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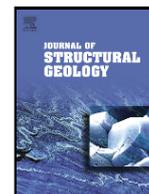


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From orogenic collapse to rifting: A case study of the northern Porcupine Basin, offshore Ireland

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ABSTRACT

Offshore Ireland, the North Atlantic opening is generally interpreted as successive, 10-to-15-Myr-long, rifting events during the Mesozoic. However, their interaction is poorly documented in terms of structural inheritance and fault reactivation. From extensive seismic and well data in the northern Porcupine Basin, we show that extension actually evolved over an abnormal period of ca. 220 Myrs with overlapping tectonic stages that, all together, reflect the Irish Atlantic Margin construction from the Palaeozoic.

During the Carboniferous, extension initiated throughout the Variscan and Caledonian thickened crusts and controlled the deposition of generally slightly-tilted, continental clastics. Two subsequent rifting events, during the Triassic-Lower Jurassic and Upper-Jurassic-Lower Cretaceous, controlled shallow-to-deep marine sedimentation in separated sub-basins that progressively widen and connect once extension localised along bounding faults.

We propose that extensional tectonics, first controlled by a general orogenic collapse reflecting an early stage of stretching, is then followed by several rifting periods that ultimately evolved toward the hyper-thinning of the margin and shaped an aborted rift propagator. This evolution is due to pre-existing orogenic-related structures and boundary conditions variations. Such a continuum of deformation, although pulsed, implies varying structural interactions of crustal scale that are often recorded in syn-tectonic sediments.

1. Introduction

The continental lithosphere deforms according to a number of geological events that successively open and close oceanic domains according to the Wilson Cycle concept (Burke and Dewey, 1974). From this theoretical view, the divergence of continental masses forms extensional systems on top of old orogenic features within a continuum of deformation during which rift basins progressively evolve to passive margin settings. Also, extension is often defined from the unique recognition of syn- and postrift unconformities that bound characteristic growth-faulting sedimentary sequences (Grow et al., 1983; Badley et al., 1984, 1988; Frostick and Steel, 1993; Prosser, 1993; Purser and Bosence, 1998). Modern data show that deformation is more complex, especially in the case of longstanding extensional history during which basins may encompass several overlapping rifting events. This is partic-

ularly well observed along the North Atlantic margins (e.g. Ziegler, 1988 & 1990; Tankard and Balkwill, 1989; Doré et al., 1999; Williams et al., 1999; Stoker et al., 2017) where basin geometries and sedimentary infills are influenced by the early basement framework or previous rifted structures (e.g. Bartholomew et al., 1993; Doré et al., 1997; Roberts et al., 1999). Nevertheless, the tectonic relationships between the various tectonic phases are not fully resolved in terms of nature, significance and timing and their integration within an overall hyper-thinning scenario leading to passive margin setting remains uncertain.

Offshore west of Ireland, the Porcupine Basin (Fig. 1) represents a typical example of such polyphased relationships between basement and shallower rifted structures. The basin is superimposed on top of two Palaeozoic orogenic belts formed during the Pangaea amalgamation and now reveals a highly-stretched continental crust covered by up to 10 km of sediments of Upper Palaeozoic, Mesozoic and Cenozoic

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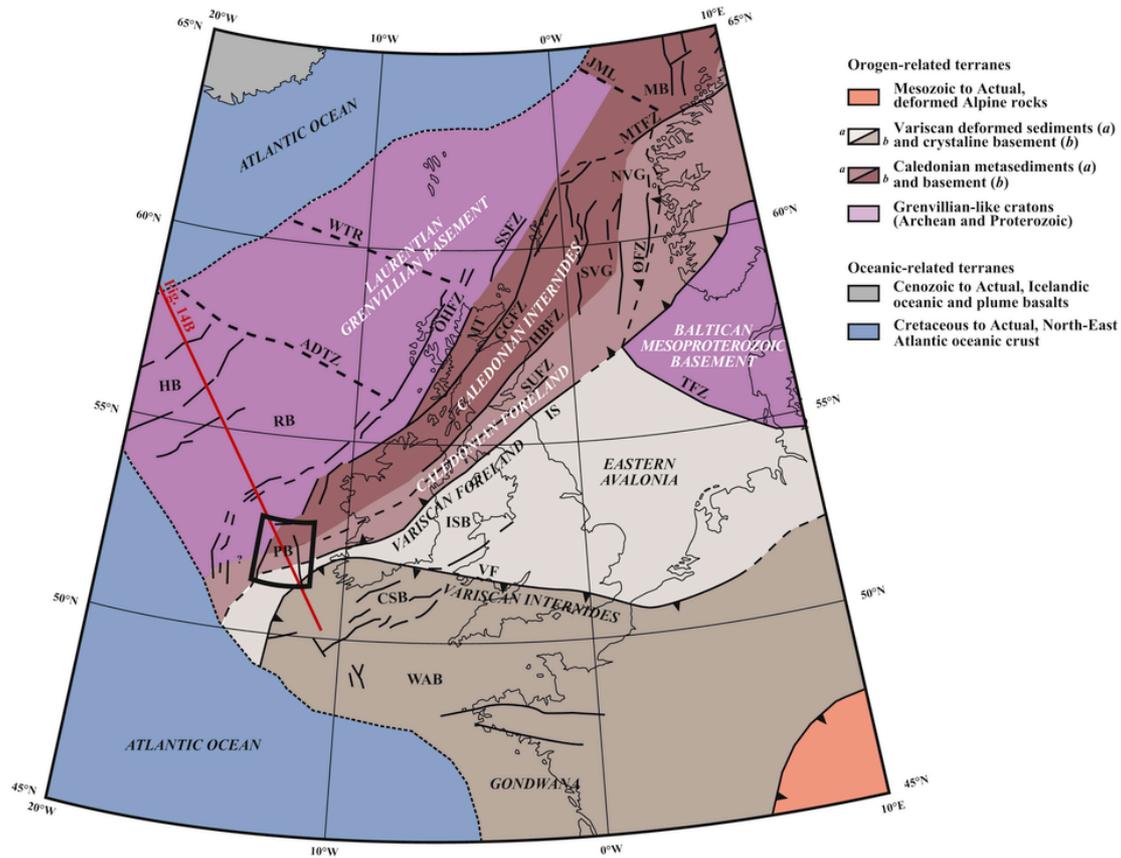


Fig. 1. Simplified terrane map of the NE European Atlantic margin. Map is adapted from Štolfová and Shannon (2009). Black box shows the location of the study area and red line the approximate position of Fig. 14B. Abbreviations: for basins: CSB - Celtic Sea Basins, HB - Hatton Basin, ISB - Irish Sea Basins, NVG - North Vøring Basin, PB - Porcupine Basin, RB - Rockall Basin, SVB - Southern Vøring Basin, WAB - Western Approaches Basin; Abbreviations for fault zones: ADTZ - Anton Dohm Transfer Zone, GGFZ - Great Glen Fault Zone, HBFZ - Highland Boundary Fault Zone, IS - Iapetus Suture, JML - Jan Mayan Lineament, MT - Moine Thrust, MTFZ - Møre-Trøndelag Fault Zone, OHFZ - Outer Hebrides Fault Zone, ØFZ - Øygarden Fault Zone, SSFZ - Shetland-Spine Fault Zone, SUFZ - Southern Uplands Fault Zone, TFZ - Törnquist Fault Zone, VF - Variscan Front, WTR - Wyville-Thompson Ridge. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

sediments and several crosscutting Cretaceous and Cenozoic igneous bodies (Fig. 2, e.g. Naylor et al., 2002; Naylor and Shannon, 2009 & 2011; Gagnevin et al., 2017). It formed during several so-called rifting events that have a variable magnitude at the scale of the basin. The main rifting event, of Upper Jurassic age, formed characteristic rotational fault-blocks sealed by the Base Cretaceous Unconformity (e.g. MacDonald et al., 1987; Sinclair et al., 1994; Robinson and Canham, 2001; Jones and Underhill, 2011). Several other thickening phases have been suggested in the Permo-Triassic (Naylor et al., 2002; Štolfová and Shannon, 2009) and Cretaceous (Naylor and Anstey, 1987; Moore, 1992). This extensional evolution remains however unclear in terms of fault geometries and reactivation mechanisms, due to poor seismic resolution and the full consideration of new crustal extension concepts.

Herein, we specifically investigate the Palaeozoic and Mesozoic extensional history of the northern part of the Porcupine region to highlight tectonic interactions between the various extensional events. Our study is based on original interpretation of 2D and 3D seismic data (19237 km and 324 km² respectively) tied to twenty six exploration wells (Fig. 1). The overall dataset was analysed using classical seismic stratigraphic methods (Mitchum et al., 1977) and correlated to lithological information by using traditional gamma-ray and sonic responses (Rider, 1990; Serra, 1995; Reading, 2007). We also further constrained the age and depositional environments by using lithologies and biostratigraphic records provided in well reports, as well as available cores

and cuttings. Sedimentary megasequences are mapped regionally and their genetics is discussed according to the formation of the Irish Atlantic Margin. They particularly demonstrate the influence of early structural frameworks on the construction of a wide Atlantic-type passive margin that acquired a certain tectonic independence over time.

2. Structural framework of the Porcupine region and aims of this study

As part of the Irish Atlantic Margin, the Porcupine Basin opened through the Caledonides and Variscides fold and thrust belts (Fig. 1). Repeated extensional events (Doré et al., 1999; Stoker et al., 2017) produced an hyper-stretched, 20-to-7.5-km thick and sometimes thinner, basement, overlain by up to 10 km of Upper Palaeozoic to Cenozoic sediments, and flanked by 30-to-35-km-thick and 25-to-28-km thick continental crusts (e.g. Buckley and Bailey, 1975; Masson et al., 1985; Makris et al., 1988; Jacob et al., 1995; Johnson et al., 2001; O'Reilly et al., 2006; Watremez et al., 2016; Prada et al., 2017). The rifting led to combined stretching factors increasing southward (White et al., 1992; Tate et al., 1993), and most likely controlled the pronounced v-shape, NS-trending Porcupine indentation through the margin. This peculiar orientation, compared to adjacent basins, infers interaction of local basement and extensional faults through time which are still poorly constrained.

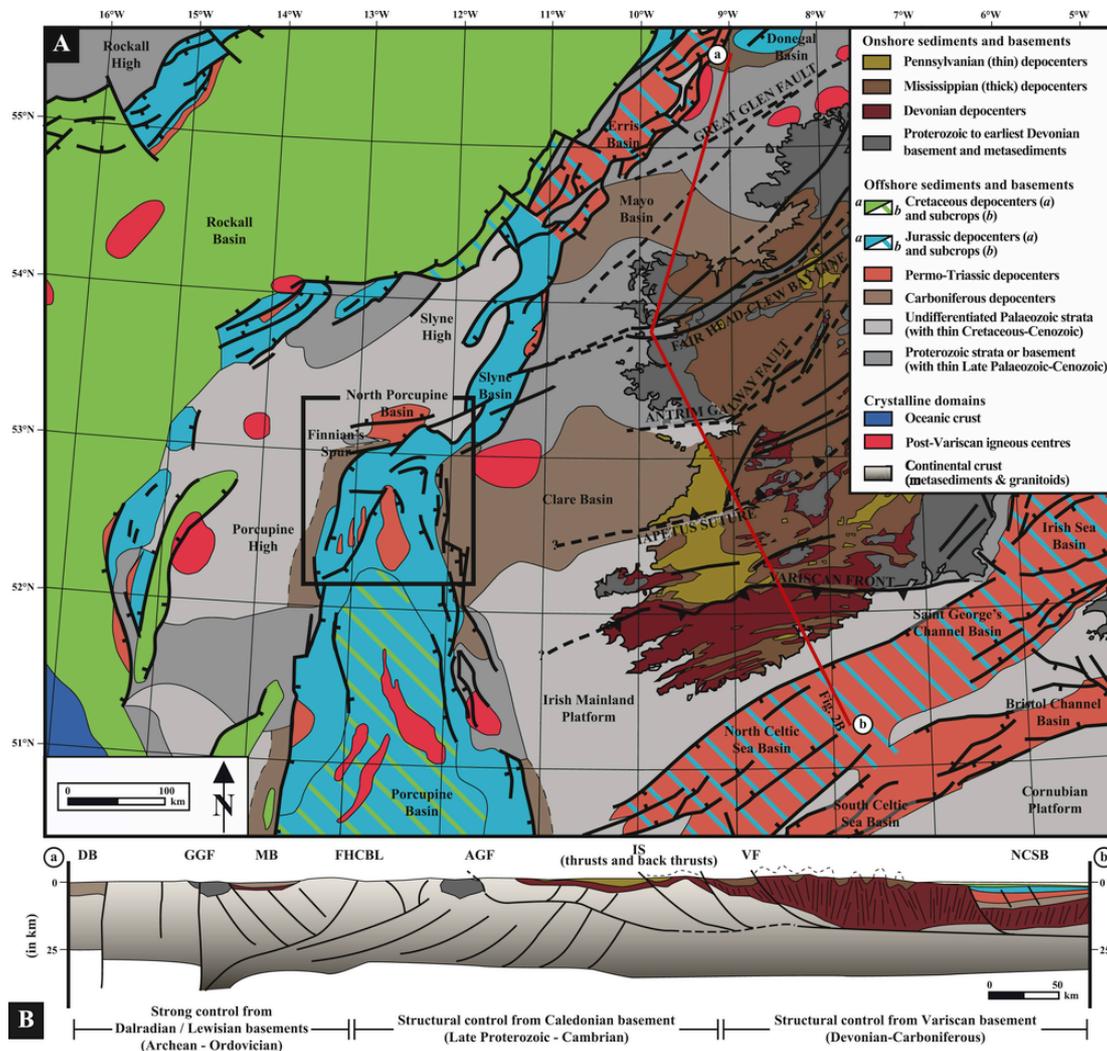


Fig. 2. Rifted basins around Ireland according to the literature. **A-** Simplified structural map of Ireland. Map is adapted from many sources, principally GSI (2006) and Naylor and Shannon (2009), from which Permo-Triassic depocentres in the study area (black box) are determined but dismissed in our study. Note that old structures (e.g. Iapetus Suture, Great Glen Fault) are not always well-defined onshore and offshore Ireland due to the resolution of subsurface data. **B-** Schematic cross-section across onshore and offshore Ireland, showing the collage of the different basements involved in the stretching of the Irish margin, and their related structures that likely have controlled subsequent basin formations. The onshore part is based from Cooper et al. (1986) and the offshore parts on deep seismic lines Wire 1 & 2 and SWAT (BIRPS & ECORS, 1986; Klemperer et al., 1991). **Abbreviations:** AGF - Antrim-Galway Fault, DB - Donegal Basin, FHCBL - Fair Head-Clew Bay Line, GGFZ - Great Glen Fault Zone, IS - Iapetus Suture, MB - Mayo Basin, NCSB - North Celtic Sea Basin, VF - Variscan Front.

2.1. Crustal development of the Porcupine region

2.1.1. Basement configuration and Irish orogenic cycles

Several Palaeoproterozoic to Palaeozoic basement types constitute structural highs around the Porcupine Basin (e.g. Auffret et al., 1979 & 1987; Masson et al., 1989) and are geologically or geophysically observed underneath thick Mesozoic-Cenozoic strata or as reworked material in the basin (Robeson et al., 1988; Tate and Dobson, 1989a; Tyrrell et al., 2007). These basements reflect several orogenic cycles that aggregated the Pangaea continent and formed early discontinuities of crustal importance (e.g. Roberts et al., 1999).

