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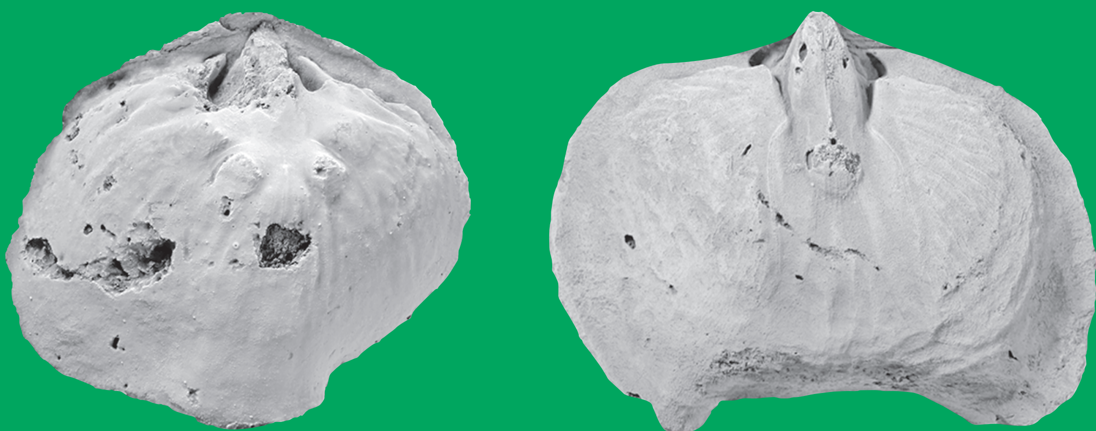

Maria Liljeroth, David A. T. Harper, Hilary Carlisle and Arne T. Nielsen

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The Irish Leinster Terrane, Co. Waterford, SE Ireland, has traditionally been associated with a palaeogeographical position close to East Avalonia, but a number of recent studies on, for example, zircon geochronology, geochemistry, isotope analyses and tectono- and lithostratigraphy strongly point to a Ganderian affinity. Together with the Monian Composite, Bellewstown, Grangegeeth, Central Newfoundland and Miramichi terranes, the Leinster Terrane formed part of the leading edge of Ganderia in association with the Popelogan-Victoria arc several hundred kilometres north of Avalonia during the Ordovician. The present faunal data together with the Ganderian studies and compiled palaeomagnetic data from other authors form the basis of new palaeobiogeographical reconstructions of the mid Darriwilian and early Sandbian palaeoplate configurations in the south Iapetus Ocean. The generic composition of the Tramore and Dunabrattin Limestone formations contains only few endemic forms and is dominated by a mix of taxa that originated in other parts of the world during the Early–early Late Ordovician including low-latitude Laurentia, high-latitude peri-Gondwana and mid-latitude Baltica. All the Ganderian terranes and East Avalonia contained mixed faunas during the mid Darriwilian – early Sandbian indicating that these sites together occupied a mid-latitudinal position comprising settling grounds for taxa from the surrounding, widely dispersed high-, low- and mid-latitude palaeoplates. The Tramore and Dunabrattin limestones furthermore contain brachiopod species that migrated to the Leinster Terrane from East Avalonia, Baltica, Laurentia and peri-Laurentia during the late Darriwilian – early Sandbian confirming the Ganderian terrane's close relationship with the other Iapetus-bordering sites. Oceanic wind-driven surface currents were the primary factor determining brachiopod dispersal in the Darriwilian, when the majority of taxa were associated with shelfal biofacies. The brachiopod migrational patterns reported for the Darriwilian in the present investigation together with the Mid Ordovician synthetic ocean surface circulation models form the basis of revised models of oceanic surface current flow for the early and late Darriwilian, respectively. The *gracilis* drowning diminished brachiopod provinciality in the early Sandbian, and the number of reported brachiopod provinces was reduced from five to four. The mid-latitude Celtic and Baltic provinces were thus obliterated and replaced by the combined Anglo-Welsh–Baltic Province. A total of 20 rhynchonelliformean brachiopod genera and 22 species are described from the upper Darriwilian – lower Sandbian Tramore and Dunabrattin Limestone formations (Leinster Terrane). Seven of these are new species and include *Atelelasma longisulcum* n. sp., *Colaptomena auduni* n. sp., *Dactylogonia costellata* n. sp., *Hesperorthis leinsterensis* n. sp., *Howellites hibernicus* n. sp., *Isophragma parallelum* n. sp. and *Platystrophia tramorensis* n. sp. as well as one new genus *Hibernobonites* n. gen. and the earliest recorded occurrence of a *Tetraphalerella*-like genus in the lowermost part of the Tramore Limestone. □ *Avalonia, biogeography, brachiopods, Darriwilian, Ganderia, Leinster Terrane, oceanic surface currents, Sandbian.*

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Introduction

The current work comprises a description of the rhynchonelliformean brachiopods from the upper Darriwilian – lower Sandbian Tramore Limestone Formation and lower Sandbian Dunabrattin Limestone Formation, Tramore area, Co. Waterford, southeast Ireland. The stratigraphy of the formations

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is updated with new lithological and faunal correlations between the formation units as well as biostratigraphical correlation with the international and British stages of Cooper & Sadler (2012) and international time-slices of Webby *et al.* (2004). New interpretations regarding the depositional settings and palaeoecology of the formations are likewise provided, including a new lithologically based model for palaeobathymetric characterization.

The Tramore fauna is unique in the sense that it contains a mixed fauna of, for example, Laurentian, Baltic and high-latitude peri-Gondwanan origins with no unequivocal relation to any of the defined biogeographical provinces in the Darriwilian. The complex faunal composition of the Darriwilian – Sandbian Leinster Terrane has led some authors to suggest a more oceanwards position for the terrane than traditionally applied, that is within the leading edge of East Avalonia (Owen & Parkes 2000) or a separate drifting/docking history (Fortey & Cocks 2003). The current work provides a detailed assessment of the brachiopod provinces described by Harper *et al.* (2013) and the faunas related to the investigated palaeoplates with focus on the Iapetus and Rheic oceans and the Tornquist Sea not only to resolve the source of the mixed faunal signature of the Leinster Terrane but also to reveal important details about the individual palaeoplates within the provinces that have hitherto not been assessed by the traditionally more general, global biogeographical analyses. The two time-slices applied herein mainly cover the early mid–latest Darriwilian and the early Sandbian, respectively, and largely include stratigraphy with a significant biostratigraphical overlap with the Tramore and Dunabrattin Limestone formations. This is an attempt to study high-resolution brachiopod biogeography on a wider geographical scale within very limited time intervals. Previous procedure for these investigations within the Darriwilian and Sandbian was often to combine the Dapingian and Darriwilian into one time-slice and to include the total Sandbian interval due to poor biostratigraphical constraint (see, e.g., Harper *et al.* 2013). By implication not all stratigraphical sections overlapping with the late Darriwilian or early Sandbian are included in the multivariate biogeographical analyses but the taxonomical compositions of the individual sites and provinces within the time-slices are compared with later and earlier faunas to give a more complete picture.

