Collin Glen Formation.

3.2 Penarth Group

The Penarth Group is divided into the Westbury and Lilstock formations, (Warrington et al., 1980; Gallois, 2009), with its base in Northern Ireland defined by an unconformity/disconformity at the base of the Westbury Formation and its top by the base of the succeeding Lias Group (Waterloo Mudstone Formation).

3.2.1 Westbury Formation

Shallow marine lithofacies of the Westbury Formation in Northern Ireland resemble those seen elsewhere in the UK (Macquaker, 1999; Swift, 1999; Simms and Jeram, 2007), with very dark grey mudstones and shales, hummocky cross-stratified sandstones, winnowed shell and vertebrate debris lags and convex-up shell pavements. It represents a major palaeoenvironmental shift to marine conditions from the largely non-marine facies of the Mercia Mudstone Group.

3.2.2 Lilstock Formation

The base of the Lilstock Formation across the UK is marked by a change from darker facies of the Westbury Formation to paler mudstones and siltstones of the Cotham Member, the lower subdivision of the Lilstock Formation. In south-west Britain there is usually a clear distinction between predominantly siliciclastic facies in the Cotham Member and the overlying carbonate-rich Langport Member (Hallam, 1960; Swift, 1995; Gallois 2009). The Cotham Member typically contains a sparse low-diversity marine fauna, with some elements suggesting freshwater influence and in places it is capped by a stromatolite horizon known as the Cotham Marble (Hamilton, 1961). In contrast, the fauna of the overlying Langport Member is often more diverse, abundant and with stenohaline taxa such as corals and rare conodonts recorded in Britain (Swift and Martill, 1999).

In Northern Ireland the transition from siliciclastic sediments of the Lilstock Formation (Cotham Member) through to the characteristic mudstones and carbonates of the Lias Group is more gradational than the type sections in south-west Britain, hence identifying a separate Langport Member in the Larne Basin is considered problematic. The top of the Cotham Member is placed above the highest microbially laminated limestone, where ripple cross-lamination becomes rare and the first organic-rich mudstones appear. Most of the 4–6 m of mudstone-dominated sediments above the Cotham Member in the Larne Basin have a low organic carbon content, reminiscent of the ‘Watchet Beds’ (Ivimey-Cook 1975) and are therefore assigned to the Langport Member (Warrington et al., 1980).

3.2.2.1 Cotham Member

The lower part of the Cotham Member has been suggested to be a regressional shoreface equivalent of the Westbury Formation (Hesselbo et al., 2004), but towards the margin of the Larne Basin this distinctive lithofacies change may have been influenced as much by increasing accommodation space due to tectonic movement as by eustatic sea-level change. The base of the Cotham Member in Northern Ireland is placed at the junction of a fine sandstone that overlies a light grey or thinly-striped mudstone, although soft sediment deformation commonly blurs this boundary (Simms, 2003, 2007). The lower Cotham Member here is generally red-brown in colour and often intensely deformed, but changes abruptly to pale grey around the upper limit of intense soft sediment deformation. A thin hummocky, cross-stratified sandstone may truncate the deformed beds, with similar sandstone beds present up to 0.6 m higher within the grey mudstones.

The base of the upper Cotham Member here is placed at a widespread 'mud-cracked' emergence surface that has been correlated with a superficially similar surface in south-west Britain (Hesselbo et al., 2004). The upper Cotham Member, although containing coarser grained sediments, shows an overall fining-upward trend and is capped by thin micritic and microbially laminated limestones with calcareous mudstones. Small bivalves (*Eotrapezium* and *Protocardia*) occur sporadically throughout the Cotham Member in Northern Ireland (Ivimey-Cook, 1975; Opazo and Page, this issue), suggesting that Northern Ireland experienced greater marine influence than elsewhere in the UK (Swift and Martill, 1999), but the presence of conchostracans (*Euestheria*), aquatic liverworts (*Naiadita*) and freshwater ostracods (*Darwinula*) suggest schizohaline intervals.

3.2.2.2 Langport Member

The Langport Member (Warrington et al., 1980) in south-west Britain includes two dominant facies types that have, at times, been placed into their own lithostratigraphic divisions, the carbonate-dominated 'White Lias' and the fine-grained siliciclastic 'Watchet Beds' (Richardson, 1911; Gallois 2007, 2009; Hallam, 1960; Swift, 1995; Poole and Whiteman, 1966; Warrington and Ivimey-Cook, 1992). These facies are lithologically similar to the Lias Group and may, in part, be lateral equivalents (e.g. Korte et al., 2009). In Northern Ireland the Langport Member is mudstone-dominated with only subordinate siltstones and limestones, the latter probably at least partly diagenetic in origin. Limestones occur only at the base of the member in the Larne Basin but persist throughout as thin beds in the Lough Foyle Basin (Raine et al., 2021). In the Waterloo Bay section the base of the Langport Member is placed beneath Bed 8, where marine bivalves become persistent, followed by an increase in organic carbon content in Bed 9 and a coarsening-up sequence of mudstones, with thin silt laminae, capped by a bed containing gutter casts at several levels. The top of the member (Bed 14 at Waterloo Bay) is marked by an intensely-burrowed muddy siltstone, rich in bivalves.

3.3 Lias Group (Waterloo Mudstone Formation)

The Waterloo Mudstone Formation encompasses the entire Lias Group in Northern Ireland, although nowhere does this extend above the Pliensbachian Stage (Simms and Edmunds, 2021). In south-west Britain the base of the Lias Group is taken at an abrupt increase in total organic carbon (TOC) content relative to the Lilstock Formation (Hesselbo et al., 2004) and has been attributed to rapid flooding and establishment of fully marine conditions (Hesselbo et al., 2004). A similar shift in the TOC can also be seen at Waterloo Bay and so the base of the Lias Group is taken immediately beneath Bed 15 where TOC content above is consistently close to, or greater than, 1% (Fig. 3). Across much of Britain limestone-shale alternations, significantly enhanced by diagenesis, characterise the Blue Lias Formation in the lowest part of the Lias Group (Simms et al., 2004). However, in the Larne Basin they do not appear until the latter part of the Planorbis Zone, although regular alternations of shale and calcareous mudstone suggest similar rhythmic bedding. The rarity of diagenetic limestone in the Larne Basin may reflect a higher sedimentation rate than other areas where these limestone-shale successions are well-developed, such as in south-west Britain (Weedon et al., 2018).

3.4 Ammonite biostratigraphy

Ammonites are key to correlating Jurassic successions across north-west Europe (Page, *in* Simms et al., 2004) but the controls on their presence or absence at particular levels in the succession remain unclear. Planorbis Zone ammonite faunas are better preserved in Northern Ireland than elsewhere in the UK and their stratigraphic distribution here has been documented in detail from the Waterloo Bay foreshore (Simms and Jeram, 2007) and from the nearby borehole cores from Carnduff (Boomer et al., 2020), with representative material held by National Museums Northern Ireland and figured here (Figs 4 and 5).

The ammonite succession recorded at Larne (Simms and Jeram, 2007) corresponds closely with that from the Carnduff-2 borehole (Boomer et al., 2020) and documented by Bloos and Page (2000), Page (*in* Simms et al., 2004) from Great Britain. Compared with other UK surface exposures, the succession here is considerably expanded and contains abundant and well-preserved ammonites at many levels rather than at the discrete narrow horizons typical elsewhere.

4. Site descriptions

4.1 Waterloo Bay, Larne

Waterloo Bay, located on the outskirts of Larne Town, 28 km NNE of Belfast (Fig. 1), is the finest exposure of the Lias Group (Waterloo Mudstone Formation) anywhere on the island of Ireland. It is best exposed on an intertidal platform (centred on coordinates 54° 51′ 40″ N, 5° 48′ 22″ W; Irish Grid Ref. D 409 037) where strata dip at 20–30° to the NW and provide almost continuous exposure, cut by minor faults (Fig. 2), from the upper part of the Mercia Mudstone Group, through the entire Penarth Group and into the Lias Group at least as far as the lowermost Sinemurian (Bucklandi Zone), where it is truncated by a major unconformity beneath the Hibernian Greensands Formation (Cretaceous, Cenomanian). The combined Penarth Group and Lias Group exposed here is ~115 m thick (Ivimey-Cook, 1975), compared with almost 177 m in the Carnduff-2 borehole (Boomer et al., 2020). The interval between the base of the Penarth Group and the first occurrence of the ammonite genus *Caloceras* has been described in detail in several other publications (Ivimey-Cook, 1975; Simms 2003, 2007; Simms and Jeram, 2007; Boomer et al. 2020) and so only a summary of the ammonite stratigraphy is presented here. The shore and cliff lie within the Waterloo geological ASSI (Area of Special Scientific Interest), which provides legal protection for its geological heritage. Requests for permission to sample or collect from the section should be directed to the geological section of the Northern Ireland Environment Agency. National Museums Northern Ireland is the official designated repository for material collected from this site.

At Waterloo Bay ammonites first appear (and with some abundance) in Bed 24 (Fig. 3) and occur at many levels above this. Intensive searching of this section and others in Great Britain has failed to find any ammonites lower in the succession despite the recent discovery of *Neophyllites* in the White Lias (upper Lilstock Formation) of South Wales (Hodges, 2021) and an indeterminate psiloceratid in the Cotham Member of Gloucestershire (Donovan et al., 1989, Hodges 2021).

At Waterloo Bay crushed examples of *Psiloceras erugatum* (Phillips), are common in the upper part of Bed 24 and base of Bed 25 (Simms and Jeram, 2007). Above this, beds 25 to 27 are dominated by the genus *Neophyllites*, with *N. imitans* Lange (Hn3-*imitans* Biohorizon of Bloos and Page, 2000) and *N. antecedens* Lange (Hn4-*antecedens* Biohorizon) in beds 26 and 27. Some, from near the top of Bed 26 and from Bed 27, have weakly developed ribbing on inner whorls and may be *Neophyllites* ex gr. *becki* (Schmidt) (Simms and Jeram, 2007).

Psiloceras planorbis is abundant in beds 28 to 33b, with the earliest examples occur 4 cm above the base of Bed 28. *Psiloceras sampsoni* (Portlock) occurs slightly higher in the Planorbis Subzone (Hn8-*sampsoni* Biohorizon) (Bloos and Page, 2000; Page, *in* Simms et al., 2004) (Simms and Jeram, 2007). Weakly plicate ammonites, assignable to *Psiloceras plicatulum* (Hn7-*plicatulum* Biohorizon), appear towards the top of Bed 28b and persist through almost to the top of Bed 33e (Simms and Jeram, 2007). A succession of *Caloceras* faunas can be recognised in the succeeding Johnstoni Subzone at Waterloo Bay and the genus is represented by material in excellent preservation from here and, *ex situ*, from other sites in Northern Ireland (Figs 4 and 5).

4.2 Cloghan Point, Whitehead

Cloghan Point lies on the north shore of Belfast Lough, 1 km south-west of the town of Whitehead and immediately north-east of the White Harbour (Fig. 1) (54° 44′ 34″ N, 5° 43′ 4″ W; Irish Grid Ref. J 470 907). A continuous, albeit faulted, section is exposed in a low cliff and adjacent intertidal foreshore from near the top of the Mercia Mudstone Group to the base of the Lias Group (Fig. 6a–c). The Cotham Member, briefly described in Simms (2007), is well exposed in the cliff with the Westbury Formation and uppermost beds of the Mercia Mudstone Group seen on the shore north-east of the slipway and the Langport Member to the south-west (Figs 6d–f). The Westbury Formation – Cotham Member boundary often is obscured by shingle (Fig. 6c). Green-grey conchoidally-weathering siltstones beneath the Westbury Formation here are lithologically identical to the underlying red Mercia Mudstone Group and lack the obvious bedding apparent at Waterloo Bay, suggesting that the Collin Glen Formation here may have been eroded and the green-grey siltstone merely represents a secondary reduction zone beneath the Westbury Formation.

The outcrop is cut by NNW–SSE and WNW–ESE faults, with vertical throws of 1–5 m. Bed thickness variations and minor slumping at the tops of calcareous siltstone beds in the upper Westbury Formation suggest synsedimentary fault movement prior to shallow burial cementation (see Macquaker, 1999). Wave-rippled sandstones up to about 0.5 m thick, with siltstone and mudstone partings, occupy the lowest Cotham Member. The unfossiliferous sandstones contain intraclasts of Westbury Formation mudstone that become more common towards the faults, where soft-sediment deformation also is more intense (Fig. 6d). Succeeding beds are mudstone-dominated, with subordinate lenticular/wavy-bedded grey siltstones. The chocolate-brown to red-brown mudstones show regular lamination, with each mudstone lamina (mm to cm) separated from the next by a silt parting <1 mm thick; these are the 'striped measures' of Ivimey-Cook (1975). Small *Isocyprina* and *Protocardia* occur sparsely at some levels, with the conchostracan *Euestheria minuta* (Zieten) present in the upper half of the brown mudstones. Bioturbation and trace fossils are largely absent, with only *Lockeia* recorded. Soft-sediment deformation occurs throughout the red-brown mudstones, increasing in intensity towards a fault (Fault B in Figure 6b, f). Its upper limit coincides with a change from red-brown to grey mudstones and the highest deformed bed is truncated by an impersistent green-grey lenticular sandstone, up to 0.1 m thick, with low-angle hummocky cross stratification, small flute casts and linear tool marks on its base.

The succeeding upper Cotham Member comprises ~1.5 m of grey laminated mudstone with thin cross-laminated sandstone/siltstone lenses in the lower part, succeeded by 2 m of laminated mudstone and marl interbedded with eight cream-weathering micritic limestones up to 16 cm thick (Fig. 6a, c). Most limestones are laminated but contain thin stromatolitic crusts with scours and laminae of reworked stromatolitic debris and silt, with a more substantial stromatolite bed up to 4 cm thick developed at 0.4 m below the top of the limestone series. The macrofauna comprises occasional microgastropods, juvenile bivalves (?*Isocyprina* sp.), fish scales and a single bedding plane of *Euestheria* fragments in a laminated limestone one metre below the top. Microfossils recovered from the limestones include the euryhaline ostracod *Darwinula* sp., the aquatic liverwort *Naiadita* and diverse insect remains. Chironomid midges are especially abundant and represented by all stadia from eggs to adults, with larval and adult head capsules extremely abundant in some samples but absent in others and further investigation of the insect remains from this interval is required.

The highest limestone in the cliff is 0.25 m thick and is more massive and argillaceous than those below. It lacks obvious sedimentary structures and grades into grey calcareous mudstone below and dark grey shaley mudstone above, the latter probably equivalent to Bed 9 at Waterloo Bay. The marine bivalve *Protocardia* is present in all three units. The base of the Langport Member is placed immediately beneath this dark mudstone which, on the shore south of the slipway, is succeeded by half metre of dark grey mudstones (Fig. 4b), with occasional bivalves and a further >3 m of alternating siltstone and mudstone. Bivalves, particularly *Protocardia* and *Liostrea*, occur in the burrow-mottled lower 2 m, with *Thalassinoides* and *Diplocraterion* burrows abundant in the upper part. Micaceous siltstone and silty mudstone alternations dominate the next metre, with bivalves confined largely to convex-up shell pavements on top of some siltstone beds. Dark grey, shaley mudstone above a hard calcareous and micaceous siltstone, 0.2 m thick, is taken as the base of the Waterloo Mudstone Formation here and probably correlates with Bed 14 at Waterloo Bay. A temporary excavation a little further up the slope exposed shaley mudstones with crushed *Neophyllites* of the Planorbis Subzone.

4.3 Cloghfin Port, Islandmagee

Cloghfin Port (54° 46′ 29″ N, 5° 41′ 39″ W; Irish Grid Ref. J 484 943) lies at the southern end of the Islandmagee peninsula, 2.4 km NNW of Whitehead (Figs 1, 7). The foreshore outcrop dips at <10° to the south-west and is truncated to the south by a NW–SE fault that downthrows Cretaceous strata (Hibernian Greensands Formation) to the south. As at Cloghan Point, 3.7 km to the south-east, two sets of minor faults cutting the Triassic have NNW–SSE and WNW–ESE trends that are repeated by intense minor fracturing, down to mm-scale, in Westbury Formation sandstone beds adjacent to some faults (Fig. 7), but they are not evident in the overlying Cretaceous cover. This soft-sediment and semi-brittle deformation adjacent to faults indicates a discrete phase of seismicity during deposition of the upper Westbury Formation, prior to that evident in the succeeding Cotham Member. Around 2 m of contorted grey and light brown coloured mudstone and silty mudstone of the lower Cotham Member are exposed above a thin basal sandstone, also strongly contorted. The upper Cotham Member is poorly exposed but includes undeformed pale grey mudstones with silt laminae and convex-up shell pavements of *Protocardia* and several limestone beds similar to those at Cloghan Point (Fig. 8). As at Cloghan Point green-grey conchoidally-weathering siltstones beneath the Westbury Formation here are lithologically identical to typical red Mercia Mudstone Group from which they are separated by a transitional ‘mottled zone’. It suggests that here too, as at Cloghan Point, the Collin Glen Formation may be missing.

The main exposure of the Westbury Formation here resembles a shallow syncline with its eastern side bounded by a NNW–SSE fault. Sandstone beds in the lower part of the Westbury Formation thicken and merge towards the centre of this ‘syncline’, but small drag folds in mudstones adjacent to the fault suggest that this ‘syncline’ actually represents enhanced sediment accumulation within a small graben or half-graben. Higher in the Westbury Formation several fine-sandstone/siltstone beds and mudstone partings form erosion-resistant ledges. The lowest of these (Bed L, Fig. 7), with regular repetitions of 0.5–1.0 cm thick planar siltstone laminae topped with convex-up shell pavements and sand or mudstone partings, forms a useful marker horizon at outcrop and in boreholes throughout the region (Boomer et al. 2020). Succeeding siltstones vary in number and thickness, perhaps reflecting synsedimentary fault movement. They are usually bioturbated in their upper part and commonly contain small slump structures.

Several minor faults appear to have propagated to the sediment surface at or near the end of Westbury Formation deposition to create an irregular topography that was subsequently eroded. Consequently, the Cotham Member basal sandstone rests on different stratigraphic levels within the Westbury Formation across the outcrop (Fig. 7) yet it is relatively uniform in thickness and not offset by these faults. The highest part of the Westbury Formation seen here (Fig. 7, sections 4 and 5) comprises contorted 'pinstriped' mudstones with very thin black, white and grey laminae, as at Cloghfin Port, indicating that the full thickness of the Westbury Formation is locally represented here. This 'pinstriped' lithofacies, unique within the Westbury Formation, may reflect background sedimentation of pale mud alternating with erosive episodes that released darker mudstone from nearby fault blocks.

Westbury Formation mudstones are intensely disturbed by soft-sediment deformation or liquefaction adjacent to the NNW-SSE trending fault, with thin sandstone stringers contorted or completely disrupted into irregular patches of sand. Sandstone beds more than 1 cm thick are largely intact but show brittle deformation, with two sets of fracture orientations matching those seen at larger scales across the outcrop. It suggests at least partial cementation by the time of their deformation, yet liquefaction of the enclosing mudstone suggests a shallow burial depth of just a few metres. Deformation appears to be related directly to movement on the NNW–SSE fault simultaneous with activity on the WNW–ESE faults.

