The influence of multiple salt layers on rift-basin development; The Slyne and Erris basins, offshore NW Ireland

Conor M. O'Sullivan [1, 2], Conrad J. Childs [1, 2], Muhammad M. Saqab [1, 2*], John J. Walsh [1, 2], Patrick M. Shannon [1, 3]

[1] Irish Centre for Research in Applied Geoscience (iCRAG), University College Dublin, Belfield, Dublin 4, Ireland

[2] Fault Analysis Group, School of Earth Sciences, University College Dublin, Belfield, Dublin 4, Ireland

[3] School of Earth Sciences, University College Dublin, Belfield, Dublin 4, Ireland

[*]Present Address: Norwegian Geotechnical Institute, 40 St. Georges Terrace, Perth, WA 6000, Australia

Corresponding author email: conor.osullivan@icrag-centre.org

Abstract:

In contrast to much of the European Atlantic margin, the influence of salt on basin evolution has received little attention to date in the basins west of Ireland, despite salt being proven in several boreholes. Using an extensive seismic reflection database coupled with data from exploration wells and shallow boreholes, this study maps the distribution and composition of salt layers and investigates their role in the structural evolution of the Slyne and Erris basins offshore west of Ireland. Two salt-prone intervals have been proven. The Upper Permian Zechstein Group is present throughout the Slyne and Erris basins, while the Upper Triassic Uilleann Halite Member is only developed in the Northern Slyne and Southern Erris sub-basins. Both sedimentary units mechanically detach pre-, post-, and intra-salt stratigraphy. Both salt layers underwent halokinesis during basin development, creating a variety of salt-related structures. Salt pillows and salt rollers formed in the Zechstein Group, causing folding and rafting in the overlying Mesozoic section, driven by active faulting within the pre-salt basement. Halokinesis in the Uilleann Halite Member caused thin-skinned crestal collapse of the overlying Jurassic section above anticlines cored by Zechstein salt. Where both Triassic and Permian salt are present, unique structural geometries are formed when two stratigraphically discrete but kinematically linked halokinetic structures develop. The most common structural configuration consists of a Zechstein salt pillow and an Uilleann Halite salt wall separated by Lower Triassic sandstones. The fold-axis of the salt pillow trends parallel to the strike of the salt wall. The results of this study provide a framework for the evolution of halokinetic structures in other basins on the Irish Atlantic margin, give a greater insight into the Permian and Triassic paleogeography of the region, and have more general implications

for the evolution of salt-related structures in rift basins with multiple stratigraphically discrete salt layers.

Highlights

- Upper Permian and Upper Triassic salt layers present in the Slyne and Erris basins.
- Zechstein Group forms salt pillows and reactive diapirs, Uilleann Halite forms reactive diapirs.
- Even thin salt layers act as prominent décollement surfaces during rifting.
- Stratigraphically discrete salt layers interact during structural evolution.

Acknowledgements

This research is funded in part by a research grant from Science Foundation Ireland (SFI) under Grant Number 13/RC/2092 and is co-funded under the European Regional Development Fund, and by the Petroleum Infrastructure Programme (PIP) and its member companies. Efstratios Delogkos is thanked for thoughtful discussions regarding the links between the Slyne and Erris basins and the Bróna and Pádraig basins. Neil Jones and Kristian Lomas are thanked for engaging discussions on the structural evolution of the Slyne and Goban Spur basins respectively. The authors would like to thank reviewers Torsten Hundebøl Hansen and Timothy Shin and associate editor Craig Magee for their constructive reviews which greatly improved the manuscript. The authors would like to thank the Petroleum Affairs Division (PAD) of the Department of Communications, Climate Action and Environment (DCCAE), Ireland, for providing access to released well, seismic, and potential field datasets. Europa Oil & Gas are thanked for providing access to the Inishkea 2018 reprocessed seismic volume and allowing a section from the volume to be shown. Shell Exploration & Production Ireland Ltd. are thanked for providing access to reprocessed volumes of the 1997 Corrib seismic. The authors would also like to thank Schlumberger for providing academic licenses of Petrel to University College Dublin.

Data Availability Statement

The data that support the findings of this study were provided by the Petroleum Affairs Division (PAD) and are available for download from https://www.dccae.gov.ie/en-ie/natural-resources/topics/Oil-Gas-Exploration-Production/data/Pages/Data.aspx. Restrictions may apply to the availability of these data, which were used under licence for this study.

1. Introduction:

Salt plays an important role in the development of sedimentary basins, acting as a layer of mechanical detachment between pre- and post-salt stratigraphy (Hudec & Jackson, 2007; Jackson & Hudec, 2017b). This leads to significant differences in the structural styles and evolution of salt-influenced basins relative to those unaffected by salt. Thick layers of salt have been encountered in several basins across the European Atlantic margin, including offshore Iberia (Wilson et al., 1989; Alves et al., 2006; Pena dos Reis et al., 2017; Ramos et al., 2017; Zamora et al., 2017), offshore France (Chapman, 1989; Ferrer et al., 2012), on the United Kingdom Continental Shelf (UKCS) (Stewart et al., 1996; Jackson & Stewart, 2017) and offshore Norway (Jackson et al., 2019; Rojo et al., 2019). Salt is also present in basins on the conjugate margin of Atlantic Canada (Jansa et al., 1980; Deptuck & Kendell, 2017). In these areas, the main layers of salt range in age from Early Permian to Early Jurassic, and have had a profound impact on basin development, commonly having undergone significant halokinesis to form distinctive salt-related structures such salt diapirs and allochthonous salt sheets and canopies (McKie, 2017; Stoker et al., 2017).

The Irish Atlantic margin has seen comparatively little research investigating the presence and impact of salt, owing to the limited well penetrations and lack of characteristic salt-related structures on seismic data. Nevertheless, Upper Triassic salt is proven in the Celtic Sea basins (Robinson et al., 1981; Van Hoorn, 1987; Shannon, 1991), the Central Irish Sea and St George's Channel basins (Naylor & Shannon, 1982) and the Kish Bank Basin (Naylor et al., 1993; Dunford et al., 2001). In the Porcupine Basin, Croker & Shannon (1987) reported the presence of salt in two wells in the north of the basin, while the 35/19-1 well encountered 24m of ?Upper Triassic allochthonous salt within Upper Jurassic sediments (Britoil, 1986; Merlin Energy Resources Consortium, 2020). Salt has also been identified onshore Ireland, within the Ulster-Larne Basin of Northern Ireland (Illing & Griffith, 1986; McCann, 1988; Quinn et al., 2010) and in a small outlier at Kingscourt, Co. Cavan (Gardiner & Visscher, 1971; Gardiner & McArdle, 1992). Previous work has noted the presence of salt in the Slyne and Erris basins (Tate & Dobson, 1989; Chapman et al., 1999; Dancer et al., 1999; Dancer et al., 2005) but limited and poor-quality seismic data, coupled with few well penetrations, made it difficult to assess the impact of these salt-prone layers on basin development. Since then, significantly more seismic data has been acquired and additional exploration wells have been drilled, allowing the nature of salt and the role it plays in the evolution of the Slyne and Erris basins to be investigated in greater detail (Fig. 1).

This study utilizes an extensive database of 2D and 3D multichannel seismic reflection data, coupled with wireline, cuttings and core data from exploration wells and shallow boreholes to understand the distribution and composition of salt in the Slyne and Erris basins, and the impact of salt on the structural evolution of these basins. Both Upper Permian (Zechstein Group) and Upper Triassic (Uilleann Halite Member) salt layers have now been identified over significant parts of the study area. The Uilleann Halite Member was referred to as the Mercia Halite Member (e.g. Corcoran & Mecklenburgh, 2005; Dancer et al., 2005) prior to recent updates to the stratigraphic framework for offshore Ireland (Merlin Energy Resources Consortium, 2020). The occurrence of two salt layers results in stacked salt-related structures with evidence for interaction between halokinetic features developed at different structural levels.