The Leinster Terrane has traditionally been illustrated as having close geographical proximity to East Avalonia based on faunal affinities and the presence of arc-related volcanic rocks (e.g. Parkes & Harper 1996; Cocks *et al.* 1997; Harper & Mac Niocaill 2002) but several analyses including detrital zircon geochronology, geochemistry, isotopic signatures, litho- and tectonostratigraphy and palaeomagnetism (e.g. van Staal *et al.* 1996, 1998, 2009, 2012; Collins & Buchan 2004; Valverde-Vaquero *et al.* 2006; Hibbard *et al.* 2007; Fyffe *et al.* 2009; Zagorevski *et al.* 2010; Pothier *et al.* 2015; Waldron *et al.* 2014) now point to a position within the leading edge of Ganderia close to the Popelogan-Victoria volcanic arc together with the Monian Composite (i.e. Rosslare and Anglesey), Bellewstown, Grangegeeth, Central Newfoundland and Miramichi terranes. Based on these results as well as compiled palaeomagnetic data from several authors (i.e. Torsvik *et al.* 1990, 1992, 1996; van der Voo *et al.* 1991; Trench & Torsvik 1992), the current study suggests new palaeobiogeographical reconstructions for the Iapetus Ocean for the mid Darriwilian and early Sandbian, respectively.

The Tramore fauna was not the only fauna of mixed origins in the late Darriwilian. In fact, East Avalonia and the Ganderian terranes contained varying numbers of biogeographically important taxa that originated in different parts of the world including Laurentia, peri-Laurentia and peri-Gondwana with an additional significant Baltic component present in the Ganderian terranes not reported from East Avalonia. This poses an interesting problem relating to geographical position and oceanic surface current systems that, when seen in context, aids explanation of the faunal affinities of the Leinster Terrane.

The studied time-slices were part of the Great Ordovician Biodiversification Event (GOBE) when global marine diversity increased dramatically and the rhynchonelliform brachiopods experienced major diversification on family, genus and species level. Orthide and strophomenide origination rates exceeded extinction rates across the Darriwilian – Sandbian transition on a global scale (Harper *et al.* 2004), although the present high-resolution study identifies sites in which diversity declined across the transition due to accelerated extinction and localized disappearance of specialized taxa.

Previous work

The continuous succession of volcanic and sedimentary deposits now assigned to the Duncannon Group was first described by Reed (1899) from a locality near Tramore town. He drew several sketches along the foreshore showing the relation between the formations of the group including the Tramore

Limestone Formation. Subsequent stratigraphical accounts by Mitchell *et al.* (1972), Williams (1976), Carlisle (1979), Harper & Parkes (2000), Wyse Jackson *et al.* (2001) and Key *et al.* (2005) and this study were based on the same area.

The brachiopod faunas of the Duncannon Group in County Waterford were described by Carlisle *in* Mitchell *et al.* (1972) and Carlisle (1979). The 1972 paper gave a preliminary palaeontological and stratigraphical account of the Duncannon Group formations, and the 1979 paper summarizes Carlisle's main work with a reinterpretation of the Tramore area faunas. Parkes (1994) published a monographic work on the brachiopod systematics from selected formations of the Duncannon Group primarily using Carlisle's original material collected in the Tramore area in the 1970s excluding the Tramore and Dunabrattin Limestone formations. Other palaeontological work includes descriptions of the bryozoans of the Tramore and Dunabrattin limestones and their palaeoenvironmental affinities (Wyse Jackson *et al.* 2001), a monographic work on the trilobites of the Duncannon Group published by Owen & Parkes (2000) and a crinoid described from the Tramore Limestone by Donovan (1985).

The early work by Williams (1976) recognized a division of Ireland based on the different faunal affinities. He divided the country into three distinct southwest–northeast oriented belts largely corresponding to (1) the Irish part of the Midland Valley Terrane (possibly together with the Grampian Terrane) of Scoto-Appalachian faunal affinity; (2) the Irish part of the Southern Uplands Terrane with a Southern Uplands faunal affinity; and (3) the Leinster Terrane with Anglo-Welsh and Baltic affinities. Palaeobiogeographical analyses of the Irish terranes were provided by, for example, Harper & Parkes (1989), Murphy *et al.* (1991), Harper (1992), Parkes (1992), Owen & Parkes (2000) and Key *et al.* (2005). Harper & Parkes (2000) recognized at least seven tectonic terranes in Ireland based on faunal evidence and the present study follows this division although with terrane names from Waldron *et al.* (2014). An overview of the palaeontological characteristics of the Irish terranes was provided by Harper & Parkes (1989).

The tectonic evolution of the Iapetus Ocean was described in detail by van Staal *et al.* (1996, 1998, 2009, 2012), Zagorevski *et al.* (2010), Pollock *et al.* (2012) and Pothier *et al.* (2015). Detailed accounts of the tectonic evolution of Avalonia and Ganderia were given by van Staal *et al.* (1996, 1998, 2009), Hibbard *et al.* (2007), Pollock *et al.* (2012) and Waldron *et al.* (2014).

Geological setting

The Tramore and Dunabrattin Limestone formations belong to the upper Darriwilian – lower Katian Duncannon Group of southeastern counties Waterford and Wexford, Ireland. The Duncannon Group comprises a suite of shallow- to deep-water impure carbonates and calcareous mudrocks overlain by basaltic, andesitic and rhyolitic arc volcanics accumulated on the Leinster Terrane (Carlisle 1979; Harper & Parkes 2000; Key *et al.* 2005).

Southeastern Ireland including the Leinster Terrane and the associated Leinster Basin formed part of the southern margin of the Iapetus Ocean through the Ordovician (e.g. Stillman 1978; Neuman & Harper 1992; Harper *et al.* 1996; Mac Niocaill *et al.* 1997; van Staal *et al.* 1998, 2012; Harper & Mac Niocaill 2002; Cocks & Torsvik 2011, 2013). Its Middle–Upper Ordovician volcanic rocks have previously been associated with subduction related arc–backarc volcanism by the leading edge, that is the northern margin, of the Avalonian microcontinent (e.g. Phillips *et al.* 1976; Stillman 1986; Parkes 1992; Tietzsch-Tyler & Sleeman 1994; Sleeman & McConnell 1995; Parkes & Harper 1996; Cocks *et al.* 1997; Mac Niocaill *et al.* 1997; Harper & Mac Niocaill 2002; Key *et al.* 2005; Brenchley & Rawson 2006; Brenchley *et al.* 2006; Harper *et al.* 2013) but recent results by other workers (see below) suggest that the volcanic rocks of the Leinster Terrane were more likely related to arc–backarc volcanism in the Popelogan-Victoria arc–Tetagouche-Exploits backarc basin (PVA-TEB) by the leading edge of the Ganderian microcontinent north of Avalonia. Owen & Parkes (2000) stressed that the Leinster Terrane had a more complex tectonic and biogeographical relationship with the Anglo-Welsh area than previously considered (i.e. by workers placing the terrane close to the northern East Avalonian margin) and suggested a more oceanwards position of this terrane. Fortey & Cocks (2003) suggested it had a separate drifting/docking history to East Avalonia based on brachiopod and trilobite faunas, although they illustrated the terrane as positioned on the northern East Avalonian margin.