The Proterozoic framework is relatively poorly constrained in the Porcupine region (Fig. 2). Palaeoproterozoic rocks are known underneath the Finnian's Spur (1.8 Ga, Daly, pers. com.) and belong to a crystalline complex extending through the Slyne-Erris and Rockall region (1.625 Ga; Miller et al., 1973; Morton and Taylor, 1991) and in northernmost Ireland (1.779–1.750 Ga, Daly et al., 1995; Daly, 1996 & 2009). Younger Mesoproterozoic-Cambrian rocks are part of the Porcupine High (1.31 Ga) and of the NW Atlantic fringes of Ireland (1.2–0.6

Ga). These relics formed during the Laurentian and Grenvillian orogenies that controlled the original NE-SW foundation of the margin (e.g. Great Glen Fault, Fig. 2a).

Next, the Caledonian Orogeny produced a second basement type with the Ordovician-Silurian suturing of the Iapetus Ocean along Laurentian and Grenvillian terranes (Lambert and McKerrow, 1976; Soper et al., 1999; McKerrow et al., 2000; Chew, 2009; Chew and Stillman, 2009). This formed pronounced NE-SW thrusts across the north of Ireland and Britain (e.g. Fair Head-Clew Bay Fault Zone, Iapetus Suture; Fig. 2a). In the Porcupine region, Caledonian rocks are mostly evidenced from reworked Lower Ordovician-Devonian pollens (Robeson et al., 1988).

Subsequent orogenic cycle resulted in the Variscides construction following the Devonian-Lower Carboniferous Rheic Ocean subduction (Stampfli et al., 2002; Cocks and Torsvik, 2006). Characteristic NE-SW-trending thrusts and folds in southern Ireland continue as E-W to NE-SW highs in the Celtic Sea region (Fig. 2; Cooper et al., 1984 & 1986). Several N-S features are also known in the southern Porcupine Basin but their relation to the Variscides remains uncertain due to generally-poor seismic imaging and little age constrains, as well as superimposed

Mesozoic extreme marginal thinning (Robinson et al., 1981; de Graciansky et al., 1985; Cook, 1987; Naylor et al., 2002). Lower Carboniferous strata are observed in the rest of the Porcupine region in lateral continuation of Carboniferous sediments across the Clare Basin (Gill, 1979; Croker, 1995) but internal deformation is poorly constrained.

2.1.2. Late Palaeozoic-Mesozoic tectonostratigraphy and Porcupine Basin formation events

Following these orogenic episodes, the Porcupine region encompassed repeated extension and subsidence events resulting in thick Late Palaeozoic-Mesozoic successions above crystalline basements and with uncertain links with previous orogenic basements. The tectonostratigraphic interpretation of rifted elements mostly depends on data resolution and on the attempt of reconstructing local events in the broad context of the Pangaea breakup.

The prerift basement is subdivided in two megasequences including Mississippian (Tournaisian-Lower Viséan) coarse and fine clastics, shelf carbonates and shales partially preserved in the eastern Porcupine region, followed by Pennsylvanian (Moscovian-Gzhelian) fine and coarse clastics recovered through much of the basin (e.g. Croker and Shannon, 1987; Robeson et al., 1988; Tate and Dobson, 1989a). Although part of the Carboniferous interval is coeval of the Variscides construction, compressional features remain uncertain due to the regional seismic resolution at such stratigraphic level. Similarly, Mississippian normal faulting is observed onshore along reactivated Caledonian trends (Fraser and Gawthorpe, 1990, 2003; Worthington and Walsh, 2011; Davies et al., 2012) but the fault extent in the Porcupine region is also rather vague. Both Mississippian and Pennsylvanian megasequences are separated by a regional unconformity (Late Viséan to Bashkirian) that is alternatively interpreted as a final compressional event in the closure of the Rheic Ocean or as an early effect of orogenic collapse (Praeg, 2004; Naylor and Shannon, 2011).

Overlying Permo-Triassic sediments are directly tested in the North Porcupine Basin together with possible Lower Jurassic synrift strata and are seismically-interpreted in limited fault-bounded clastic depocentres in the rest of the Porcupine region (Fig. 2a; Croker and Shannon, 1987; Naylor and Anstey, 1987; Johnston et al., 2001; Naylor et al., 2002; Štolfova and Shannon, 2009), which formed during the so-called *Early Cimmerian rifting event* (e.g. Sinclair et al., 1994). Following postrift intervals show Lower and Middle Jurassic shallow marine clastics and carbonates of in the North Porcupine Basin and Middle Jurassic fluvial to lacustrine clastics in the Porcupine Basin. These likely reflect the thermal subsidence of the overall margin but may also relate to the “onset warp setting” of Sinclair et al. (1994).

A second rifting phase, called *Late Cimmerian rifting event*, produced the most of rotational fault-blocks during the Upper Jurassic to lowermost Cretaceous (Masson and Miles, 1986; MacDonald et al., 1987; Naylor and Anstey, 1987; Croker and Klemperer, 1989; Sinclair et al., 1994; Williams et al., 1999). In these studies, the rifting onset varies between Bajocian and earliest Tithonian time, controlling a northward migration of transgressive marine facies which submerged fault-blocks by the end of the Kimmeridgian and Tithonian. The rifting termination is generally picked with the Base Cretaceous Unconformity overlain by Berriasian-Barremian shale-prone strata (postrift sediments). Yet, recent 3D seismic interpretation revealed Tithonian-Valanginian 'transitional sequences' prior the development of 'true' postrift conditions (Jones and Underhill, 2011). Further minor extension in the Aptian-Albian resulted in progradational deltas sealed by undeformed Late Cretaceous chalk (Moore, 1992; Shannon et al., 1993). Therefore, the interval between syn- and postrift strata combines several events including uplift and thermal subsidence, the latter of which implies to reconsider the overall sequences definition.

2.2. Aim of the present study

The various Proterozoic-Palaeozoic orogenic episodes produced the original structural foundations of the Porcupine region, which likely shaped younger basins during Mesozoic rifting episodes (Fig. 3). Nonetheless, several major uncertainties regarding their definition and structural interactions over time still remain. For instance, the extent of Caledonian and Variscan features, largely determined from deep seismic profiles and gravity or magnetic and data, are partially known in the northernmost Porcupine Basin (Young and Bailey, 1974; Max et al., 1982; Masson et al., 1985; Klemperer, 1989; Klemperer et al., 1991) but are not accurately mapped southward due to Mesozoic and Cenozoic sedimentary thicknesses. Moreover, most studies dealt on small areas with specific hydrocarbon aspects and only a few mapped the rift-related fault zones and associated regional syn- and post-rift unconformities (Naylor and Anstey, 1987; McCann et al., 1995). In addition, these studies do not necessarily integrate the overall basin evolution in a global framework of hyper-extension (Naylor et al., 2002; PAD, 2006; Naylor and Shannon, 2011; Stoker et al., 2017), even if such scenarios have been debated in the south of the basin (e.g. Reston et al., 2001; Calvès et al., 2012; Watremez et al., 2016; Prada et al., 2017). In this context, the synrift elements recognition differs widely in the literature, implying variations of timing and significance for each event.

Our detailed mapping shows well-separated extensional episodes based on an extensive 2D and 3D seismic dataset correlated to all available wells in the study area (Fig. 4). Extension clearly started from the Carboniferous to form small and localised half-graben truncated by the Top Carboniferous Unconformity. It is followed by extension in the Rhaetian-Sinemurian, which controlled tilted blocks in the North Porcupine Basin and did not extend south of the Finnian's Spur. The third episode produced pronounced Oxfordian-Tithonian highly-rotated blocks in the Porcupine Basin and spread in the latest stage across the Finnian's Spur. Reactivation of the main bounding faults occurred during the Neocomian to form poorly-tilted and variably thick depocentres. Thus, it appears that deep crosscutting structures (e.g. Finnian's Spur) intermittently localised subsequent deformation or acted as natural barriers to the deformation. This infers fault interactions through time.

Thus, our study aims to demonstrate the extension initiation and the structural reorganisation and highlights fault reactivation processes during the rifting evolution. We also speculate on the sequences genetics in the broad context of a hyper-extended passive margin.

3. Palaeozoic structural framework

Pre-Mesozoic rocks, usually described as prerift basement, invariably incorporate sedimentary, metamorphic or magmatic lithologies developed during the Precambrian to the Late Palaeozoic. Therefore, they spanned several orogenic cycles, with related structures having a preponderant role on subsequent depocentres formation. Tectonic controls are, for instance, normal faulting in the Carboniferous or rifting shift across the Finnian's Spur during the Mesozoic (Fig. 4). Herein, we present well and seismic correlations of Proterozoic-Palaeozoic packages to highlight such controls across the study area.

3.1. Lithologies

Pre-Mesozoic lithologies are regrouped into four distinct packages made of highly metamorphosed to undeformed sedimentary rocks (Fig. 5). They are bounded by first-order stratigraphic surfaces that link to the various Precambrian and Palaeozoic orogenic cycles. Their distribution reflects a lateral continuum of depocentres, already-known across the surrounding structural highs.

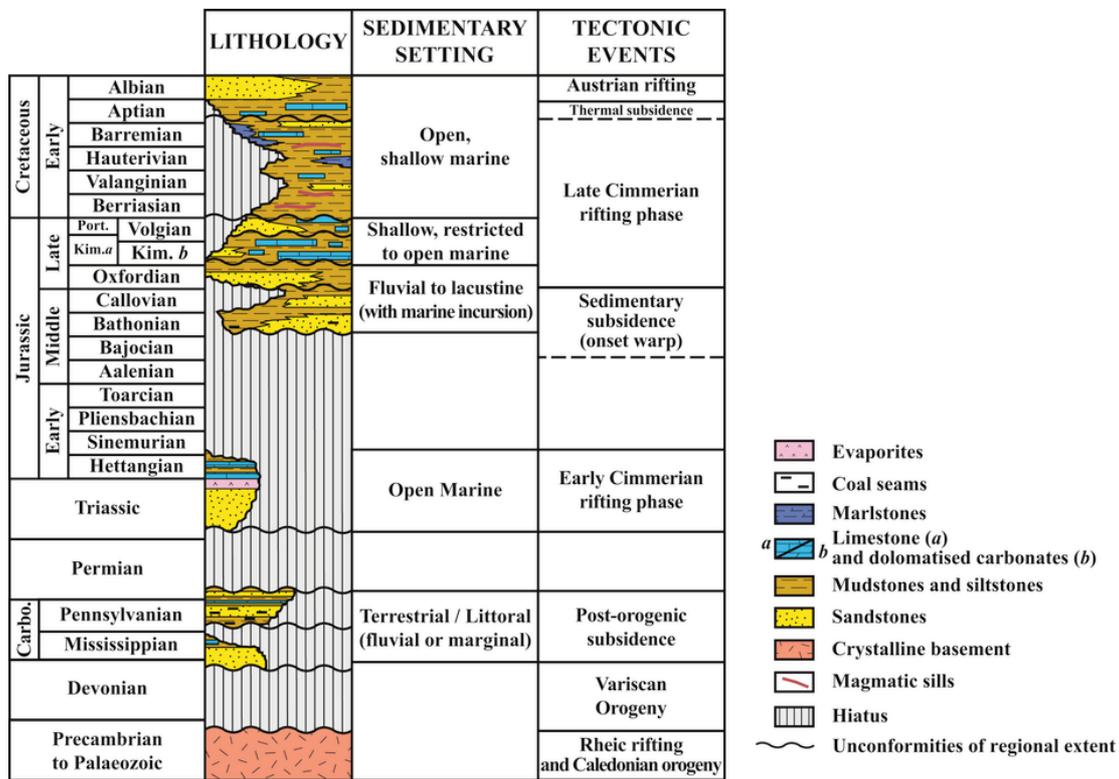


Fig. 3. Simplified lithostratigraphy affected by the long-lasting extension in the Porcupine region. The present log, based on lithologies and ages published in well reports and academic publications, shows the two principal Mesozoic rifting episodes (Early Cimmerian and Late Cimmerian) in the Porcupine region on top of orogenic-related terranes (see namely Sinclair et al. (1994), Williams et al. (1999) and Jones and Underhill (2011) for further information).

3.1.1. Grenvillian-equivalent basement

The oldest known basement rocks underlie structural highs west of the Porcupine Basin, such as the Finnian's Spur. Well 26/26-1 tested fractured metasediments resting on Palaeoproterozoic schists and gneisses (Fig. 5). They are probably equivalent to Dalradian rocks onshore Ireland formed during or slightly later the Grenvillian orogenic cycle.

The so-called Grenvillian Basement (GB) is topped by the Top Dalradian Unconformity (Table 1), of which the genesis is unknown due to the lack of data. Coeval unconformities may correspond to Grenvillian or Caledonian deformation phases described onshore (e.g. Hutton and Aslop, 2004; Corfu et al., 2014).

3.1.2. Caledonian-equivalent basement

A second basement type, composed of anchizonal to unmetamorphosed coarse clastic sediments, form a discontinuous package through the northern Porcupine region (Fig. 5). The most complete succession (Well 26/26-1) consists in a 60-to-70m-thick basal section made of conglomerates and coarse sandstones followed by finer clastics. Top units are correlatable to poorly deformed shales, siltstones and mudstones (Well 26/21-1) and quartzitic sandstones (wells 26/28-1, 26/28-3 and 34/5-1). Numerous carbonised spores and lithoclasts of magmatic or metamorphic origins infer a crystalline basement proximity. Basal quartzite in Well 26/28-1 was radiometrically dated as Devonian to earliest Carboniferous (Tournaisian), so that this basement type is referred herein as Caledonian Basement (CB).

It is truncated by the so-called Top Devonian and Base Mississippian unconformities, sometimes observed in dipmeter data but more surely confirmed by sedimentary hiatuses spanning the Tournaisian interval (Fig. 5, Table 1). The surfaces either relate to a late compress-

sional phase of the Caledonides or to the subsequent Variscides construction.

3.1.3. Variscan-equivalent basement

The Top Devonian and possibly the Top Dalradian unconformities are overlain by unmetamorphosed rocks, deposited during the Mississippian and forming the so-called Variscan Basement (VB). As for other basements, the distribution is unequal due to syn- and post-deposition tectonics (discontinuous depocentres, Fig. 5) but related unconformities may be predicted from well and seismic correlation (Fig. 6). The most complete succession (Well 35/15-1) shows a first section (VB₁) composed of calcareous sandstones and micaceous siltstones passing to micritic limestones and siltstones and terminated by mudstones and fine sandstones. It is followed by a second section (VB₂) opening on basal conglomerate overlain by limestones with brachiopods and crinoids, dolomites and volcanoclastics. The transition between both sections is genetically unclear (possible sedimentary hiatus) and may reflect localised relative uplift consistent with cyclic terrestrial to shallow-marine conditions expected from the lithology (e.g. carbonates vs shales occurrences). The Variscan Basement is further interpreted in wells 26/26-1 and 26/28-1 based on similarities in lithologies and fossil content. The biostratigraphic information suggests a latest Tournaisian-earliest Namurian age (i.e. Viséan to lower Bashkirian).