In our study the distribution of salt on the Irish Atlantic margin is placed in regional context to provide insights into Late Permian and Late Triassic paleogeography of the north-western European Atlantic margin. The influence of salt on the petroleum systems of the Slyne and Erris basins is also discussed. The evolutionary model for halokinetic structures involving multiple thin salt layers may be applicable to other rift basins beyond the Irish Atlantic margin, particularly across NW Europe where several basins have multiple, stratigraphically discrete layers of salt.

2. Geological Setting:

The Slyne and Erris basins are contiguous rift basins located on the Irish Mainland Shelf off the north-western coast of Ireland in water depths of 150m to 3000m. They are narrow, elongate and broadly NE-SW oriented basins, which belong to a framework of rift basins extending westward from the coast of Ireland across the Irish Atlantic margin to the Atlantic Abyssal Plain. They form part of chain of rift basins stretching along the European Atlantic margin from the Barents Sea offshore northern Norway to offshore Portugal (Fig. 1). These rift basins formed during episodic extensional periods beginning with Variscan orogenic collapse and culminating with the onset of oceanic crust formation in the North Atlantic Ocean during the Eocene (Doré et al., 1999, Stoker et al., 2017; Schiffer et al., 2019).

2.1. Tectonostratigraphic evolution of the Slyne and Erris basins:

The Slyne and Erris basins began to form during the Permian breakup of Pangea. Extension created a series of narrow, NE-SW and NNE-SSW oriented half-grabens (Fig. 1; Chapman et al., 1999; Dancer et al., 1999). The arid Permian climate led to the deposition of the Zechstein Supergroup, a large and widely studied 'salt giant' present across north-western Europe (Coward, 1995; Stewart, 2007; Duffy et al., 2013; Jackson & Stewart, 2017). This salt body formed through the ingress and subsequent evaporation of marine waters from the Boreal Ocean to the north (McKie, 2017). Possible pathways connecting the Irish Atlantic margin and the Boreal Ocean include the Faroe-Shetland Basin, the Hebridean basins, and an incipient Rockall rift system (Štolfová & Shannon, 2009; McKie & Shannon, 2011; McKie, 2017). Extension ceased by the Early Triassic, with thick fluvial and aeolian sandstones being deposited regionally, followed by the widespread deposition of playa-lake mudstones and siltstones and locally thick halite deposits during the Late Triassic (Štolfová & Shannon, 2009; Merlin Energy Resources Consortium, 2020).

The end of the Triassic was marked by a regional marine transgression and the deposition of shallow marine limestones, sandstones and mudstones during the Rhaetian to the Sinemurian (Trueblood & Morton, 1991; Raine et al., 2020). The area experienced mild extension during this time, with subtle syn-extensional thickening of the Lower Jurassic section occurring in the hanging-walls of active basin-bounding faults (Dancer et al., 1999). Intrabasinal NE-SW and NNE-SSW striking listric faults formed throughout the basin above small salt rollers and salt pillows. A minor break during the early Pliensbachian created a subtle unconformity, above which Late Pliensbachian to Bajocian marine sandstones, limestones and mudstones were deposited.

A major unconformity separates the Lower and Middle Jurassic marine sediments from the overlying Upper Jurassic fluvio-estuarine sediments, with the unconformity locally incising deeply enough to place the Oxfordian above the Pliensbachian and Sinemurian on the basin margins. The main phase of rifting occurred during this time, with movement on basin-bounding faults creating accommodation space for the deposition of several kilometres of Upper Jurassic sediments (Merlin Energy Resources Consortium, 2020). The Upper Jurassic sediments consist of Oxfordian terrestrial, fluvial and estuarine sandstones and mudstones with associated coal horizons, which grade upwards into marine mudstones, limestones and sandstones, indicating a regional marine transgression occurred during the Kimmeridgian and Tithonian (Fig. 2).

Rifting in the Slyne and Erris basins ceased at the end of the Jurassic, with the area experiencing kilometre-scale uplift and erosion during the Early Cretaceous. As rifting occurred in the Rockall Basin to the west, the Erris Basin in particular was subject to severe rift-shoulder uplift, undergoing greater uplift along the western margin of the basin while thick Cretaceous sediments were deposited along the basin’s eastern margin (Chapman et al., 1999; Walsh et al., 1999). Areas that were separated from the Rockall Basin by intervening basement highs, such as the Erris Ridge, did not experience the same extent of rift-shoulder uplift. The Slyne Basin remained a relative high throughout the Cretaceous, shielded from rift-related subsidence in the Rockall Basin by the Porcupine High, with only a thin veneer of Lower and Upper Cretaceous sediments deposited throughout the basin.

As rifting in the Rockall Basin ceased towards the end of the Cretaceous, the basin underwent thermal subsidence, with the western margins of the northern Slyne and the Erris basins that had been subject to rift-shoulder uplift now experiencing kilometre-scale subsidence. Post-rift tectonic activity continued throughout the Paleocene, Eocene and Early Miocene, expressed as subtle normal and reverse movement on faults throughout the basins, and in the formation of E-W oriented strike-slip faults, likely related to along-strike movement on major Caledonian crustal lineaments like the Great Glen and Fair Head-Clew Bay lineaments (Cooper et al, 2012; Le Breton et al., 2013; Anderson et al., 2018). The development of the North Atlantic Igneous Province during the mid-Eocene had an impact on the Slyne and Erris basins, with the intrusion of several sills into the Mesozoic basin-fill and the extrusion of thick basaltic lavas of the Druid Formation (Jolley & Bell, 2002). These layered basalt flows are thickest on the western margin of the Southern Slyne Sub-basin, the Northern Slyne Sub-basin and in the

Northern Erris Sub-basin, where they degrade the quality of seismic data beneath these volcanic layers (Dancer & Pillar, 2001).

2.2. Structural Framework & Basin Morphology

The Irish Mainland Shelf separates the Slyne and Erris basins from the island of Ireland to the southeast, while the Rockall Basin bounds the Erris Basin along its north-western margin, with the Slyne and Porcupine highs bounding the Slyne Basin along its western margin (Fig. 1). The Erris Ridge is a NE-SW oriented, discontinuous basement high that separates the Rockall Basin from the Erris Basin and the northern Slyne Basin (Cunningham & Shannon, 1997). The Porcupine Basin is located to the southwest of the Slyne Basin and separated from it by a narrow basement horst.

The present-day morphology of the Slyne and Erris basins is largely controlled by their location on the Irish Continental Shelf and the development of the neighbouring Rockall Basin; the seabed above the Slyne Basin is topographically flat with no bathymetric expression, while the Erris Basin dips westwards along the shelf break into the Rockall Basin. This dip is more subtle in the Northern Erris Sub-basin, where the Erris Ridge is present, and more pronounced in the Southern Erris Sub-basin, beyond the extent of the Erris Ridge. The Erris Basin is transected by several present-day canyon systems that feed into the Rockall Basin from the Irish Mainland Shelf.