4.4 The Gobbins, Islandmagee

A composite succession from the upper Cotham Member through into the Johnstoni Subzone of the Waterloo Mudstone Formation (Lias Group), mostly with a dip of about 10–15° NW, is patchily exposed on the shore along the landslipped eastern side of Islandmagee, about one kilometre south of The Gobbins and 4 km NNW of Whitehead, (54° 47′ 53″ N, 5° 41′ 29″ W; Irish Grid Ref. J 485 969) (Fig. 1). These exposures, although not previously described, are significant because all biohorizons of the Planorbis Subzone and basal Johnstoni Subzone are present in mudstones that have not been thermally metamorphosed. The northern end of the outcrop is also the source of the only dinosaur remains yet found in Ireland (Simms et al., 2020). The exposures are described here from south to north and the succession summarised as a composite log and correlated with the other exposures in Figure 8.

In the most southerly exposure, Section 1 (54° 47′ 31″N, 5° 41′ 33″ W; Irish Grid Ref. J 4845 9622), ~2 m of light grey calcareous mudstone and shale, with thin shelly bands containing abundant *N. antecedens*, are exposed at the top of the beach. These beds lie above 0.3 m of very shelly calcareous mudstone, its top covered with crushed *Neophyllites imitans*. This interval correlates with beds 25–27 at Waterloo Bay. *Ex-situ* carbonate nodules containing *P. erugatum* have been found on the shore nearby, while slipped material nearby includes blocks of dark shale containing crushed *P. planorbis*. A few metres higher and to the north, *P. sampsoni* and *P. plicatulum* have been found in situ, with *Caloceras* sp. recovered from a mudflow higher on the bank.

Landslip obscures the outcrop until Section 2 is reached (54° 47′ 35.5″ N, 5° 41′ 29.4″ W; Irish Grid Ref. J 4851 9635), where the 'pre-planorbis' beds are exposed for about 40 m along the intertidal area. Two hard limestone bands exposed near low water mark, each 5–6 cm thick and with contorted 'clasts' of mudstone and discontinuous mudstone partings, correlate with shelly limestone beds near the base of the Waterloo Mudstone Formation at Waterloo Bay (Bed 18). Softer contiguous beds are obscured by shingle, but ~0.6 m of finely interbedded siltstone and micaceous mudstone, with 3 or 4 thin impersistent limestone ribs towards the top, are exposed further down-dip and probably correlate with Bed 21 at Waterloo Bay. It is succeeded by ~0.7 m of dark grey micaceous mudstone, calcareous in the top 0.2 m. Above this lies 3 m of paler micaceous mudstone with bands of *Liostrea* in its lower part and an impersistent lenticular shelly limestone, up to 8 cm thick, at its top. Abundant thick-shelled *Cardinia ovalis* (Stutchbury) allow tentative correlation of this limestone with Bed 23 at the Waterloo Bay section. Higher beds are represented by a small, isolated exposure beneath the cliff where ~1 m of grey calcareous mudstone, with two 0.25 m thick shelly beds, has yielded indeterminate ammonite fragments suggesting they may correlate with beds 24 and 25 at Waterloo Bay.

Section 3, further down-dip (54° 47′ 37.4″ N, 5° 41′ 29.9″ W; Irish Grid Ref. J 4850 9641), a section exposes more than 6 m of Waterloo Mudstone Formation along some 20 m of the upper foreshore and adjacent low cliff. The lower part of the succession is dominated by dark shaley mudstones with subordinate calcareous mudstones and pyritic bands. Higher beds tend to be paler mudstones and include several orange-weathering siltstone bands with abundant *Chondrites* burrows. *Psiloceras planorbis* occurs in the lowest beds, succeeded by *P. sampsoni* (1.0 m above base), *P. plicatulum* (1.5–2.5 m above base), *Caloceras* cf. *johnstoni* (4.3 m above base) and *Caloceras* sp. indet. (4.9 m above base), with individual units here correlating with beds 28–34 at Waterloo Bay (Simms and Jeram 2007). A few metres below this exposure, in the intertidal zone, two small isolated outcrops each expose ~0.5 m of grey mudstone, with the stratigraphically higher containing crushed *Neophyllites* ?*antecedens* and the lower containing *Neophyllites* sp. fragments.

Section 4 (not shown on Figure 8) is located ~200 m south of the start of The Gobbins cliff path and north of a rotational slip that brings Ulster White Limestone Formation (Cretaceous, Chalk Group) down to beach level (54° 47′ 53.9″ N, 5° 41′ 26.1″ W; Irish Grid Ref. J 4855 9692). It exposes ~2 m of pale grey laminated mudstone with several cream-coloured limestones that clearly correlate with those in the upper Cotham Member, as seen at Waterloo Bay and Cloghan Point. The outcrop here dips to the south-west, unlike those further to the south that dip north-westwards, suggesting that they may lie either side of a synclinal axis orientated NE–SW.

5. Triassic–Jurassic boundary events in Northern Ireland

5.1. Carbon stable-isotope excursions

The succession at Waterloo Bay was sampled for geochemical analysis at 10 cm intervals from 0.5 m below the ‘mud-cracked’ horizon of the Cotham Member (0 m in Fig. 3) up to the first frequent occurrence of *P. plicatulum* at the top of Bed 28b (159 samples) (Fig. 3). This sampling resolution is at least twice that for the same interval in the nearby Carnduff-2 borehole (Boomer et al., 2020) and substantially greater than that for St Audrie’s Bay (Hesselbo et al., 2002). Lower strata in the Penarth Group were not sampled because of more intense thermal alteration and/or soft-sediment deformation. Geochemical analyses were undertaken at the University of Oxford. Bulk organic $\delta^{13}C$ values (‰), calibrated relative to the Vienna-Pee Dee Belemnite

(VPDB) standard. Total organic carbon (TOC) percentage and % $CaCO_3$ were measured in samples and are shown in Figure 3 beside the isotope data.

The carbon stable-isotope curve shows a broad pattern of positive and negative trends comparable with those identified from south-west England (Hesselbo et al., 2002, Clémence et al., 2010) and the Carnduff-2 borehole (Boomer et al., 2020). The expanded stratigraphy and greater sample density at Waterloo Bay produced a curve where the 'excursions' appear more gradual and less pronounced than those for south-west England, but with additional minor fluctuations that are not resolvable in these more coarsely sampled successions. A drop in $\delta^{13}C$ values around Bed 10 at Waterloo Bay can be correlated with the top of the 'initial' negative CIE of Hesselbo et al. (2002) and the interval between beds 2 and 10 shows four oscillations in $\delta^{13}C$ of ~ 2–3‰. Similar oscillations are seen in Hungary (Pálfy et al., 2007) and Morocco (Dal Corso et al., 2014) and also in the nearby core from Carnduff-2 (Boomer et al., 2020, figure 10B) but they are not evident in the coarsely sampled curves of north Somerset. A return to more positive values precedes another negative excursion, around beds 21 and 22a, which corresponds to the start of the 'main' negative CIE (Fig. 3). The negative trend in $\delta^{13}C$ is mirrored by a corresponding slight positive trend in TOC (Fig. 3).

It has been shown in sections from Denmark that sharp negative spikes in the carbon stable-isotope record correspond to peaks in algal sphaeromorph abundance (Lindström et al., 2012) and Bonis et al. (2010) argued that the palynological record at St Audrie's Bay reflected the influence of orbitally forced climate cyclicity on the input and composition of organic matter into the system, and there is a striking relationship between isotope values and palynological composition of samples from Germany (van de Schootbrugge et al., 2013). However, in the absence of palynological records from Waterloo Bay it is difficult to explore these relationships. Palynological samples were collected by Simms and Jeram (2007) but they were too thermally altered to be useful and only sparse palynological records have been published from the nearby Larne-1 Borehole (Warrington and Harland, 1975). Further palynological sampling and analysis from the Carnduff-1 Borehole, <3 km distance (Boomer et al., 2020) could be carried out explore the relationships between carbon isotope excursions and palynology in the Larne Basin, where the stratigraphy is relatively expanded. Some of the minor variations in the Waterloo Bay stable-isotope record may have similar climate cycle causes, although Fox et al. (2020) have claimed that the 'initial' CIE is a consequence of ecological and biotic changes linked to marine to non-marine changes, associated with eustatic sea-fall, rather than reflecting input of light volcanogenic carbon. Implications of the Waterloo Bay stable-isotope record for wider correlation are discussed in sections 6.1 and 6.2.

5.2. Depositional setting

Marine indicators in parts of the Collin Glen Formation of the Carnduff boreholes (Boomer et al., 2020) record the initial stages of a diachronous onlap associated with the basal Rhaetian transgression (Mayall, 1981; Hesselbo et al. 2002; Barth et al., 2018). The Westbury Formation was deposited in a relatively shallow, storm influenced, offshore marine environment, with winnowing and re-suspension of mud perhaps discouraging benthic colonization (Hesselbo et al. 2004, Barras and Twitchett, 2007). Six or seven sedimentary cycles can be recognised in the studied sections in the Larne Basin, with sand/silt dominated sediments alternating with mud. Synsedimentary fault control, similar to that seen at Cloghfin Port, may have influenced the number and thickness of individual sandstone beds in the Westbury Formation and the thickness of the unit across the basin. Although evidence for shallowing of facies in the upper Westbury Formation is reported from southern Britain (Hesselbo et al., 2004) in Northern Ireland black pyritic shaley mudstones persist to the top of the formation in most parts of the Larne Basin studied. The upper boundary of the Westbury Formation however corresponds to a period of erosion, either through tectonic uplift or eustatic sea-level fall and possibly post-deposition of the Westbury Formation, with pronounced erosion of the formation top toward the margin of the Larne Basin. Soft sediment deformation in the lower Cotham Member (Simms, 2007; Laborde-Casadaban et al., 2021), discussed in Section 6.3, also affected the upper part of the Westbury Formation. It may have been linked with minor (metre-scale) tectonic uplift, but renewed transgression above the soft sediment deformed beds and into the lower part of the Langport Member is evident in all sections.

Silty mudrocks of the lower Cotham Member mark an abrupt change (Fig. 9a) from a relatively offshore situation to very shallow water, with a scarcity of trace fossils or bioturbation and marine bivalves suggesting rapid deposition and/or fluctuating salinity. No consistent fining- or coarsening-up pattern is seen above the Cotham Member basal sandstone and individual units cannot be correlated easily between outcrops. It is difficult to construct a facies model for the Cotham Member from the limited exposures studied here, but flooding of the NW European epicontinental seaway and a subsequent regression, may have produced a series of islands among shallow quasi-marine seaways over a vast area (e.g. see figure 1 in Lindström et al., 2015). Tidal currents, influenced by the location and disposition of land masses and eustatic effects (Reynaud and Dalrymple, 2012), probably were complex and locally variable. As such, the Cotham Member in the Larne Basin may represent a continuously changing mixed system, at times showing sedimentological features of estuarine, tidal flat, shallow shoreface, or lagoonal deposits, but without the clear facies associations characteristic of any of them. For the most part, the heterolithic facies of the Lower Cotham Member exhibit features that indicate deposition on shallow subtidal flats. The lower Cotham Member at Waterloo Bay has a higher content of fine sand and silt than at Cloghan Point or Cloghfin Port, suggesting a more offshore subtidal setting in which stronger tidal currents pushed mud further inshore. A weak fining-up trend is discernible, perhaps a result of shoaling or shallowing due to eustatic sea-level fall towards the 'mud-cracked' horizon. The succession appears to have been laid down under generally quiet peritidal conditions, with frequent evidence of rhythmic bedding (Fig. 9c-d), channel erosion (Fig. 9c), and ripples containing internal mudstone drapes (Fig. 9b). Scours are present at various levels above and below the 'mud-cracked' surface, attesting to intermittent storm-related erosion, and a few thin sandstone beds contain very low angle hummocky cross stratification. Other thin sandstone bodies are comprised of unidirectional cross-stratified sandstone, with multiple reactivation surfaces.

Fox et al. (2020) have suggested that algal biomarkers from the upper part of the Cotham Member (across the ‘initial’ CIE) at the St Audrie’s section indicate deposition within very shallow waters that received an influx of fresh and brackish water due to a marked relative sea-level fall. They proposed that the drop in sea-level could result from rising of hot asthenosphere that caused doming of the crust and uplift of the European basins, or closure of marine gateways into the already restricted European basins, or eustatic sea-level drop due to polar ice growth resulting from CAMP related SO_2 emissions. Sedimentation following an event such as this would be less connected to eustatic change and more reliant on climate, water chemistry and facies shoaling and progradation.

The ‘initial’ CIE in the Larne Basin starts immediately below the Cotham Member carbonates and peaks immediately above it (Fig. 3), coinciding with a change in the marine flora from dinoflagellate-dominated in the Westbury Formation and lower Cotham Member, to acritarch/prasinophyte-dominated assemblages above in the Carnduff-1 Borehole (Boomer et al., 2020). In Northern Ireland, where the upper boundary of the Cotham Member is somewhat gradational and the upper part of ‘initial’ CIE seems to extend into the lower Langport Member, the return to more fully marine conditions may be better preserved or be more expanded.

Minor shallowing in the early Langport Member coincides with the end of the ‘initial’ CIE while higher beds show a gradual diversification of the marine fauna (Ivimey-Cook, 1975; Simms and Jeram, 2007) and development of lenticular bedded siltstone and silty mudstone indicative of slightly deeper water sedimentation, perhaps as sub-littoral, storm-generated sheet deposits. There is no evidence for erosion at the top of the Langport Member here and higher parts of the member elsewhere in SE County Antrim suggest relative environmental stability compared with beds above and below, as indicated by minimal variation in % organic carbon or % carbonate and relatively little fluctuation in the $\delta^{13}C$ record (Fig. 3).

The base of the Waterloo Mudstone Formation marks a flooding event (Fig. 10), with fully-marine offshore conditions rapidly established followed by transgression to an early Planorbis Zone highstand, before a eustatic fall towards the top of that zone (Simms and Jeram, 2007; Barth et al., 2018). This may have been associated with hypoxia below storm wave base and corresponds to the most positive $\delta^{13}C$ values immediately prior to the onset of the ‘main’ carbon stable-isotope excursion and high TOC (Figs 3, 10), similar to the excursion at the lower/upper Cotham Member junction.

5.3. Seismic events

The intense soft sediment deformation in the lower Cotham Member at Waterloo Bay and Cloghan Point was initially ascribed to the effects of a single large magnitude seismic event (Simms, 2003, 2007), but similar deformation in the upper Westbury Formation testifies to several episodes of pre-Cotham Member seismic activity (Fig. 10) (see also Laborde-Casadaban et al., 2021; Lindström et al., 2015). Seismic shock need not be the only cause of soft-sediment deformation and it should be acknowledged that the typical Cotham Member mudstone-siltstone facies (Fig. 9) would be particularly susceptible, but the uniformly low gradients of the Rhaetian environment across much of the UK and a lack of comparable deformation in contiguous strata of similar facies, suggests that other mechanisms, such as gravity sliding, can be discounted in this instance.

The sandstone at the base of the Cotham Member is undeformed in some places, such as Cloghan Point, but at Waterloo Bay it is highly contorted, locally intrudes up to 0.15 m into the underlying Westbury Formation, and is overlain by highly-contorted sandstone-mudstone interbeds (Fig. 9a). The overlying Cotham Member contains a strongly deformed horizon, which exhibits intermittent recumbent folding where alternations of silt and clay make it visible, but deformation occurs within the more argillaceous intervals also (Laborde-Casadaban et al., 2021). Supposed tsunami 'rip-up clasts' towards the top of the most intensely deformed beds at Larne (Simms 2003, 2007) probably represent 'pseudo-nodules' of more-cohesive sediment that failed to liquefy under the lower pore pressures at the top of the seismite. Similar features have been recorded from Rhaetian strata by Lindström et al. (2015, figure 2D).

Overlying the deformation a 'mud-cracked' surface at Waterloo Bay (Fig. 11a–c) has been interpreted as evidence for emergence (Simms, 2003, 2007) but these cracks lack the 90° T-junctions characteristic of desiccation cracks (Goehring, 2013), with intersection angles for many of less than 45° and cross-cutting relationships that may involve up to four generations of cracks. Most are less than 10 cm deep, yet some narrow cracks run straight for more than 1.5 m, whilst spindle-shaped cracks may be curved, taper rapidly in either direction, or lack intersections (Fig. 11a). In vertical section most are at low angles to the bedding, ptygmatic and usually without sharp sides. They often change angle abruptly and/or branch (Figs 11b-c), commonly show sub-surface crack intersections and some appear to have been secondarily deformed by horizontal compression and shear. Together these features are suggestive of subaqueous sedimentary, or synaeresis, cracks (*sensu* McMahon et al. 2016) rather than subaerial desiccation cracks. Synaeresis cracks require a cohesive substrate susceptible to brittle deformation (McMahon et al., 2016) and may have been seismically induced (Pratt, 1998), although salinity changes or gas formation have been proposed as alternative mechanisms (e.g. McMahon et al., 2016; Siebach et al., 2014). The Waterloo Bay cracks were clearly initiated at or near the sediment surface, perhaps implying brief emergence and drying to confer a degree of cohesiveness on otherwise unconsolidated mud, but they are overlain by a thin lenticular sandstone with interference ripples that suggest shallow subtidal or intertidal deposition. Although this cracked surface is unique within a 6 m succession of similar facies, it seems probable that the 'mud-cracked' surface and at least one of the underlying deformed intervals may stem from the same seismic event. Correlation of these surfaces within the UK (Mayall, 1983; Simms, 2007; Laborde-Casadaban, 2021), and a similar synaeresis-cracked surface in the Schandelah-1 core of the Germanic Basin (Lindström et al., 2015, 2017), is indicated by their position immediately below the start of the 'initial' CIE (Fig. 3). Whether these features relate to a series of different seismic events across separate basins that due to sediment characteristics or water column depth were expressed in the same way or one single seismic event remains unclear.

The 30 cm thick bed of wave-rippled sandstone/mudstone heterolith that overlies the 'mud-cracked' horizon undulates gently (wavelength of ~1 m and amplitude of ~0.05 m) but is cut by narrow sub-vertical fracture zones, resembling kink bands, that are associated with contorted bedding (see Moretti and van Loon 2014, figure 2, for a modern example). These deformation zones cannot be traced into contiguous beds and perhaps formed through hydrofracturing. Its presence above the 'mud-cracked' horizon suggests further seismic activity in the upper Cotham Member.

6. Discussion

6.1 Correlation of the Waterloo Bay section with Somerset (St Audrie's and Doniford bays)

Correlation has been attempted many times between the St Audrie's Bay record and the GSSP in Kuhjoch, Austria and there still remains some uncertainty as to the precise level of the TJB in the GB curves (Wignall and Atkinson, 2020). Correlating the succession in Northern Ireland with that in North Somerset, more than 400 km to the south-east, may assist correlation with the Austrian GSSP 1600 km to the south-east of Waterloo Bay, Larne (Fig. 12). Northern Ireland and Somerset share some lithostratigraphic events which, if synchronous rather than diachronous, may aid correlation between those sites and with the GSSP. The carbon isotope profile from Waterloo Bay offers significantly finer resolution than published data from south-west Britain and corroborates the first-order trends seen in other curves from the UK.

The Westbury Formation is broadly similar across the UK, with its top marked by a relative sea-level fall presumed to be a regional event. The succeeding Cotham Member also is fairly uniform in lithology and fauna across the UK and includes an apparently synchronous period of seismically-induced soft-sediment deformation in its lower part and stromatolitic horizons both in south-west Britain and in Northern Ireland. The 'initial' CIE of Hesselbo et al. (2002) lies above the 'mud-cracked' horizon found in many parts of the UK, supporting a correlation, but the finer resolution and expanded stratigraphy in County Antrim also suggest that the upper part of the 'initial' CIE may be attenuated or truncated in south-west Britain, where the top of the Cotham Member is represented by the locally developed stromatolitic Cotham Marble (Hamilton, 1961), a bed that is in some locations bored and eroded at the base of the Langport Member (Richardson, 1911; Swift, 1995; Benton et al. 2002). In County Antrim the lower part of the excursion coincides with microbially laminated limestones, claystones and a thin stromatolitic limestone, that together are perhaps broadly equivalent to the Cotham Marble. The peak of the excursion at Waterloo Bay lies in higher beds that can be correlated lithologically with the lower Langport Member of the Bristol Channel Basin. Boomer et al. (2020) recorded the peak of the 'initial' CIE near the top of the Cotham Member in the Carnduff-2 Borehole, sited just 3 km south west of the Waterloo Bay section.