Variscan Basement is bounded by the Top Mississippian Unconformity of Namurian-Westphalian A age (i.e. Bashkirian to lowermost Moscovian, Table 1). The surface is consistent with the poor preservation of Mississippian strata in the study area and is coeval to the Variscides construction onshore Ireland.

3.1.4. Post-Variscan Megasequence

Carboniferous sedimentation resumed during the Pennsylvanian resulting in the regional Post Variscan Megasequence deposition (Fig. 5). A

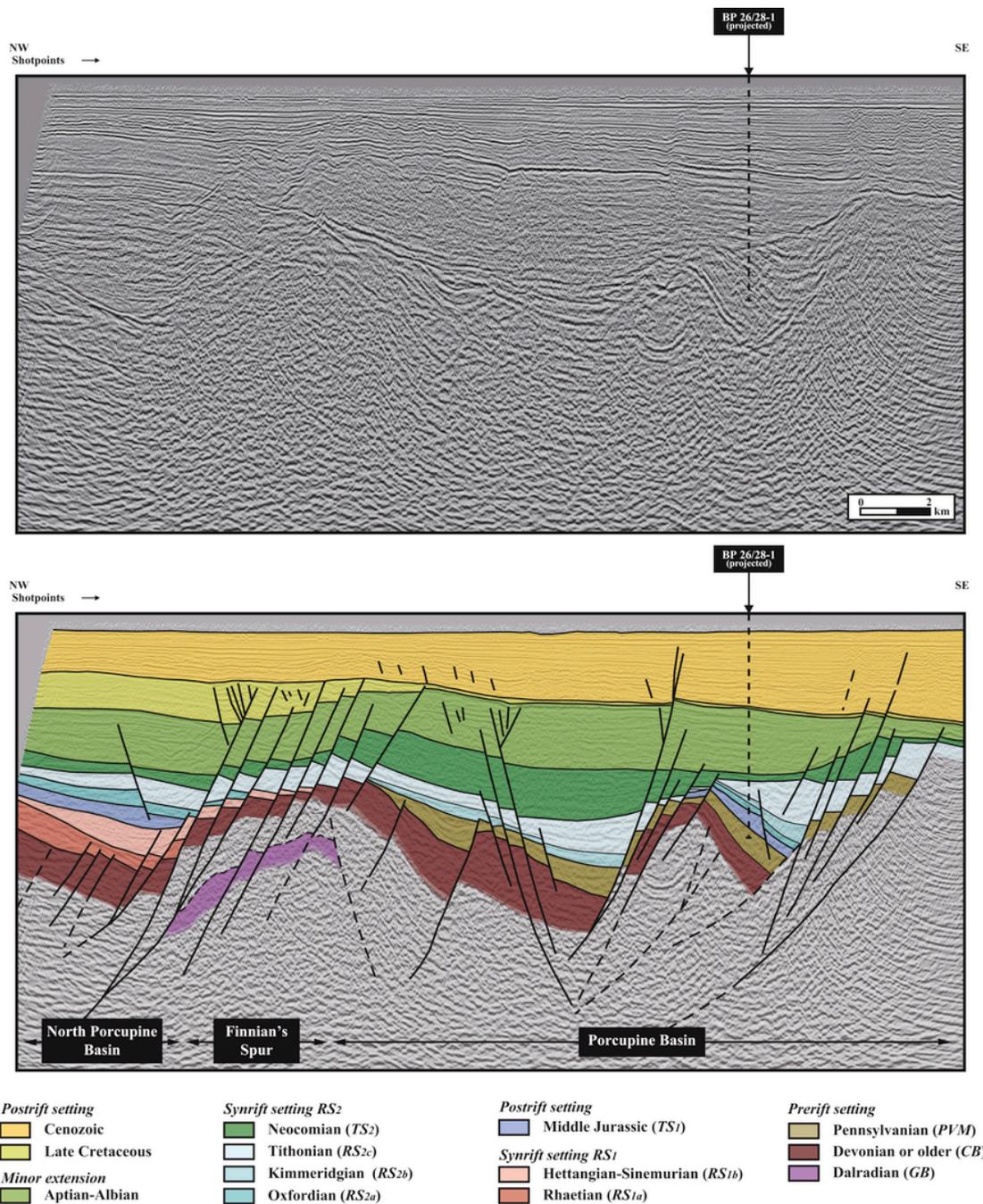


Fig. 4. 2D seismic cross-section showing three temporarily- and spatially-defined extensional phases in the Porcupine region. Three main extensional phases of Carboniferous, Triassic-Lower Jurassic and Upper Jurassic-Neocomian are recognised together with minor reactivations in Aptian-Albian and computational faults in Upper the Cretaceous and Cenozoic. They shaped the Porcupine and North Porcupine basins differently across the Finnian's Spur. Seismic line location can be seen on Fig. 7 and 11. Basement types as displayed on Fig. 5 may appear slightly different at well site (herein Well 26/28-1 which is located about 1-km south of the line), due to intense faulting and unequal Palaeozoic topography controlling lateral variations.

first sequence (PVM_1) is composed of Westphalian (*i.e.* ~Moscovian), fining-upwards clastics alternating between conglomeratic and fine sandstones, mudstones, claystones and coal seams, which together suggest an alluvial-lacustrine environment passing progressively to littoral conditions. This is consistent with the facies distribution suggesting a progressive deepening during Westphalian B/C and getting generalised during Westphalian D (respectively ~Duckmantian, ~lower and ~upper Bolsovian). A second section (PVM_2), composed of mudstones and siltstones containing diverse brackish-water ostracods infers littoral persistence during the Stephanian (~upper Kasimovian-Gzhelien). A

third section (PVM_3 , Well 34/15-1) consists in shales, siltstones and poorly-sorted sandstones interspaced by occasional limestones, evaporates and coal patches in which Autunian, brackish and shallow-marine ostracods are observed.

Post Variscan Megasequence is characterised by drastic thickness variations related to the remains of sequence PVM_1 and PVM_2 , which may be accentuated by the Top Carboniferous Unconformity which locally merges with the Top Autunian Unconformity (Table 1). Both surfaces mark the transition Carboniferous basins with Mesozoic deposition.

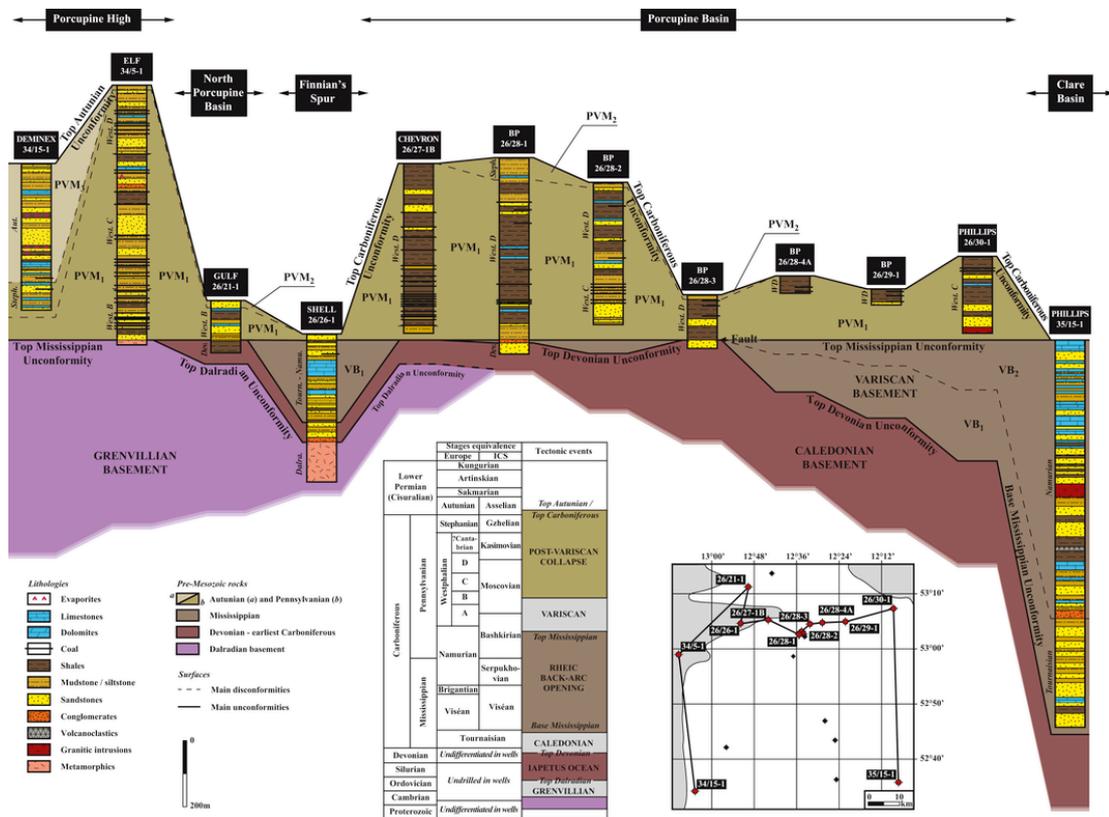


Fig. 5. Synthetic correlations of the Late Palaeozoic lithofacies. This simplified lithostratigraphic panel shows megasequences and their relative bounding sequences, notably the Top Devonian Unconformity marking the construction of the Caledonian Orogeny and the Mississippian Unconformity of the Variscan Orogeny. The Top Carboniferous/Top Autunian unconformities characterise the transition of Late Palaeozoic basins generated by orogenic collapse to basins controlled by Middle Jurassic thermal subsidence or by Late Jurassic-Early Cretaceous extensional forces. Ages are based on information published in composite wells and reports (Elf Aquitaine, 1976 & 1981; Deminex, 1977; BP, 1979a, 1979b, 1980a, 1980b, 1981a, 1981b, 1981c, 1982a, 1982b & 1982c, Gulf, 1979 & 1980, Chevron, 1981a & 1981b, Phillips Petroleum Company, 1982 & 1983) as well as in Robeson et al. (1988), Tate and Dobson (1989a) and Croker (1995). The reader can also refer to Bulois (2016) for further lithofacies and biostratigraphic information.

3.2. Palaeozoic tectonic phases

Well correlation revealed four distinct basement packages, of specific ages and lithologies and separated by regional unconformities (Fig. 5). Their mapping through the seismic volume enables to identify different phases of regional Late Palaeozoic deformation (Fig. 6).

3D seismic data tied to Well 26/28-1 (Fig. 6A) show well-developed *Caledonian Basement*, resting on top of interpreted *Grenvillian Basement* and unconformably overlain by the *Post-Variscan Megasequence*. The Top Devonian and Top Mississippian unconformities merge together but their seismic distinction is difficult due to relatively thin remaining Mississippian strata (c. 10m at well site). This supposes differential erosion of *Caledonian Basement* during the Variscan uplift. Internally, Devonian and Pennsylvanian sediments show tenuous but discontinuous growth-faulting, implying at least two main phases of extension. Additional syn-tectonic thickening is also observed in the *Post-Variscan Megasequence*. All together, this suggests succeeding extensional and compressional events linking to the Caledonides and Variscides evolution.

Correlation with Well 26/27-1B shows clearer thickening in the *Post-Variscan Megasequence*, controlled by normal faults rooting in the *Caledonian* or *Grenvillian* basements (Fig. 6B). The absence of Mississippian strata witnesses of the Variscan uplift incidence despite clear compression evidence.

The Variscan compression is well observed in the southeast where Mississippian strata are arranged in tectonic nappes (Fig. 6C) in lateral continuation of those observed onshore. They probably involve Devon-

ian rocks, appearing in a chaotic seismic basement with some continuous reflectors that are in turn are overlain by definite Mississippian strata (Well 35/15-1) shaped in open folds controlled by décollement faults. The latter constitutes local highs (e.g. Ruadan High), partially sealed by Pennsylvanian strata of the *Post-Variscan Megasequence*. Overlying Pennsylvanian succession is affected by numerous normal faults, implying that the Top Mississippian Unconformity marks a transition from thrust-dominated strata (?Devonian and Mississippian) to normal-faulted depocentres (Pennsylvanian). Variscan compression indicators decrease westward, resulting in a global thickening of the *Post-Variscan Megasequence* along the Porcupine High (i.e. basin tilt to the west). Extension is sealed by the Top Carboniferous Unconformity in most of the central part of the basin and by the Top Autunian Unconformity in limited fault-blocks in the southwest (Well 34/15-1).

Many other rotated fault-blocks are observed through the region (Fig. 6D and E) but remain undrilled, so that it is difficult to determine an accurate age for each basin. Nonetheless, a striking element is the variation in the rotation amount that may directly result from Variscan and Caledonian basement structures reactivated during the extension. In other words, structural directions and basements rheologies have influenced the overall structural style of Late Palaeozoic extensional elements.

3.3. Late Palaeozoic extensional tectonic patterns and fault reactivation

Seismic analysis highlights fault-blocks principally filled in by Pennsylvanian to Autunian sediments (*Post-Variscan Megasequence*) on top of *Caledonian* or *Variscan* basements. Normal faults developed along E-W to ENE-WSW trends in the North Porcupine and northern Porcupine

Table 1
Material and geometric data defining the shell natural configuration.