The Slyne and Erris basins are transected by several crustal-scale structural lineaments (Fig. 1), representing suture zones and terrane boundaries separating Caledonian and Pre-Cambrian basement terranes that were accreted during the Grenville and Caledonian orogenies (Chew & Stillman, 2009). These structural lineaments trend NE-SW across onshore Ireland, rotating to trend E-W as they continue westwards into the offshore domain (Hutton & Alsop, 1996). Younger Mesozoic rift basins are segmented where the cross these Caledonian lineaments to form sub-basins that exhibit differences in structural style and geology and that are separated by structural complex transfer zones (Fig. 1; Trueblood, 1992; Dancer et al., 1999). The Slyne Basin can be subdivided into three distinct sub-basins, the Southern, Central, and Northern Slyne sub-basins. The offshore extension of the Fair Head-Clew Bay lineament separates the Southern and Central Slyne sub-basins, while the offshore extension of the Great Glen Fault Zone separates the Central and Northern Slyne sub-basins (Fig. 1; Dancer et al., 1999). The Erris Basin has previously been subdivided into three sub-basins based on the predominant dip of the faults in the Mesozoic section (e.g. Chapman et al., 1999); for the purposes of this study the Northern and Central Erris sub-basins of previous literature have been combined.

3. Dataset and Methodology:

This study utilises an extensive, multi-vintage seismic dataset covering the majority of the Slyne and Erris basins as well as extending into neighbouring regions (Fig. 3). The seismic database contains both 2D and 3D seismic reflection data. The 2D database consists of 25 surveys, acquired between 1975 and 2014 that total over 49,000 km in line-length. The 3D database comprises 12 seismic surveys with a total area of over 6000 km^2, although there is a significant area of overlap in the Northern Slyne Sub-basin. Most of the 3D surveys were acquired between 1997 and 2003, with the 1997 Corrib 3D (Dancer & Pillar, 2001) reprocessed in 2006, 2012 and 2018. Seismic quality in the Slyne and Erris basins varies from very poor to good and is dependent on the near-seabed geology. Extensive Eocene volcanics of the Druid Formation extruded during the formation of the North Atlantic Igneous Province, as well as exceptionally hard limestones of the Upper Cretaceous Chalk Group cause widespread imaging problems, principally multiple generation, energy scattering and signal attenuation (Dancer & Pillar, 2001). The volcanics are thickest in the Northern Slyne Sub-basin and the Southern Erris Sub-basin, as well as atop the Erris Ridge, while the Chalk Group is present throughout the Erris Basin and in the Northern Slyne Sub-basin. Seismic resolution varies across the study area due to different frequencies used by individual seismic surveys. In general, the vertical seismic resolution used for identifying salt layers varies between 10-20 m near the seabed to 70-120 m at c. 5 km below the seabed (one-quarter wavelength sensu Brown, 2011). Seismic sections are presented in European polarity (Brown, 2001), where a positive downwards increase in acoustic impedance corresponds to a positive (red) reflection event and a decrease corresponds to a negative (blue) reflection event. All sections are vertically exaggerated by a factor of three. Ball-ends are used to highlight where a fault terminates within a certain stratigraphic package, while faults without ball-ends are truncated by a younger unconformity.

The seismic database was tied to released exploration and production wells and shallow boreholes across the study area. To date, two exploration wells have been drilled in the Erris Basin (19/5-1 and 12/13-1A), while eight exploration wells have been drilled in the Slyne Basin; these include the 18/20-1 Corrib gas discovery well, in addition to four near-field exploration wells in the Northern Slyne Sub-basin (19/8-1, 19/11-1A, 18/20-7, 18/25-2), with a further three exploration wells drilled in the Central Slyne Sub-basin (27/4-1, 27/5-1, 27/13-1). In addition to exploration wells, seven appraisal and production wells from the Corrib gas field are also incorporated into this study. The 27/13-1 well terminated in the Lower Jurassic, five other wells penetrated the Permian (12/13-1A, 19/5-1, 19/8-1, 18/25-2, and 27/5-1), with the remainder terminating in the Lower Triassic.

Exploration wells from neighbouring basins were also included to assess the distribution of salt beyond the boundaries of the Slyne and Erris basins; these include the 12/2-1z and 12/2-2 wells from the Rockall Basin, the 13/3-1 and 13/12-1 wells from the Donegal Basin, and the 26/22-1A, 26/21-1, 26/30-1 and 35/19-1A wells from the Porcupine Basin. The well database is supplemented by three shallow boreholes; a single shallow borehole (11/20-sb01) drilled on the crest of the Erris Ridge (Haughton et al., 2005), and two shallow boreholes (19/13-sb01 and 27/24-sb01) drilled in the Northern and Southern Slyne sub-basins respectively (Fugro, 1994). Data from the deep exploration wells include full suites of wireline logs (caliper, gamma, density, neutron-porosity, resistivity, sonic), biostratigraphically-constrained formation tops, cuttings descriptions, core photos, and time-depth relationships in the form of checkshots or vertical seismic profiles (VSPs). The shallow borehole data include lithological descriptions, formation tops, core photos, and select geochemical and geotechnical samples.

Evaporites in both the Late Triassic and Late Permian sections were identified using a combination of wireline log data, cutting observations taken from both well completion reports and composite logs, and core data, where available. With the relatively limited well database available in the Slyne and Erris basins, the Permian and Late Triassic sections were sub-divided simply; the Permian section was divided into three categories based on the proportion of salt encountered, these being salt-dominated, transitional and clastic-dominated. Salt-dominated sections are composed overwhelmingly of salt lithologies such as halite and anhydrite, while clastic-dominated sections contain only sub-metre stringers of salt lithologies in a background of sandstones, mudstones and carbonates. The transitional category contains salt beds greater than a metre in thickness in a section largely composed of clastic and carbonate lithologies. Stratigraphic sub-division has already been established for the Late Triassic section, this being the presence or absence of the Uilleann Halite Member within the Currach Formation (Fig. 2).

Seismic reflection data were used to map the extent of salt beyond areas where it has been proven in borehole data. Halite mechanically detaches sub- and supra-salt sections, forming distinct décollement surfaces on seismic sections, and can form distinct structures including salt rollers, pillows and diapirs which can be used to indicate the presence of halite in the section of interest (sensu Hudec & Jackson, 2007). Detailed seismic interpretation throughout the Slyne and Erris basins alongside identification of salt-related structures therefore provided a framework for mapping the distribution of both Permian and Triassic salt intervals within the study area.

4. Salt Distribution and Composition:

Two layers of salt have been identified in the Slyne and Erris basins; the Zechstein Group, and the Uillean Halite Member within the Currach Formation. As well penetrations are relatively limited in the Slyne and Erris basins, seismic character was used to constrain the composition of salt-prone intervals away from areas with well-control.

4.1. Zechstein Group

The Zechstein Group has been proven in all five exploration wells that penetrate the pre-Triassic section in the Slyne and Erris basins (12/13-1A, 19/5-1, 19/8-1, 18/25-2, 27/5-1), with variable lithologies encountered (Fig. 4). In the 12/13-1A in the Northern Erris Sub-basin, the Zechstein Group was largely composed of dolomite and anhydritic siltstones, with centimetre-scale stringers of anhydrite encountered throughout the section and reported from sidewall cores (Amoco, 1979). The Zechstein Group encountered in the 19/5-1 well in the Southern Erris Sub-basin and the 19/8-1 well in the Northern Slyne Sub-basin consisted of interbedded brown-red-grey mudstones and grey, microcrystalline dolomite accompanied by metre-scale stringers of anhydrite (Amoco, 1978; StatoilHydro, 2009). In the 18/25-2 well in the Northern Slyne Sub-basin, the Zechstein is composed of massive anhydrite alongside thin layers of microcrystalline dolomite and limestone at the top of the section, and thin layers of red-black mudstone towards the base of the sequence (Enterprise, 2000a). In the 27/5-1 well in the Central Slyne Sub-basin over 150 metres of massive halite was encountered, with thin magnesium salts encountered at the top of the section and interbedded anhydrite and claystone present towards the base of the section (Enterprise, 1996a). A 21-metre core was cut in the halite-prone section in the 27/5-1 well, described as white-pink-orange brittle halite (Fig. 4). These five well penetrations indicate a broad southward increase in the salt content of the Zechstein Group in the Slyne and Erris basins. Sediments belonging to the Zechstein Group may have been encountered at the base of some appraisal and production wells from the Corrib gas field; a mudstone-dominated section with minor anhydrite is present at the base of the Corrib Sandstone Formation in the 18/20-4 and 18/25-3 wells (Enterprise, 2000b, c). However, as these intervals are biostratigraphically barren (P. Copestake, pers. comm.) this remains unproven.