As a lithostratigraphic unit the Langport Member may not be isochronous across the UK. Comparing $\delta^{13}C$ data from the key sites of Lavernock Point in south Wales, Pinhay Bay in Devon, (Korte et al., 2009, figure 6) and St. Audrie's Bay in Somerset (Hesselbo et al., 2002, 2004) suggests that much of the Langport Member at Lavernock Point and Pinhay Bay may correlate with part of the basal Blue Lias Formation at St. Audrie's Bay (Figs 10 and 12). Cyclostratigraphy also suggests that the base of the Blue Lias Formation may be diachronous (Weedon et al. 2018, figure 14). Similarly, if a minor (1.5‰) negative shift in $\delta^{13}C$ at 1.8 m above the base of the Langport Member at Waterloo Bay (base of Bed 13, Fig. 3) does correlate with the minor negative shift at the base of the Blue Lias Formation in St Audrie's and Doniford bays (marked 'C' on Fig. 12), then the base of the Blue Lias Formation at St Audrie's Bay may be older than elsewhere. Hence the upper Langport Member at Lavernock Point and Pinhay Bay, and beds 13 and 14 of the Langport Member at Waterloo Bay, may be lateral, possibly shallower water, equivalents of the basal Blue Lias Formation on the North Somerset coast. If correct, then this implies that the organic-rich mudrock that commonly lies at the base of the Lias Group in the UK may also be diachronous, implying that anoxia developed at different times depending on water depth or sedimentation rates (Hesselbo et al., 2004; Korte et al., 2009).

Above the base of the Lias Group the carbon isotope curves at St Audrie's and Doniford bays are near identical while that of Waterloo Bay is broadly similar but shows more detail and irregularity due to the higher sampling resolution (Fig. 12). In fact the expanded stratigraphy and greater sampling resolution of the isotope curve at Waterloo Bay presents its own issues with regard to correlating peaks against those of less highly resolved records. Comparison can also be made with the curve from the Carnduff-2 borehole (Boomer et al. (2020), <3 km from the Waterloo Bay section, which although of lower resolution offers greater coverage of the stratigraphy by sampling the entire Penarth Group and extending to higher levels in the Lias Group.

A gradual decline at the start of the 'main' CIE in all four curves steepens towards the first negative trough beyond which the first minor positive peak (Peak A in Figure 12), evident in the Waterloo Bay and Doniford Bay curves, but more subtle in the Waterloo Bay curve and appears to be shown in the Carnduff-2 curve (Boomer et al. 2020, figure 10). The next positive peak seen in the Doniford Bay curve may represent an average of three small peaks in the Waterloo Bay curve (B in Fig. 12), with *P. erugatum* in the succeeding negative trough at both sites lending support to this correlation. Neither peak nor trough can be resolved in the more coarsely sampled and condensed succession at St Audrie's Bay although *P. erugatum* is present at this level and it is not observed in the coarsely sampled interval in the Carnduff-2 data (Boomer et al., 2020). Minor positive peaks, corresponding to the first appearances of *P. planorbis* and *P. plicatulum*, can also be matched between Waterloo Bay and the two curves in Somerset (Fig. 12), although the stratigraphic occurrence of these ammonites is the main factor in verifying this correlation. It should be noted that in Figure 12 the blue shading used to indicate the 'initial' and 'main' carbon stable-isotope excursions *sensu* Hesselbo et al. (2002) marks the primary negative trend of each excursion only and not the ensuing positive trend. Hesselbo et al. (2002) did not define an upper limit to the 'main' CIE and so, for the purposes of discussion comparison with other carbon isotope records, the 'main' CIE is restricted here to the rapid 3.5–4.0‰ decline in $\delta^{13}C$ that follows the positive excursion seen at the base of the Blue Lias Formation at St Audrie's Bay (Fig. 12). At Waterloo Bay and the two sites in Somerset the rapid $\delta^{13}C$ decline is interrupted near its top by a minor positive excursion (peak A in Fig. 12) above which $\delta^{13}C$ values decline to a minimum that can define the top of the 'main' negative CIE and above which there is a slight positive trend up to the first appearance of *P. planorbis*. This trend lies within a sample gap in the Carnduff-2 record, but its likely position constrained by peak negative values slightly shallower than the base of the *plicatulum* Biohorizon at 345 m depth (Boomer et al., 2020).

6.2 The Triassic–Jurassic boundary in Northern Ireland

The Triassic–Jurassic boundary (TJB) has been defined by the first occurrence (FO) of *Psiloceras spelae tyrolicum* Hillebrandt and Krystyn, in the GSSP at Kuhjoch, Eiberg Basin of Austria (Hillebrandt et al., 2013). This ammonite taxon has not been found in NW Europe nor can it be readily correlated with any of the early Hettangian ammonite biohorizons recognized in the region. In NW Europe, the base of the Planorbis Zone is drawn below the *imitans* Biohorizon (Hn3) (based on *N. imitans*) and the underlying strata, that includes the *erugatum* Biohorizon (Hn2) (based on *P. erugatum*) down to the base of the Hettangian Stage, now assigned to the Tilmanni Zone (Page, 2010; Hillebrandt et al., 2013; Weedon et al., 2019). Only three ammonites have been found below the Hn2 Biohorizon in the UK (Opazo and Page, 2021), with all of Late Triassic age. A single indeterminate psiloceratid, reportedly from the top of the Westbury Formation in Gloucestershire (Donovan et al., 1989), is actually from near the base of the Cotham Member (Hodges, 2021). More recently two ammonite specimens described as *Neophyllites lavernockensis* Hodges have been found in the White Lias (Langport Member) of South Wales (Hodges, 2021).

With such a dearth of biostratigraphically useful ammonite or other macrofossil taxa, low abundance and/or poor recovery of calcareous microfossils and lack of diagnostic marine marker palynomoprhs in this interval; in Northern Ireland (Boomer, et al., 2020) carbon isotope excursions offer perhaps the best potential for correlating the TJB to this region, but current resolution of the isotope data allows for more than one possible correlation.

The ammonite-defined Triassic–Jurassic boundary in the Eiberg Basin, Austria has been correlated with three different levels in the St Audrie's Bay succession, each of which in turn can be correlated with the more finely resolved Waterloo Bay carbon stable-isotope curve (Fig. 12).

The inflection in the 'main' CIE, shown as Level 1 in Figure 12, offers one possible correlation to the TJB level in the GSSP (Kürschner 2007; Hillebrandt et al., 2007) and has been accepted in several subsequent publications (e.g. Simms and Jeram, 2007; Ruhl et al., 2009, Whiteside et al., 2010; Ruhl and Kürschner, 2011; Steinthorsdottir et al., 2011; Jaraula et al., 2013; Hüsing et al., 2014; Dal Corso et al., 2014; Kent et al., 2017). It places the TJB above the start of the 4‰ 'main' negative CIE at St Audrie's Bay (Hesselbo et al., 2002) but others (Guex et al., 2004; Clémence et al., 2010; Bartolini et al., 2012) have correlated the first occurrence of *P. spelae* in Nevada with a level below the start of the 'main' CIE. Correlating the TJB to Level 1 would, therefore, imply that the first occurrence of *P. spelae* in North America might be earlier than that of *P. spelae tyrolicum* in Austria (Ruhl et al., 2009; Korte and Kozur, 2011). However, since *P. spelae* occurs only within restricted stratigraphic intervals separated from other psiloceratid occurrences by strata barren of ammonites, this apparent time gap may be an artefact of preservation.

Two biotic events of potential correlative value between Level 1 and the TJB are the first occurrence of *Isocrinus angulatus* 1 m above the base of Bed 22a at Waterloo Bay (Simms and Jeram, 2007; Hillebrandt et al., 2013; Simms, 2021) and the flood appearance (one sample showing a ten-fold increase in abundance) of the robertininid foraminifera *Reinholdella*? *planiconvexa* (Fuchs) in the Carnduff-1 Borehole at a level which correlates to Bed 22b at Waterloo Bay (Boomer et al., 2020). This flood of foraminifera is an event that can be widely recognised, including in the Lough Foyle Basin of Northern Ireland (Raine et al., 2021), at Doniford Bay in Somerset (Clémence and Hart, 2013), and possibly also in Austria Hillebrandt et al., (2013), although more work is required on the taxonomy of the UK examples. Although both events may have been environmentally controlled, nevertheless, they maintain a remarkable relationship to each other and to the carbon isotope stratigraphy (Fig. 12).

Correlation at Level 2 (Fig. 12) has been suggested by Ruhl and Kürschner (p. 193 and figs 18–19 in Hillebrandt et al., 2013) who considered that the FO of *P. spelae* in the Austrian GSSP section lay within the 'main' CIE. However, comparing data from the GSSP, St Audrie's Bay and New York Canyon (Nevada) offered an alternative interpretation (fig. 27 of Hillebrandt et al., 2013) and correlated the 4‰ negative excursion above the 'Schattwald Beds' of the Tiefengraben Member with a minor 1.6‰ shift at the base of the Blue Lias Formation in St. Audrie's Bay (C in Fig. 12), rather than with the main 4‰ 'main' negative excursion (see also Korte et al., 2009). The correlation is based on the assumption that *P. spelae tyrolicum* at the GSSP and *P. spelae spelae* in the Nevada section are isochronous and the correlation has been adopted, with minor variations, by recent authors (e.g. Percival et al., 2017; Korte et al., 2019; Ruhl et al. 2020).

The final option (Level 3 in Figure 12) for the TJB within the UK places the TJB within the 'initial' CIE (Hesselbo et al., 2002) at St Audrie's Bay (Lindström et al, 2017, 2019), based upon the argument that a distinct 6‰ negative CIE at the junction of the Kössen and Kendelbach formations in the Northern Calcareous Alps (Ruhl et al., 2009) was earlier than the 'initial' excursion at St Audrie's Bay. This interpretation could be supported by an abundance peak of the spore taxon *Polypodiisporites polymicroforatus* (Orłowska- Zwolińska) below the 'initial' CIE in NW Europe, which has been correlated with a similar peak above the Kössen–Kendelbach isotope excursion in the Eiberg Basin, Austria. This would imply that the last appearance of the latest Triassic ammonites *Choristoceras marshi* Hauer and *C. crickmayi* Tozer, marking the primary marine extinction level, correlates with a level in the Westbury Formation of the UK rather than with the start of the 'initial' CIE at the lower/upper Cotham Member boundary. This correlation was rejected by Korte et al. (2019) because it failed to consider other available stratigraphic markers.

As suggested by Boomer at al. 2020, who looked at microfossil, palynology and carbon isotope records for the Carnduff boreholes, if the 'initial' CIE at Carnduff and in the Kuhjoch section represent the same event, then the Triassic–Jurassic boundary must be within the very highest part of the Langport Member or above it (i.e. in the Waterloo Mudstone Formation). It must, therefore, lie between the top of the 'initial' CIE and the first occurrence of ammonites, a 10–11 m interval in the cores. Palynological data would suggest it lies at the very top of the Langport Member in the Carnduff cores, based on the first occurrence of *Cerebropollenites* *thiergartii* (Level 2 in Figure 12) (Boomer et al. 2020). This point on the carbon isotope curve at Waterloo Bay lies above a ~1–1.5‰ negative shift in the Langport Member, which appears to correlate with similar shifts in the Doniford and St Audrie's bay records that lie in the lower part of the Blue Lias Formation (point C in Fig. 12). Unfortunately this shift was not identified in the Carnduff-2 Borehole record (Boomer et al. 2020).

6.3 Atmospheric carbon dioxide concentration (pCO_2)

Carbon dioxide concentrations, derived from stomatal index values of plant cuticle, have been reported from the Larne Basin T–J succession (Fig. 10) and compared with data from East Greenland (Steinthorsdottir et al., 2011). Cuticle samples of *Brachyphyllum*, a cheirolepidacean conifer that was the only morphotype present at all sampled levels, were obtained from the sections described here at Cloghan Point, The Gobbins and Cloghfin Port and are correlated with the Waterloo Bay section to compare with the carbon isotope record documented here (Fig. 8). The primary trend suggests increasing *p*CO_2 from the Westbury Formation through into the Planorbis Zone of the Waterloo Mudstone Formation (Fig. 10) and is evident in other cuticle morphotypes in the Larne Basin and in East Greenland (Steinthorsdottir et al., 2011, 2018).

The Larne Basin data show that *p*CO_2 continued to rise, between WL2 and G3 to reach a peak around the G3 level (Steinthorsdottir et al., 2011, figure 5) that corresponds to the start of the 'main' CIE and the onset of interpreted rapid relative sea-level rise in the Larne Basin (Fig. 10). Above the G3 level *p*CO_2 estimates from different plant groups diverge. Conifer cuticle indicates no significant change but ginkgoalean and bennettitalean cuticle suggest declining *p*CO_2 (Steinthorsdottir et al., 2011, figure 6). These differences suggest that one or other plant groups may have been responding to drivers other than *p*CO_2 at that time. The relatively low-resolution dataset of *p*CO_2 estimates from the Larne Basin can provide only an approximate indication of *p*CO_2 change through the T–J interval and is unlikely to have sampled the maxima or minima, nor does it allow resolution of the pulsed nature of *p*CO_2 change suggested by the data of Schaller et al. (2011, 2012). Nevertheless, it does identify a significant rise in *p*CO_2 associated with the 'initial' CIE and indicates that *p*CO_2 generally remained at elevated levels for some time. The *p*CO_2 proxy data indicate a fairly sustained doubling of *p*CO_2 from Late Rhaetian background levels above the 'initial' CIE (Schaller et al., 2011, 2012; Steinthorsdottir et al., 2011), suggesting a mean global temperature increase of ~2.5–5 °C between the 'initial' CIE and the Planorbis Zone (e.g. Royer et al., 2007; Steinthorsdottir et al., 2011) and perhaps linked to pulsed CO_2 emissions from the later phases of CAMP basalt eruptions.

6.4 Seismic activity

The soft sediment deformation seen in the Larne Basin is ascribed to seismic activity during the TJB interval (Simms, 2003, 2007; Laborde-Casadaban et al., 2021). Widespread soft-sediment deformation through the TJB interval in north-west Europe has in the past been ascribed to seismicity associated with rifting of the proto-Atlantic (Swift, 1999; Hesselbo et. al. 2002), associated with CAMP activity (e.g. Hallam and Wignall, 1999; Wignall and Bond, 2008; Lindström et al., 2015), or due to bolide impact (Simms, 2003, 2007). A direct connection between CAMP volcanism and seismicity seems unlikely considering the distance of the UK from the CAMP itself, and seismic effects of rifting during this time (Tate and Dobson, 1989, Stoker et al., 2017) are more likely. However, it should be noted that the predominant shallow-water heterolithic sandstone/siltstone facies seen in the Cotham Member seismites at Larne and elsewhere (Simms, 2007; Lindström et al., 2015) are particularly prone to soft-sediment deformation (e.g. Couëffé et al., 2004; Owen and Moretti, 2011), whether caused by seismic triggers or not (Owen et al., 2011). Hence it may be that the distribution of supposed seismites in the Rhaetian of NW Europe is a function more of facies distribution during this interval rather than the temporal distribution of seismicity per se. However, the very narrow stratigraphic distribution, with comparable deformation largely absent from similar facies above and below, remains somewhat enigmatic.

6.5 Controls on sedimentation

The broad pattern of sedimentation and resulting lithostratigraphy in the Larne Basin (see Section 5; Fig. 11) is consistent with that seen in south-west Britain and has similarities with lithostratigraphic units in the Central European Basin (see Gravendyck et al. 2020). This is interpreted primarily as a response to changes in eustatic sea-level as many of the sedimentological changes can be traced into the Central European Basin (Hesselbo et al., 2004; Barth et al., 2018). Sea-level change during this time included a second-order eustatic rise from Late Triassic into Early Jurassic (Early Sinemurian) that transgressed from west to east, with third-order offlap/onlap cycles superimposed upon this (Barth et al., 2018). The earliest evidence of Late Triassic marine incursion into south-east County Antrim occurs in the grey/green mudstones of the Collin Glen Formation (Boomer et al. 2020) at the top of the Mercia Mudstone Group, probably a lithostratigraphic equivalent of the Blue Anchor Formation of south-west Britain and linked to the Rh1 third-order sequence identified in the Central European Basin (Barth et al., 2018). The base of the overlying Westbury Formation is generally considered erosive across Northern Ireland (Mitchell, 2004) and in south-west Britain (Howard et al., 2008, Gallois 2009, Wilson et al., 1990). Differential uplift and erosion, prior to deposition of the Westbury Formation, may have removed the Collin Glen Formation entirely at the section near Whitehead, which lies toward the basin margin, but the formation appears more complete in the basin centre in the Larne area.

The marine sediments of the Westbury Formation reflect a renewed extension of marine environments to form a storm-dominated, shallow epeiric sea (Warrington and Ivimey-Cook, 1995). Movement of faults may have led to differences in the distribution of facies and the thickness, as witnessed at Cloghfin Port (Fig. 7). Overall, the formation across the basin records a change to laminated very dark grey shales and sandstones with marine fossils. The Westbury Formation was interpreted to represent the upper part of the transgressive systems tract by Hesselbo et al. (2004). The formation may equate to much of the second Rhaetian 3rd Order sequence (Rh2) sequence identified by Barth et al. (2018) in the North German Basin, although there is no clear evidence of a sequence boundary within the upper Westbury Formation in the Larne Basin nor, indeed, across the rest of the UK.

An abrupt change to shoreface and tidal flat deposits in the lower Cotham Member may reflect local tectonic control of relative sea-level, with the 'mud-cracked' surface at the top of the lower Cotham Member in the Larne Basin representing a sequence boundary and lowstand surface. At St Audrie's Bay this same sequence boundary (Hesselbo et al., 2004) was ascribed to a c.2 m tectonically driven fall in relative sea-level (Mayall, 1983) but in the correlative strata of the Larne Basin any effects of sea-level fall, such as facies shifts and erosion, appear more subdued. In sequence stratigraphic terms, the lower Cotham Member was viewed as a lowstand systems tract or falling stage systems tract (Hesselbo et al., 2004), with the overall fining-up trend in the upper Cotham Member (above the 'mud-cracked' surface) interpreted as the start of the transgressive systems tract formed by the Hettangian transgression (Hesselbo et al., 2004; Barth et al., 2018), reaching its highstand low in the Waterloo Mudstone Formation at around the *plicatulum* Biohorizon of the Planorbis Zone (Simms and Jeram, 2007).