Stratigraphic surface	Abbreviated name	Well tie	Stratigraphic formations involved	Bounding seismic units	Seismic definition
Top Autunian Unconformity	TAU	34/15-1	<i>Top:</i> Middle Jurassic	<i>Sequence PVM₃</i>	Moderate-amplitude reflector, tending to lose its signal when approaching faults (see Fig. 5c). Overlying and underlying sediments are usually well imaged away from the surface and sometimes appear as transparent to chaotic facies.
Top Carboniferous Unconformity	TCU	26/21-1	<i>Bottom:</i> Autunian	<i>Sequence PVM₁</i>	Usually moderate- to high-amplitude reflector (especially in the centre of the basin, see Fig. 6a and b). Many truncated reflectors are observed throughout the basin, the surface being often located above high-amplitude, continuous reflectors. Sometimes, it is associated with more transparent to chaotic strata or basement rocks.
			<i>Top:</i> Triassic	<i>Sequence PVM₂</i>	
		26/28-1, 26/28-2, 26/28-3	<i>Bottom:</i> Westphalian B	<i>Sequence PVM₂</i>	
		26/27-1B, 26/28-4A, 26/29-1	<i>Top:</i> Middle Jurassic	<i>Sequence PVM₁</i>	
		26/30-1	<i>Bottom:</i> Westphalian D	<i>Sequence PVM₁</i>	
			<i>Top:</i> Middle Jurassic	<i>Sequence PVM₁</i>	
			<i>Bottom:</i> Westphalian C	<i>Sequence PVM₂</i>	
34/5-1	<i>Top:</i> ?Albian	<i>Sequence PVM₂</i>			
34/15-1	<i>Bottom:</i> Stephanian	<i>Sequence PVM₂</i>			
35/15-1	<i>Top:</i> Autunian	<i>Sequence PVM₂</i>			
Top Mississippian Unconformity	TMU	26/26-1, 26/28-1	<i>Bottom:</i> Stephanian	<i>Sequence PVM₂</i>	Equivalent to a moderate-amplitude reflector that generally top folded and/or thrustured Mississippian sediments (see Fig. 6c).
			<i>Top:</i> Cenozoic	<i>Sequence PVM₂</i>	
		Likely under 26/28-4A, 26/29-1, 26/30-1	<i>Bottom:</i> Mississippian, pos. Westphalian A	<i>Sequence VB₂</i>	
		35/15-1	<i>Top:</i> latest Viséan to lower Bashkirian	<i>Sequence VB₂</i>	
Base Mississippian Unconformity (merged with the Top Devonian Unconformity)	BMU	26/26-1, 26/28-1	<i>Bottom:</i> Mississippian	<i>Sequence VB₂</i>	Moderate- to locally high-amplitude reflector, with onlaps, toplaps and downlaps locally well observed. The overlying seismic sections are usually well imaged but dating may differ laterally.
			<i>Top:</i> Westphalian B/C	<i>Sequence VB₂</i>	
		35/15-1	<i>Bottom:</i> Mississippian, pos. Westphalian A	<i>Sequence VB₂</i>	
Possible below 26/28-4A, 26/29-1, 26/30-1	34/15-1	<i>Top:</i> Wesphalian B	<i>Sequence VB₁</i>		
		<i>Bottom:</i> ?earliest Tournaisian			
			<i>Top:</i> Westphalian B		
			<i>Bottom:</i> probably Mississippian		
			<i>Top:</i> Westphalian B		

Table 1 (Continued)

Stratigraphic surface	Abbreviated name	Well tie	Stratigraphic formations involved	Bounding seismic units	Seismic definition
Top Devonian Unconformity	TDU	26/21-1, 26/26-1, 26/28-1	<p><i>Bottom:</i> Palaeoproterozoic (untested)</p> <p><i>Top:</i> Viséan to Serpukhovian</p>	<i>Megasequence</i> CB	Most often unclear on seismic due to seismic resolution (see Fig. 6a) but the mergence with the Base Mississippian Unconformity implies similarities in seismic characters.
Top Dalradian Unconformity	TDaU	26/26-1 34/5-1 Likely under 26/21-1, 26/26-1, 26/27-1B, 34/15-1	<p><i>Bottom:</i> Devonian <i>Top:</i> Westphalian D <i>Bottom:</i> Devonian</p> <p><i>Top:</i> Devonian or Westphalian B <i>Bottom:</i> Palaeoproterozoic</p>	Granite basement <i>Megasequence</i> GB	Most often unclear on seismic due to seismic resolution. The (see Fig. 6a and b).

Basin (north of $\sim 53^{\circ}05'N$), corresponding to the local Caledonian orientation (Fig. 7). South of $53^{\circ}N$, faults have a predominant N-S orientation that mark the continuation of southernmost structural highs formed during the Variscan compression. Between these two groups, faults turn to an intermediate NE-SW orientation that suggests interaction between both basements.

This implies fault clusters, whose distribution corresponds to key zones with specific deformation pattern that align along crustal basement discontinuities (Fig. 7). In the north, E-W structures are parallel to the Finnian's Spur direction, a structural fault-bounded basement feature made of Dalradian tonalitic gneisses (*Grenvillian Basement*) drilled in Well 26/26-1 (Figs. 4–6A; e.g. Tate and Dobson, 1989a; Tate, 1993; Naylor et al., 2002). Also, the high and other discrete narrow horsts intermittently separated the Porcupine and North Porcupine basins by localising the deformation. Adjacent *Caledonian Basement* appears poorly deformed (Fig. 6A and B) and its role on controlling the deformation may be only due to rheological contrasts with the adjacent *Grenvillian Basement*. To the west, N-S structures are parallel to the Porcupine High that is mostly composed of Precambrian and Palaeozoic rocks (Riddihough and Max, 1976; Max, 1978; Naylor et al., 1999). To the east, they run along the Ruadan High, originally described as a Mesozoic shearing and inversion feature (Tate, 1993; Naylor et al., 2002) but herein interpreted as part of a buried Variscan nappe gently reactivated afterwards separating the North Mohling and Porcupine basins (Fig. 6C).

Overall, the Palaeozoic fault distribution results in a dog-leg geometry that directly relates to the Caledonian and Variscan basements collage (Fig. 7). This strongly influenced the shape and orientation of subsequent Mesozoic extensional basins.

4. Rhaetian and Hettangian-Sinemurian rift setting RS₁

Subsequent to Palaeozoic tectonism, the Porcupine region encompassed a period of uplift forming the Top Carboniferous and the Top Autunian unconformities, followed by an early rifting phase during the Permo-Triassic that may have affected the Porcupine region in various places (e.g. Štolfová and Shannon, 2009; Stoker et al., 2017). However, the occurrence of Permo-Triassic strata is regionally debatable as only two wells in the North Porcupine Basin (26/21-1 and 26/22-1A) directly penetrated through Triassic strata and the Top Carboniferous

and Top Autunian unconformities mark clearly the contact with Jurassic strata in the Porcupine Basin (Fig. 4; Table 1). This implies to redefine this rift setting, called herein RS₁ (for Rift Setting 1).

4.1. Stratigraphy of the Rhaetian and Hettangian-Sinemurian succession

In the North Porcupine Basin, Rift Setting RS₁ controlled *Megasequence* RS₁ development drilled in wells 26/21-1 and 26/22-1A (Table 2). Herein, we propose to focus on Well 26/22-1A in which sediments and related biostratigraphic content are more complete (Fig. 8A). Two main sequences, called RS_{1a} and RS_{1b}, deposited on top of the Top Carboniferous Unconformity (not drilled but recognised from regional mapping around Well 26/21-1).

Sequence RS_{1a} consists of thick sandstones and intercalations of thin mudstones and siltstones with occasional anhydrites (Fig. 8A). Fossil fragments of undetermined gastropods, enchinoids, palynomorphs and fresh-to brackish-water ostracods increasing topward suggest a littoral to very shallow marine depositional environment. Palynomorphs belong to the Rhaetian-Lower Hettangian interval, assigned to the entire *Sequence* RS_{1a}.

The boundary with overlying Lower Jurassic *Sequence* RS_{1b}, called Top Triassic Unconformity, is picked at the level of the first carbonates occurrence in Well 26/22-1A (Fig. 8A). These usually occur in 20m-thick limestone beds and dolomites interbedded within mudstones and shales at the base and mudstones and calcareous sandstones upwards. *Sequence* RS_{1b} presents abundant palynomorphs and frequent diverse brackish to marine ostracods, and diverse marginal foraminiferas and microplanktonic specimens are getting more important compare to underlying *Sequence* RS_{1a}. The age of the sequence is not very well-constrained although definite Sinemurian ostracods and Rhaetian to Hettangian palynofloras infer an overall Hettangian- Sinemurian age.

Paleontological information are different in nature and age from overlying strata deposited during the Middle and Upper Jurassic. This implies an unconformity on top of *Sequence* RS_{1b}, called Top Lower Jurassic Unconformity, which merges with younger Mesozoic unconformities on top of the Finnian's Spur (Fig. 4).

Megasequence RS_{1a} is mapped through the seismic volume based on the recognition of the three above-mentioned bounding unconformities. It extends northward to fill in the entire North Porcupine Basin and is limited by the Finnian's Spur to the south (Table 2, Figs. 4–8B). Thus, Permo-Triassic pockets proposed in the Porcupine Basin (e.g.

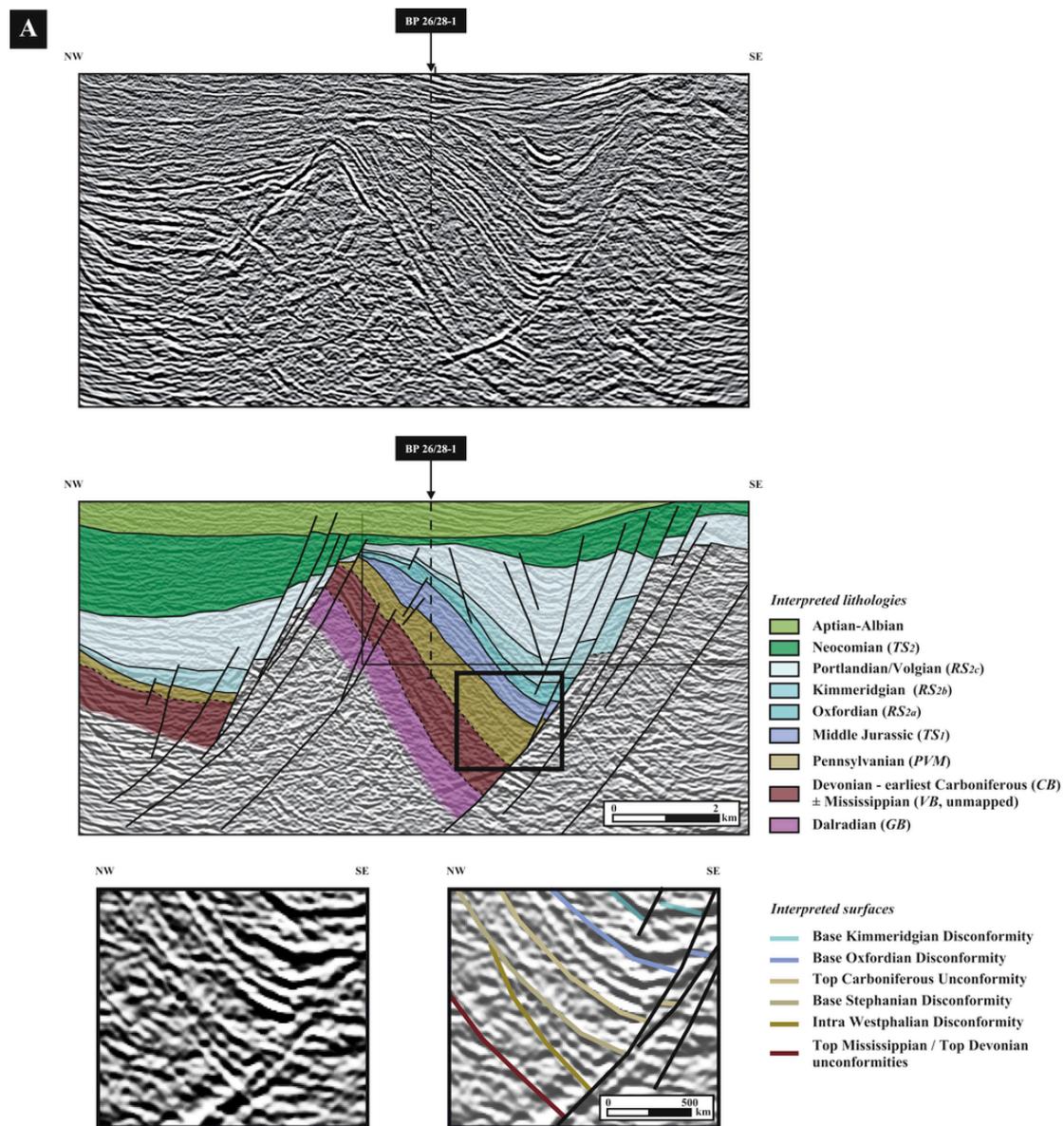


Fig. 6. 2D and 3D seismic lines highlighting the main Late Palaeozoic growth faulting episodes and their related unconformities. A- 3D seismic line calibrated to Well 26/28-1, showing two different episodes of growth in the Devonian (or older) and Pennsylvanian successions, at the scale of a fault-block and within a fault-block. Note that the Variscan Basement, although present therein, is not mapped due to seismic resolution (~10m-thick conglomerate in the well). Black box represents the position of the seismic close-up. B- 2D seismic line calibrated to Well 26/27-1B showing growth in the Pennsylvanian succession. C- 2D seismic line showing the difference between Mississippian, Pennsylvanian-Autunian tectonic extension in the southern part of the study area. The two black boxes represent the position of the seismic close-ups of Fig. 12. D & E- 2D seismic lines showing undrilled fault-blocks in which Palaeozoic rocks are differentiated according to the seismic characters and the internal deformation patterns. Seismic lines and wells location can be seen on Fig. 7.

Naylor et al., 2002) are most likely Westphalian-to-Stephanian in age according to our seismic interpretations. In the North Porcupine Basin, the Top Carboniferous Unconformity corresponds to truncated Carboniferous reflectors overlapped by *Sequence RS_{1a}*. The Top Triassic Unconformity is characterised by medium-to strong-amplitude reflectors correlative to the top of massive sands and the first occurrence of carbonates in *Sequence RS_{1b}*. The Top Lower Jurassic Unconformity is determined from localised Middle Jurassic truncations and onlaps. The three surfaces merge the one another north of the North Porcupine Basin (i.e. southward basin tilt).

4.2. Rhaetian and Hettangian-Sinemurian normal faults

Several normal faults have controlled the deposition of both sequences *RS_{1a}* and *RS_{1b}* (Fig. 8B). *Sequence RS_{1a}* affects that north-tilted

normal faults is most generally limited into small hemi-graben. Faulting did not propagate up to the Top Triassic Unconformity, implying a partially tectonically-driven subsidence. This is consistent with the general base-level rise observed in Well 26/22-1A. Largest faults have been later reactivated during the Hettangian-Sinemurian to control *Sequence RS_{1b}* deposition. This lead us to consider two distinct extensional episodes during the Triassic-Lower Jurassic period, whose the transition is marked by the Top Triassic Unconformity.