Tectonomagmatic analyses of West Avalonian and west Ganderian basement rocks in the Appalachian orogen by Barr & White (1996) showed that Avalonia and Ganderia have different basement composition. Several other authors, applying one or more of the following types of data and methods including detrital zircon geochronology, geochemistry, isotopic signatures, litho- and tectonostratigraphy and palaeomagnetism (e.g. van Staal *et al.* 1996, 1998, 2009, 2012; Collins & Buchan 2004; Valverde-Vaquero *et al.* 2006; Hibbard *et al.* 2007; Fyffe *et al.* 2009; Zagorevski *et al.* 2010; Pothier *et al.* 2015; Waldron *et al.* 2014), identified Ganderia and its associated islands and volcanic arc terranes and/or the mutual palaeogeographical relationship between a selection of these and other terranes and microcontinents. Pollock *et al.* (2012) reviewed the palaeogeographical development of the peri-Gondwanan realm of the Appalachian orogeny including the history of Ganderia and Avalonia and summarized their definitions.

The regional distribution of Ganderia and Avalonia in Ireland and Great Britain is shown by Pollock *et al.* (2012, fig. 4). Terranes included in Ganderia are the Bellewstown (east Ireland), Grangegeeth (east Ireland) and Leinster–Lakesman (south Ireland–north England) terranes and the Monian Composite Terrane (Anglesey of northwest Wales and Rosslare of southeast Ireland). The Southern Uplands Terrane was also included in Ganderia by Pollock *et al.* (2012), but zircon geochronology studies by Waldron *et al.* (2014) strongly suggested a Laurentian affinity for the terrane. The regional distributions of the northern Appalachian terranes associated with Ganderia are illustrated in Pollock *et al.* (2012, fig. 3) and include the Central Newfoundland and Miramichi (New Brunswick, Maine) terranes. Following the results of van Staal *et al.* (1996, 1998, 2009, 2012), these terranes formed part of the Popelogan-Victoria arc–Tetagouche-Exploits backarc basin system created by subduction at the leading edge of Ganderia during the progressive closure of the Iapetus Ocean. Harper & Mac Niocaill (2002) associated the Central Newfoundland and Miramichi terranes of Ganderia with the western part of the Popelogan-Victoria arc north of Avalonia but they still included the Leinster and Monian Composite terranes as part of the East Avalonian margin. The Welsh Basin of East Avalonia includes Tremadocian arc volcanics but the development of the Popelogan-Victoria arc–Tetagouche-Exploits backarc basin system in the Floian (ca. 475 Ma; van Staal *et al.* 2012) changed both location and chemistry of the volcanism and transformed the Welsh Basin into a backarc basin (Brenchley & Rawson 2006; Brenchley *et al.* 2006). The Leinster Terrane and Basin includes Sandbian acidic volcanics typical of arc–backarc volcanism and was located oceanwards of the Welsh and Anglian basins (Brenchley & Rawson 2006), possibly in close proximity to the Popelogan-Victoria arc.

Tectonic history of Ganderia and Avalonia

Ganderia and Avalonia are peri-Gondwanan microcontinents that were situated along the northern margin of West Gondwana (Amazonia) and close to or juxtaposed against the West African margin, respectively, in the late Neoproterozoic (Fyffe *et al.* 2009; van Staal *et al.* 2009, 2012; Pothier *et al.* 2015; Waldron *et al.* 2014). Avalonia was situated at ca. 65°S during the mid–late Cambrian with Ganderia located north of this, and with a present-day strike length of at least 2500 km; Ganderia may have extended for over 23° of latitude allowing for a possible along-strike connection with Avalonia (van Staal *et al.* 2012). The presence of the Cambrian trilobites *Kootenia* and *Baliella* in a limestone block of the Dunnage Mélange, central Newfoundland, shows that Ganderia formed at high latitudes along the Gondwanan margin (Pollock *et al.* 2012).

Ganderia started to separate from Amazonia around 505 Ma, opening the northern arm of the Rheic Ocean. The Rheic Ocean may initially have opened as a backarc basin with the Penobscot volcanic arc positioned along the leading edge of Ganderia from 584 to 515 Ma (Zagorevski *et al.* 2010; van Staal *et al.* 2012). Subsequent dextral-oblique motion moved most of Avalonia to a position just south of Ganderia, along the Amazonian margin and created a narrow intervening seaway of trapped oceanic lithosphere between the two microcontinents (van Staal *et al.* 2012). Avalonia rifted from Gondwana in the late Tremadoc (479 Ma) (Murphy *et al.* 2004) opening the southern arm of the Rheic Ocean (van Staal *et al.* 2012). Comparable faunal assemblages support Gondwanan linkages with Avalonia until the Tremadocian (Cocks *et al.* 1997; Fortey & Cocks 2003; Harper *et al.* 2013) after which the faunal provinciality indicates changing affinities from Gondwanan to Laurentian (Harper *et al.* 2013).

The Popelogan-Victoria arc was initiated around 475 Ma when subduction commenced again by the leading edge of Ganderia. The volcanic arc existed until the collision with Laurentia in the late Sandbian (van Staal *et al.* 2012) or early Katian. It may have extended from beyond the eastern tip of Ganderia along its complete east–west strike length, continuing into the Famatina arc to the west along the present-day western margin of South America (see van Staal *et al.* 2012). Subduction of Avalonia beneath Ganderia took place during the Silurian–early Devonian after Ganderia had accreted to composite Laurentia.

Calculated drift rates of ca. 9 cm/a for the leading edge of Ganderia (500–455 Ma) and for Avalonia (490–460 Ma) indicate that they were situated on the same microplate after they had parted from Gondwana (van Staal *et al.* 2012) and they subsequently moved northeastwards by sinistral-oblique movement towards Laurentia through the Early–Late Ordovician (Pollock *et al.* 2012). The latitudinal drift rate for Avalonia decreased to 5 cm/a by ca. 460 Ma, which van Staal *et al.* (2012) considered to be a proxy for the drift rate of the trailing edge of Ganderia at this time. The ca. 4 cm/a discrepancy in drift rates between the Popelogan-Victoria arc and the trailing Ganderia margin is attributed to rifting in the intervening Tetagouche-Exploits backarc basin, which initiated at ca. 475 Ma when drift rates of Ganderia and Avalonia slowed down (van Staal *et al.* 2009). The rate discrepancy suggests a half-spreading rate of ca. 2 cm/a in the Tetagouche-Exploits basin producing a 600- to 800-km-wide ocean prior to 455 Ma (van Staal *et al.* 2012).

Pothier *et al.* (2015) presented an alternative tectonic model for Ganderia and Avalonia. In their mid Cambrian (ca. 500 Ma) and late Tremadocian (ca. 480 Ma) reconstructions, Ganderia and Avalonia are rotated more than 90° counterclockwise with the present (palaeo)northern margin of Ganderia juxtaposed against Amazonia and the (palaeo)southern margin of Avalonia facing eastwards towards an open ocean with Baltica in the distance. Pothier *et al.* (2015) suggested that after Avalonia had moved to a position just north of Ganderia by sinistral transpression in the late Tremadocian, Ganderia and Avalonia (incl. Meguma in which they included North Wales and Nova Scotia) moved northwestwards together along the Amazonian margin to leave Amazonia at a latitude of about 30°S while rotating clockwise to face the Laurentian margin. Their model was based on sediment provenance and a possible sinistral movement of Avalonia north of Ganderia the latter implying the necessity of placing these microcontinents in an 'upside down' orientation relative to the Gondwanan margin. The faunal analyses of this study do not readily support their model, however, as the Darriwilian Ganderian sites would be expected to include less Laurentian and Baltic brachiopod genera and a higher proportion of Gondwanan taxa than reported. The palaeomagnetically inferred latitudinal positions of central Newfoundland and the Welsh Basin through the Early–Late Ordovician, described below, do not support this either. The reconstruction of van Staal *et al.* (2012) does not contradict the influx of West African and Amazonian sediment to Meguma and Ganderia, respectively, in the mid Cambrian and late Tremadocian as inferred by Pothier *et al.* (2015) as they placed Meguma and Avalonia very close to the West African margin, and juxtaposed Ganderia against Amazonia during these times.