6.6 Biotic change

Various studies (e.g. Barras and Twitchett, 2007; Mander et al., 2008; Wignall and Bond, 2008; Atkinson et al., 2019; Opazo and Page, 2021) suggest an increase in standing marine biodiversity in the UK through the Westbury Formation into the base of the Cotham Member, followed by a sharp decline to a minimum in the upper Cotham Member and Langport Member and then a gradual recovery into the Planorbis Zone. Wignall and Atkinson (2020) identified two periods of extinction (top Westbury Formation/base Cotham Member and the top of the Langport Member. The lower event was presumed by them to lie within the brackish water deposited upper Cotham Member, but to be 'hidden' by these changes in environment (Wignall and Atkinson, 2020). These data are consistent with modest extinction, predominantly of bivalves, through the lower Cotham Member to lower Langport Member interval, as seen in the Waterloo Bay succession (Opazo and Page, 2021). It suggests that these diversity changes began just before the 'initial' CIE and reached a peak by the end of the excursion, with recovery underway even as CAMP volcanism continued (Wignall and Bond, 2008). Facies changes linked to sea level through the TJB interval probably influenced benthic faunas (Cope in Radley et al., 2008; Lucas and Tanner, 2008), although they may have had little effect on the difference between faunas of the Westbury Formation and those of the Langport Member and basal Blue Lias Formation because the depositional environments were similar (Twitchett and Mander, in Radley et al., 2008; Mander and Twitchett, 2008). However, if last occurrences of marine invertebrate taxa in the Lilstock Formation were facies controlled then the precise timing and cause of their extinction must remain uncertain.

7. Conclusions and summary

The Rhaetian to Hettangian succession in south-east County Antrim shows continuous sedimentation through a time interval encompassing the End Triassic Extinction, the known eruptive phase of the Central

Atlantic Magmatic Province and the Triassic–Jurassic Boundary. The key stratigraphic levels recording events associated with the ETE and CAMP are concentrated in and around the Lilstock Formation which preserves a more complete and detailed history of events in the Larne Basin than in south-west Britain. The high-resolution $\delta^{13}C_{org}$ profile obtained from the Waterloo Bay section can be correlated with profiles from other regions and allows the events occurring in the Larne Basin and south-west Britain to be placed in the broader context of Pangaea and to tentatively reach the following conclusions:

(1) Whilst the Westbury Formation and Cotham Member appear to be affected by regional or eustatic fluctuations in sea-level, the return to normal marine conditions during deposition of the Langport Member may be either a more completely preserved or an expanded section across a gradational transition. This appears to be supported by a more expanded 'initial' CIE that extends into the lower Langport Member in the Waterloo Bay carbon isotope curve.

(2) As suggested by other authors, the lithostratigraphic base of the Lias Group, as defined by an abrupt increase in TOC preservation, may be diachronous across the UK and therefore reflects differences in water depth and sediment accumulation rate. The upper part of the Langport Member in south-east County Antrim may thus represent a shallow water equivalent of the basal beds of the Blue Lias Formation in the Bristol Channel Basin.

(2) In the Larne Basin ammonites appear 5.6 m above the base of the Waterloo Mudstone Formation at Waterloo Bay. The full faunal succession found in south-west Britain, up to the top of the Planorbis Zone, is also present at outcrop in south-east County Antrim, but there is a greater stratigraphic thickness to the biohorizons, particularly in the Planorbis Subczone than in south-west Britain.

(3) The $\delta^{13}C_{org}$ data obtained from the Waterloo Bay section show an overall pattern through the 'initial' CIE similar to the data previously recovered from the nearby Carnduff-2 core and the Bristol Channel Basin, but it is at a significantly higher resolution as a result of finer sample spacing and a stratigraphically expanded succession (compared with the Bristol Channel Basin). Differences in the amplitude of minor (second order) peaks and troughs, probably influenced by local factors, suggest that caution is required if applied to high resolution correlation over longer distances.

(4) Based on correlations of the carbon isotope curve proposed here, the Triassic–Jurassic boundary lies between the top of the 'initial' CIE (upper part of Bed 13 at Waterloo Bay) and the first ammonites in Bed 24. It therefore rests either within the upper Langport Member (Level 2 on Figure 12) or within the 'Pre-Planorbis Beds' of the Waterloo Mudstone Formation (Level 1).

(6) The Larne Basin was tectonically active during the TJB interval, as evidenced by synsedimentary fault movements and the occurrence of soft sediment deformed strata that are considered to be seismically disturbed. At Cloghfin Port and Cloghan Point, which are located above the geophysical trace of the Southern Uplands fault zone, there is evidence that tectonic activity exacerbated or influenced a fall in relative sea-level at the transition from the Westbury Formation to the Lilstock Formation. This was followed by further seismicity affecting the lower Cotham Member, representing a protracted series of

seismic events. Seismites of similar age are widely distributed in NW Europe and suggest that those in the Larne Basin reflect region-wide tectonism during this time period. This interval is tentatively correlated with a phase of intrusive activity that immediately preceded flood basalt volcanism in the CAMP, potentially indicating an indirect connection between extensional tectonics of the CAMP and the tectonics of the proto-North Atlantic margin.

(7) Although tectonics affected sedimentation in the Larne Basin, the major lithological changes are interpreted to relate to regional, presumably eustatic, sea-level change. Facies trends in the Larne Basin broadly resemble those in south-west Britain basins and further into the Central European Basin (Hesselbo et al. 2004; Barth et al., 2018; Gravendyck et al., 2020). There is some evidence for Rhaetian marine influence in the Collin Glen Formation (Boomer et al. 2020), above which the Westbury Formation records a late Rhaetian transgressive-regressive cycle culminating in the lower Cotham Member of the Lilstock Formation. However, evidence suggests that there was subdued erosion at the 'mud cracked' surface, marking the top of this sequence at Waterloo Bay. The upper Cotham Member marks the start of a second transgressive sequence that culminated at the Hn7-*plicatulum* Biohorizon in the Planorbis Zone (based on TOC content).

(8) The rapid and sustained transgression recorded in the base of the Waterloo Mudstone Formation corresponds with the 'main' CIE and peak levels of $p\mathrm{CO_2}$. There is also a loose correspondence between the $p\mathrm{CO_2}$, δ^{13}C and sea level records through the T–J boundary in the Larne Basin. Major biotic turnover in the Larne Basin had already occurred before $p\mathrm{CO_2}$ rose significantly above late Rhaetian background levels so this turnover is unlikely to be due to CO_2-induced climate warming. Although the timing of diversity loss and/or turnover can be constrained only to an interval between the top of the Westbury Formation and the early part of the 'initial' CIE in the upper Cotham Member, that interval lies within strata that were deposited under fluctuating salinities.

Acknowledgements

We thank Kamini Manick for performing many of the Waterloo Bay sample geochemical analyses and Paul Wignall and John Walsh for helpful discussions in the field. The Department of the Environment for Northern Ireland are thanked for permission to conduct geochemical sampling at the Waterloo Bay ASSI. This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

References

Anderson, T.B., Parnell, J., Ruffell, A.H., 1995. Influence of basement on the geometry of Permo-Triassic basins in the northwest British Isles. In: Boldy, S.A.R. (Ed.). Permian and Triassic rifting in Northwest Europe. Geological Society Special Publication 10, pp. 103–122.

Atkinson, J.W., Wignall, P.B., Morton, J.D., Aze, T., 2019. Body size changes in bivalves of the Family Limidae in the aftermath of the end-Triassic mass extinction: The Brobdingnag Effect. Palaeontology 62, 561–582. Doi:/doi/10.1111/pala.12415.

Barras, C.G., Twitchett, R.J., 2007. Response of the marine ichnofauna to Triassic-Jurassic environmental change: Ichnological data from southern England. Palaeogeography, Palaeoclimatology, Palaeoecology 244, 223–241. Doi: 10.1016/j.palaeo.2006.06.040.

Barth, G., Franz, M., Heunisch, C., Ernst, W., Zimmermann, J., Wolfgramm, M., 2018. Marine and terrestrial sedimentation across the T–J transition in the North German Basin. Palaeogeography, Palaeoclimatology, Palaeoecology 489, 74–94. Doi: 10.1016/j.palaeo.2017.09.029.

Bartolini, A., Guex, J., Spangenberg, J., Schoene, B., Taylor, D., Schaltegger, U., Atudorei, V., 2012. Disentangling the Hettangian carbon isotope record: Implications for the aftermath of the end-Triassic mass extinction. Geochemistry, Geophysics, Geosystems 13, Q01007. Doi:10.1029/2011GC003807.

Benton, M.J., Cook, E., Turner, P., 2002. Permian and Triassic Red Beds and the Penarth Group of Great Britain: Geological Conservation Review Series 24, Joint Nature Conservation Committee, Peterborough, 337 pp.

Blackburn, T.J., Olsen, P.E., Bowring, S.A., McLean, N.M., Kent, D.V., Puffer, J., McHone, G., Rasbury, T.E., Et-Touhami, M., 2013. Zircon U–Pb geochronology links the end-Triassic extinction with the central Atlantic Magmatic Province. Science 340, 942–945. Doi:10.1126/science.1234204.

Bloos, G., Page, K.N., 2000. The basal Jurassic ammonite succession in the North-West European Province – Review and new results. GeoResearch Forum 6, 27–40.

Bond, D.P.G., Wignall, P.B., 2014. Large igneous provinces and mass extinctions: An update. In: Keller, G., Kerr, A.C., (Eds.), Volcanism, Impacts, and Mass Extinctions: Causes and Effects. Geological Society of America Special Paper 505, 29–55. Doi:10.1130/2014.2505(02).

Bonis, N.R., Ruhl, M., Kürschner, W.M, 2010. Milankovitch-scale palynological turnover across the Triassic-Jurassic transition at St. Audrie's Bay, SW UK. Journal of the Geological Society 167, 877–888. doi:10.1144/0016-76492009-141.

Boomer, I., Copestake, P., Raine, R., Azmi, A., Fenton, J., Page, K., O'Callaghan, M., 2020a. Palaeoenvironments and Geochemistry of the Late Triassic to Early Jurassic Interval of County Antrim, Northern Ireland. Proceedings of the Geologists' Association.

Clémence, M.-E., Hart, M. B. 2013. Proliferation of Oberhauserellidae during the recovery following the Late Triassic extinction: paleoecological implications. Journal of Paleontology 87, 1004–1015.

Clémence, M.-E., Bartolini, A., Gardin, S., Paris, G., Beaumont, V., Page, K.N., 2010. Early Hettangian benthic-planktonic coupling at Doniford (SW England): Palaeoenvironmental implications for the aftermath of the end-Triassic crisis. Palaeogeography, Palaeoclimatology, Palaeoecology 295, 102–115. Doi:10.1016/j.palaeo.2010.05.021.

Couëffé, R., Tessier, B., Gigot, P., Beaudoin, B., 2004. Tidal Rhythmites as Possible Indicators of Very Rapid Subsidence in a Foreland Basin: An Example from the Miocene Marine Molasse Formation of the Digne Foreland Basin, SE France. Journal of Sedimentary Research 74, 746–759. Doi: 10.1306/040904740746.

Dal Corso, J., Marzoli, A., Tateo, F., Jenkyns, H.C., Bertrand, H., Youbi, N., Mahmoudi, A., Font, E., Buratti, N., Cirilli, S., 2014. The dawn of CAMP volcanism and its bearing on the end-Triassic carbon cycle disruption. Journal of the Geological Society 171, 153–164. Doi:10.1144/jgs2013-063.

Donovan, D., Curtis, M., Curtis, S., 1989. A psiloceratid ammonite from the supposed Triassic Penarth Group of Avon, England. Palaeontology 32, 231–235.

Fox, C.P., Cui, X., Whiteside, J.H., Olsen, P.E., Summon, R.E., Grice, K., 2020. Molecular and isotopic evidence reveals the end-Triassic carbon isotope excursion is not from massive exogenous light carbon. PNAS, 117, 30171–30178.

Gallois, R.W., 2007. The stratigraphy of the Penarth Group (late Triassic) of the East Devon coast. Geoscience in south-west England 11, 287–297.

Gallois, R.W., 2009. The Lithostratigraphy of the Penarth Group (late Triassic) of the Severn Estuary area. Geoscience in south-west England 12, 71–84.

Goehring, L., 2013. Evolving fracture patterns: columnar joints, mud cracks and polygonal terrain. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences 371, 20120353. Doi:10.1098/rsta.2012.0353.

Gravendyck et al., 2020

Griffith, A.E., Wilson, H.E., 1982. Geology of the country around Carrickfergus and Bangor. Geological Survey of Northern Ireland Memoir, Sheet 29. 118 pp.

Guex, J., Bartolini, A., Atudorei, V., Taylor, D., 2004. High resolution ammonite and carbon isotope stratigraphy across the Triassic-Jurassic boundary at New York Canyon (Nevada). Earth and Planetary Science Letters 225, 29–41. Doi:10.1016/j.epsl.2004.06.006.

Guex, J., Schoene, B., Bartolini, A., Spangenberg, J., Schaltegger, U., O'Dogherty, L., Taylor, D., Bucher, H., Atudorei, V., 2012. Geochronological constraints on post-extinction recovery of the ammonoids and carbon cycle perturbations during the Early Jurassic. Palaeogeography, Palaeoclimatology, Palaeoecology 346–347, 1–11. Doi:10.1016/j.palaeo.2012.04.030.

Hallam, A., 1960. The White Lias of the Devon Coast. Proceedings of the Geologists' Association 71, 47-60.

Hallam, A., Wignall, P.B., 1999. Mass Extinctions and Sea-level Changes. Earth-Science Reviews 8, 217–250.

Hamilton, D. 1961. Algal growths in the Rhaetic Cotham Marble of southern England. Palaeontology 4, 324–333.

Heimdal, T.H., Callegaro, S., Svensen, H.H., Jones, M.T., Pereira, E., Planke, S., 2019. Evidence for magma–evaporite interactions during the emplacement of the Central Atlantic Magmatic Province (CAMP) in Brazil. Earth and Planetary Science Letters 506, 476-492. doi:10.1038/s41598-017-18629-8.

Heimdal, T.H., Svensen, H. H., Ramezani, J., Iyer, K., Pereira, E., Rodrigues, R., Jones, M.T., Callegaro, S., 2018. Large-scale sill emplacement in Brazil as a trigger for the end-Triassic crisis. Scientific Reports, 8, 141 (2018). Doi:10.1038/s41598-017-18629-8.

Hesselbo, S.P., Robinson, S.A., Surlyk, F., Piasecki, S., 2002. Terrestrial and marine mass extinction at the Triassic–Jurassic boundary synchronized with major carbon-cycle perturbation: A link to initiation of massive volcanism? Geology 30, 251–254. Doi:10.1130/0091-7613(2002)030<0251:TAMEAT>2.0.CO;2.

Hesselbo, S.P., Robinson, S.A. and Surlyk, F., 2004. Sea-level change and facies development across potential Triassic–Jurassic boundary horizons, SW Britain. Journal of the Geological Society, London 161, 365–379. Doi:10.1144/0016-764903-033.

Hillebrandt, A.v., 1994. The Triassic/Jurassic boundary and Hettangian biostratigraphy in the area of the Utcubamba Valley (northern Peru). Geobios 27, supplement 2, 297–307. doi: 10.1016/S0016-6995(94)80148-7.

Hillebrandt, A. v., Krystyn, L., 2009. On the oldest Jurassic ammonites of Europe (Northern Calcareous Alps, Austria) and their global significance. Neues Jahrbuch für Geologie und Paläontologie – Abhandlungen 253, 163–195. Doi: 10.1127/0077-7749/2009/0253-0163.

Hillebrandt, A.v., Krystyn, L., Kürschner, W.M., 2007. A candidate GSSP for the base of the Jurassic in the Northern Calcareous Alps (Kujoch section, Karwendel Mountains, Tyrol, Austria). International Subcommission on Jurassic Stratigraphy Newsletter 34, 2–20.

Hillebrandt, A.v., Krystyn, L., Kürschner, W.M., Bonis, N.R., Ruhl, M., Richoz, S., Urlichs, M., Bown, P.R., Kment, K., McRoberts, C.A., Simms, M.J., Tomãsových, A., 2013. The Global Stratotype Sections and Point (GSSP) for the base of the Jurassic System at Kuhjoch (Karwendel Mountains, Northern Calcareous Alps, Tyrol, Austria). Episodes 36, 162–198.

Hodges, P. 2021. A new ammonite from the Penarth Group, South Wales and the base of the Jurassic System in south-west Britain. Geological Magazine 158, 1109–1114.

Hüsing, S.K., Beniest, A., van der Boon, A., Abels, H.A., Deenen, M.H.L., Ruhl, M., Krijgsman, W., 2014. Astronomically-calibrated magnetostratigraphy of the Lower Jurassic marine successions at St. Audrie's Bay and East Quantoxhead (Hettangian–Sinemurian; Somerset, UK). Palaeogeography, Palaeoclimatology, Palaeoecology 403, 43–56. Doi:10.1016/j.palaeo.2014.03.022.

Ivimey-Cook, H.C., 1975. The stratigraphy of the Rhaetic and Lower Jurassic in East Antrim. Bulletin of the Geological Survey of Great Britain 50, 51–69.

Jaraula, C.M.B., Grice, K., Twitchett, R.J., Böttcher, M.E., LeMetayer, P., Dastidar, A.G., Opazo, L-F., 2013. Elevated pCO_2 leading to Late Triassic extinction, persistent photic zone euxinia, and rising sea levels. Geology 41, 955–958. Doi:10.1130/g34183.1.

Kent, D.V., Olsen, P.E., Muttoni, G., 2017. Astrochronostratigraphic polarity time scale (APTS) for the Late Triassic and Early Jurassic from continental sediments and correlation with standard marine stages. Earth Science Reviews 166, 153–180. Doi:10.1016/j.earscirev.2016.12.014.

Korte, C., Hesselbo, S.P., Jenkyns, H.C., Rickaby, R.E.M., Spötl, C., 2009. Palaeoenvironmental significance of carbon- and oxygen-isotope stratigraphy of marine Triassic–Jurassic boundary sections in SW Britain. Journal of the Geological Society, London 166, 431–445. Doi:10.1144/0016-76492007-177.

Korte, C., Kozur, H.W., 2011. Bio- and chemostratigraphic assessment of carbon isotope records across the Triassic–Jurassic boundary at Csővár quarry (Hungary) and Kendlbachgraben (Austria) and implications for global correlations. Bulletin of the Geological Society of Denmark 59, 101–115.

Korte, C., Ruhl, M., Pálfy, J., Ullmann, C.V., Hesselbo, S.P., 2019. Chemostratigraphy across the Triassic–Jurassic Boundary. In: Sial, A.N., Gaucher, C., Ramkumar, M., Ferreira, V.P. (Eds.), Chemostratigraphy Across Major Chronological Boundaries. Geophysical Monograph 2, 185–210. Doi:10.1002/9781119382508.ch10.

Kürschner, W.M., Bonis, N.R., Krystyn, L., 2007. Carbon-isotope stratigraphy and palynostratigraphy of the Triassic–Jurassic transition in the Tiefengraben section: Northern Calcareous Alps (Austria). Palaeogeography, Palaeoclimatology, Palaeoecology 244, 257–280. Doi:10.1016/j.palaeo.2006.06.031.

Laborde-Casadaban, M., Homberg, C., Schnyder, J., Borderie, S., Raine, R., 2021. Do soft sediment deformations in the Late Triassic and Early Jurassic of the UK record seismic activity during the break-up of Pangea? Proceedings of the Geologists' Association (This Volume).

Lindström, S., van de Schootbrugge, B., Dybkjaer, K., Pedersen, G.K., Fiebig, J., Nielsen, L.H., Richoz, S., 2012. No causal link between terrestrial ecosystem change and methane release during the end-Triassic mass extinction. Geology 40, 531–534. Doi:10.1130/g32928.1.