Fig. 9 displays the subcrop map of fault trends that controlled *Sequence RS_{1a}* (Rhaetian). They are oriented along E-W and ENE-WSW directions that are parallel to the Finnian's Spur and therefore correspond to reactivated Late Palaeozoic faults (Fig. 7). In the absence of Triassic-Lower Jurassic strata south of the Finnian's Spur, it is likely that these faults mark the southernmost boundary of the Rift Setting *RS₁*. Also, we propose that most of the northern part of the Porcupine Basin was

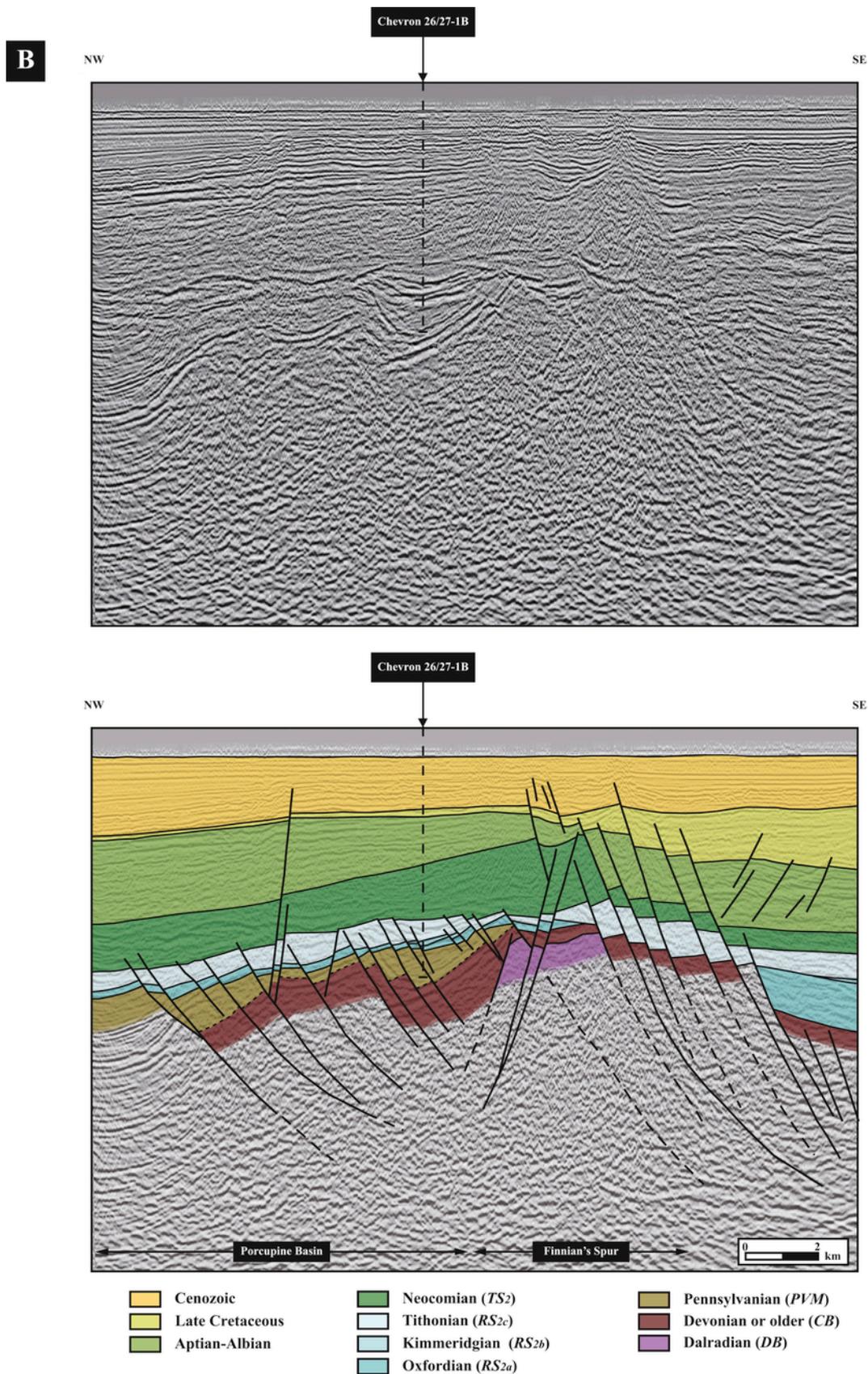


Fig. 6. (Continued)

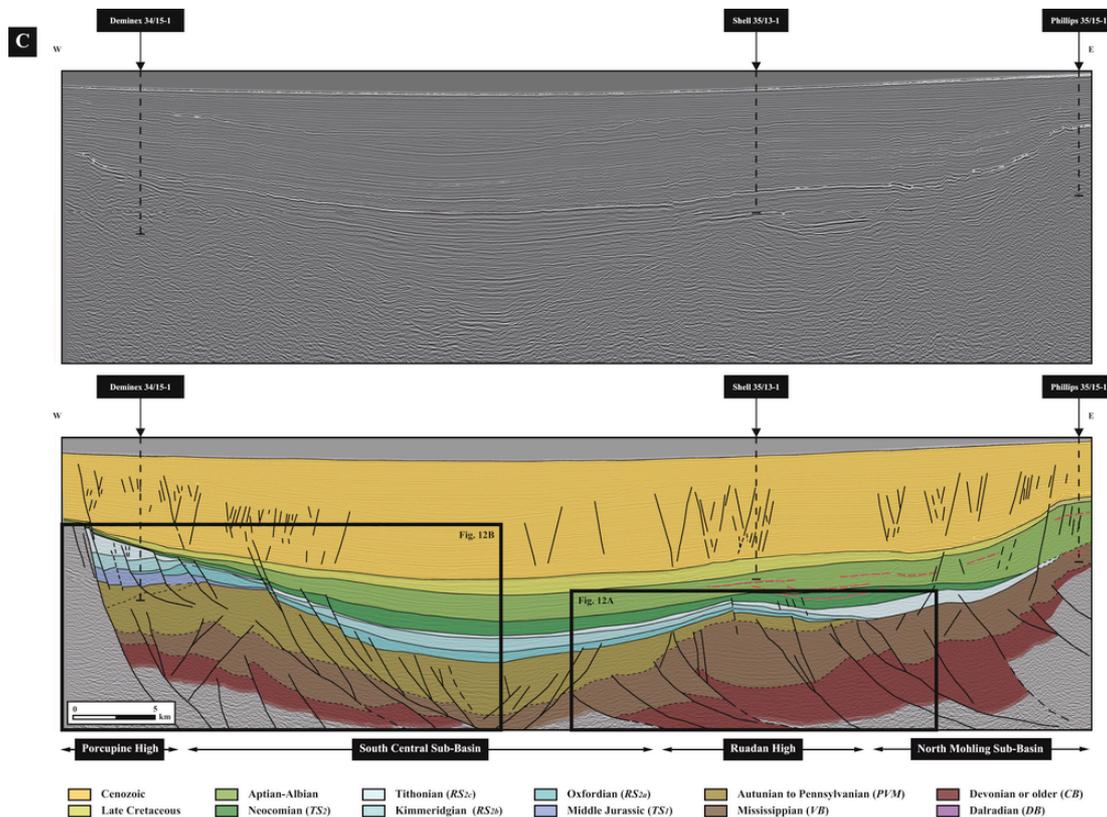


Fig. 6. (Continued)

uplifted between the latest Carboniferous to Middle Jurassic interval, and that the North Porcupine Basin evolved independently of the Porcupine Basin at the time.

5. Upper Jurassic to Lower Cretaceous rift setting RS_2

A second, generally more intense rift episode affected most of the Porcupine region and is here called RS_2 (for Rift Setting 2) for similar reasons than previous Rift Setting RS_1 . Although its definition widely differs in the literature due to internal facies recognition, the synrift unconformity is generally assumed running at the base of the Upper Jurassic and the postrift unconformity at the Base Cretaceous Unconformity (Late Cimmerian rifting phase on Fig. 3). Herein, we redefine this overall synrift setting using all available well and seismic data and reconsider the such surface definitions at basin scale.

5.1. Stratigraphy of the Mid-to Upper Jurassic and Lower Cretaceous intervals

To define the synrift interval, we take the example of Well 26/28-A1 that shows a complete Middle Jurassic to Lower Cretaceous succession deposited on top of Carboniferous strata (Fig. 10A). The first sediments, contained in *Megasequence* TS_1 (for Transitional Setting 1, 369m-thick), are composed of shally, silty and muddy material interbedded with repeated thick (1-to-10m) clastic levels (coarse or conglomeratic sands) and occasional coal (seams or patches), deposited within a fluvial-lacustrine environment. Numerous plant articles, bisaccate pollens and increasing upward fresh-to brackish-water ostracods, belong to the Bathonian interval. *Megasequence* TS_1 is topped by the Base Oxfordian Unconformity witnessed by a regional absence of Callovian strata (Table 3).

Subsequent *Megasequence* RS_2 (for Rift Setting 2, 242 m-thick) is subdivided into three Upper Jurassic sequences (Fig. 10A). *Sequence* RS_{2a} (Oxfordian) contains sandstones, mudstones and siltstones and the first occurrence of carbonates (patches or thin beds). Terrestrial and brackish species, including palynofloras, plant articles, dinoflagellates and ostracods, are observed with brackish to shallow-marine foraminiferas, brachiopods, echinoderms and gastropods. Strata are therefore interpreted to have deposited in an estuarine to coastal plain context. Following *Sequence* RS_{2b} (Kimmeridgian) is picked from the absence of sands and the first appearance of thick limestone beds (>5 m) interbedded within siltstones and mudstones. A very diverse assemblage of dinoflagellates, ostracods, foraminiferas, marine bivalves, brachiopods or echinoderms is observed throughout. The *sequence* therefore deposited in a marginal marine environment. Overlying *Sequence* RS_{2c} (uppermost Kimmeridgian and Tithonian) is mudstone-dominated and incorporates almost exclusively marine species (varied dinoflagellates, foraminiferas and fragmented of echinoderms, gastropods and bivalves). Overall, *Megasequence* RS_2 shows a progressive base-level rise that most likely terminated with the construction of the Base Cretaceous Unconformity.

Following *Megasequence* TS_2 (for Transitional Setting 2, ca. 40 m-thick) consists in mudstones and limited sandy and carbonate levels (Fig. 10A), sealed by disconformable massive Aptian-Albian sandstones and mudstones. The lowermost part of the sequence is poorly dated and the contact pattern with overlying Aptian-Albian strata, although disconformable in the well, may represent a clear unconformity in other wells (see Bulois (2016) for further discussion). *Megasequence* TS_2 contains almost exclusively marine species including foraminiferas, dinoflagellates and more minor ostracods that belong to the Berrisian-Barremian interval. It is topped by a regional unconformity, called Top Neocomian Unconformity that produced a condensed succession at well site (Fig. 10B). The thickness and facies nature vary throughout

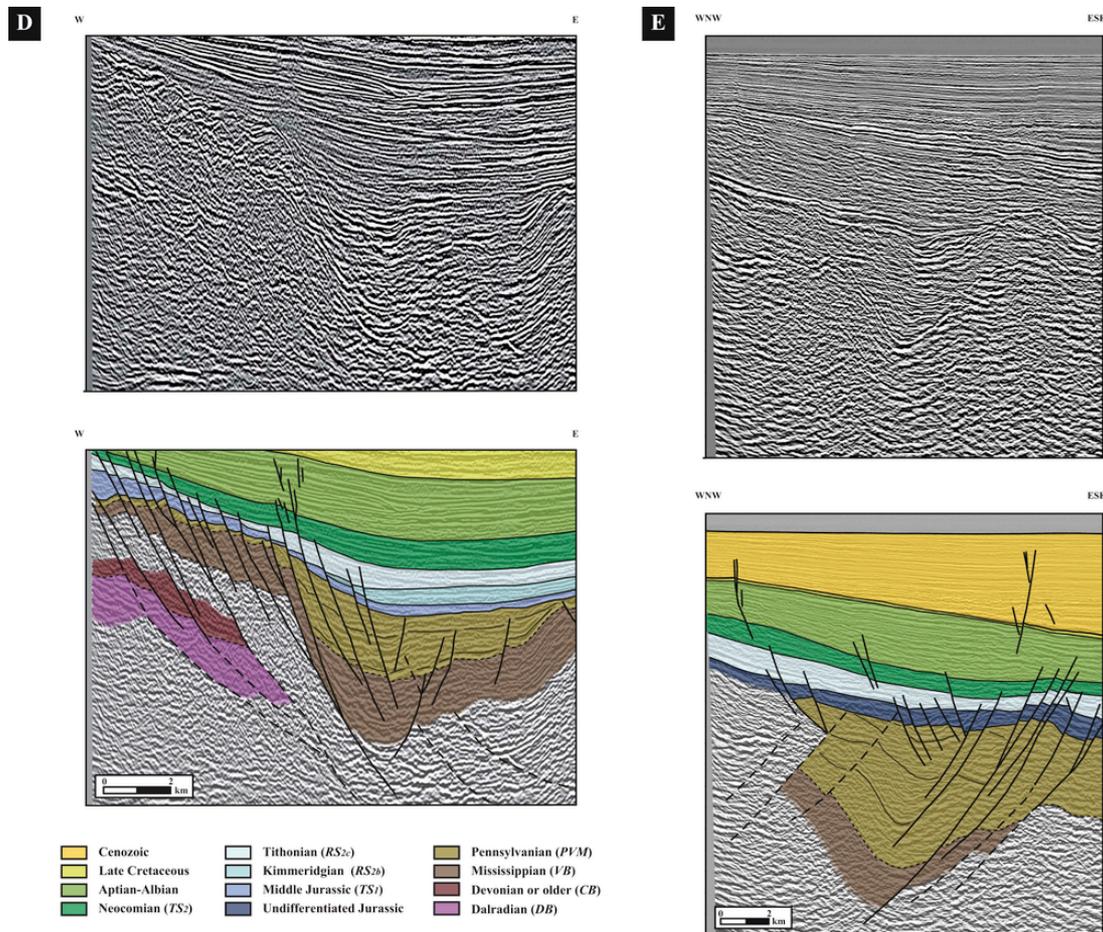


Fig. 6. (Continued)

the study area, as a result of the installation of the Rift Setting RS_2 (see differences between Figs. 8A–10A).

5.2. Seismic expression of the Middle Jurassic-Lower Cretaceous interval

The three previously-described megasequences are correlated to the entire seismic volume (Fig. 10B), together with unconformities of regional extent (Table 3). All of these have specific varying depositional controls.

Above the Top Carboniferous Unconformity, *Megasequence* TS_1 is characterised by parallel to subparallel, subcontinuous reflectors of medium-to-strong amplitude (Fig. 10B). This geometry implies the absence of faulting but, instead, a strong subsidence as witnessed by the generalised fluvial-alluvial to lacustrine transition. Subsidence relates to thermal cooling following Rift Setting RS_1 in the North Porcupine Basin and clearly predates the installation of the Upper Jurassic-Neocomian Rift Setting (RS_2).

Megasequence RS_2 , bounded by the Base Oxfordian and the Base Cretaceous unconformities, is characterised by intense growth-faulting. Oxfordian *Sequence* RS_{2a} displays subparallel to slightly oblique, subcontinuous reflectors, witnessing of subtle thickening (Fig. 10B). Subsequent Kimmeridgian *Sequence* RS_{2b} shows continuous reflectors and much more pronounced thickening toward the bounding faults. Finally, Tithonian *Sequence* RS_{2c} shows medium-to strong-amplitude, continuous reflectors that expand beyond the limits of sequences RS_{2a} and RS_{2b} . This confirms the overall Upper Jurassic marine transgression as described in the above. Nonetheless, deposition and deformation are not homogeneous as observed on regional seismic lines (Figs. 4 and 6).

This implies timing or magnitude variations of regional extent that directly link to fault expression.

Upper Jurassic strata are followed by *Megasequence* TS_2 , sandwiched by the Base Cretaceous and the Top Neocomian unconformities (Fig. 10B). Depocentres are only limited by the main Upper Jurassic faults that progressively die out during the Neocomian. Strata are generally sub-horizontal, implying a rather reduced tectonic control compare to underlying *Megasequence* RS_2 . Thus, *Megasequence* TS_2 suggests a progressive and uniform sag.

5.3. Upper Jurassic-Lower Cretaceous tectonism and relations with earlier structural trends

The analysis of the present 2D and 3D seismic dataset enabled the recognition of several fault orientations to Late Palaeozoic trends (Figs. 7 and 11). EW and ENE-WSW faults are dominant in the northwestern part of the Porcupine Basin and in the North Porcupine Basin, where they run parallel to the Finnian's Spur, before turning to NE-SW trend in the northeastern part of the Porcupine Basin. N-S faults appear locally in the north but prevail south of latitude 53°N , in continuation of the Ruadan High. They rotate to a NNE-SSW orientation in the southeastern part of the Porcupine Basin. Such a fault cluster marks the strong v-shape of the overall Porcupine Basin.