The variation in lithology of the Zechstein Group creates distinct wireline log profiles for both the salt-dominated and salt-poor forms. Salt-dominated sections have a characteristic blocky profile with low gamma ray values and high sonic velocities, while interbedded mudstone- and limestone-prone sections produces a more typical serrated wireline log character, higher gamma ray values and slower sonic velocities (Fig. 4).

When imaged on seismic data, the seismic response of the top Zechstein Group is often determined by the lithology at the base of the overlying Corrib Sandstone Formation. Where the Corrib Sandstone Formation is sandstone dominated towards the base, such as the Northern Slyne Sub-basin, a distinct negative impedance (blue) ‘top-salt’ reflector is observed (e.g. Fig. 5A, B). In areas where there is a greater proportion of mudstone and siltstone towards the base of the Corrib Sandstone Formation, such as the 27/5-1 well in the Central Slyne Sub-basin (Fig. 4), there is a less distinct ‘top-salt’ reflector (e.g. Fig. 6A). The unit itself is characterised by low-amplitude, bedded to chaotic reflectors, while local high-amplitude reflectors are occasionally observed and may represent clastic or carbonate bodies interbedded within halite-dominated areas (Fig. 7), although none of these high-amplitude bodies have been drilled to date. In areas of thinner, clastic-dominated Zechstein Group facies, the Permian section is often only represented by a single seismic wavelet (e.g. 19/5-1 well and seismic wavelet comparison in Figure 4).

Well penetrations and seismic data suggest the proportion of salt within the Zechstein Group decreases northwards, with only sub-metre scale stringers of anhydrite present in the 12/13-1A well, the most northerly in the basin (Fig. 1, 4). Seismic data from the undrilled Southern Erris Sub-basin suggests the presence of a salt-prone Permian section, where a distinct detachment surface is observed beneath the Triassic section.

4.2. Currach Formation & Uilleann Halite Member

The Upper Triassic Currach Formation has been encountered in every well in the Slyne and Erris basins, except the 18/25-2 well where the Upper Triassic succession was faulted out. The formation consists predominantly of red mudstone, locally accompanied by minor siltstone, limestone, dolomite and anhydrite. Towards the base of the formation, a series of metre-scale halite beds is present. In the Northern Slyne and Southern Erris sub-basins, a halite-dominated section, termed the Uilleann Halite Member, is developed at the base of the Currach Formation. This comprises brittle, crystalline white to pinkish grey halite (Enterprise, 1996b). The sediments of the Currach Formation reflect the arid lacustrine and sabkha conditions present in the Slyne and Erris basins during the Early Triassic, while the Uilleann Halite Member is indicative of a marine incursion into the Northern Slyne and Southern Erris sub-basins during the Middle to Late Triassic (Stoker et al., 2017).

The wireline log profiles of the Currach Formation consist of high gamma ray values and high sonic velocities associated with the mudstones that make up the bulk of the formation (Fig. 8). Interbedded siltstones, sandstones and carbonates typically have lower gamma ray values and slightly slower sonic velocities. The Uilleann Halite Member and smaller halite beds at the base of the Currach Formation have very low gamma ray values and high sonic velocities, producing blocky wireline log profiles (Fig. 8). The Uilleann Halite Member is compositionally distinct from the Upper Permian salt, containing significantly more interbedded layers of red mudstone compared to the purer halite section in the Zechstein Group.

The top of the Currach Formation is marked by a high-amplitude soft or blue reflector on seismic data while the base of the formation is marked by a hard or red reflector representing the contact with the underlying Corrib Sandstone Formation (e.g. Fig. 5). The Currach Formation has a predominantly low-amplitude and chaotic seismic facies, with no clear distinction on seismic data with the Uilleann Halite Member. This is demonstrated in Figure 5B where the Upper Triassic section in the 18/20-7 well is predominantly red mudstone with only 13 metres of halite present while the 18/20-3 and 18/20-6 wells drilled a halite section over 600 metres thick (Fig. 8) with little seismic variation between the two well locations.

While the Currach Formation has been proven in every well except 18/25-2 for reasons described above, well data suggest the Uilleann Halite Member is restricted to the Northern Slyne Sub-basin. The Uilleann Halite Member has been proven in the wells associated with the Corrib gas field (blocks 18/20 and 18/25) in addition to 18/20-7, 19/11-1A and 19/8-1. No salt is present in the Currach Formation in either the 12/13-1A or 19/5-1 wells on the margins of the Erris Basin, while only very minor stringers of anhydrite were encountered in the 27/5-1 and 27/4-1 wells in the Central Slyne Sub-basin. The 27/13-1 well terminated at the base of the Lower Jurassic section, while the 27/24-sb02 shallow borehole in the Southern Slyne Sub-basin encountered sub-metre beds of gypsum towards the base of the Currach Formation (Fugro, 1994). Seismic data from the Southern Erris Sub-basin suggests the Uilleann Halite Member extends northwards into this part of the basin, with two detachment surfaces visible; the lower detachment occurring on the salt of the Zechstein Group, while the upper detachment occurs within the Uilleann Halite Member.

4.3. Other salt-prone intervals in the Slyne & Erris basins

In addition to the Permian and Triassic salt present in the Slyne and Erris basins, several metres of anhydrite are interbedded with the sandstones, mudstones and limestones of the Lower Jurassic Meelagh Formation (Fig. 2). This anhydrite is developed in the Northern and Central Slyne sub-basins, with beds up to 20 metres thick encountered throughout the Meelagh Formation in the 18/20-1 well (Enterprise, 1996b), but thinning northwards, with no salt observed in the 19/11-1A well (Statoil, 2004). Only sub-metre-scale anhydrite stringers are recorded in the 19/8-1 well in the Northern Slyne Sub-basin, as well as the 19/5-1 and 12/13-1A wells in the Erris Basin (Amoco, 1978; Amoco, 1979; StatoilHydro, 2009). The

Meelagh Formation was deposited in an arid climate (Merlin Energy Resources Consortium, 2020), with the rapid vertical variation in facies representing an unstable and variable marginal marine to marine environment. Like the salt-prone intervals in the Zechstein Group and Uilleann Halite Member, the anhydrite beds within the Meelagh Formation have very low gamma-ray values and high sonic velocities on wireline logs. There is no evidence of mechanical detachment on the anhydrite beds of the Meelagh Formation seen on seismic sections from the Slyne and Erris basins, although it is possible that local, sub-seismic bed-parallel slip has occurred where these evaporites are present.

Within the Visean section of the 19/5-1 well in the Erris Basin, a sidewall core and cuttings at 2141 metres Measured Depth (mMD) are described as claystones containing stringers of white anhydrite (Amoco, 1978). Gypsum has been encountered onshore Ireland in the equivalent section in the Lough Allen Basin (Ambassador, 1962; Grennan, 1992). While this section was only reached in a single well in the Erris Basin, it indicates the presence of salt-prone strata at four discrete stratigraphic levels (Carboniferous, Upper Permian, Upper Triassic, and Lower Jurassic) in the Slyne and Erris basins.