The Iapetus Ocean

The Iapetus Ocean existed for about 170 millon years (ca. 580–420 Ma) and may have been as wide as 3000–5000 km estimated by faunal evidence and palaeomagnetic records (e.g. Cocks & Fortey 1982; Fortey & Cocks 1988; Harper 1992; Trench & Torsvik 1992; Harper *et al.* 1996). Palaeomagnetic analyses place the Early Ordovician Scottish segment of the Laurentian margin in low southerly latitudes of about 15–20°S (Torsvik *et al.* 1990, 1996) and East Avalonia about 60°S ±5–10°, the same latitude as the West African margin (Channel *et al.* 1992; Trench *et al.* 1992). The Miramichi Terrane may have been positioned at ca. 53°S in the early–mid Darriwilian although the age constraint on the Miramichi Group from which this palaeolatitude was obtained is not very precise (see McNicoll *et al.* 2002). During the Floian, Avalonia had moved to a position of about 41°S ±8° (Pollock *et al.* 2012) and in the latest Floian (470 Ma) palaeomagnetic analyses by Van der Voo *et al.* (1991) indicate that some Central Newfoundland Terrane localities, including Summerford, were at a latitudinal position of 31°S ±8°, corresponding to a minimum distance from west Newfoundland to the southern margin of Laurentia of ca. 1500 km. By this time, the Laurentian margin was positioned at about 15°S (Van der Voo *et al.* 1991). Trench & Torsvik (1992) estimated that the latitudinal distance between East Avalonia and the peri-Laurentian terranes was reduced from ca. 5000 to 3300 km between the late Tremadocian and latest Darriwilian, and placed the Welsh Basin of East Avalonia at 45°S in the latest Darriwilian – earliest Sandbian, based on palaeomagnetic studies of volcanic rocks from this basin.

The Iapetus Ocean closed due to northeastward drift of Ganderia and Avalonia towards latitudes of about 11–19°S in the Late Ordovician – mid Silurian (van Staal *et al.* 2012), which resulted in the collision of a number of terranes and microcontinents and ultimately the formation of the North American Appalachians and the northwest European, Scandinavian and Greenland Caledonides. The first sign of initial closure of the Iapetus Ocean was recorded in the rocks from the north and south margins of the ocean by the onset of volcanic activity in association with subduction of oceanic crust (Tietzsch-Tyler & Sleeman 1994). In southeast Ireland, evidence of this event is observed in the arc-associated volcanic rocks of the Lower Ordovician Maulin Formation (Ribband Group) underlying the Duncannon Group and separated from this by a hiatus (Tietzsch-Tyler & Sleeman 1994; Harper & Parkes 2000; Key *et al.* 2005). The collisions involving Ganderia and Avalonia commenced with the arc–arc collision of the western part of the Popelogan-Victoria arc and the Red Indian Lake arc, which at this time formed the leading edge of the Laurentian plate, during the Taconic Orogeny 3 (460–450 Ma) (van Staal *et al.* 2009). This was followed by the accretion of the active leading edge of Ganderia to Laurentia and progressive closure of the Tetagouche-Exploits back-arc basin during the Salinic Orogeny (450–423 Ma) and was concluded in the late Silurian–Early Devonian (421–400 Ma) by the Acadian orogeny involving accretion of Avalonia to Laurentia (van Staal *et al.* 2009). The arc–arc collision between the western Popelogan-Victoria arc and Red Indian Lake arc is today represented by the Red Indian Line, which is the principal Iapetan suture in the northern Appalachians (van Staal *et al.* 2009; Pollock *et al.* 2012).

Ireland

The presence of an Ordovician volcanic arc in south-east Ireland and the English Lake District have been the subject of discussion for many years (e.g. Phillips *et al.* 1976; Stillman 1986; Tietzsch-Tyler & Sleeman 1994; Sleeman & McConnell 1995; Key *et al.* 2005; Brenchley *et al.* 2006). The Anglo-Irish part of the Popelogan-Victoria arc is represented by the present-day Longford-Down Inlier in Ireland and England (Fig. 1). Earlier workers referred to the island arc as the Irish Sea Horst (Williams 1969; Bevins *et al.* 1992; Brenchley *et al.* 2006), the Irish Sea Landmass (Fitton & Hughes 1970; Phillips *et al.* 1976) or the Longford-Down arc (van Staal *et al.* 1998).

Ireland was formed by accretion of at least seven arc terranes within the Iapetus Ocean during the Ordovician–Silurian orogenies (Harper & Parkes 2000; see Fig. 1). Faunal evidence from Harper & Parkes (1989), Parkes (1992) and Harper *et al.* (2013) suggests that the South Mayo Terrane and the Irish–Scottish Midland Valley and Southern Uplands terranes occupied a peri-Laurentian

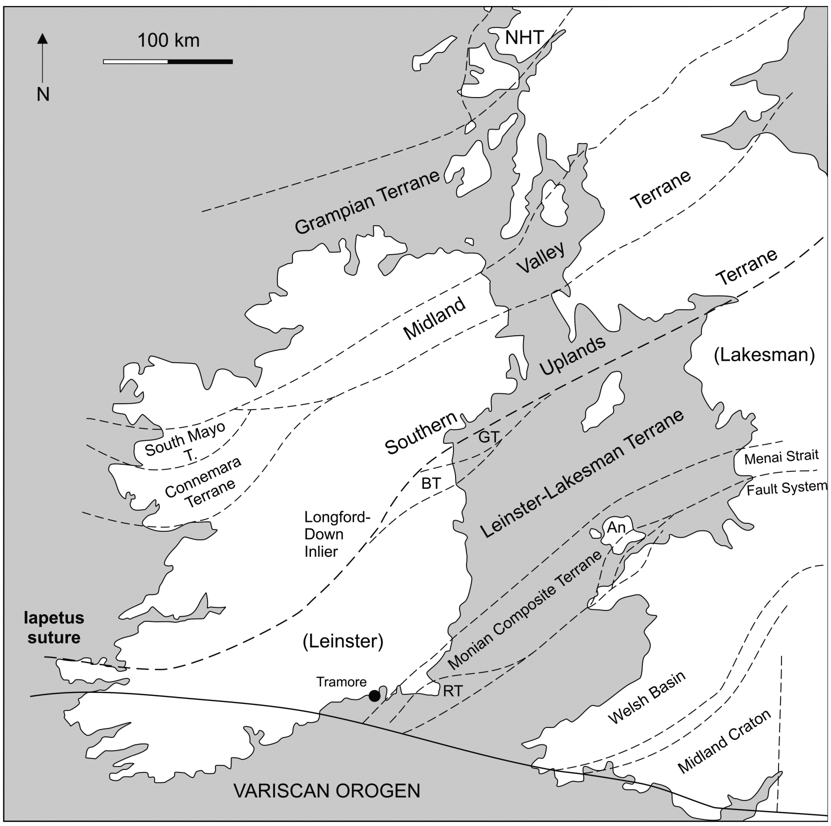

Fig. 1. Map of Irish and British terranes. An, Anglesey; BT, Bellewstown Terrane; GT, Grangegeeth Terrane; NHT, Northern Highlands Terrane; RT, Rosslare Terrane. Modified from Woodcock (2000) and Waldron *et al.* (2014).