Fig. 12 shows the structural relationships existing between Rift Setting RS_2 and underlying Palaeozoic structures. In the southern part of the basin, high-resolution seismic imaging show Carboniferous folds and thrusts, that relate to characteristic thin-skinned Variscan deformation (Fig. 12A). They form buried structural highs, such as the Ruadan

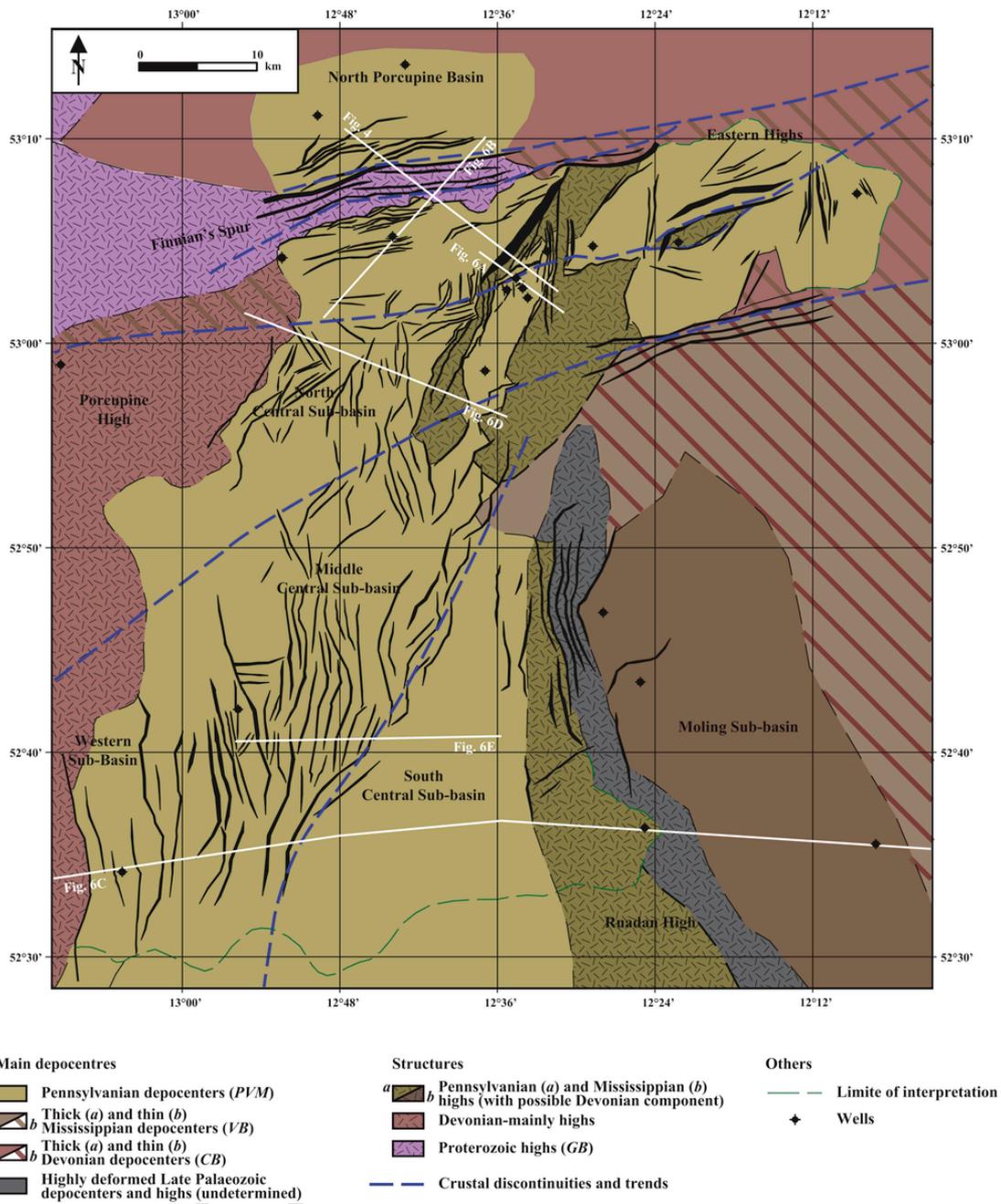


Fig. 7. Map showing the fault network affecting Megasequence PVM (Pennsylvanian) in the Porcupine region.

High, which clearly controlled the thickness of subsequent Upper Jurassic-Lower Cretaceous strata. To the west (Fig. 12B), extension produced normal faults flattening along Pennsylvanian sedimentary levels interpreted as lithological changes (e.g. higher rate of shale) or variation of structural styles (e.g. change in the fault dips and lesser compressional faults). This produced sliding packages that link onto faults basinward. In the northern part of the Porcupine Basin (Fig. 12C), asymmetrical to slightly overturned folds, locally associated with thrusts, controlled subsequent Pennsylvanian and Upper Jurassic-Lower Cretaceous normal faults that root on their forelimbs (flat part) and progressively upright in the upper part of the sedimentary succession. These structural relations imply a strong control of the Variscan structures onto the RS₂-related extension, which decreases northward due to the Caledonian Basement predominance.

6. Discussion

Our seismic analysis has shown various extensional megasequences that each reflects specific periods encompassed by the Porcupine region. Herein, we discuss them in terms of margin dynamics in order to constrain the structural response to the faulting propagation at a crustal scale and to conceptualise how inheritance and fault reactivation processes shaped the region in separated extensional frameworks.

6.1. Overlapping extensional megacycles

In the study area, several structural trends have been intermittently active since the Late Palaeozoic and relate to the internal basement geometries issued from the Variscan, Caledonian and, to a minor ex-

Table 2
Well and seismic characteristics of unconformities associated with the rift system RS1 in the North Porcupine Basin.

Stratigraphic surface	Abbreviated name	Well tie	Stratigraphic formations involved	Bounding seismic sequence	Seismic definition
Top Lower Jurassic Unconformity	TLJU	26/21-1, 26/22-1A	<i>Top:</i> Bathonian, locally Neocomian <i>Bottom:</i> Hettangian-Sinemurian (Zone RS _{1b})	<i>Sequence RS_{1a}</i>	Medium- to strong-amplitude reflector, with many onlap or downlap patterns in overlying Zone TS ₁ and/or clear truncational reflectors and erosional features in underlying Zone RS _{1b} .
Top Triassic Unconformity	TTU	26/21-1, 26/22-1A	<i>Top:</i> Hettangian-Sinemurian (Zone RS _{1b}) <i>Bottom:</i> Rhaetian (Zone RS _{1a})	<i>Sequence RS_{1b}</i>	Medium- to strong-amplitude reflector, without clear onlap, downlap or clear truncational reflectors or erosional features.
Top Carboniferous Unconformity	TCU	26/21-1	<i>Top:</i> Triassic <i>Bottom:</i> Westphalian B	<i>Sequence PVM₂</i>	Medium reflectors, usually continuous, and that locally display internal deformation due to prior Palaeozoic tectonism.

tent, Grenvillian compression phases. In the present study, we argue that the deep crustal structures had varying controls on the structural development over a long period of time, resulting in three overlapping extensional systems. These events can be considered as separated extensional megacycles (*sensu* Bulois et al., 2017), controlled by either volume or plate dynamics forces (*i.e.* orogenic collapse or true rifting). They therefore express differently the overall faulting propagation through the region.

Upper Palaeozoic extension results in slightly-rotated extensional basins formed along E-W and NE-SW Caledonian trends in the north of the basin and N-S Variscan thrusts and folds directions in the south (Fig. 13A). In the Porcupine Basin, Upper Palaeozoic depocentres seem to propagate from east to west and south to north, inferring a progressive collapse of the Variscan Orogen and a poorer control of Caledonian structures at the time of deposition. This type of extension is confirmed by the continental to very-shallow-marine conditions identified throughout *Megasequence PVM₂* (our study) and extensional stages identified onshore (Praeg, 2004). Subsequent Rift Setting RS₁ corresponds to an Upper Triassic-Lower Jurassic rifting phase, restrained to the North Porcupine Basin as it abutted the Finnian's Spur (Fig. 13B). As a result, reactivation of E-W/ENE-WSW Caledonian trends controlled shallow marine depocentres (*Megasequence RS₁*) interpreted as the southern extent of a southwards-propagating rift setting linked to the early Permo-Triassic Arctic rift setting (Ziegler, 1988; Roberts et al., 1999). Final Rift Setting RS₂ took place mostly in the Porcupine Basin during the Upper Jurassic and continued during the Neocomian (Fig. 13C). It resulted in shallow-to-deep-marine depocentres through both basins, with deposition due to the tectonic development of the northward-propagating North Atlantic Ocean (Ziegler, 1988; Roberts et al., 1999; Doré et al., 1999) and, to a certain extent, of the Central Atlantic Ocean (Stampfli and Borel, 2002; Nirrengarten et al., 2017). Further extensional episodes in the Aptian-Albian and the Cenozoic are not taken into account in our study as they have had very minor effects on the overall geometry of the Porcupine Basin (Figs. 6, 8 and 10). They are likely to represent deviatoric stresses arising from other plate settings (*e.g.* opening of the Bay of Biscay or of the North Atlantic Ocean *sensu stricto*).

In our overall evolutionary concept (Fig. 13), extension progressively migrated from the initial deformation core by reactivating pre-existing orogenic structures and stopped when abutting transversal lineaments. Thus, Caledonian faults initiated and stopped both Triassic-

Lower Jurassic and Upper Jurassic-Neocomian extensional phases, while the Variscan Fold Belt, concordant with the Ruadan High, localised Upper Jurassic extension alongside to give the general N-S direction but also stopped the extension further northeast when bending to the more characteristic E-W orientation. Previous palaeogeographic reconstructions showed similar dog-leg shape for the regional Variscan trends (*e.g.* Ziegler, 1988; Ballèvre et al., 2013). Nonetheless, we consider herein that such shape is produced by the collage and internal structures of both Variscan and Caledonian terranes.

Our dataset also suggests that such structural interactions controlled, at least partially, the characteristic v-shaped geometry of the overall Porcupine Basin. This implies a propagator mechanism developing accordingly to two different thickened continental crusts (Caledonian and Variscan) of specific structural patterns. This is confirmed by higher finite extension to the south with lithospheric stretching factors (β) grading from 1.1 to 1.7 to the north to more than 6 to the south (Tate et al., 1993). In parallel, extreme crustal thinning and serpentinised mantle is observed on deep refraction profiles southward (Readman et al., 2005; O'Reilly et al., 2006; Watremez et al., 2016; Prada et al., 2017) and new seismic refraction models suggest the presence of oceanic crust in the southernmost part of the Porcupine Basin (Chen et al., 2017, submitted). This likely relates to the uppermost Jurassic and Neocomian continental rifting in the Porcupine Basin and coeval uplift in the North Porcupine Basin, resulting in thick strata in the south than thin northward. In that sense, the differential response of the Caledonian and Variscan structures provided, at least partially, the shape of the overall basin within the Irish Atlantic Margin evolution framework.

This global mechanism is similar to the ones considered for other propagator settings such as the Coral, South China or southwestern Barents seas where heterogeneities at crustal and lithospheric scales partly controlled the development of rift propagators in addition of sequent extensional systems (Gernigon et al., 2014; Savva et al., 2014; Bulois et al., 2017). Therefore, their evolution combines successive extensional megacycles developing according to the reactivation of early crustal discontinuities and in respect of the overall boundary conditions variations. In the case of the Porcupine Basin, the Aptian-Albian Bay of Biscay opening probably stopped extension in the Porcupine Basin and forced reactivation of the deformation in the Rockall and Hatton region (*e.g.* Srivastava and Verhoef, 1992; Doré et al., 1999; Roberts et al., 1999; Tugend et al., 2015).

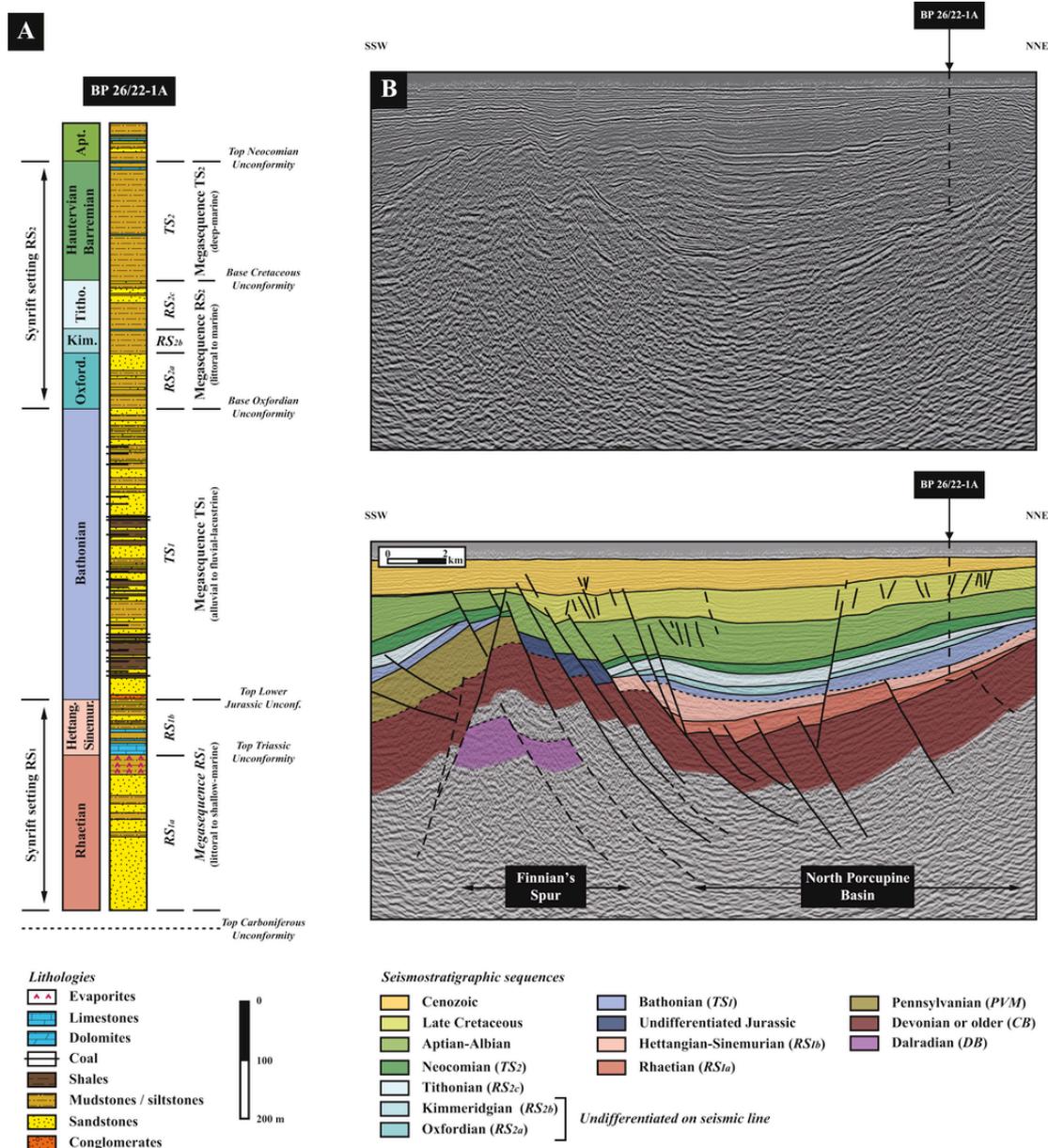


Fig. 8. Rift Setting RS₁ in the North Porcupine Basin. A- Synthetic lithological information of Well 26/22-1A showing the various sequences in the North Porcupine Basin. Well information is adapted from BP (1978a & 1978b). & B- 2D seismic line in the North Porcupine Basin, showing the two subsequent faulting episodes affecting RS_{3a} (diffused, Triassic) and RS_{3b} (localised, Lower Jurassic). Seismic line location can be seen on Fig. 9.