5. Salt structures in the Slyne and Erris basins

In areas of sparse well control, evidence of salt-related structures is supported by the identification of characteristic features on seismic data. The distribution and types of salt structures observed within the Slyne and Erris basins varies significantly between different sub-basins. This section analyses several of these structures and their implications for understanding salt composition and distribution.

5.1. Southern and Central Slyne Sub-basins

In the south of the study area only the Zechstein Group is salt prone, whereas the Uilleann Halite Member is not developed within the Currach Formation. In this area the Zechstein Group acts as a décollement between the pre-salt basement and the post-salt Mesozoic section. The Southern and Central Slyne sub-basins are two contiguous half-graben which dip steeply westwards towards the basin-bounding fault running along their western margins, across which they are downthrown relative to the Porcupine High. The Central Slyne Sub-basin is downthrown relative to the Southern Slyne Sub-basin across the offshore extension of the Highland Boundary-Fair Head Clew Bay Lineament (Fig. 1).

In the Southern Slyne Sub-basin, a single, relatively large salt roller is identified in the centre of the sub-basin (Fig. 7). The Triassic, Lower Jurassic and Middle Jurassic sections dip more steeply north-westwards than both the underlying Carboniferous basement and the overlying Upper Jurassic section, with the Base Upper Jurassic Unconformity eroding the crest of the structure.

In the Central Slyne Sub-basin there are several high-relief, broadly anticlinal structures in the immediate hanging-wall of the bounding fault along the western margin of the basin (Fig. 6). While ostensibly similar, each structure exhibits subtle variations in geometry and composition. The Triassic to Middle Jurassic section penetrated in the 27/4-1 well in the immediate hanging-wall of the bounding fault was encountered at similar depths in the 27/5-1 well on the eastern margin of the Central Slyne Sub-basin (Fig. 6A). The Upper Jurassic section onlaps the steeply dipping eastern flank of the 27/4-1 structure, consistent with a predominately Late Jurassic age for the basin-bounding fault. The Upper Jurassic section also thickens eastwards into the hanging-wall of a major listric fault (Fig. 6A), indicating that movement on this fault occurred in tandem with the basin-bounding fault. The southern-most hanging-wall structure (Fig. 6B) is another high-relief anticlinal closure, with the Lower and Middle Jurassic section adjacent to the bounding-fault at a similar depth to the same section on the eastern margin of the basin. There is a distinct rotation of the Lower and Middle Jurassic section facilitated by a detachment surface above the Triassic, suggesting the presence of halite within the Currach Formation at this location.

Between these two high-relief structures there is a relative saddle abutting the basin-bounding fault, forming a gently dipping dome. A distinct angular unconformity is observed beneath the Upper Jurassic section (Fig. 6C) which is not observed at the crests of the structures along-strike (Fig. 6A & B). Correlation from the 27/4-1 well indicates that the Middle Jurassic Kite Group and a significant portion of the Lower Jurassic Lias Group, down to the Pabay Formation, are absent from the crest of this saddle (Fig. 6C), while being preserved along-strike at the higher relief 27/4-1 location (Fig. 6A). This indicates that this location was at a higher relief relative to the present-day high-relief structures to the north and south during the period of uplift and erosion that preceded Oxfordian rifting. This elevated area was likely to have been cored by a gentle salt pillow before the emergence of the basin-bounding fault. As the main phase of rifting initiated during the Oxfordian, the structures to the north and south of this small salt pillow began to form, evidenced by onlap onto their flanks by the Upper Jurassic section in this part of the basin.

Similar to the structure shown in Fig. 6C, a significant section of the Middle and Lower Jurassic stratigraphy has been eroded from the eastern margin of the Central Slyne Sub-basin. The Kite Group and part of the Lias Group, down to the Pabay Formation, are absent beneath the base-Upper Jurassic unconformity in the 27/5-1 well while being present in the 27/4-1 well (Fig. 6A). The base-Upper Jurassic unconformity is encountered at a relatively similar depth present-day in both wells, 700 mMD and 845 mMD respectively (Merlin Energy Resources Consortium, 2020), while having significantly different subcrops, highlighting the variation in Zechstein Group salt topography during different extensional episodes.

The Central Slyne Sub-basin likely represents the erosional remnants of a significantly wider basin that included the Slyne Embayment and a smaller disconnected half-graben to the west of the Central Slyne Sub-basin (Fig. 1, 6A). The Slyne Embayment has a similar sedimentary fill to that of the Central Slyne Sub-basin, with the Triassic and Jurassic sections overlying a salt-prone Zechstein Group (Fig. 6A). Kilometre-scale erosion of the Jurassic section during the Cretaceous and Cenozoic (Dancer et al., 1999; Biancotto et al., 2007) is interpreted to have isolated the Slyne Embayment from the Central Slyne Sub-basin by eroding the footwall of the bounding fault along the western margin of the Central Slyne Sub-basin (Fig. 6A).

5.2. Northern Slyne Sub-basin

Several salt-cored folds are observed in the Northern Slyne Sub-basin, typically oriented NE-SW and NNE-SSW, parallel to the syn-rift faults. Composed of Zechstein salt, these pillows are between 5 to 15 kilometres in length and up to 10 kilometres wide, often flanked by salt withdrawal synclines which likely developed by salt movement into the pillows (Fig. 5). The folded Mesozoic stratigraphy above these salt pillows has been the target of several exploration wells in this part of the basin, including the 18/20-1 (Corrib), 18/20-7 and 19/11-1A wells (Fig. 5B, C). Changes in the thickness of the Jurassic section in the flanking synclines indicate that the polarity of these salt pillows varied during basin evolution. The Lower and Middle Jurassic section in the syncline to the NW of the Corrib anticline is thicker than the syncline to the SE, while a thicker Upper Jurassic section is observed in the SE syncline relative to the NW (Fig. 5B).

Several of these salt-cored folds have large delamination faults above their crests which sole out into the Uilleann Halite Member at the base of the Currach Formation. These faults are parallel to the axes of the salt-cored folds and are likely to have developed in tandem with the pillows of Permian salt, representing outer-arc extension and gravitational collapse at the apex of the salt-cored folds. These delamination faults are often accompanied by the formation of salt rollers in their footwalls (Fig. 5A, B), in addition to faulted rollovers in their hanging-walls.

These delamination faults have been reactivated at several stages during the Cretaceous and Cenozoic post-rift period; significant growth sequences in the Cretaceous section are observed in the hanging-walls of these large delamination faults, particularly in the Lower Cretaceous Spurdog Formation (Fig. 5A, B). The delamination faults also offset the top of the Druid Formation lavas and a portion of the overlying Cenozoic sediments, which are dated as 40-43 Ma in the 18/20-1 well (Dancer et al., 1999). The lack of folding in this Cretaceous and Cenozoic section indicates the later fault movement is more likely related to continued growth of the Upper Triassic salt roller rather than growth of the underlying Permian salt pillows and associated salt-cored folds.