Lindström, S., Pedersen, G.K., van de Schootbrugge, B., Hansen, K.H., Kuhlmann, N., Thein, J., Johansson, L., Petersen, H.I., Alwmark, C., Dybkjær, K., Weibel, R., Erlström, M., Nielsen, L.H., Oschmann, W., Tegner, C., 2015. Intense and widespread seismicity during the end-Triassic mass extinction due to emplacement of a large igneous province. Geology 43, 387–390. Doi: https://doi.org/10.1130/G36444.1

Lindström, S., van de Schootbrugge, B., Hansen, K.H., Pedersen, G.K., Alsen, P., Thibault, N., Dybkjær, K., Bjerrum, C.J., Nielsen, L.H., 2017. A new correlation of Triassic–Jurassic boundary successions in NW Europe, Nevada and Peru, and the Central Atlantic Magmatic Province: A time-line for the end-Triassic mass extinction. Palaeogeography, Palaeoclimatology, Palaeoecology 478, 80–102. Doi: 10.1016/j.palaeo.2016.12.025.

Lindström, S., Sanei, H., van de Schootbrugge, B., Pedersen, G.K., Lesher, C.E., Tegner, C., Heunisch, C., Dybkjær, K., Outridge, P.M., 2019. Volcanic mercury and mutagenesis in land plants during the end-Triassic mass extinction. Science Advances 5, eaaw4018. Doi: 10.1126/sciadv.aaw4018.

Lucas, S., Tanner, L., 2008. Reexamination of the end-Triassic Mass Extinction. In: Elewa, A.F.T. (Ed.), Mass Extinction. Springer-Verlag, Berlin, Heidelberg, pp. 66–103. Doi: 10.1007/978-3-540-75916-4.

Lucas, S.G., Tanner, L.H., 2015. End-Triassic nonmarine biotic events. Journal of Palaeogeography 4, 331–348. Doi:10.1016/j.jop.2015.08.010.

Macquaker, J.H.S., 1999. 4. Aspects of the Sedimentology of the Westbury Formation. In: Swift, A. and Martill, D.M. (Eds.), Fossils of the Rhaetian Penarth Group. The Palaeontological Association, London, pp. 39–48.

Mander, L., Twitchett, R.J., 2008. Quality of the Triassic–Jurassic bivalve fossil record in northwest Europe. Palaeontology 51, 1213-1223. Doi:10.1111/j.1475-4983.2008.00821.x.

Mander, L., Twitchett, R.J., Benton, M.J., 2008. Palaeoecology of the late Triassic extinction event in the SW UK. Journal of the Geological Society, London 165, 319–332.

Manning, P.I., Robbie, J.A., Wilson, H.E., Hawkes, J.R., Hughes, M.J., McAllister, J.S.V., Pattison, J., Warrington, J., 1970. Geology of Belfast and the Lagan Valley. Memoirs of the Geological Survey of Northern Ireland, sheet 36.

Manning, P.I., Wilson, H.E., 1975. I. The stratigraphy of the Larne Borehole, County Antrim. Bulletin of the Geological Survey of Great Britain 50, 1–50.

Mayall, M.J., 1981. The Late Triassic Blue Anchor Formation and the initial Rhaetian marine transgression in south-west Britain. Geological Magazine 118, 377–384.

Mayall, M.J., 1983. An earthquake origin for synsedimentary deformation in a late Triassic (Rhaetian) lagoonal sequence, southwest Britain. Geological Magazine 120, 613–622.

McElwain, J.C., Beerling, D.J., Woodward, F.I., 1999. Fossil plants and global warming at the Triassic–Jurassic Boundary. Science 285, 1386–1390. Doi:10.1126/science.285.5432.1386.

McElwain, J.C., Wagner, P.J., Hesselbo, S.P., 2009. Fossil plant relative abundances indicate sudden loss of Late Triassic biodiversity in east Greenland. Science 324, 1554–1556. Doi:10.1126/science.1171706.

McHone, J.G., 2003, Volatile emissions from Central Atlantic magmatic province basalts: Mass assumptions and environmental consequences. In: Hames, W.E., McHone, J.G., Renne, P.R., Ruppel, C., (Eds.), The Central Atlantic Magmatic Province: Insights from Fragments of Pangea. American Geophysical Union Geophysical Monograph 136, pp. 241–254.

McMahon, S., van Smeerdijk Hood, A., McIlroy, D., 2016. The origin and occurrence of subaqueous sedimentary cracks. Geological Society, London, Special Publications 448, 285–309. Doi:10.1144/SP448.15.

Mitchell, W.I. (Ed.), 2004. The Geology of Northern Ireland – Our Natural Foundation. Geological Survey of Northern Ireland, Belfast, pp. 318.

Moretti, M., van Loon, A.J. (Tom), 2014. Restrictions to the application of 'diagnostic' criteria for recognizing ancient seismites. Journal of Palaeogeography, 3, 162–173. Doi: 10.3724/SP.J.1261.2014.00050.

Onoue, T., Sato, H., Yamashita, D., Ikehara, M., Yasukawa, K., Fujinaga, K., Kato, Y., Matsuoka, A., 2016. Bolide impact triggered the Late Triassic extinction event in equatorial Panthalassa. Scientific Reports 6, 29609 (2016). Doi:10.1038/srep29609.

Opazo, L-F., Page, K.N., 2021. Palaeoecological patterns of change in marine invertebrate faunas across the end-Triassic mass extinction event: evidence from Larne, Northern Ireland. Proceedings of the Geologists' Association (This Volume).

Owen, G., Moretti, M., 2011. Identifying triggers for liquefaction-induced soft-sediment deformation in sands. Sedimentary Geology 235, 141–147. Doi:10.1016/j.sedgeo.2010.10.003.

Owen, G., Moretti, M., Alfaro, P., 2011. Recognising triggers for soft-sediment deformation: Current understanding and future directions. Sedimentary Geology 235, 133–140. Doi:10.1016/j.sedgeo.2010.12.010.

Page, K.N. 2010. Ammonites. In: Lord, A.R., Davis, P.G., (Eds.), Fossils from the Lower Lias of the Dorset Coast, Palaeontological Association Field Guide to Fossils 13, pp 169-261.

Pálfy, J., Demény, A., Haas, J., Carter, E.S., Görög, Á., Halász, D., Oravecz-Scheffer, A., Hetényi, M., Márton, E., Orchard, M.J., Ozsvárt, P., Vető, I., Zajzon, N., 2007. Triassic-Jurassic boundary events inferred from integrated stratigraphy of the Csővár section, Hungary. Palaeogeography, Palaeoclimatology, Palaeoecology 244, 11–33. Doi:10.1016/j.palaeo.2006.06.021.

Pálfy, J., Kocsis, Á.T., 2014. Volcanism of the Central Atlantic magmatic province as the trigger of environmental and biotic changes around the Triassic-Jurassic boundary. In: Keller, G., Kerr, A.C., (Eds.), Volcanism, Impacts, and Mass Extinctions: Causes and Effects. Geological Society of America Special Paper 505, 245–261. Doi:10.1130/2014.2505(12).

Percival, L.M.E., Ruhl, M., Hesselbo, S.P., Jenkyns, H.C., Mather, T.A., Whiteside, J.H., 2017. Mercury evidence for pulsed volcanism during the end-Triassic mass extinction. Proceedings of the National Academy of Sciences of the United States of America 114, 7929–7934. Doi:10.1073/pnas.1705378114.

Poole, E.G., Whiteman, A.J., 1966. Geology of the country around Nantwich and Whitchurch. British Geological Survey Memoir, One-inch Sheet 122.

Portlock, J.E., 1843. Report on the geology of the county of Londonderry and parts of Tyrone and Fermanagh. Andrew Milliken, Dublin and London, 784 pp.

Pratt, B., 1998. Syneresis cracks: Subaqueous shrinkage in argillaceous sediments caused by earthquake-induced dewatering. Sedimentary Geology 117, 1–10. Doi: 10.1016/S0037-0738(98)00023-2.

Radley, J.D., Twitchett, R.J., Mander, L., Cope, J.C.W., 2008. Discussion on palaeoecology of the Late Triassic extinction event in the SW UK. Journal of the Geological Society 165, 988–992. Doi:10.1144/001676492008-014.

Raine, R., Copestake, P., Simms, M.J., Boomer, I., 2020. Uppermost Triassic to Lower Jurassic sediments of the island of Ireland and its surrounding basins. Proceedings of the Geologists' Association (This Volume).

Raine, R., Fenton, J.P.G., Boomer, I., Azmi, A., Copestake, P., 2021. Uppermost Triassic to Lower Jurassic stratigraphy in the Lough Foyle Basin of County Londonderry, Northern Ireland. Proceedings of the Geologists' Association (This Volume).

Reynaud, J.-Y., Dalrymple, R. W., 2012. Shallow-marine tidal deposits. In: Davis Jr., R.A., Dalrymple, R.W. (Eds.), Principles of tidal sedimentology. Springer, Berlin, Heidelberg, pp. 335–369. Doi: 10.1007/978-94-007-0123-6_13.

Reid, C.G.R., Bancroft, A.J., 1986. The Irish Lower Jurassic type ammonites of Major-General J.E. Portlock (1843): *Leptechioceras macdonnelli, Psiloceras (Caloceras) intermedium,* and *Psiloceras (Psiloceras) sampsoni*. Irish Journal of Earth Sciences 8, 41–51.

Richardson, L., 1911. The Rhaetic and contiguous deposits of West, Mid and part of East Somerset. Quarterly Journal of the Geological Society, London 67, 1–74.

Ruhl, M., Hesselbo, S.P., Al-Suwaidi, A., Jenkyns, H.C., Damborenea, S.E., Manceñido, M.O., Storm, M., Mather, T.A., Riccardi, A.C., 2020. On the onset of Central Atlantic Magmatic Province (CAMP) volcanism and environmental and carbon-cycle change at the Triassic–Jurassic transition (Neuquén Basin, Argentina). Earth-Science Reviews 208 (2020) 103229.

Ruhl, M., Kürschner, W.M., 2011. Multiple phases of carbon cycle disturbance from large igneous province formation at the Triassic-Jurassic transition. Geology 39, 431–434. Doi:10.1130/g31680.1.

Ruhl, M., Kürschner, W.M., Krystyn, L., 2009. Triassic-Jurassic organic carbon isotope stratigraphy of key sections in the western Tethys realm (Austria). Earth and Planetary Science Letters 281, 169–187. Doi:10.1016/j.epsl.2009.02.020.

Schaller, M.F., Wright, J.D., Kent, D.V., 2011. Atmospheric pCO2 perturbations associated with the Central Atlantic Magmatic Province. Science 331, 1404–1409. Doi:10.1126/science.1199011.

Schaller, M.F., Wright, J.D., Kent, D.V., Olsen, P.E., 2012. Rapid emplacement of the Central Atlantic Magmatic Province as a net sink for CO2. Earth and Planetary Science Letters 323-324, 27–39. Doi:10.1016/j.epsl.2011.12.028.

Schobben, M., van de Schootbrugge, B., Wignall, P.B., 2019. Interpreting the carbon isotope records of mass extinctions. Elements 15, 331–337. Doi: 10.2138/gselements.15.5.331.

Siebach, K.L., Grotzinger, J.P., Kah, L.C., Stack, K.M., Malin, M., Léveillé, R., Sumner, D.Y., 2014. Subaqueous shrinkage cracks in the Sheepbed mudstone: Implications for early fluid diagenesis, Gale crater, Mars. Journal of Geophysical Research, Planets 119, 1597–1613. Doi:10.1002/2014JE004623.

Simms, M.J., 2003. Uniquely extensive seismite from the latest Triassic of the United Kingdom: evidence for bolide impact? Geology 31, 557–560. Doi:10.1130/0091-7613(2003)031<0557:UESFTL>2.0.CO;2.

Simms, M.J., 2007. Uniquely extensive soft-sediment deformation in the Rhaetian of the UK: evidence for earthquake or impact? Palaeogeography, Palaeoclimatology, Palaeoecology 244, 407–423. Doi:10.1016/j.palaeo.2006.06.037.

Simms, M.J., 2021. Fossil echinoderms from the Triassic and Jurassic of Ireland. Proceedings of the Geologists' Association (This Volume).

Simms, M.J., Chidlaw, N., Morton, N., Page, K.N., 2004. British Lower Jurassic Stratigraphy. Geological Conservation Review Series, Joint Nature Conservation Committee, pp. 458.

Simms, M.J., Edmunds, M. 2021. Ammonites from the Lias Group (Lower Jurassic, Sinemurian and Pliensbachian) of White Park Bay, Co. Antrim, Northern Ireland. Proceedings of the Geologists' Association (This Volume)

Simms, M.J., Jeram, A.J., 2007. Waterloo Bay, Larne, Northern Ireland: a candidate Global Stratotype Section and Point for the base of the Hettangian Stage and Jurassic System. International Subcommission on Jurassic Stratigraphy Newsletter 34, 50–68.

Simms, M.J., Smyth, R.S.H., Martill, D.M., Collins, P.C., Byrne, R., 2020. First dinosaur remains from Ireland. Proceedings of the Geologists' Association (This Volume).

Smith, A.B., McGowan, A.J., 2007. The shape of the Phanerozoic marine palaeodiversity curve: How much can be predicted from the sedimentary rock record of Western Europe? Palaeontology 50, 765–774. Doi:10.1111/j.1475-4983.2007.00693.x.

Steinthorsdottir, M., Elliott-Kingston, C., Bacon, K.L., 2018. Cuticle surfaces of fossil plants as a potential proxy for volcanic SO_2 emissions: observations from the Triassic–Jurassic transition of East Greenland. Palaeobiodiversity and Palaeoenvironments 98, 49–69. Doi:10.1007/s12549-017-0297-9.

Steinthorsdottir, M., Jeram, A.J., McElwain, J.C., 2011. Extremely elevated CO_2 concentrations at the Triassic/Jurassic boundary. Palaeogeography, Palaeoclimatology, Palaeoecology 308, 418–432. Doi:10.1016/j.palaeo.2011.05.050.

Storm, M.S., Hesselbo, S.P., Jenkyns, H.C., Ruhl, M., Ullmann, C.V., Xu,W., Leng, M.J., Riding, J.B., Olga Gorbanenko, O., 2020. Orbital pacing and secular evolution of the Early Jurassic carbon cycle. PNAS, 117, 3974–3982.

Stoker, M.S., Stewart, M.A., Shannon, P.M., Bjerager, M., Nielsen, T., Blischke, A., Hjelstuen, B.O., Gaina, C., McDermott, K., Ólavsdóttir, J., 2017. An overview of the Upper Palaeozoic–Mesozoic stratigraphy of the NE Atlantic region. Geological Society, London, Special Publications 447, 11–68. Doi:10.1144/SP447.2.

Svensen, H., Planke, S., Chevallier, L., Malthe-Sorenssen, A., Corfu, F., Jamtveit, B., 2007. Hydrothermal venting of greenhouse gases triggering Early Jurassic global warming. Earth and Planetary Science Letters, 256, 554–566.doi:10.1016/j.epsl.2007.02.013.

Swift, A., 1995. A review of the nature and outcrop of the 'White Lias' facies of the Langport Member (Penarth Group: Upper Triassic) in Britain. Proceedings of the Geologists' Association 106, 247-258.

Swift, A. 1999. 2. Stratigraphy (including biostratigraphy). In: Swift, A., Martill, D.M. (Eds.), 1999. Fossils of the Rhaetian Penarth Group. Field Guide to Fossils No. 9, Palaeontological Association, London, pp. 15–30.

Tate, R., 1867. On the Lower Lias of the north-east of Ireland. Quarterly Journal of the Geological Society, London 23, 291–305.

Tate, M., Dobson, M., 1989. Late Permian to early Mesozoic rifting and sedimentation offshore NW Ireland. Marine and Petroleum Geology 6, 49–59. doi:10.1016/0264-8172(89)90075-5.

Thibodeau, A.M., Ritterbush, K., Yager, J.A., West, A.J., Ibarra, Y., Bottjer, D.J., Berelson, W.M., Bergquist, B.A., Corsetti, F.A., 2016. Mercury anomalies and the timing of biotic recovery following the end-Triassic mass extinction. Nature Communications 7, 11147 (2016). doi:10.1038/ncomms11147.

van de Schootbrugge, B., Bachan, A., Suan, G., Richoz, S., Payne, J.L., 2013. Microbes, mud and methane: Cause and consequence of recurrent Early Jurassic anoxia following the end-Triassic mass extinction. Palaeontology 56, 685–709. doi:10.1111/pala.12034.

Warrington, G., Audley-Charles, M.G., Elliott, R.E., Evans, W.B., Ivimey-Cook, H.C., Kent, P.E., Robinson, P.L., Shotton, F.W., Taylor, F.M., 1980. A correlation of Triassic rocks in the British Isles. Geological Society of London Special Report, 13, Blackwell Scientific, pp. 78.

Warrington, G., Cope, J.C.W., Ivimey-Cook, H.C., 1994. St Audrie's Bay, Somerset, England: A candidate Global Stratotype Section and Point for the base of the Jurassic System. Geological Magazine 131, 191–200. doi:10.1017/S0016756800010724.

Warrington, G., Cope, J.C.W., Ivimey-Cook, H.C., 2008. The St Audries Bay – Doniford Bay section, Somerset, England: Updated proposal for a candidate Global Stratotype Section and Point for the base of the Hettangian Stage, and of the Jurassic System. International Subcommission on Jurassic Stratigraphy Newsletter 35, 2–66.

Warrington, G., Harland, R., 1975. Palynology of the Trias and Lower Lias of the Larne Borehole. Bulletin of the Geological Survey of Great Britain 50, 37-50.

Warrington, G., Ivimey-Cook, H.C., 1992. Triassic. In: Cope, J.C.W., Ingham, J.K. and Rawson, P.F. (Eds.), Atlas of palaeogeography and lithofacies. Memoirs of the Geological Society, London 13, pp. 97–106.

Weedon, G., Jenkyns, H., Page, K., 2018. Combined sea-level and climate controls on limestone formation, hiatuses and ammonite preservation in the Blue Lias Formation, South Britain (uppermost Triassic – Lower Jurassic). Geological Magazine 155, 1117–1149. doi:10.1017/S001675681600128X.

Weedon, G., Page, K., Jenkyns, H., 2019. Cyclostratigraphy, stratigraphic gaps and the duration of the Hettangian Stage (Jurassic): Insights from the Blue Lias Formation of southern Britain. Geological Magazine 156, 1469–1509. doi:10.1017/S0016756818000808.

Whiteside, J.H., Olsen, P.E., Eglinton, T., Brookfield, M.E., Sambrotto, R.N., 2010. Compound-specific carbon isotopes from Earth's largest flood basalt eruptions directly linked to the end-Triassic mass extinction. Proceedings of the National Academy of Sciences of the USA 107, 6721–6725.

Wignall, P.B., Atkinson, J.W., 2020. A two-phase end-Triassic mass extinction. Earth-Science Reviews 208 (2020) 103282.

Wignall, P.B., Bond, D.P.G., 2008. The end-Triassic and Early Jurassic mass extinction records in the British Isles. Proceedings of the Geologists' Association 119, 73–84. doi:10.1016/S0016-7878(08)80259-3.

Wilson, H.E, Manning, P.I., 1978. Geology of the Causeway Coast. Memoir of the Geological Survey of Northern Ireland, Sheet 7 (Northern Ireland).

Wilson, D., Davies, J.R., Fletcher, C.J.N., Smith, M., 1990. Geology of the South Wales Coalfield, Part VI, the Country Around Bridgend. Memoir of the British Geological Survey England and Wales Sheets 261 and 262. HMSO, London, pp. 62.

Yager, J.A., West, A.J., Corsetti, F.A., Berelson, W.M., Rollins, N.E., Rosas, S., Bottjer, D.J., 2017. Duration of and decoupling between carbon isotope excursions during the end-Triassic mass extinction and Central Atlantic Magmatic Province emplacement. Earth and Planetary Science Letters 473, 227–236. doi:10.1016/j.epsl.2017.05.031.