6.2. Regional significance of extensional megasequences

Conceptual views of the extensional development within single rifted basins traditionally focus on the fault system evolution and not necessarily on the stratigraphic record at the scale of a basin or of a passive margin (e.g. Leeder and Gawthorpe, 1987; Prosser, 1993; Ravnås and Steel, 1998; Purser and Bosence, 1998; Gawthorpe and Leeder, 2000). The most advanced regional models (e.g. Manatschal, 2004; Péron-Pinvidic and Manatschal, 2009) suggest discrete stages of evolution of a passive margin that reflects the lateral geometry of fault systems, with block faulting in the stretching domain and highly-rotated half-graben in the hyper-thinning domain oceanward (Fig. 14A). These models usually complete the rifting within 5–20 Myrs (Patton et al., 1994; Gupta et al., 1998; Sharp et al., 2000a, 2000b; Dawers and Underhill, 2000).

In the Porcupine Basin, deformation is organised in successive extensional episodes that are geographically and temporarily separated regionally. They combine an original orogenic collapse stage passing to classical stretching-thinning episodes. This reflects, on one hand, the large part of the extensional history of the Irish Atlantic Margin and follows, on the other hand, the classical stages of the formation of a passive margin, but on a 220Myr duration. It produces vertically-stacked megasequences bounded by synrift and postrift unconformities, and the relocation of the deformation during the extensional process. From our observation, we therefore discriminate extension driven by the orogenic collapse from the rifting *sensu stricto*. Collapse-generated extension, directly controlled by folds and thrusts of the Variscan Orogen, produced adjacent, slightly- or highly-rotated fault-blocks (Megasequence PVM, Fig. 6). In comparison, rifting forms numerous fault-blocks before extension focuses along the main bounding faults (Figs. 8 and 10). For both rift settings, this implies a diffuse rifting (high rota-

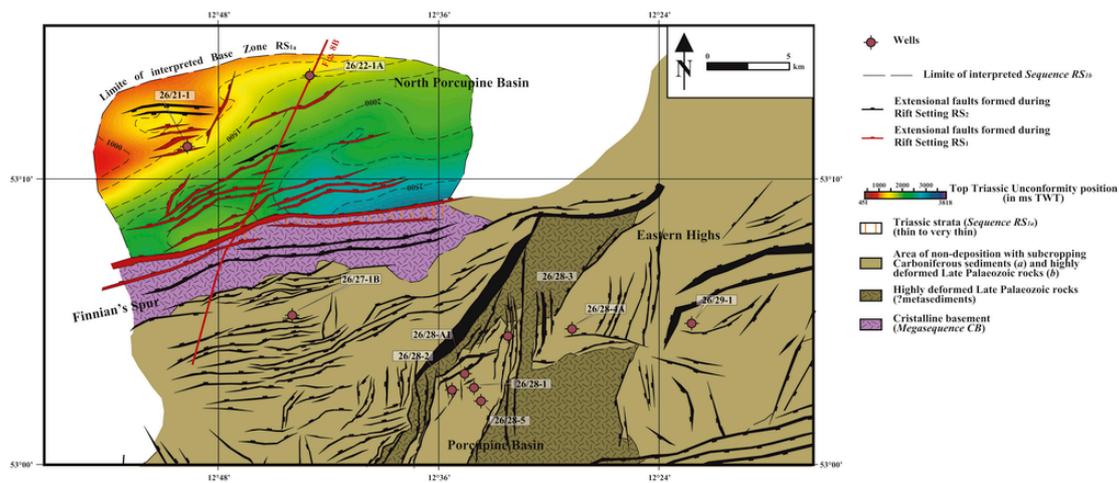


Fig. 9. Fault pattern in the North Porcupine Basin at the level of the Top Triassic Unconformity (*Sequence RS_{1a}*).

tion) responsible of a rift megasequence (*RS*), followed by a localised rifting (sag), responsible of the deposition of a transitional megasequence (*TS*). These transitions from orogenic collapse to the rifting and from diffuse to localised rifting produced regional unconformities, which articulate within the extensional megacycle concept in a basin and also into the evolution from stretching to hyper-thinning modes at a margin scale.

Deep seismic data in the Porcupine Basin (e.g. Reston et al., 2001 & 2004; O'Reilly et al., 2006) show a striking crustal asymmetry, expressing the Variscan Front that was likely reactivated as a detachment to produce basin hyper-thinning (Fig. 14B). Similar observation in the adjacent Rockall Basin (e.g. Morewood et al., 2005) are interpreted as an evidence of the Iapetus Suture (i.e. Caledonian crust) while, in the Hatton Basin, the absence of hyper-thinning is interpreted as an effect of the thick Archean crust (i.e. Grenvillian terranes, Smith et al., 2005). At the same time, a generalised migration of the deformation as proposed in the literature reflects the re-arrangement of the margin from the Triassic to the Upper Cretaceous before Cenozoic breakup west of the Hatton Bank (e.g. Doré et al., 1999; Stoker et al., 2017). Somehow, this lateral configuration infers a crustal boudinage prior seafloor spreading.

Two different extensional modes are therefore proposed with, on one side, the initiation of the extension (orogenic collapse) and, on the other side, the crustal denudation (diffused rifting and localised hyper-stretching). Both modes are driven by the old crustal architecture and are sensitive to far-field forces. In that sense, extension may be regarded as a long-lived deformation period taking place with discontinuous events, just like in a classical passive margin formation (Fig. 14A), but our study also suggests a strong dependence to continental discontinuities (i.e. ancient orogenic structures) with an oceanward deformation migration at a margin scale (Fig. 14B). In addition, internal basin dynamics arranges in a diffuse and wide rift setting followed by deformation relocation along the main bounding faults towards the ocean. As a result, the stretching and the hyper-thinning stages are typically observed in rifted and transitional megasequences respectively, with a tectonic control along specific faults. In such a way, this succession episode implies extension on a 220Myr-duration with a succession of internal extensional megacycles of 15–20 Myrs, the last one leading to hyper-extension.

7. Conclusion

In this study, we have documented several extensional megacycles that successively developed in the Porcupine Basin over a long period of time evaluated at 220 Myrs (Carboniferous to Neocomian). Each ex-

tensional megacycle is thought to represent a specific period encompassed by the Irish Atlantic Margin and may be defined by characteristic extensional megasequences bounded by precise syn- and postrift unconformities. These extensional megacycles are defined as such:

- 1 A late Palaeozoic event (Upper Carboniferous) shows rapid extension with little wedging and reactivates E-W and ENE-WSW trends of the southern boundary of the Caledonian Orogen and NE-SW and N-S faults along the northwestern part of the Variscan Orogen. The localisation of the deformation suggests a strong reactivation of orogenic structures in a general orogenic collapse. In particular, the Variscan crust, with a clear thin-skinned geometry, mostly controlled the formation of extensional fault blocks.
- 2 An early Triassic to Lower Jurassic extension (*RS₁*) took place in the North Porcupine Basin and did not propagate southward in the Porcupine Basin. It controlled the deposition of *Megasequence RS₁*, which shows diffuse deformation during the Rhaetian (*Sequence RS_{1a}*) getting localised along the main boundary faults during the Hettangian-Sinemurian (*Sequence RS_{1b}*). Synchronous to the Slyne-Erris formation, the rifting localised along Caledonian trends in a global NW-SE extensional direction. It corresponds to the southern extent of coeval Arctic rift system.
- 3 An Upper Jurassic-Neocomian extension (*RS₂*), characterising a strong rifting in the Porcupine Basin, controlled its v-shape development by reactivating NE-SW and N-S Variscan structures. To the north, it abutted the Caledonian crustal root avoiding extensional tectonics to propagate in the North Porcupine Basin. Related megasequences *RS₂* and *TS₂* deposited in several fault-blocks in a diffuse rift system, followed by more localised faulting along the bounding faults, which controlled a marine transgression at the scale of the basin. We therefore observe that Neocomian extension is a continuation of the Upper Jurassic rifting due to the North Atlantic opening, although faulting is progressively replaced by postrift thermal subsidence. This expresses the ultra-thinning and Moho rise in the south of the Porcupine Basin.

This apparent overlap of extensional settings reflects the formation of a typical Atlantic-type passive margin. It particularly shows a vertical stack of extensional megasequences, separated by characteristic unconformities bounding each extensional megacycles. Also, the structure of the continental crust has a dominant role in the initiation of the rifting (i.e. orogenic collapse) and then decreases as long as extension evolves. In this way, the Porcupine Basin opened as a typical rift propagator, with extension progressively migrating northward and oceanward, as well as differential uplift in the North Porcupine Basin and

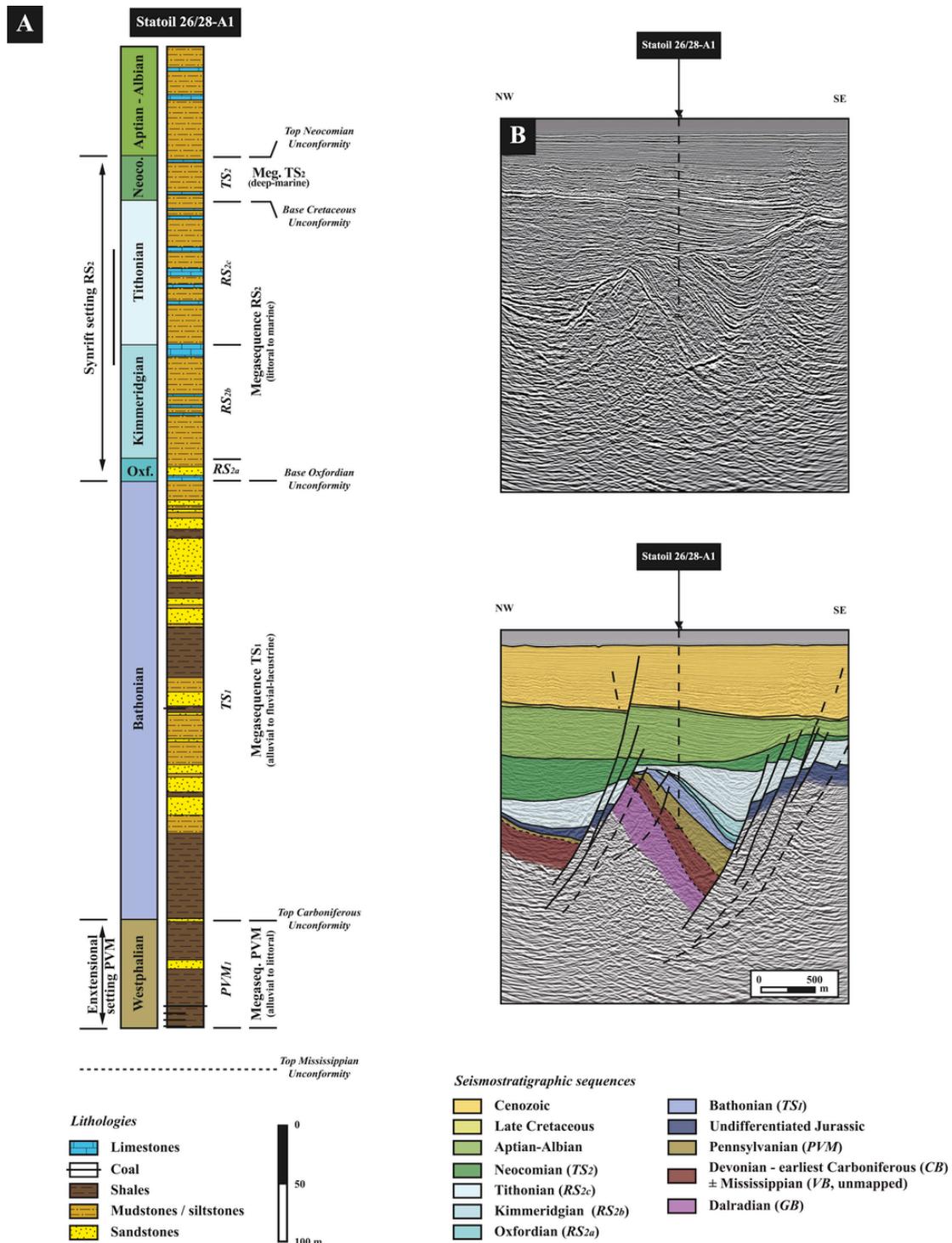


Fig. 10. Rift Setting RS₂ in the Porcupine region. A- Synthetic lithological information of Well 26/28-A1 showing the main lithological packages TS₁ (prerift) and RS_{2a} to RS_{2c} and TS₂ (syn-to postrift). Well information is adapted from Statoil (1997). B- 3D seismic line, showing the absence of obvious deformation in the Middle Jurassic and two subsequent faulting episodes affecting megasequences RS₂ (high rotation, possibly diffused, Upper Jurassic) and TS₂ (localised, Neocomian). Seismic line location can be seen on Fig. 11.

surrounding highs. This implies unsuccessful continental tears and may explain such a long-standing extensional history along the Irish Atlantic Margin.

Uncited references

Dancer et al., 1999; Tate and Dobson, 1989b.

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Table 3
Well and seismic characteristics of unconformities associated with the rift system RS2 in the northern Porcupine region.