position during the Ordovician and were associated with the Red Indian Lake volcanic arc by the northern border of the Iapetus Ocean. A number of workers applying non-faunal data (e.g. van Staal *et al.* 1996, 1998, 2009, 2012; Woodcock 2000; Collins & Buchan 2004; Valverde-Vaquero *et al.* 2006; Pollock *et al.* 2012; Pothier *et al.* 2015; Waldron *et al.* 2014) associated the Leinster–Lakesman, Monian Composite (Anglesey, Rosslare), Bellewstown and Grangegeeth terranes with the leading edge of Ganderia (PVA-TEB) by the southern border of the Iapetus Ocean. Together, these terranes make up present-day Ireland and the Iapetus suture marks the boundary between the rocks formed in the north and south Iapetus Ocean (Fig. 1).

The Leinster Terrane

The Irish part of the Leinster–Lakesman Terrane is termed the Leinster Terrane. It makes up most of the southern part of Ireland (Fig. 1) and covers an area of 24 000 km^2 (Murphy *et al.* 1991). The Leinster Terrane is bounded by the Irish Southern Uplands Terrane and the Bellewstown Terrane to the north and northeast, respectively, along major fault lines running from Dingle in the west to Bellewstown in the east and by the Monian Composite Terrane represented by the Rosslare Terrane to the southeast (Murphy *et al.* 1991; Harper & Parkes 2000; Woodcock 2000; Waldron *et al.* 2014) (Fig. 1). The English part of the Leinster–Lakesman Terrane is termed the Lakesman Terrane. It extends northeast from Ireland through England along the southern border of the Scottish Southern Uplands Terrane (Bluck *et al.* 1992; Woodcock 2000). Max *et al.* (1990) divided the Leinster Terrane into five separate terranes. Harper & Parkes (2000) noted, however, that the stratigraphical development across the terrane is broadly similar and differences in facies may be related to lateral facies changes rather than significant geographical separation.

Docking history

The amalgamation of the Irish terranes may have commenced between the early Cambrian and the Floian with the docking of the Monian Composite Terrane, including the Anglesey and Rosslare terranes, onto the Leinster–Lakesman part of Ganderia (van Staal *et al.* 1998; Valverde-Vaquero *et al.* 2006; Pothier *et al.* 2015). Pothier *et al.* (2015) suggested that Monian deformation juxtaposed a portion of Ganderia, probably represented by present-day Anglesey, against the margin of the Welsh Basin in East Avalonia along the present-day Menai Strait Fault System (Fig. 1) causing an influx of 'Monian' detritus into the Welsh Basin by the Tremadocian. Following van Staal *et al.* (1998, 2012), the Welsh Basin gradually became separated from the Leinster–Lakesman and Monian Composite terranes by the initiation and continued development of the Tetagouche-Exploits backarc basin from the Floian and onwards. Derivation of sediment from the Monian Composite Terrane into the Welsh Basin continued at least until the Hirnantian (Pothier *et al.* 2015). The Irish Southern Uplands and Bellewstown terranes amalgamated with the northern and northeastern margin of the Leinster Terrane, respectively, in the Llandovery to Wenlock during the Salinic Orogeny (450–423 Ma), in turn followed by amalgamation of the Irish Midland Valley and Grampian terranes (Murphy *et al.* 1991).

The Tramore area

The Tramore Limestone Formation was deposited in a shallow to deep shelf environment on the southeastern Leinster Terrane which deepened westwards into the local Leinster Basin (Fig. 2), into which the Dunabrattin Shale and Limestone formations were deposited (Phillips *et al.* 1976; Key *et al.* 2005). Most of the sedimentary successions belonging to the Duncannon Group represented a period of local relative quiescence before the extensive volcanism, which dominated the Caradoc volcanogenic Carrighalia and Campile formations (Brück *et al.* 1979; Carlisle 1979; Key *et al.* 2005). Most of the upper Darriwilian – lower Sandbian Tramore Limestone Formation was not directly affected by volcanic activity except for the lower and upper parts of the formation. The upper Darriwilian Dunabrattin Shale Formation and the lower part of the lower Sandbian Dunabrattin Limestone Formation accumulated in a volcanically active area of the Leinster Basin. Volcanic activity in this area subsided during deposition of the upper part of the Dunabrattin Limestone, but commenced again and became widespread in southeast Ireland during deposition of the middle Sandbian – lower Katian Carrighalia and Campile formations (Carlisle 1979; Harper & Parkes 2000). The lower Katian (late Caradoc) Raheen contains an abundant deeper-water fauna, dominated by *Onniella* and *Sericoidea* (Harper *et al.* 2016). The chemical composition of the Leinster volcanics including basaltic, andesitic and rhyolitic rocks suggests that the terrane was likely located in a transitional position between the Popelogan-Victoria arc and Tetagouche-Exploits backarc basin (Parkes 1992; Tietzsch-Tyler & Sleeman 1994).