Figure captions

Figure 1. Geology of south-east County Antrim showing localities described or referred to in the paper. Left inset shows the locations of Waterloo Bay and the Larne-1 Borehole. Bottom right inset shows location of the Rathlin-Foyle (RF) and Larne-Lough Neagh (LLN) basins within Northern Ireland.

Figure 2. Sketch map of the Triassic–Jurassic boundary succession exposed on the wave-cut platform at Waterloo Bay, Larne (modified after Ivimey-Cook, 1975). Strata dip to the northwest at 20° –30° .

Figure 3. Carbon stable isotopes and TOC plotted against graphic log of the section at Waterloo Bay, Larne. Samples span the interval from above the 'mud cracked' horizon at the base of the upper Cotham Member to the first common occurrence of *P. plicatulum* in the Waterloo Mudstone Formation. **A**, carbon stable-isotopes (bulk organic carbon); **B**, carbonate (%); **C**, total organic carbon (%). Sedimentary log after Simms and Jeram (2007), with bed numbers referred to in text.

Figure 4. Ammonites from the basal Hettangian. All specimens from Waterloo Bay, Larne, Co. Antrim, unless stated otherwise. **S**pecimens to same scale, except b, c and k. Scale bar = 5 cm.

a *Psiloceras erugatum* (Phillips, 1829). Large uncrushed plicate example from nodule in middle of Bed 24. K2014.1.9

b, c Detail of sutures on K2014.1.9

d *Psiloceras erugatum* (Phillips, 1829). From ex situ nodule, shore below Mullaghdubh House, Islandmagee, Co. Antrim. K2014.1.23

e *Psiloceras erugatum* (Phillips, 1829). From same nodule as 'a'

f *Psiloceras planorbis* (J. de C. Sowerby, 1824). Crushed example, 20 cm above base of Bed 28a. K2014.1.47

g *Psiloceras planorbis* (J. de C. Sowerby, 1824). Crushed examples, 4cm above base of Bed 28a. These are stratigraphically the earliest examples of this species found at Larne.

h *Psiloceras* sp.. Crushed involute specimen, 15 cm above base of Bed 25 or possibly Bed 26. A specimen of *Modiolus minimus* and part of an ambulacrum of *Diademopsis*, are visible in the lower part of the block. K2014.1.138

i *Psiloceras sampsoni* (Portlock, 1843). Partly crushed pyritic example, 6 cm above the base of Bed 29. K2014.1.49

j *Neophyllites cf. antecedens* Lange, 1941. Pyritic example, Ex situ, The Gobbins, Islandmagee, Co. Antrim. K2014.1.12

k Detail of sutures on K2014.1.12

l *Psiloceras plicatulum* (Quenstedt, 1883). Crushed example, top of Bed 28b. K2014.1.48

Figure 5. Ammonites from the basal Hettangian. All specimens from Waterloo Bay, Larne, Co. Antrim, unless stated otherwise. Specimens to same scale, except b, d, f and g. Scale bar = 5 cm.

a *Neophyllites imitans* Lange, 1941. Uncrushed example from marl in middle of bed 25. K2014.1.16

b, f Detail of sutures on K2014.1.16

c, d *Neophyllites antecedens* Lange, 1941. Pyritic internal cast, 6 cm below the top of bed 26. K2014.1.14

e *Neophyllites antecedens* Lange, 1941. 25 cm above base of bed 27. K2014.1.15

g Drawing of suture, specimen K2014.1.14 (c, d)

h *Neophyllites* sp. ex grp. *Becki* (Schmidt, 1925). Strongly ribbed specimen from top of bed 26. K2014.1.13

i *Psiloceras plicatulum* (Quenstedt, 1883). Uncrushed pyritic internal cast, *ex situ*, Minnis North, near Glenarm, Co. Antrim. K2014.1.7

j *Caloceras intermedium* (Portlock, 1843). Uncrushed example from limestone, *ex situ*, Minnis North, near Glenarm, Co. Antrim. K2014.1.120

k *Caloceras intermedium* (Portlock, 1843). Partly crushed example, Johnstoni Subzone. K2014.1.52

l *Caloceras johnstoni* (J. de C. Sowerby, 1824). Uncrushed example, *ex situ* from limestone, Johnstoni Subzone. A specimen of *Pinna* cf. *similes* obscures the right-hand side of this specimen. K2014.1.1

m *Psiloceras plicatulum* (Quenstedt, 1883). Crushed example (left) associated with *Caloceras* sp., 20 cm below top of Bed 33e. K2014.1.50

Figure 6. Cloghan Point, Whitehead.

a, Lithostratigraphy and composite log of the section.

b, Sketch map of outcrop, with mapped units coloured according to lithostratigraphy in **a**.

c, Cliff section, with upper Cotham Member limestone interval starting approximately across centre of image, and red-brown lower Cotham Member mudstones 1.5 m below. Dashed red line indicates Fault A (see map **b**).

d–f, Junction between Westbury Formation and Lilstock Formation exposed after beach deposits stripped away by storms.

d, Exposure below cliff section showing soft-sediment deformation in grey Westbury Formation mudstones, basal Cotham Member sandstone thickening away from Fault A, mounded and contorted wavy-bedded sandstones immediately above the basal sandstone.

e, Basal sandstone of Cotham Member showing contorted cross-bedded sand from its base mixed into deformed mudstone of the underlying Westbury Formation.

f, Minor fault offsetting the base of the Cotham Member, downthrow to right. Contorted wavy-bedded sandstones overlying the basal sandstone to the right are absent on the downthrown side. The grey-brown homogenous silty mudstone overlying the basal sandstone shows whisps and inclusions of black mudstone, some of which appears to have flowed across the fault plane (centre of image). Note the stub of sandstone (lower right) on the 'wrong' side of the fault. Ruler = 30 cm in **d–f**.

Figure 7. Cloghfin Port, Islandmagee. Sketch map of Penarth Group outcrop at Cloghfin Port, with measured sections (1–11) through Westbury Formation (at top) to illustrate the influence of synsedimentary fault movement on deposition and the stratigraphic constraints on the timing of fault movement.

Figure 8. Correlation of coastal exposures of the Triassic-Jurassic boundary succession in south-east County Antrim. Sample levels indicated in the Cloghan Point (Whitehead), Cloghfin Port and The Gobbins sections are those used in Steinthorsdottir et al. (2011), with their correlative positions indicated against the continuous Waterloo Bay section.

Figure 9 a–d. Cotham Member at Waterloo Bay.

a, Basal sandstone of Cotham Member above dark mudstone of Westbury Formation. Note highly contorted sand-mud alternations above basal sandstone, with large recumbent fold at top right.

b–d, all from top 1.2 m of lower Cotham Member.

b, Tidalite of mud-silt couplets with alternating planar-bedded and rippled units. Ripples across centre of image have bidirectional mud drapes indicating flow-ebb current reversal.

c, Top of lower Cotham Member, with ruler at upper limit of soft sediment deformation. Blue arrow indicates sandstone bed overlying 'mud-cracked' horizon; white arrows indicate erosion surface on a channel flank.

d, Tidalite ~40 cm below 'mud-cracked' surface, with bundles of very finely interlaminated sand and mud alternating with mud-dominated units. Ruler is 30 cm in all images.

Figure 10. Summary of Triassic–Jurassic boundary events in south-east County Antrim. See text for further explanation. The $p\mathrm{CO_2}$ proxy data are derived from *Brachyphyllum* cuticle in Steinthorsdottir et al. (2011); carbon stable-isotopes, seismicity and relative sea-level are from this study. The correlated position of the

Triassic–Jurassic boundary is indicated by the red horizontal line according to option 1 (see Figure 12 and text).

Figure 11 a–c. Subaqueous sedimentary cracks at ‘mud-cracked’ surface in Cotham Member, Waterloo Bay.

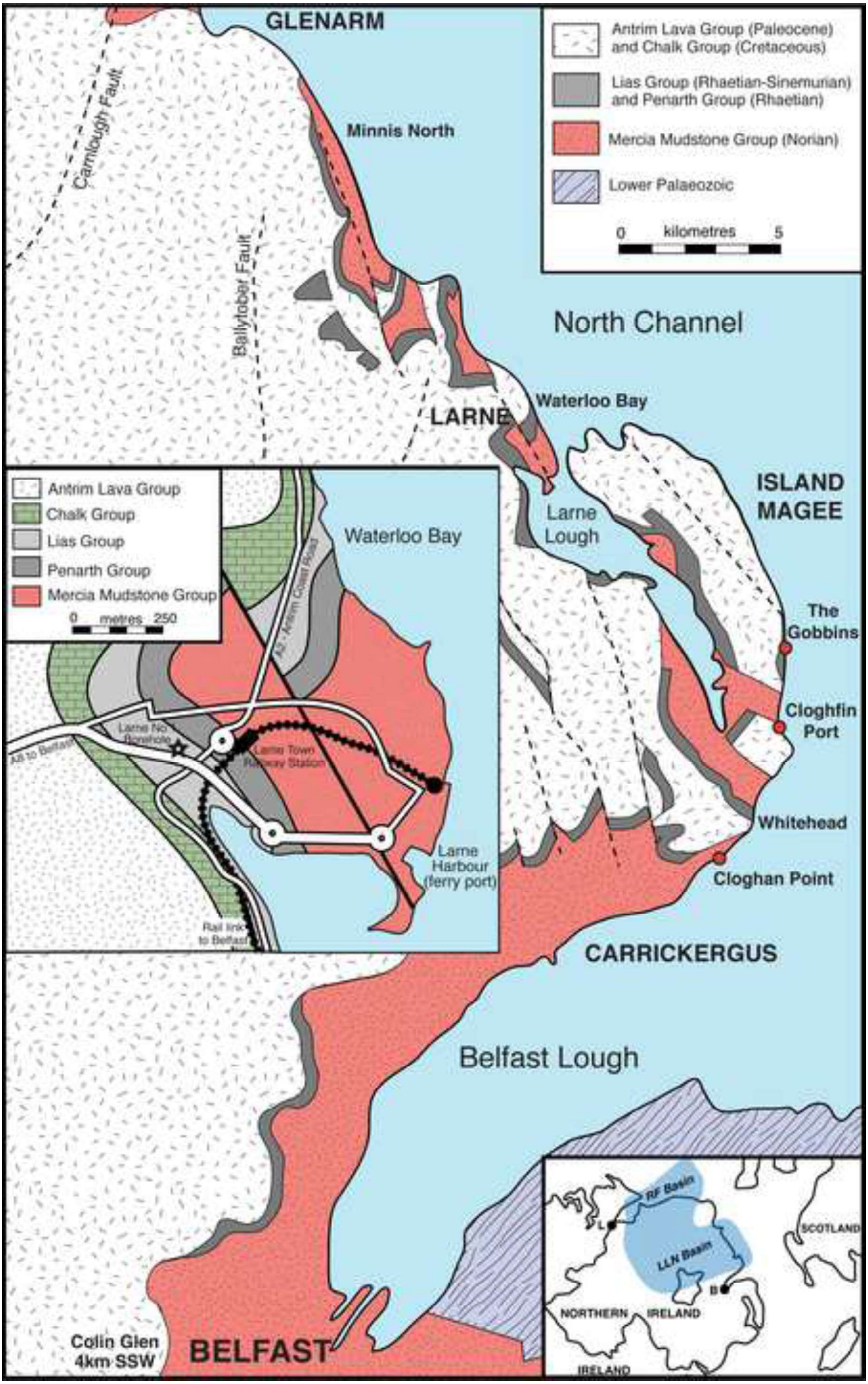
a, Top surface of ‘mud-cracked’ horizon.

b, Vertical section, with ‘mud-cracked’ surface indicated by blue arrow. White arrow to left indicates a low-angle crack which kinks to follow bedding and then kinks downward again. White arrow to right indicates small ptygmatic intersecting cracks.

c, Vertical section through ‘mud-cracked’ surface (blue arrow), with white arrow indicating large low-angle anastomosing crack. Note continuity of sedimentation across surface and deformed cross-laminated sets (lower right).

Figure 12. Correlation of the Waterloo Bay carbon stable-isotope curve with curves from the TJB GSSP section at Kujoch, the Tiefengraben (Eiberg Basin) section and the St Audrie’s Bay and Doniford Bay sections in the Bristol Channel Basin. The Tiefengraben and Kujoch isotope curves have been correlated by palynology (see Hillebrandt et al., 2013). Tiefengraben simplified isotopes and biostratigraphical markers after Kürschner et al. (2007), Kujoch simplified lithostratigraphy and isotopes after Hillebrandt et al. (2013). Note that the start of the ‘main’ excursion is missing in the Kujoch curve due to a fault omitting strata near to the top of the Schattwald Beds (indicated in pink) and the points joined by the blue line in the Tiefengraben curve are from the Eiberg section. St Audrie’s Bay carbon stable-isotopes are after Hesselbo et al. (2002, 2004), biostratigraphic markers after Warrington et al. (2008). Doniford Bay carbon stable-isotopes, lithostratigraphy (simplified) and biostratigraphic markers are after Clémence et al. (2010). The Doniford Bay and St Audrie’s Bay isotope curves are to the same vertical scale, whilst the Waterloo Bay curve is reduced by 50% relative to them. The Triassic–Jurassic boundary (TJB) marked by the first appearance of *Psiloceras spelae tyrolicum* at Kujoch is indicated by the green line, with correlation Level 1, Level 2 and Level 3 being shown. The negative shift of the ‘initial’ and ‘main’ CIE intervals are indicated with blue shading. Letters A–C indicate features of the isotope curves discussed in the main text. *Psiloceras erugatum* is correlated with *P. calliphyllum* after Hillebrandt and Kment (2015).

Figure 1



GLENARM
Antrim Lava Group (Paleocene) and Chalk Group (Cretaceous)
Lias Group (Rhaetian-Sinemurian) and Penarth Group (Rhaetian)
Mercia Mudstone Group (Norian)
Lower Palaeozoic
0 kilometres 5
Carnlough Fault
Minnis North
Ballytober Fault
North Channel
Waterloo Bay
LARNE
Larne Lough
ISLAND MAGEE
The Gobbins
Cloghfin Port
Whitehead
Cloghan Point
CARRICKERGUS
Belfast Lough
Colin Glen 4km SSW
BELFAST
Antrim Lava Group
Chalk Group
Lias Group
Penarth Group
Mercia Mudstone Group
0 metres 250
Waterloo Bay
A2 - Antrim Coast Road
Larne No Borehole
A8 to Belfast
Larne Town Railway Station
Larne Harbour (ferry port)
Rail link to Belfast
RF Basin
LLN Basin
SCOTLAND
NORTHERN IRELAND
IRELAND