Stratigraphic surface	Abbreviated name	Well tie	Stratigraphic formations involved	Seismic megasequence	Seismic definition
Top Neocomian Unconformity	TNU	All wells (except 26/ 21-1) 26/21-1	<i>Top:</i> Aptian-Albian <i>Bottom:</i> Neocomian <i>Top:</i> Lower Aptian <i>Bottom:</i> Barremian	<i>Megasequence</i> <i>TS₂</i>	High-amplitude reflector generally associated with onlaps of Aptian-Albian reflectors
Base Cretaceous Unconformity	BCU	All wells with Cretaceous (except 26/ 21-1) 26/21-1	<i>Top:</i> Lower Cretaceous <i>Bottom:</i> Portlandian (or older) <i>Top:</i> Neocomian <i>Bottom:</i> Lower Jurassic	<i>Megasequence</i> <i>RS₂</i>	High-amplitude reflector, with overlying Early Cretaceous strata onlapping on truncated Upper Jurassic (or older) sediments.
Base Oxfordian Unconformity	BOU	All wells with Middle Jurassic (except 26/ 27-1B, 26/ 28-2 & 34/ 15-1) 26/27-1B 26/28-2 & 34/ 15-1 26/21-1	<i>Top:</i> Oxfordian (Zone LC _{II}) <i>Bottom:</i> Bathonian (Zone LC _I) <i>Top:</i> Oxfordian (Zone LC _{II}) <i>Bottom:</i> Westphalian D No unconformities	<i>Megasequence</i> <i>TS₁</i>	Medium-, locally strong-amplitude reflector, with many onlap and downlap patterns in overlying Zone RS _{IIb} . The truncation of underlying reflectors of Zone RS _{IIa} is uneven. Locally, the unconformity is associated with more transparent strata.
Top Carboniferous Unconformity	TCU	26/21-1 26/28-1, 26/ 28-2, 26/28-3 26/27-1B, 26/ 28-4A, 26/ 29-1 26/30-1	<i>Top:</i> Triassic <i>Bottom:</i> Westphalian B <i>Top:</i> Middle Jurassic <i>Bottom:</i> Stephanian <i>Top:</i> Middle Jurassic <i>Bottom:</i> Westphalian C <i>Top:</i> Middle Jurassic <i>Bottom:</i> Westphalian B	<i>Megasequence</i> <i>VB₂</i>	Usually moderate- to high-amplitude reflector (especially in the centre of the basin). Many truncated reflectors are observed throughout the basin, the surface being often located above high-amplitude, continuous reflectors. Sometimes, it is associated with more transparent to chaotic strata and basement.

access to the well and processed seismic data, as well as Professor Patrick M. Shannon from University College Dublin (Ireland) and Professor Jacques Déverchère from Université Bretagne Occidentale

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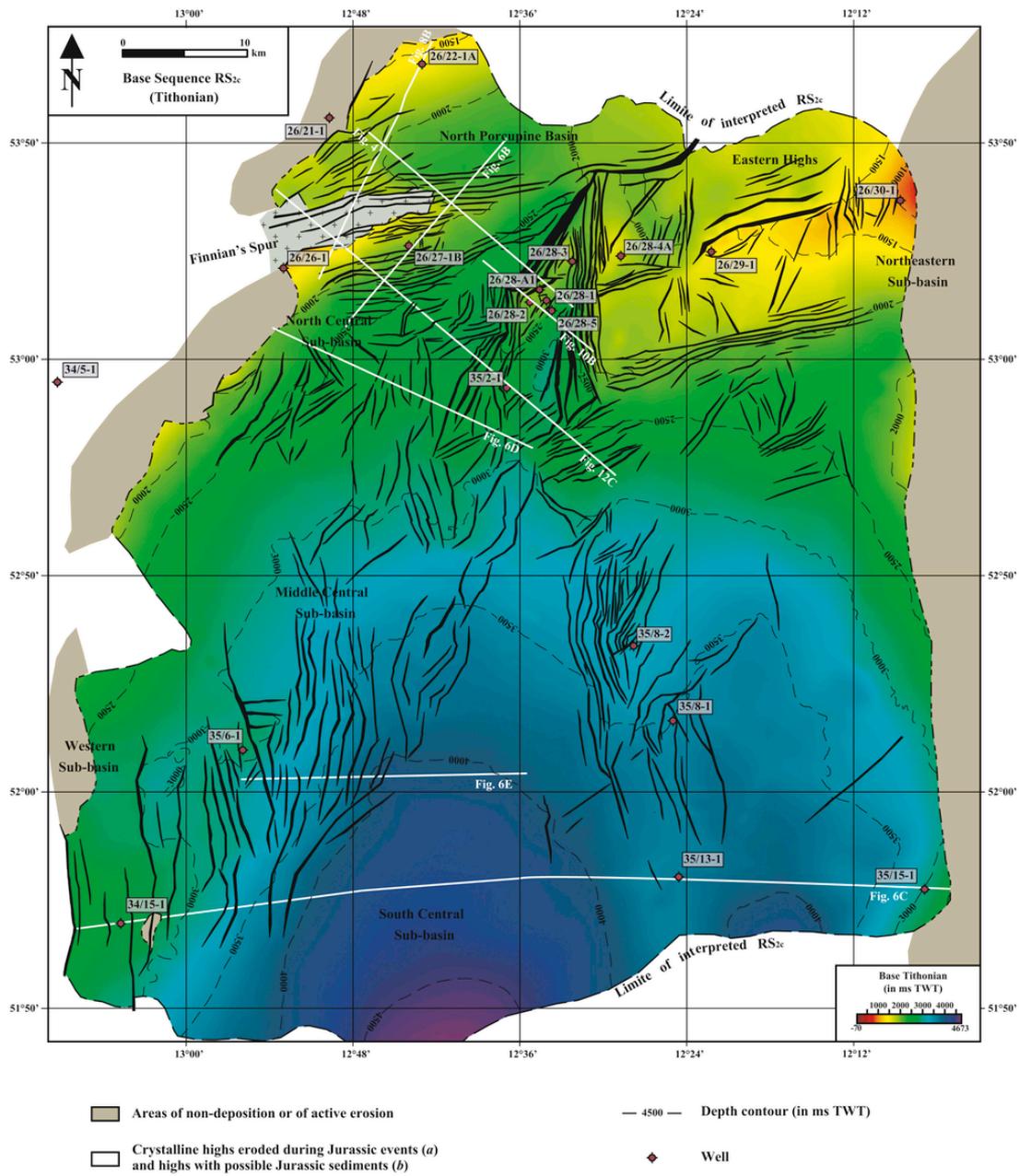


Fig. 11. Fault pattern within Sequence RS_{2c} (Tithonian). Tithonian faulting characterises the main rotation in the fault blocks and the generalisation of the extension in the northern Porcupine region. Note the v-shape drawn by the various faults.

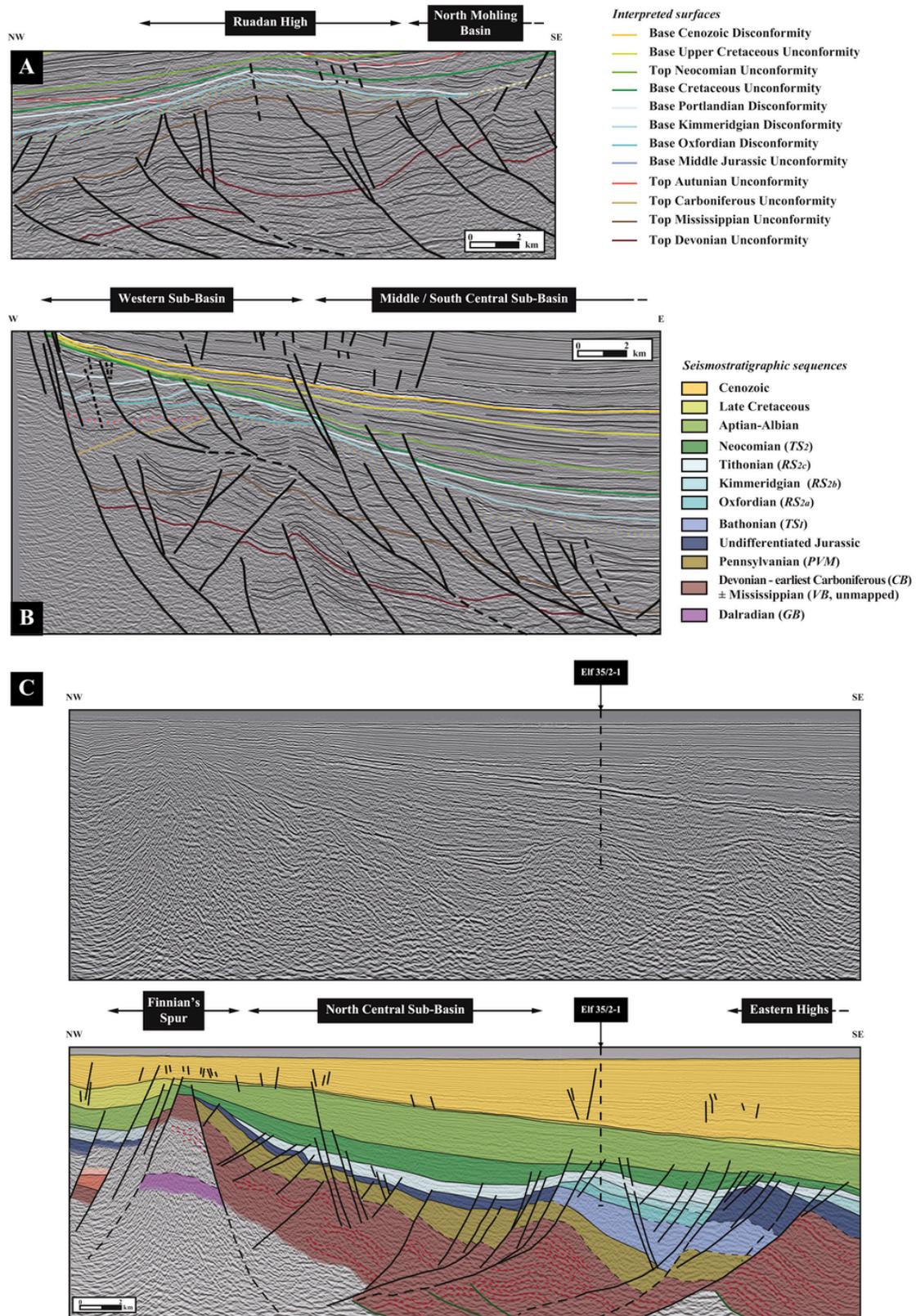


Fig. 12. Type of controls of Palaeozoic features during the Upper Jurassic-Lower Cretaceous rifting *RS*₂. **A-** Control of structural highs (Ruadan High complex) related to the Variscan thin-skin deformation onto the thickness of subsequent Upper Jurassic-Lower Cretaceous sequences as a major intrabasinal discontinuity (?Variscan Front). **B-** Relation of intra-Pennsylvanian discontinuities and subsequent sliding packages developed during the Rift Setting *RS*₂. **C-** Development of extensional faults on the forelimb of Variscan or Caledonian folds (dashed red lines) and their associated thrusts (full green lines). Location is shown on Fig. 11, except for Fig. 12B which relates to zoomed pictures from Fig. 6C. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

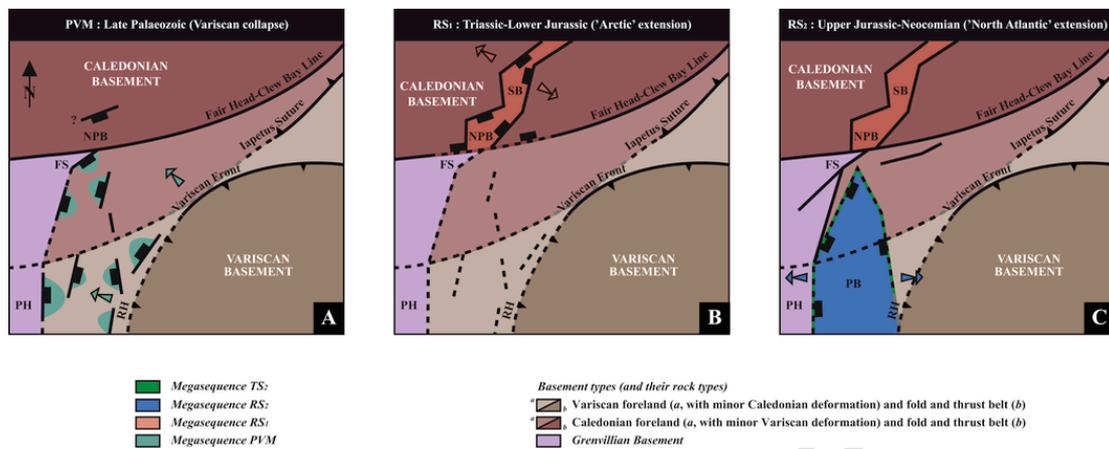


Fig. 13. Schematic evolution of the extensional propagation in the Porcupine Basin. A- Late Palaeozoic extension (*Post-Variscan Megasequence*) controlled by the Variscan orogenic collapse. Note the separated extensional basins forming along various structural directions. B- Triassic-Lower Jurassic extension (*Megasequence RS₁*) in the North Porcupine Basin and controlled by the southernmost arm of the Arctic rifting. Note the rift system abutting the Caledonian terranes. C- Upper Jurassic-Neocomian extension (*megasequences RS₂* and *TS₂*) in the Porcupine Basin and controlled by the northward propagation of the North Atlantic Ocean.; **Abbreviations:** FS - Finnian's Spur, NPB North Porcupine Basin, PB - Porcupine Basin, PH - Porcupine High, RH - Ruadan High, SB - Slyne Basin.

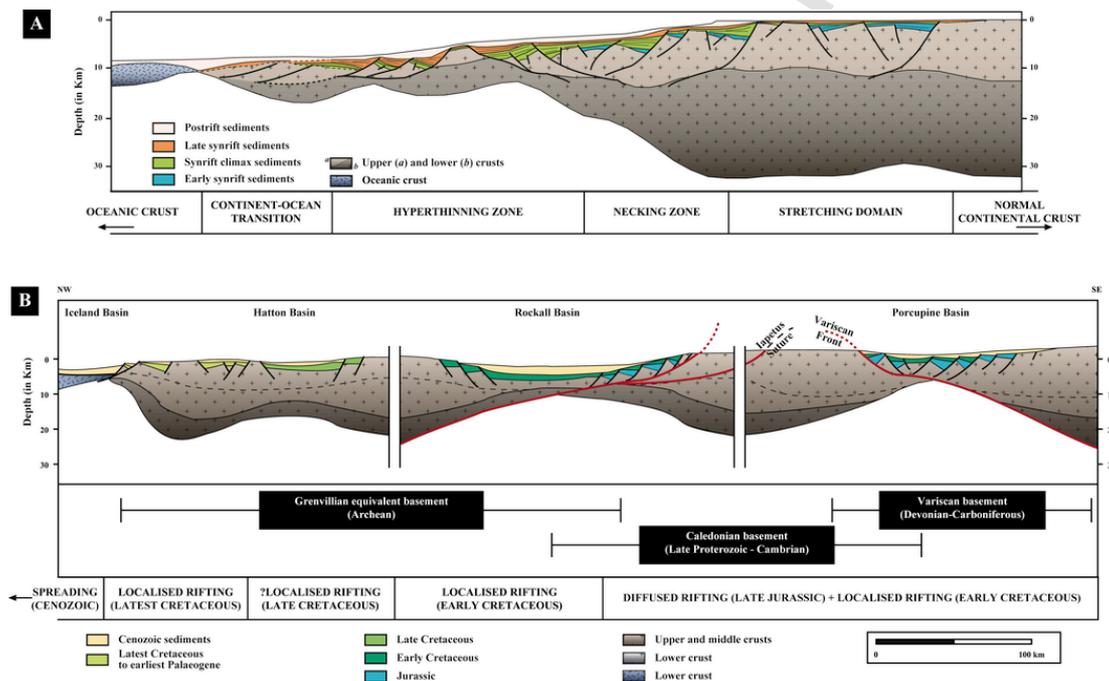


Fig. 14. Comparison between a classical model of an Atlantic-type margin and the Irish Atlantic Margin with reactivation of orogens prior rifting as suggested in this study. A- Theoretical rifted style along a typical hyperstretched Atlantic margin as a function of the lateral position along the margin and comparison with the various rifted domains. This schematic margin shows three successive rift megacycles that all have a different structural style spatially and temporarily. Note the specific migration of the deformation along the margin. B- Schematic cross-sections of the Irish Atlantic Margin based on Bulois (2016). The characteristic geometry is based on the asymmetry of the various basins imaged from deep seismic lines (Morgan et al., 1989; Morewood et al., 2005; Smith et al., 2005; O'Reilly et al., 2006). It infers three different basements (Archean, Caledonian and Variscan) that are likely to have controlled younger extension during the rifting of the North Atlantic Ocean. Only main rifting stages are represented for each basin; note their apparent westward migration across the margin.

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