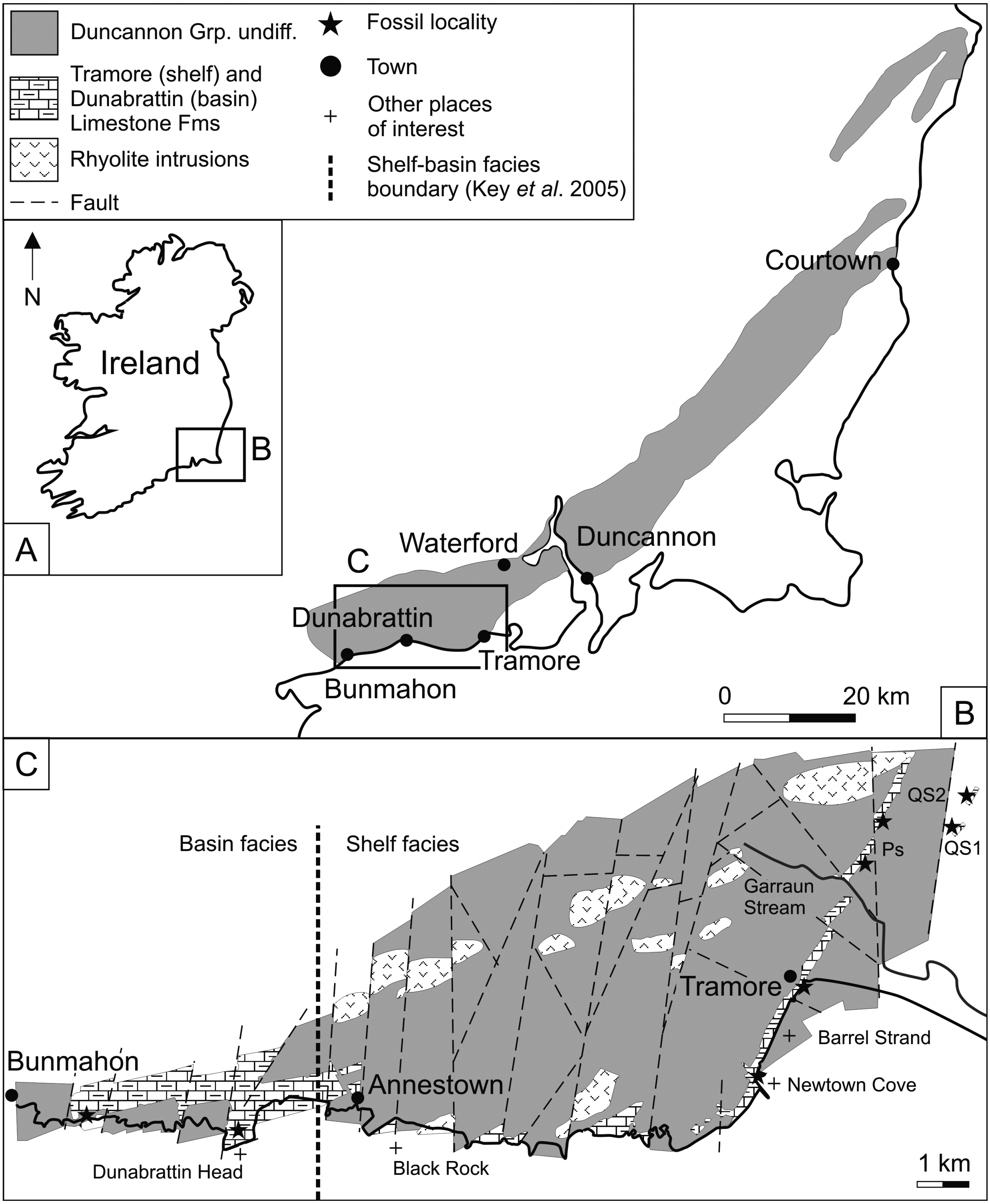

Fig. 2. Locality map. **A**, Ireland. **B**, Extent of the Duncannon Group (simplified from Key *et al.* 2005). **C**, Study area with fossil localities (simplified from Carlisle 1979). Shelf-basin facies boundary from Key *et al.* (2005). Ps, Pickardstown sections; QS1, Quillia Section 1; QS2, Quillia Section 2.

Material

The brachiopod material described in the present study was collected by Carlisle in the 1970s in an area 10 km SW of Waterford city extending from Tramore in the east to Bunmahon in the west. The area is located on the southern margin of a belt of Lower Palaeozoic rocks, which spans southeast Ireland (Fig. 2). The brachiopods were collected from the contemporary shallower-water Tramore and deep-water Dunabrattin Limestone formations.

Carlisle (1979) defined and described the stratigraphical units from which the genera were recorded but most of the samples were not labelled according to locality, formation and level within the stratigraphical column. The present study used Carlisle's personal notes and her 1979 paper to organize the brachiopod occurrences and arrived at three groupings, which define three separate palaeobiogeographical localities in the analyses: Tramore Limestone, shelf-facies brachiopods of late Darriwilian age (Units 1–2); Tramore Limestone, shelf-facies brachiopods of early Sandbian age (Units 3–5 and the barren Unit 6); and Dunabrattin Limestone, outer shelf to basin facies brachiopods of early Sandbian age (Units I–IV).

The collection is currently deposited at the Natural History Museum of Denmark, but will later be transferred to the Natural History Museum, London. During severe flooding in the museum and subsequent relocation of the invertebrate collections, a small number of the figured specimens were mislaid. These specimens are indicated on the plate descriptions and if they do come to light, will be assigned NHM numbers and transferred to the collections in the Natural History Museum, London.

Stratigraphy and fauna

The Tramore and Dunabrattin Limestone formations represent local sedimentary developments in the lower parts of the lower middle Darriwilian to lower Katian Duncannon Group, which comprises a suite of limestones, black shales and basaltic, andesitic and rhyolitic arc volcanics. Both formations are dominated by calcareous clastic sediments interbedded with rhythmically developed, massive to nodular limestone bands. Their stratigraphical relationships to other Duncannon Group formations within and near the study area are shown in Figure 3.

The Duncannon Group occurs in a band trending northeastwards from Dungarvan, County Waterford, towards the south County Wicklow (Key *et al.* 2005) (Fig. 2B). The successions cropping out in the study area (Fig. 2C) are dominated by the southern development of the Duncannon Group comprising a variety of volcanic and volcaniclastic facies (Harper & Parkes 2000). Harper & Parkes (2000) noted that the volcanogenic Bunmahon Formation in the western part of the study area possibly correlates with the Dunabrattin Shale as well as the lower part of the Tramore Limestone Formation, which is supported by this study. The Tramore Limestone Formation and the contemporary Bunmahon and Tramore Shale formations form the oldest parts of the Duncannon Group reaching into the Abereiddian Stage of the Llanvirn Series (Fig. 3). Many local stratigraphies have been described in the Geological Survey of Ireland's 1:100 000 map compilations for the region (e.g. McConnell *et al.* 1994; Tietzsch-Tyler & Sleeman 1994; Sleeman & McConnell 1995).

The age of the various formations belonging to the Duncannon Group is constrained by microfossils, graptolites, brachiopods and trilobites (see Harper & Parkes 2000). These authors also discussed stratigraphy and correlation of the formations.

Age of the Tramore Limestone Formation

Previous studies have assigned the Tramore Limestone Formation to the lower Sandbian based on shelly faunas (Williams 1976; Brenchley *et al.* 1977; Carlisle 1979; Parkes 1994), as well as to the late mid Darriwilian based on conodonts representing the *Eoplacognathus lindstroemi* Subzone of the *Pygodus serra* Zone (Bergström & Orchard 1985). In a revision of Ordovician chronostratigraphy by Fortey *et al.* (1995), the formation was suggested as ranging in age from the latest Darriwilian to the early Sandbian (Llandeilian–Aurelucian). This was also applied by Owen & Parkes (2000) following Bergström & Orchard (1985). Further refinements tabulated in Harper & Parkes (2000) indicated that the formation ranges in age from the upper part of the upper Darriwilian *murchisoni* Zone to the lower Sandbian *gracilis* Zone. Within the Tramore Limestone Formation, the Darriwilian – Sandbian boundary is likely located between lithological Units 2 and 3 or in the lowermost part of Unit 3. This has not been confirmed by graptolite or conodont biostratigraphy but Carlisle (1979) recorded a brachiopod fauna similar to that in Unit 3 of the Tramore Limestone Formation, immediately above the lower boundary of the Dunabrattin Limestone Formation, which was correlated by Harper & Parkes (2000) with the Darriwilian – Sandbian boundary. Hence, this study places the Darriwilian – Sandbian boundary at the