Figure 2

Click here to access/download;Figure;Jeram et al Fig 2.jpg

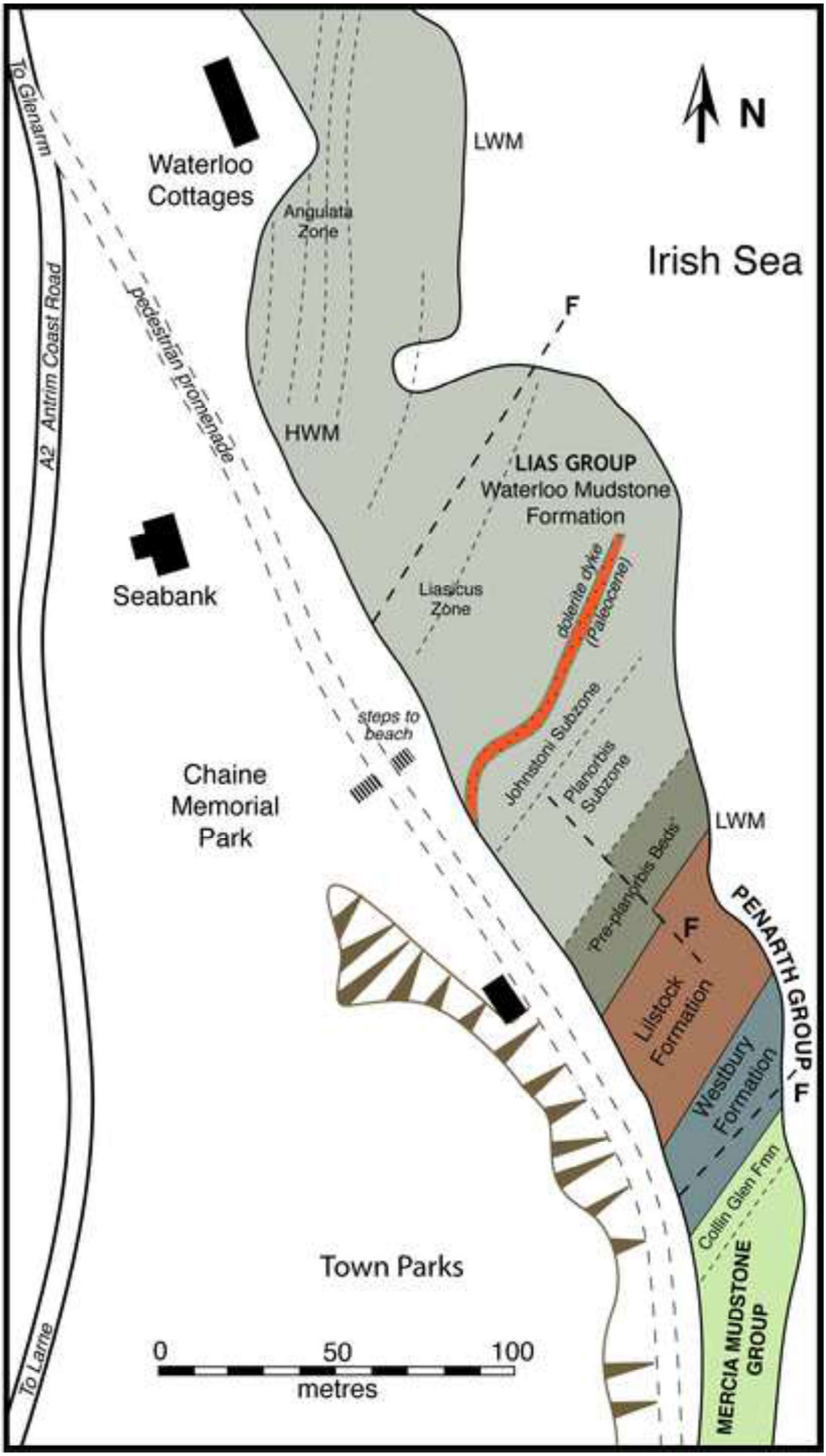


Figure 3

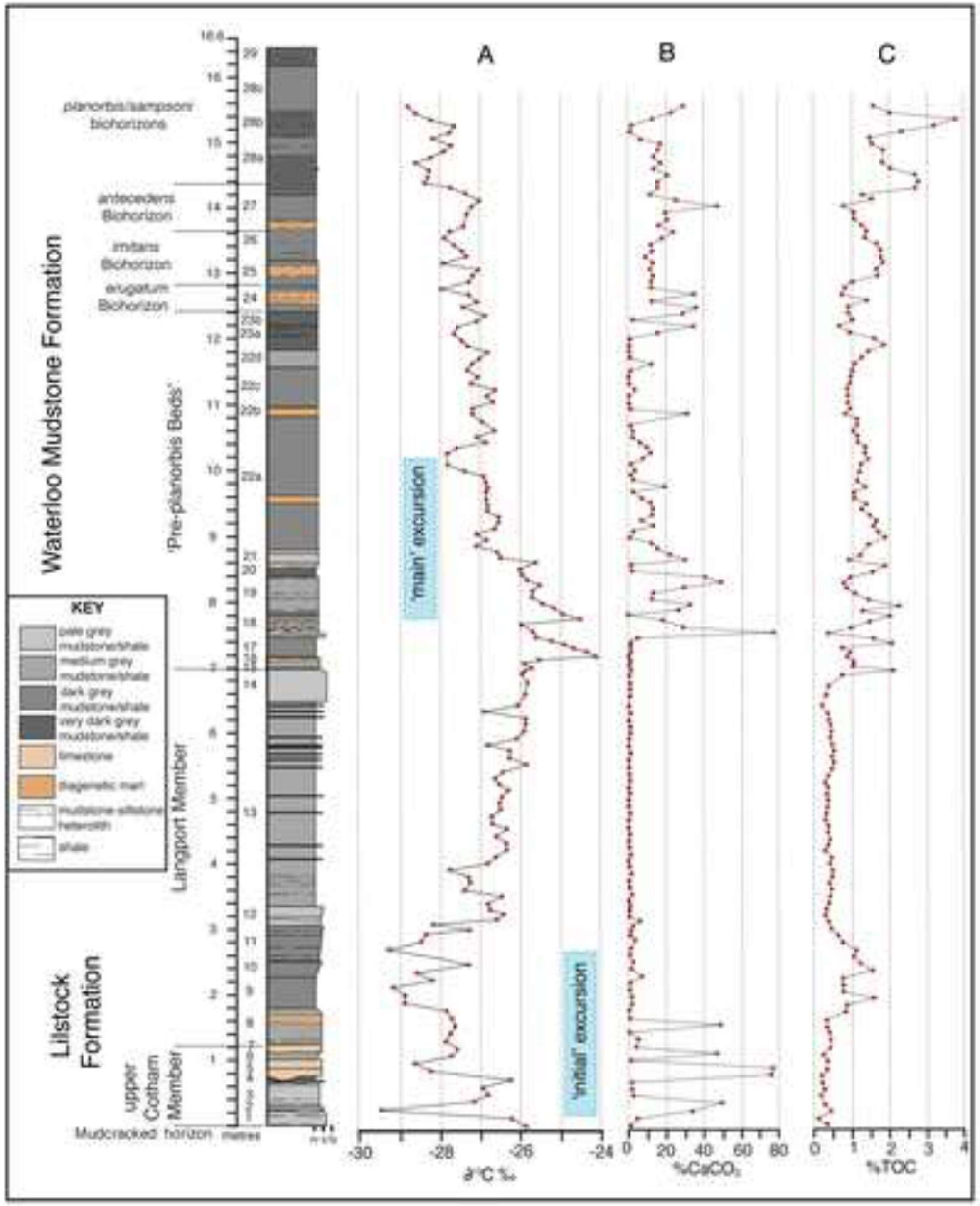

A
B
C
Waterloo Mudstone Formation
Lilstock Formation
planorbis/sampsoni biohorizons
antecedens Biohorizon
imitans Biohorizon
erugatum Biohorizon
'Pre-planorbis Beds'
Langport Member
upper Cotham Member
Mudcracked horizon
metres
KEY
pale grey mudstone/shale
medium grey mudstone/shale
dark grey mudstone/shale
very dark grey mudstone/shale
limestone
diagenetic marl
mudstone-siltstone heterolith
shale
'main' excursion
'initial' excursion
-30
-28
-26
-24
%CaCO₃
%TOC

Figure 4

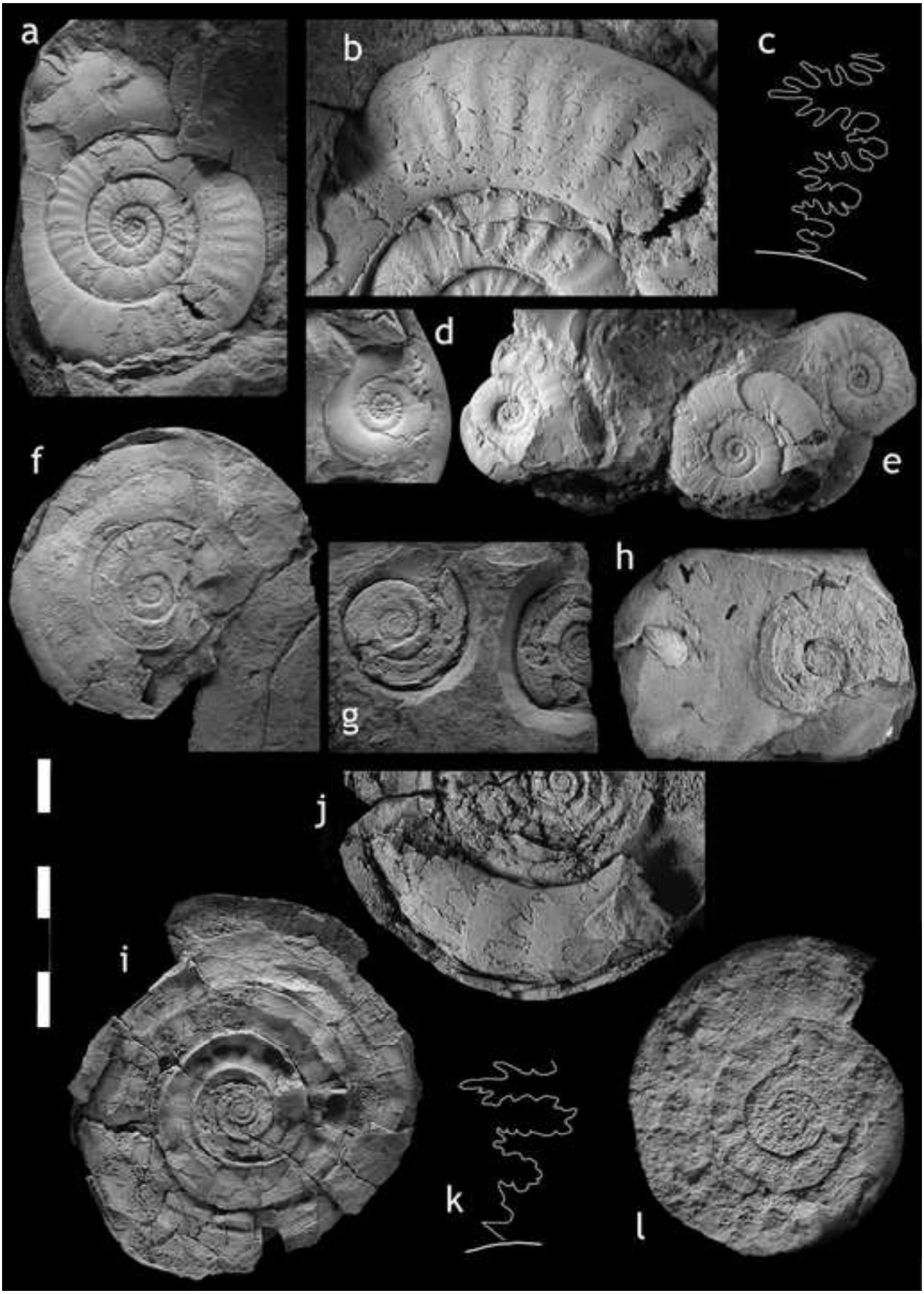


Figure 5

Click here to access/download;Figure;Jeram et al Fig 5.jpg

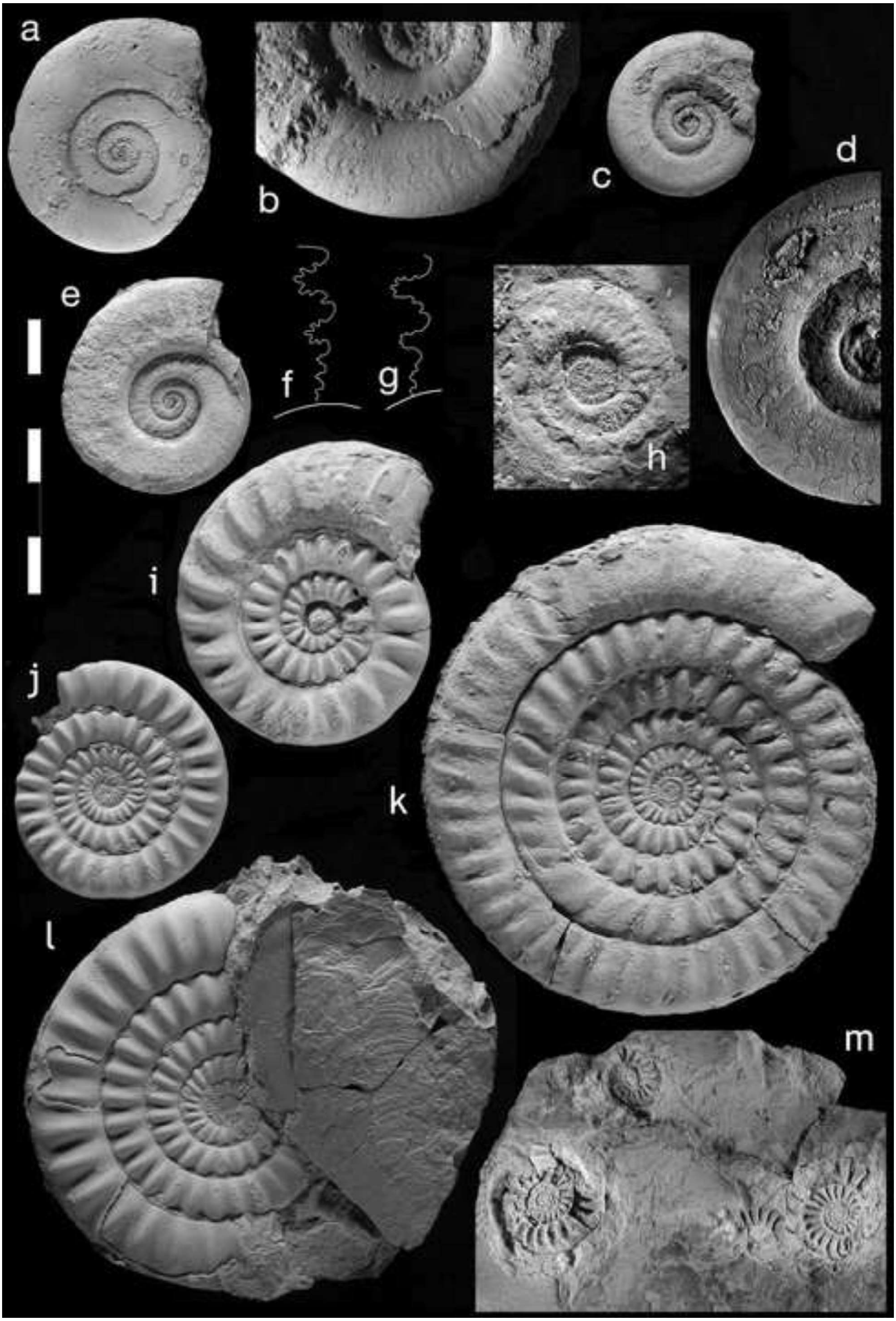
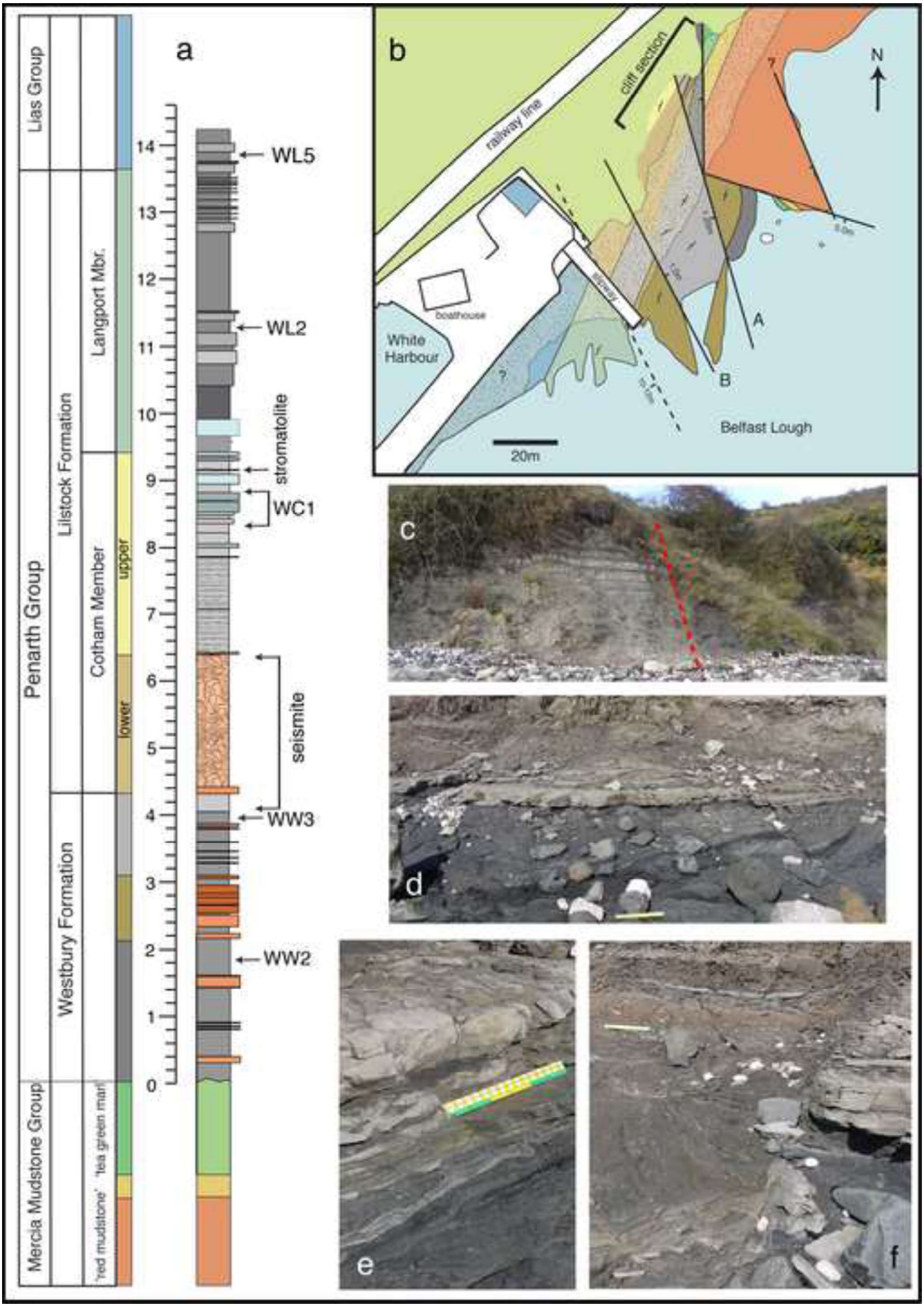


Figure 6



a
Lias Group
Penarth Group
Mercia Mudstone Group
Lilstock Formation
Westbury Formation
Langport Mbr.
Cotham Member
upper
lower
'red mudstone'
'tea green marl'
WL5
WL2
stromatolite
WC1
seismite
WW3
WW2
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
b
railway line
cliff section
N
boathouse
White Harbour
slipway
A
B
Belfast Lough
20m
c
d
e
f

Figure 7 Click here to access/download;Figure;Jeram et al Fig 7.jpg

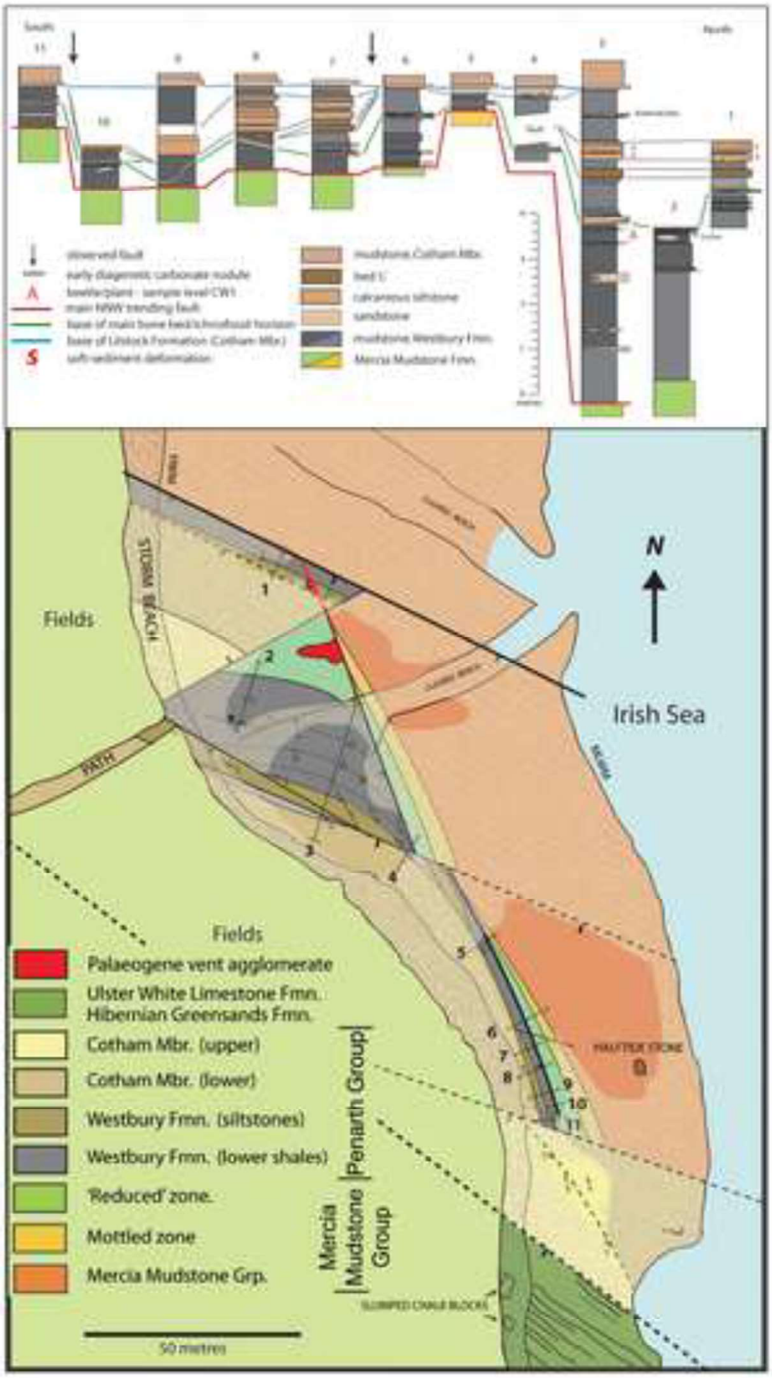
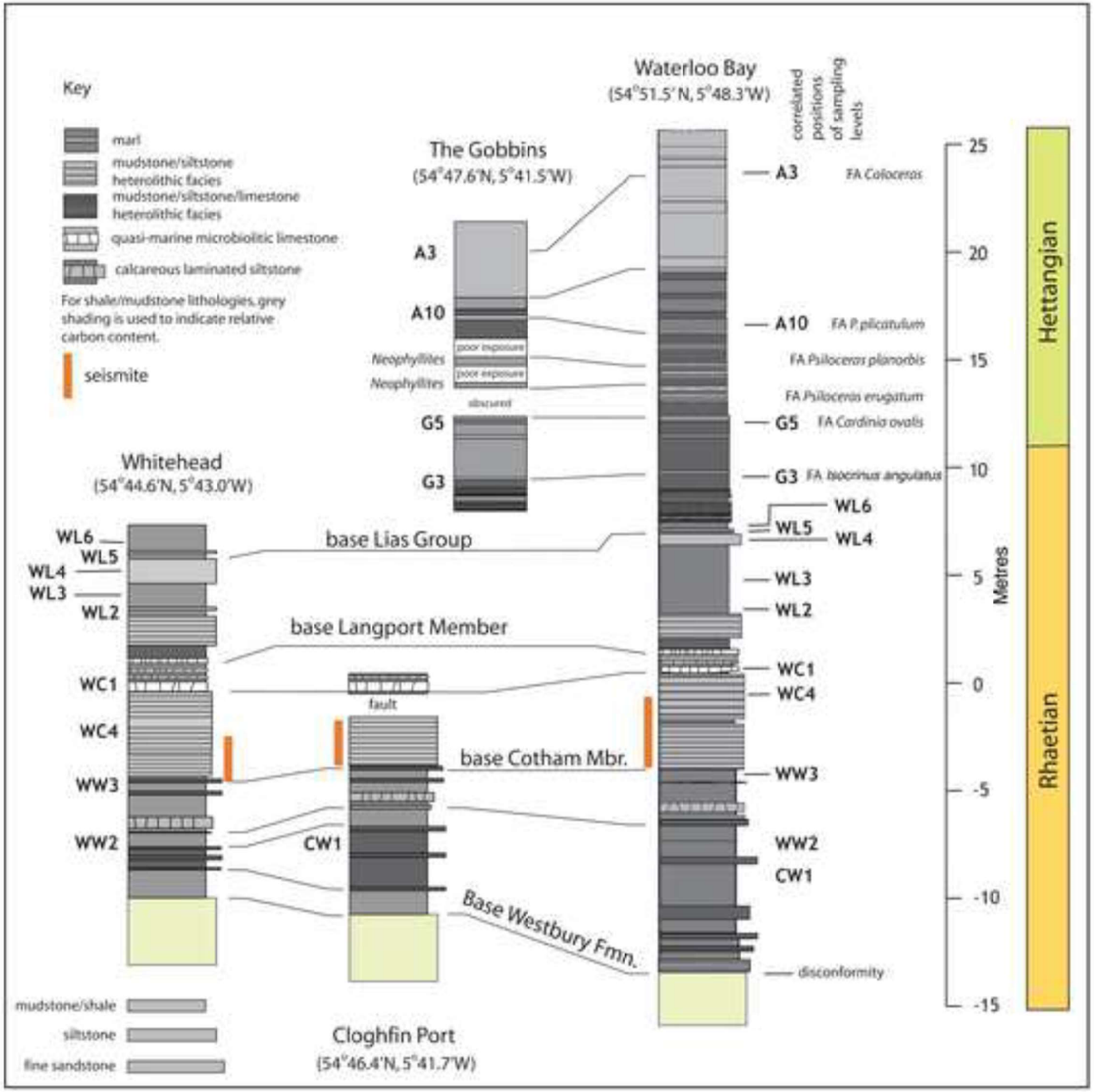