5.3. Southern Erris Sub-basin

The Southern Erris Sub-basin dips steeply north-westwards as a result of post-rift thermal subsidence in the neighbouring Rockall Basin during the Cenozoic (Fig. 9-12). The western margin of the Erris Basin experienced significant rift-shoulder uplift during the Cretaceous, related to rifting in the Rockall Basin, with a kilometre-scale section of Jurassic stratigraphy removed. This part of the Erris Basin is dominated by a series of closely spaced (c. 1-2 km separation) westward-dipping faults in the Jurassic section (Fig. 9). Previous authors had interpreted these faults as through-going basement-linked structures (e.g. Shannon & Naylor, 1998; Chapman et al., 1999; Corfield et al., 1999). However more recent seismic profiles reveal their listric nature, with many faults detaching on the Uilleann Halite Member above closely spaced salt rollers (e.g. Fig. 9). The Zechstein Group also acted as a décollement in this part of the basin, mechanically detaching the Corrib Sandstone Formation from the underlying Carboniferous basement. Salt pillows formed in the Zechstein Group and folded the overlying Corrib Sandstone Formation in a similar manner to those in the Northern Slyne Sub-basin (Fig. 5)

More faults are through-going across the Permian section in the Southern Erris Sub-basin than in the Slyne Basin, suggesting that the Zechstein Group in this part of the basin may contain a greater proportion of clastic lithologies. The proportion of salt decreases towards the eastern margin of the Erris Basin, with faults being hard-linked through the Mesozoic and Palaeozoic sections (Fig. 10). Only a thin layer of anhydrite was encountered in the 19/5-1 well drilled on the eastern edge of the Southern Erris Sub-basin (Fig. 4).

5.4. Northern Erris Sub-Basin

The Northern Erris Sub-basin is an asymmetric graben, bounded along its eastern margin by the Irish Mainland Shelf, and separated from the Rockall Basin to the west by the narrow, elongate Erris Ridge. The single well (12/13-1A) drilled in this part of the basin encountered only sub-metre-scale stringers of anhydrite in a 19 m thick Zechstein Group section, while no evaporite lithologies were present in the Currach or Meelagh formations. There is little evidence on seismic sections to indicate the presence of significant thicknesses of salt in this part of the basin, with all clearly imaged faults hard-linked through the Zechstein Group with little evidence for growth sequences in the pre-Triassic sections (Fig. 11, 12).

There is similarly scarce evidence for salt in neighbouring areas; both wells in the Donegal Basin to the northeast, 13/3-1 and 13/12-1 (Fig. 1), encountered the Pennsylvanian Blackthorn Group directly beneath the Base-Cenozoic Unconformity (Texaco, 1978; Lundin, 2006), while the 12/2-1 and 12/2-2 wells in the Rockall Basin to the west encountered the Triassic Cot Sandstone Formation (lateral equivalent to the Corrib Sandstone Formation) and Upper Jurassic Dawros Formation respectively lying directly above the Pennsylvanian Sorrel Group, with no Permian, Upper Triassic or Lower Jurassic sediment encountered (Merlin Energy Resources Consortium, 2020).

6. Discussion:

6.1. Timing and drivers of halokinesis in the Slyne and Erris basins

Understanding the timing of salt movement during basin development is important both for unravelling the structural evolution and for understanding the development of the petroleum system. There is evidence of halokinesis occurring at several stages during basin evolution, including during both the Early to Middle Jurassic and Late Jurassic phases of rifting, in addition to post-rift modification of salt structures during the Cretaceous and Cenozoic.

In the Southern Slyne Sub-basin, the Triassic and Lower Jurassic section tilted above the large Zechstein Group salt roller is truncated by the Base Upper Jurassic unconformity (Fig. 7). This suggests that inflation of the salt roller in the footwall of the fault began forming during the Early-Middle Jurassic before the crest was eroded, resulting in the angular unconformity, followed by further inflation during Late Jurassic rifting (Fig. 13). In the Central Slyne Sub-basin growth sequences are observed in the Lower Jurassic section in the hanging walls of small intra-basinal listric faults which sole out in the Upper Permian Zechstein Group (Fig. 6). The faults controlling these growth sequences are then truncated by the Base Upper Jurassic Unconformity, indicating discrete extension confined to the Early-Middle Jurassic. There is further evidence of Early Jurassic halokinesis in the Northern Slyne Sub-basin with subtle thinning of the Lower Jurassic section onto the crest of the Corrib anticline (Fig. 5B), indicating that the Zechstein Group salt pillow was creating relief during the Early Jurassic (Fig. 13). Faults of a similar age are also interpreted in the Southern Erris Sub-basin, where faults which sole out above rollers of Uilleann Halite are truncated by the Base Upper Jurassic Unconformity. Several of these faults have hanging-wall sequences that record limited growth during the Early Jurassic (Fig. 9) and were reactivated during the main phase of rifting during the Late Jurassic and subsequently truncated by the Base-Cretaceous Unconformity.

The main phase of rifting in the Slyne and Erris basins, during the Late Jurassic, was preceded by the formation of the regional Base Upper Jurassic Unconformity mentioned previously (Fig. 13). The majority of intra-basinal faulting during this time occurred as thin-skinned, basement-detached deformation (Figs 5-7, 9) apart from in the Northern Erris Sub-basin where the Uilleann Halite Member is absent and the Zechstein Group is composed of carbonates and clastics (Fig. 11 & 12). In the Central Slyne Sub-basin growth sequences (Fig. 6A) and onlap (Fig. 6B) are observed on the flanks of the high-relief structures in the immediate hanging-wall of the basin-bounding fault. Unlike other high-relief structures where distinct crestal erosion is recorded at the Base Upper Jurassic Unconformity, these structures likely emerged during Late Jurassic basin extension (Fig. 13). Their geometry, as well as the likely presence of salt in the Slyne Embayment to the west, indicate that these structures may have formed as forced folds above the active footwall of the basin-bounding fault, creating the topography for onlap and growth sequences (e.g. Withjack & Callaway, 2000; Coleman et al., 2017). The interpretation of salt in the undrilled Slyne Embayment to the west of the Central Slyne Sub-basin (Fig. 6A), further supports the idea that Permian salt and the overlying Mesozoic section may have overstepped the now eroded footwall of the bounding fault before kilometre-scale uplift and erosion during the Cretaceous and Cenozoic (Fig. 6A).

Along-strike variation in the anticlinal structures adjacent to the bounding fault in the Central Slyne Sub-basin suggests there may be more complexity to their evolution beyond a breached salt-detached monocline. Dancer et al. (1999) suggested five potential mechanisms for the formation of the structure targeted by the 27/4-1 well (Fig. 6A), with one being salt diapirism. Crucially, that paper predated the acquisition of good-quality 3D seismic data (2000) and the drilling of the 27/4-1 well (2009), datasets which highlight the modification of these structures during basin evolution. Specifically, the preservation of the Middle and Lower Jurassic section proven in the 27/4-1 well, combined with the absence of the Kite Group and Dun Caan Shale and Whitby Mudstone formations along-strike (Fig. 6C), highlights the modification of structures during basin evolution, with the eroded crest of the structure in Fig. 6C being over 600ms TWT (c. 1200m) deeper than the seemingly uneroded crest of the structure in Fig. 6A. This evidence suggests there may have been a high-relief salt-cored structure during the Early and Middle Jurassic at the location of Fig. 6C, possibly a salt pillow or a large salt roller similar to that imaged in Fig. 7 which exhibits comparable crestal erosion. This salt pillow or salt roller collapsed during the Late Jurassic rifting with along-strike migration of the Permian salt into the present-day higher elevation structures. As the apparent volume of salt present between these anticlinal closures and the basin-bounding fault is relatively small, salt may also have been extruded into salt diapirs on the now eroded footwall of the basin bounding fault.