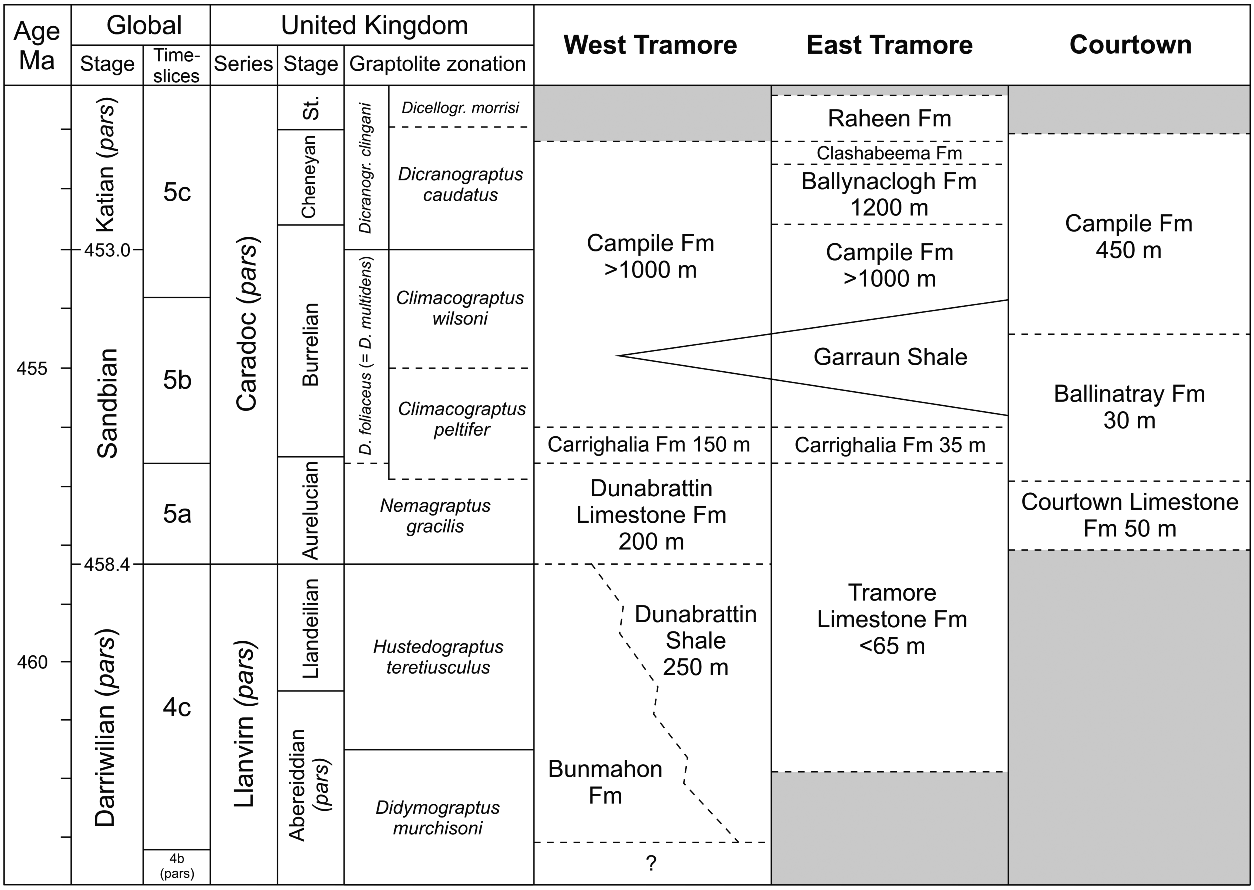

Fig. 3. Correlation chart showing formations of the Duncannon Group including the Tramore Limestone Formation and its correlatives for selected outcrop areas in southeast Ireland. Chronostratigraphy, global stages, British series and stages and graptolite zonation are redrawn from Cooper & Sadler (2012); time-slices are redrawn from Webby *et al.* (2004); and stratigraphical sections, their biostratigraphical correlation and fossil content are redrawn from Harper & Parkes (2000). Abbreviations: *D.*, *Diplograptus*; *Dicellogr.*, *Dicellograptus*; *Dicranogr.*, *Dicranograptus*; St., Streffordian.

boundary between lithological Units 2 and 3, within the Tramore Limestone Formation. The Tramore Limestone is overlain by the thin, middle Sandbian Carrighalia Formation which is in turn overlain by the middle Sandbian – lowermost Katian Campile Formation (Stillman 1978; Carlisle 1979; Harper & Parkes 2000).

Tramore and Dunabrattin/Bunmahon sections

The Tramore Limestone Formation crops out between Tramore Bay in the east and Ballydowane Bay in the west, approximately 8.5 km west of Bunmahon town (Key *et al.* 2005) (Fig. 2). The exposures are excellent along the 30- to 60-m-high sea cliffs although they are only accessible by trenched gullies (Wyse Jackson *et al.* 2001; Key *et al.* 2005). The Tramore Limestone grades from a shallower shelf facies in the east to a deeper basinal facies, the Dunabrattin Limestone Formation, in the west with maximum thicknesses of 65 and 450 m, respectively (Carlisle 1979; Harper & Parkes 2000; Key *et al.* 2005). The transition from shelf to basinal facies occurs between Black Rock and Dunabrattin Head (Key *et al.* 2005) (Fig. 2).

The stratigraphy of the Tramore Limestone Formation and its basinal correlatives was described and measured by Carlisle (1979) from the type sections and other exposures. The Tramore Limestone is primarily described from its type section in the Barrel Strand area, the Dunabrattin Limestone from its type section at Dunabrattin Head and the Dunabrattin Shale Formation from its type section along 1500 m of the foreshore east of Dunabrattin Head and from other sections near Bunmahon town (Fig. 2). The measured sections are shown on the logs in Figure 4. Brachiopods were collected at the fossil localities shown in Figure 2.

Carlisle (1979) divided the Tramore Limestone Formation into informal units and fauna associations and correlated the Tramore Limestone with the Dunabrattin–Bunmahon stratigraphy based on fauna associations. This correlation is mainly