Figure 8



Key
marl
mudstone/siltstone heterolithic facies
mudstone/siltstone/limestone heterolithic facies
quasi-marine microbiolitic limestone
calcareous laminated siltstone
For shale/mudstone lithologies, grey shading is used to indicate relative carbon content.
seismite
Waterloo Bay
(54°51.5′N, 5°48.3′W)
correlated positions of sampling levels
The Gobbins
(54°47.6′N, 5°41.5′W)
Whitehead
(54°44.6′N, 5°43.0′W)
Cloghfin Port
(54°46.4′N, 5°41.7′W)
A3
A10
G5
G3
Neophyllites
poor exposure
obscured
FA Caloceras
FA P. plicatulum
FA Psiloceras planorbis
FA Psiloceras erugatum
FA Cardinia ovalis
FA Ixiocrinus angulatus
WL6
WL5
WL4
WL3
WL2
WC1
WC4
WW3
WW2
CW1
base Lias Group
base Langport Member
base Cotham Mbr.
Base Westbury Fmn.
fault
disconformity
Metres
25
20
15
10
5
0
-5
-10
-15
Hettangian
Rhaetian
mudstone/shale
siltstone
fine sandstone

Figure 9

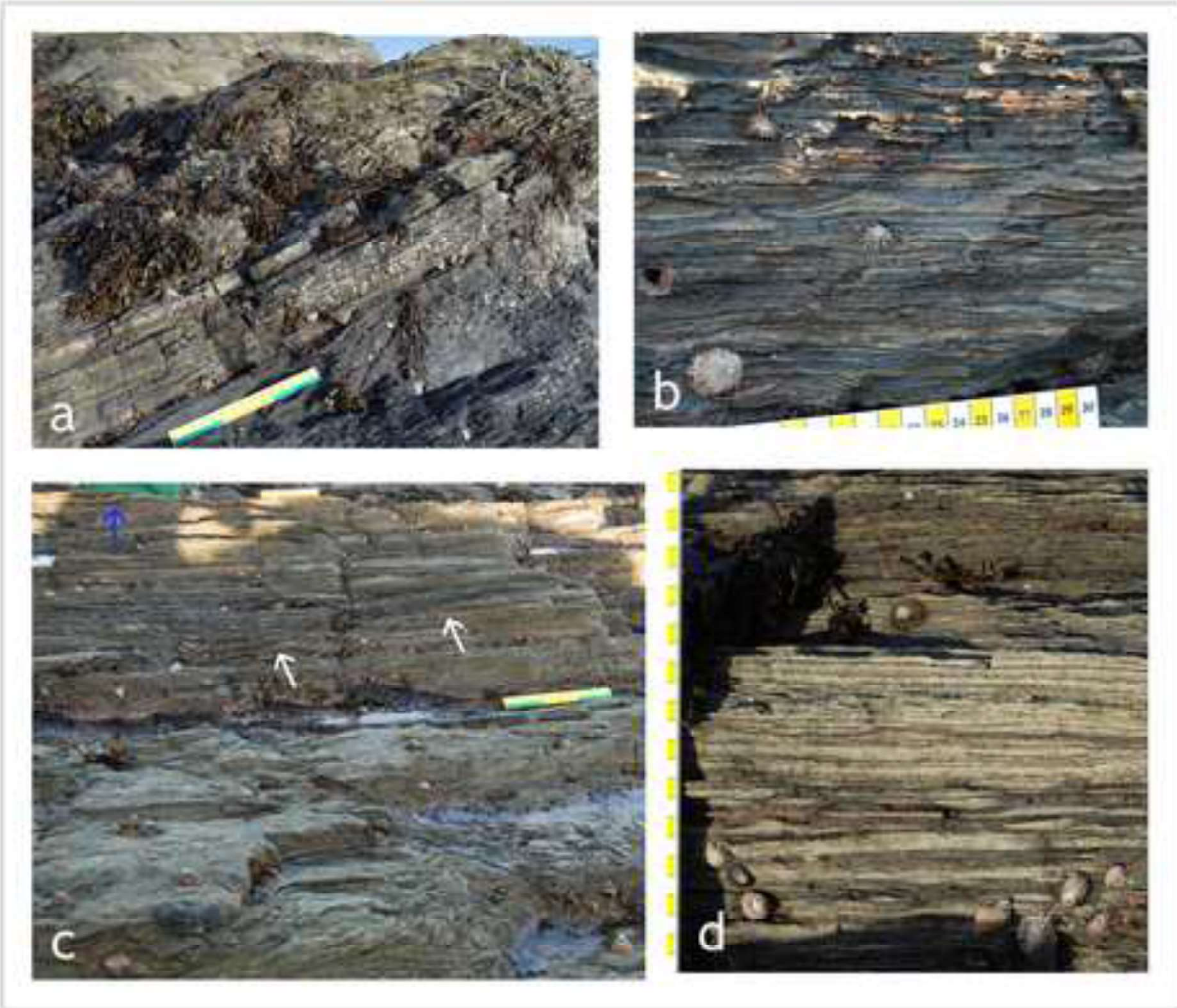


Figure 10

Click here to access/download;Figure;Jeram et al Fig 10.jpg

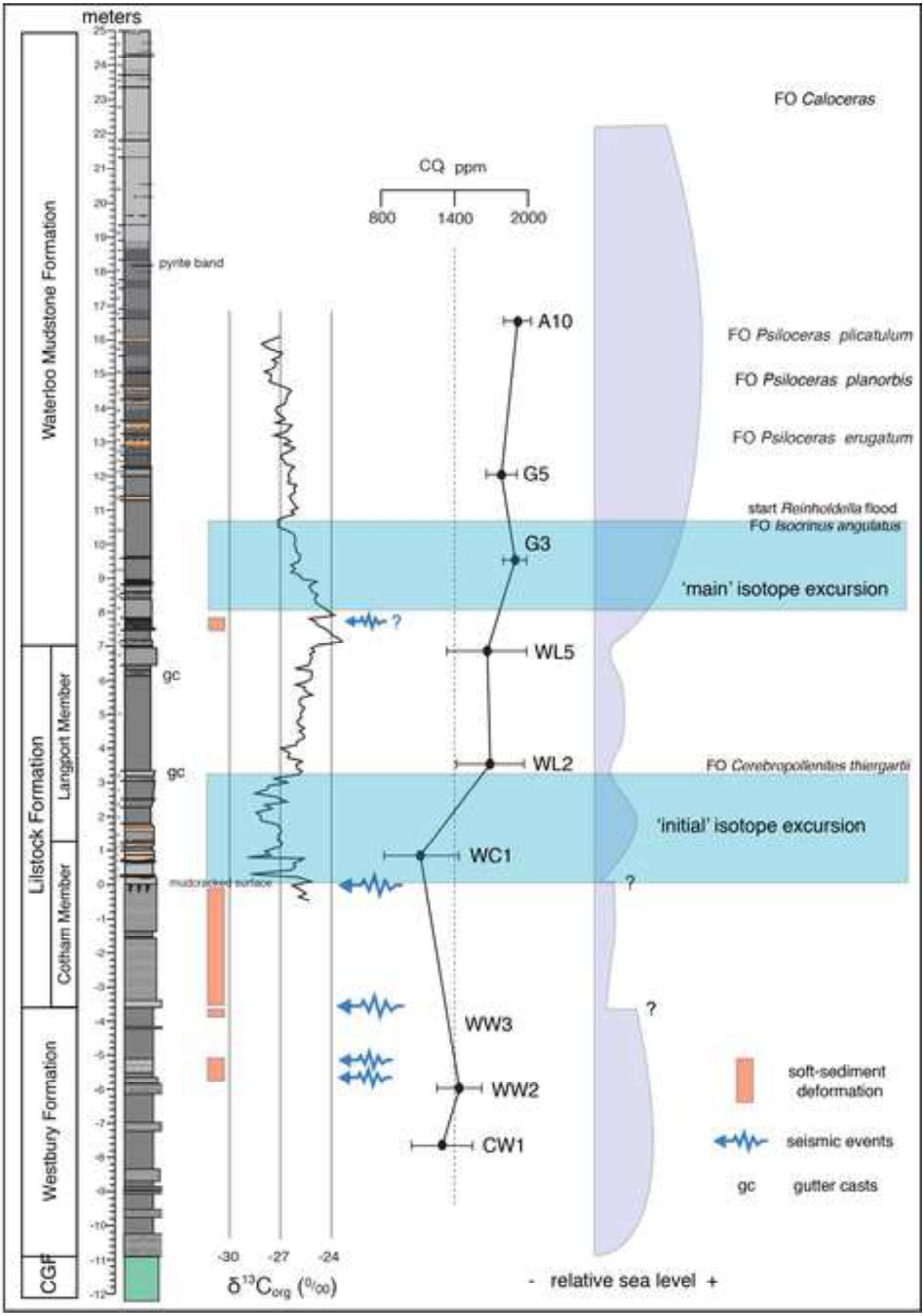


Figure 11

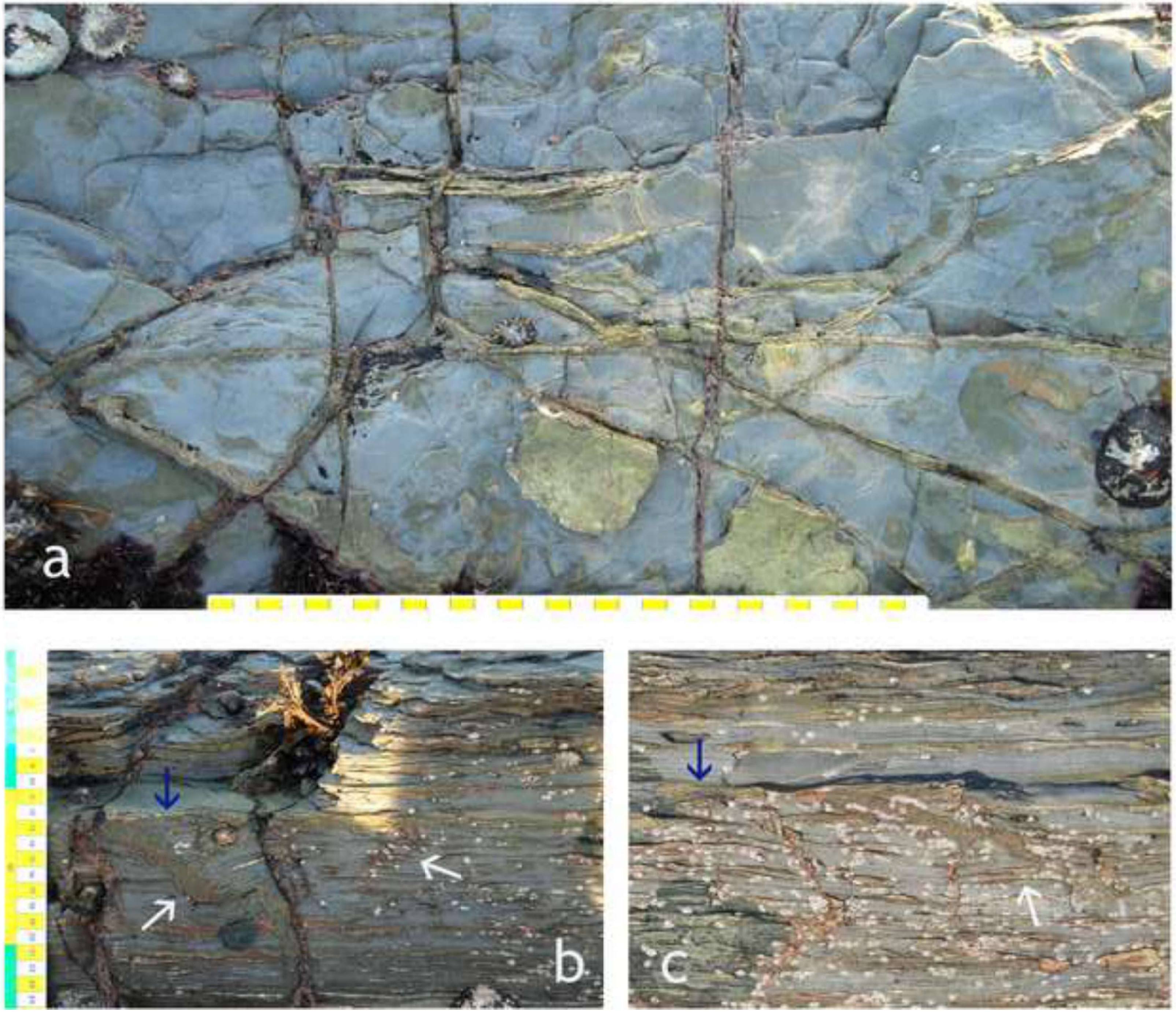
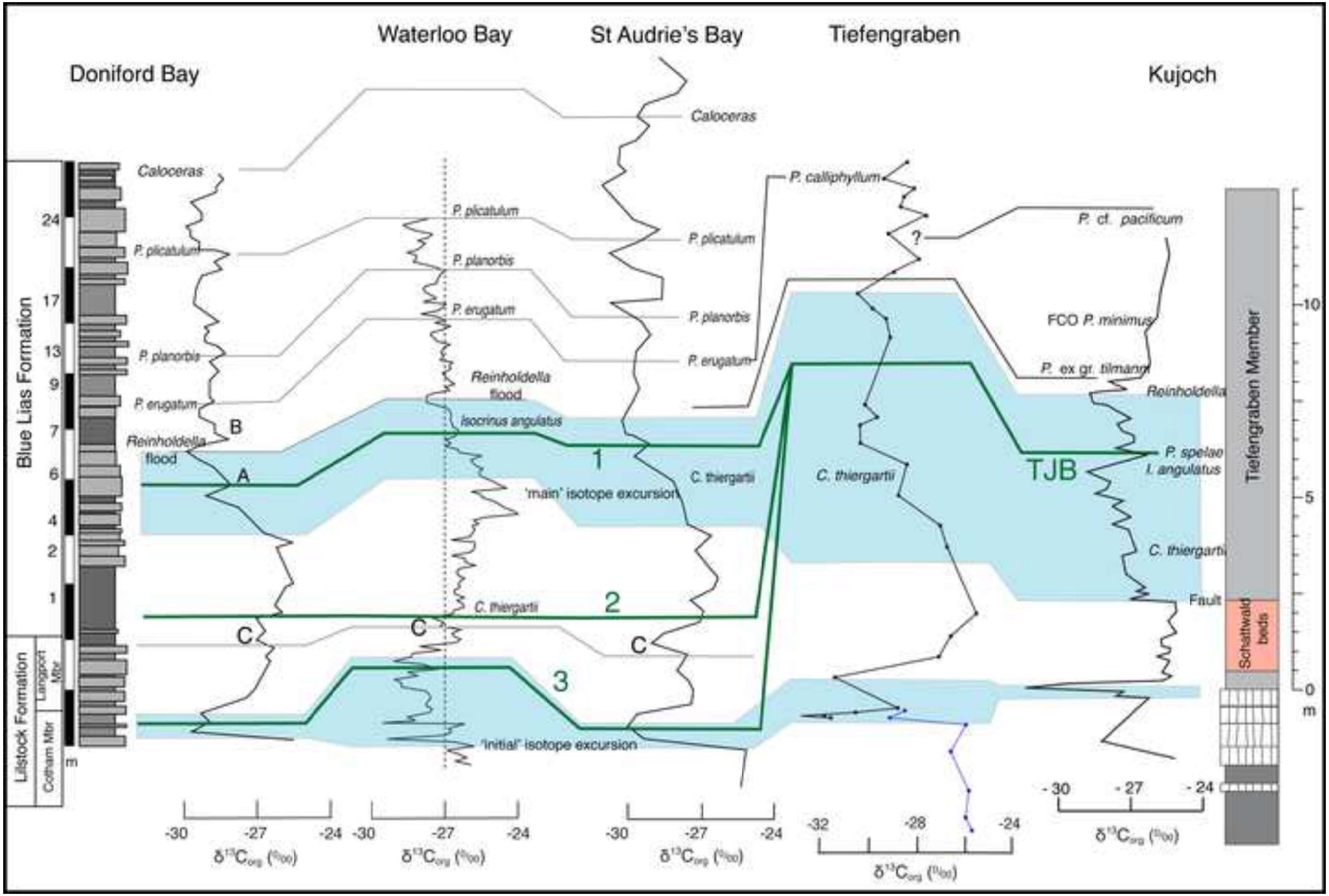


Figure 12



Doniford Bay
Waterloo Bay
St Audrie's Bay
Tiefengraben
Kujoch
Blue Lias Formation
Lilstock Formation
Langport Mbr
Cotham Mbr
Caloceras
P. plicatulum
P. planorbis
P. erugatum
Reinholdella flood
Isocrinus angulatus
C. thiergartii
P. calliphyllum
P. cf. pacificum
FCO P. minimus
P. ex gr. tilmanni
Reinholdella
P. spelae
I. angulatus
Fault
Tiefengraben Member
Schattwald beds
TJB
1
2
3
A
B
C
'main' isotope excursion
'initial' isotope excursion
$\delta^{13}C_{org}$ (‰)
m