Several salt structures in the Slyne Basin underwent significant post-rift modification during the Cretaceous and Cenozoic, driven by rifting in the Rockall Basin during the Cretaceous, and subsequent Cenozoic post-rift thermal subsidence, mid-Atlantic ridge-push and the development of the Icelandic plume (Dancer et al., 1999). There is evidence throughout the Slyne and Erris basins of fault reactivation, with several of these reactivations occurring in salt-prone areas where the faults are listric and sole out in either the Zechstein Group or the Uilleann Halite Member (Fig. 6 & 9). Other structures appear not to have been reactivated during this post-rift activity (e.g. Fig. 7), although the lack of Cretaceous sediments in the Central and Southern Slyne Sub-basins means that any fault movement during this phase of post-rift deformation is not recorded. This Cretaceous and Cenozoic reactivation is subtle, with movement on reactivated faults being in the order of 10s of metres, much lower than the syn-rift fault offsets which are in the order of several hundred metres to kilometres in scale.

Regional extension is recognised as a common mechanism for the initiation of salt tectonics (Jackson & Vendeville, 1994; Jackson & Hudec, 2017b) and is the most likely trigger for halokinesis in the Slyne and Erris basins. The seismic data analysed above indicates that there were two main phases of syn-rift halokinesis in the Slyne and Erris basins; the first of these occurred during Early to Middle Jurassic extension with a subsequent phase of salt movement during Late Jurassic rifting. Some salt structures formed during the first phase of halokinesis were reactivated and continued to grow during the Late Jurassic period of salt movement (e.g. Fig. 5-7), while others collapsed during this second phase of rifting (e.g. Fig. 6C). It is also possible that other structures such salt diapirs formed above the footwalls of active faults due to extrusion of salt from collapsed structures which were subsequently eroded during Cretaceous uplift. Several salt-related structures underwent minor modification during post-rift tectonic activity in the Cretaceous and Cenozoic.

6.2. Kinematic interaction between salt layers

In the Northern Slyne and Southern Erris sub-basins, two distinct layers of autochthonous salt are present at different stratigraphic intervals, which has previously been termed ‘double-decker’ salt tectonics (Corcoran & Mecklenburgh, 2005). In these areas a clear relationship between the timing of halokinesis in each layer can be observed. The most well imaged of these is the structure containing the Corrib gas field, where two discrete salt-related structures are visible: a Zechstein Group salt pillow and an Uilleann Halite Member salt wall (Fig. 5B). These structures have parallel trends, oriented NE-SW (Fig. 5D). The Uilleann Halite diapir has a distinct pointed crest, indicating it is likely to be a reactive diapir which formed during delamination faulting of the Jurassic overburden. As the Zechstein salt pillow grew and folded the overlying Triassic and Jurassic section, outer-arc extension triggered listric delamination faulting in the Jurassic section at the crest of the fold, with these faults soling out in the Uilleann Halite (Fig. 13). The throw on these delamination faults is greatest at the apex of the Zechstein salt pillow and resultant Lower Triassic fold, where outer-arc extension facilitates the inflation of an Uilleann Halite salt roller (Fig. 5A) or in the case of the Corrib structure, a reactive diapir oriented parallel to the fold axis of the salt pillow (Fig. 5B, D).

While the Zechstein salt pillow controlled the initial evolution of the Uilleann Halite diapir, the subsequent growth of this diapir during continued extension may have in turn influenced the development of the salt pillow. As regional extension continued during the Late Jurassic, the delamination fault above the Corrib anticline experienced further normal movement. This fault movement displaced the overburden section downwards off the crest of the anticline, creating thicker sedimentary sections in the flanking synclines (Fig. 5B) while reducing the sediment thickness at the apex of the fold. These thicker sedimentary sections on the flanks of the anticline are suggested to have inflated the Zechstein salt pillow further through differential loading, creating a steeper structure which would then lead to further movement on the crestal delamination fault. The delamination fault above the Corrib gas field was reactivated again during the Cretaceous and the Cenozoic, with distinct growth sequences observed in the Cretaceous section in the immediate hanging-wall of the delamination fault (Fig. 5B), which also offsets the top of the Druid Formation volcanics. This volcanic sequence is dated between 54.3 and 40 Ma (early-mid Eocene) in the 18/20-1 well and the 19/13-sb02 shallow borehole in the Northern Slyne Sub-basin (Fugro, 1994; Corcoran & Mecklenburgh, 2005), indicating how recently this Permian-Triassic salt relationship was active. A similar relationship likely drove the syn- and post-rift evolution of other salt pillow and diapir pairs observed in the Northern Slyne and Southern Erris sub-basins (e.g. Fig. 5A, 9).

Previous structural models for the Corrib structure (e.g. Corcoran & Mecklenburgh, 2005; Dancer et al., 2005) have suggested a polarity reversal in the delamination fault at different stages of basin evolution, with an initial westward-dipping fault plane during the Early Jurassic changing to the dominant eastward-dipping fault observed today during the Late Jurassic. A thinner Lower and Middle Jurassic section encountered on the eastern flank of the anticline was interpreted as the eroded footwall of the westward-dipping fault relative to the thicker section observed on the western flank (Fig. 5B). Recent biostratigraphic analysis has revealed that complete Lias Group and Kite Group sections have been encountered in all wells drilled in the Corrib gas field, with an attenuated but complete section encountered in the Lower and Middle Jurassic on the eastern flank of the anticline (Merlin Energy Resources Consortium, 2020). This attenuated section was likely deposited on the crest of a salt-cored fold during the Early and Middle Jurassic and is commonly observed above salt pillows (Jackson & Hudec, 2017a). Significant heave on the delamination fault during the Late Jurassic moved the attenuated crestal section of Lower and Middle Jurassic sediments eastwards down the flank of the anticline. It is therefore more likely that the delamination fault above the Corrib salt-cored fold is a largely Late Jurassic structure which downthrows to the southeast. The polarity reversal of faults above salt walls is a common feature of mature halokinetic structures (e.g. Quirk & Pilcher, 2012) but due to the relative immaturity of the Upper Triassic salt wall a simpler structural model prevails. Polarity reversal is observed in thickness variations in the synclines flanking the Corrib anticline, with thicker Lower and Middle Jurassic section in the NW syncline and a thicker Upper Jurassic section in the SE syncline. This reversal is likely a result of the emergence of the kilometre-scale faults bounding the eastern margin of the Northern Slyne Sub-basin during the Late Jurassic.

The kinematic interaction of stratigraphically discrete salt layers observed in the Slyne and Erris basins may act as a structural template for other basins which have multiple thin layers of salt (Fig. 13). Examples include the Sole Pit Basin and Danish Central Graben in the North Sea, where delamination faults sole out in the Triassic Muschelkalk Halite above folds cored by Zechstein Group salt (Glennie, 1997; Hansen et al., 2020).

6.3. Relationship between timing of halokinesis and the petroleum system

The timing of formation and subsequent modification of the Corrib structure played a crucial role in both the success and failure of the 18/20-1 discovery well. The well was drilled to the northwest of the main delamination fault, passing through the tilted fault block above the Uilleann Halite diapir (Fig. 5B, D). The well encountered oil-stained sandstones throughout the Upper Jurassic section, evidence of a breached paleo-accumulation, before discovering the gas accumulation in the Corrib Sandstone Formation, sealed by the Uilleann Halite Member (Enterprise, 1996b; Dancer et al., 2005). Geochemical fingerprinting of these hydrocarbon fluids indicates that the oil is sourced from the Lower Jurassic Whitby Mudstone, Pabay Shale and Dun Caan Shale formations while the gas is presumed to be generated by coal layers in the Carboniferous basement (Dancer et al., 1999; Scotchman et al., 2018). Post-rift movement on the main delamination fault bounding the Jurassic structural trap (Fig. 5D) during both the Cretaceous (Fig. 5D) and Cenozoic (Fig. 5B) post-dates the main phase of hydrocarbon generation and migration at the end of the Jurassic (Petroleum Affairs Division, 2005). This late movement on the delamination fault likely caused cross-fault juxtaposition of Upper Jurassic sandstones, possible dilation of the fault plane and breaching of the top seal, leading to the loss of the oil accumulation. However, since the delamination fault soles out in the Uilleann Halite Member, this post-charge fault movement did not interact with the Corrib Sandstone Formation and the gas accumulation.