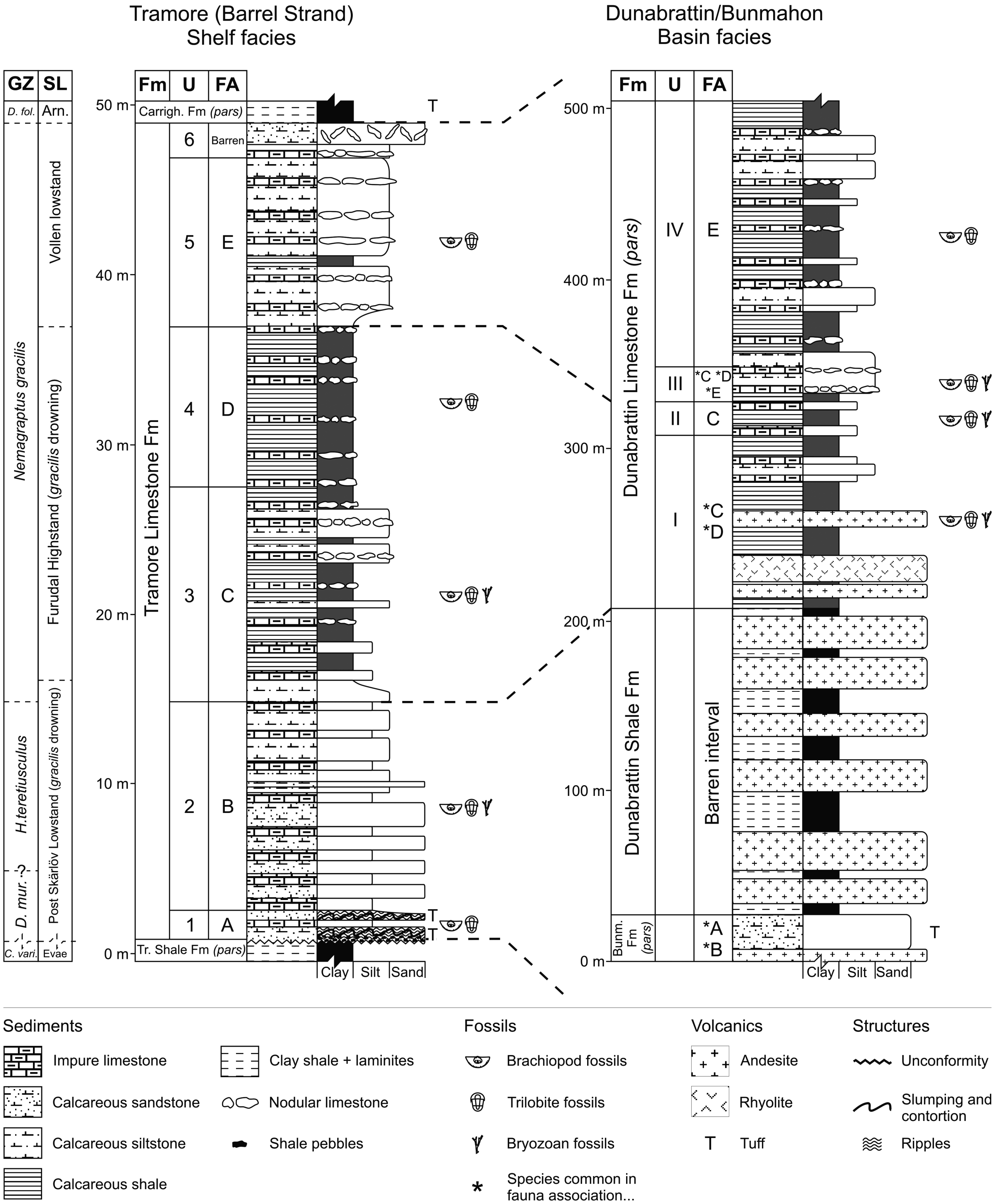

Fig. 4. Sedimentary logs modified from Carlisle (1979). GZ = British graptolite zonation (after Harper & Parkes 2000). SL = Sea-level changes correlated with the likely global events interpreted for Baltica by Nielsen (2004); Evae, Evae Drowning Event; Arn., Arnestad Drowning Event; U, units; FA, fauna association (reinterpreted from Carlisle 1979); Fm, formation. *Species common in the given fauna association of the Tramore Limestone. Graptolites: *C. vari.*, *Corymbograptus varicosus*; *D. mur.*, *Didymograptus murchisoni*; *H. teretiusculus*, *Hustedograptus teretiusculus*; *D. fol.*, *Diplograptus foliaceous*. Formations: Tr. Shale Fm, Tramore Shale Formation; Carrigh. Fm, Carrighalia Formation; Bunm. Fm, Bunmahon Formation.

followed in this study but supplemented by lithological correlation and the graptolite zonation from Harper & Parkes (2000), therefore providing a different correlation of the units than originally suggested by Carlisle (1979).

Tramore Shale Formation – Tramore area

The Tramore Shale Formation is a local correlative of the upper part of the mainly Lower Ordovician Ribband Group and it is separated from the Tramore Limestone Formation by a marked disconformity (Harper & Parkes 2000). Carlisle (1979) recorded exposures of the formation from the east Tramore area: the formation comprises over 1300 m of highly deformed unfossiliferous dark grey shale with subordinate grey/brown siltstone and sandstone. Massively bedded, strongly cleaved, tuffaceous shale containing numerous flattened lenticular lapilli crops out in the region of Perry's Bridge and represent the earliest volcanic activity in the area (Carlisle 1979). The top of the formation is eroded in this area (Carlisle 1979) and Harper & Parkes (2000) described a package of slumped units between the Tramore Shale and Limestone probably masking a disconformity. The depositional disturbance was considered by Sleeman & McConnell (1995) to have been caused by slumping alone and not representing a significant time period. If the slumped units represent a major hiatus, the time interval between the two formations may represent up to 12 Ma and range from the uppermost *Corymbograptus varicosus* Zone to the uppermost *Didymograptus murchisoni* Zone as inferred by Harper & Parkes (2000).

Tramore Limestone Formation – type section at Barrel Strand, Tramore area

The informal units of Carlisle (1979) are used here. The units, referred to as Unit 1–6 in ascending order, are characterized by their lithology and fauna associations (see Fig. 4 and Table 1) and the unit boundaries are coincident with those of the fauna associations.

Lithology

Unit 1, the lowermost unit, is approximately 2 m thick and consists of slumped, calcareous and tuffaceous sandstone with contorted siltstone ribs. Shale pebbles up to 4 cm long are recorded from the lower parts of the unit (Carlisle 1979). The upper boundary of Unit 1 is characterized by the transition from a gradational, tuffaceous calcareous sandstone layer to an impure limestone band followed by calcareous sandstone without tuff as well as a shift from Fauna Association A to B (Table 1).

Unit 2 is approximately 13 m thick and composed of calcareous sandstone in the lower part changing to calcareous siltstone in the upper part. Both sediment types are interrupted by rhythmically occurring impure limestone bands up to 20 cm thick formed by concentrations of shelly fauna and comprising about 35% of the unit thickness (Mitchell *et al.* 1972; Carlisle 1979). The lower boundary is defined at the boundary between the uppermost tuffaceous sandstone of Unit 1 and the lowermost impure limestone band of Unit 2. In the lower part of the unit, some limestone bands make up coquinas of disarticulated *Colaptomena* shells and a sample comprising a coquina of several layers of oriented *Sowerbyella* (*Sowerbyella*) valves in a calcareous siltstone was probably collected from the upper part of this unit (see the systematics section). The fauna is dominated by filter feeders and includes only one common trilobite species *Calyptaulax jamesii*. The fauna has been somewhat exposed to sorting and reorientation of valves but is otherwise fairly well preserved. The upper boundary of Unit 2 is characterized by the transition from an impure limestone band to a gradational calcareous siltstone layer followed by an impure limestone band and calcareous shale as well as a shift from Fauna Association B to C (Table 1).

Unit 3 is approximately 14 m thick and consists of calcareous shale and siltstone. Impure limestone bands up to 15 cm thick comprising about 25% of the unit thickness occur rhythmically (Mitchell *et al.* 1972; Carlisle 1979). The limestone bands make up coquinas formed by shell beds in the lower part of the unit. Upwards these bands become nodular and concomitantly the content of the shelly fauna declines (Carlisle 1979). The shelly fauna is fragmented and sorted. The upper boundary of Unit 3 is characterized by the gradational transition from calcareous shale to an impure nodular limestone band a little more than 1 m above a 3-m-thick horizon of dominantly calcareous siltstone as well as a shift from Fauna Association C to D (Table 1).

Unit 4 is approximately 10 m thick and constitutes a dark shale with rhythmically occurring impure nodular limestone bands up to 10 cm thick, which comprise up to 12% of the unit thickness (Mitchell *et al.* 1972; Carlisle 1979). A sparse fauna dominated by small trilobites is concentrated in the limestone bands and the preservation of the shelly fauna is excellent (Carlisle 1979). The upper boundary of Unit 4 is characterized by the transition from dominantly calcareous shale to dominantly calcareous siltstone. The boundary is defined between an