Similarly, post-rift modification of the underlying Zechstein Group salt pillow may explain the nature of the Corrib anticlinal trap. The anticline is significantly underfilled, with potential associated mechanisms including the presence of a small leaking fault at the current gas-water contact or leakage through the sealing Uilleann Halite Member during Cretaceous and Cenozoic exhumation (Corcoran & Doré, 2002; Corcoran & Mecklenburgh, 2005). The modest overpressure within the reservoir section (Corcoran & Doré, 2002) and halite composition of the top-seal indicate that the original charge pre-dating exhumation is preserved and that leakage without clear evidence of salt-welding is difficult. Salt tectonics may instead be responsible for the underfilled nature of the Corrib anticline, with post-rift movement on the delamination fault and growth of the Uilleann Halite Member diapir perhaps driven by post-rift growth of the Zechstein Group salt pillow. Additional post-rift (and post-charge) growth of this salt pillow would have increased the vertical relief of the anticline and its trap capacity. The volume of the structural trap from the Late Cretaceous onwards would therefore be larger than the volume of gas trapped during the Late Jurassic and Early Cretaceous, resulting in its underfilled nature observed at present. This highlights the multiphase evolution of this and probably other structures within the Slyne and Erris basins and illustrates how understanding their structural history will be critical to improving exploration success in the future.

6.4. The Slyne and Erris basins in context with other salt-prone basins of the North Atlantic

Results presented thus far have highlighted the importance of salt during the structural evolution of the Slyne and Erris basins and defined a range of structures that are characteristic of salt-involved deformation in this area. By applying a similar methodology to that demonstrated above, we can delimit the occurrence of salt in neighbouring basins where the lack of well data has made interpretation of salt more speculative. A more detailed understanding of salt distribution can in turn be used to refine paleogeographic models for the Late Permian and Late Triassic of the Irish Atlantic margin.

6.4.1. Irish Atlantic Margin

No Permian rocks have been encountered outside of the Slyne and Erris basins on the Irish Atlantic margin to date, although Permian ages have been suggested for a sandstone section encountered above the Carboniferous in the 12/2-1 and 12/2-2 wells on the eastern margin of the Rockall Basin, adjacent to the northern Erris Basin (Shell, 2009; Tyrrell et al., 2010). Conversely, Early and Late Triassic-aged sections have been proven in several basins, including the Porcupine and Celtic Sea basins.

In the North Porcupine Basin metre-scale anhydrite layers were encountered towards the top of the Currach Formation in well 26/22-1A (BP, 1979), while the 35/19-1A well encountered 24m of allochthonous salt in Upper Jurassic sediments on the eastern margin of the Porcupine Basin (Britoil, 1986). In this well the salt is composed of massive halite with thin slivers of red mudstone likely representing rafted sections of Currach Formation mudstones, suggestive of Upper Triassic salt, equivalent to the Uilleann Halite Member in the Slyne and Erris basins. As an Uilleann Halite Member equivalent has not been encountered in the northern Porcupine Basin to date, this Triassic salt is likely to have migrated from a more central, undrilled part of the basin to the south.

The Goban Spur Basin, along the southern margin of the Porcupine Basin (Fig. 1), may also contain Triassic salt, with evidence on seismic data of décollement surfaces and salt pillows beneath the Base-Cretaceous Unconformity (Fig. 14). A pronounced fold occurring above near-horizontal, unfolded reflectors (Fig. 14) is interpreted as local Lower Triassic sediments deposited within the Variscan fold and thrust belt but since the single well drilled in the Goban Spur Basin terminated in Lower Jurassic sediments, this interpretation remains speculation (Colin et al., 1992).

Previous authors have noted décollement surfaces in the perched basins along the margins of the Irish sector of the Rockall Basin, including the Bróna and Fursa basins on the eastern margin (Thomson & McWilliam, 2001; Štolfová & Shannon, 2009) and the Conall and Rónán basins on the north-western margin (Corfield et al., 1999; Walsh et al., 1999). Distinct detachment horizons are visible on seismic data from these basins, with faults observed soling out in these horizons. In the Rónán Basin on the western margin of the Rockall Basin, a subtle décollement is visible within the steeply dipping reflectors, mechanically detaching faults above and below it, with a distinct local thickening along the south-eastern margin of the basin interpreted as a salt pillow (Fig. 15A). Similarly, two distinct sets of faults are observed either side of a décollement in the Fursa Basin (Fig. 15B). While these basins are undrilled at present, these décollement surfaces likely represent lateral equivalents to Permian salt proven in the Slyne Basin, as interpreted by Štolfová & Shannon (2009). In these basins this layer of salt plays a similar role in mechanically detaching the Mesozoic basin fill, which displays similar seismic facies to those observed in the Slyne and Erris basins, from the Palaeozoic basement.

6.4.2. Neighbouring basins on the European Atlantic margin

The basins of the Irish Atlantic margin belong to a chain of basins that extend along the European Atlantic margin, many of which also contain significant salt deposits that correlate with those proven in the Slyne and Erris basins. Directly north of the study area, a series of interconnected basins off the north-western coast of the UK contain significant thicknesses of sediments defined broadly as Permo-Triassic due to the relative lack of biostratigraphic control (Steel & Wilson, 1975; Hitchen et al., 1995). Both wells drilled in the West Orkney Basin encountered several hundred metres of halite interbedded with sandstones and mudstones with anhydrite stringers belonging to the West Orkeny Evaporite Formation interpreted as being Permian in age and representing Zechstein Group equivalents (Elf, 1991; Hitchen et al., 1995; McKie, 2017). Along-strike in the West Shetland Basin the 205/27a-1 well encountered interbedded Upper Permian sandstones and mudstones with anhydrite stringers (Hitchen et al., 1995). There is little evidence of salt in the Upper Triassic section in this region, instead being dominated by sandstone (Swiecicki *et al.* 1995).

6.4.3. Implications for the Permian & Triassic paleogeography of the Irish Atlantic margin

Paleogeographic reconstructions of north-western Europe during the Permian and Triassic often present the Irish Atlantic margin in simplified terms at the fringes of regional maps, owing to the relative lack of well penetrations and published data when compared with neighbouring regions. The Early Triassic is an exception, due to its significance in the petroleum system of the Corrib gas field (Dancer et al., 2005), with a relatively well understood paleogeography in which the Slyne and Erris basins are host to southwards-verging braided fluvial systems (e.g. Tyrell et al., 2007; McKie & Williams, 2009; Franklin et al., 2019). No Early Permian rocks have been encountered on the Irish Atlantic margin to date. Existing paleogeographic reconstructions (e.g. Doré, 1991; Knott et al., 1993; McKie & Shannon, 2011; McKie, 2017; Scotese & Schettino, 2017) present the Irish Atlantic margin as the terminus of tortuous seaways that extended into the Pangean supercontinent; During the Late Permian ingress of marine waters came from the Boreal Ocean to the north through the West of Shetland region, but during the Late Triassic a seaway extended from the Tethys Ocean to the southeast across Central and Western Europe to reach Ireland through the Cheshire Basin in the UK. Using the results presented in this study as well as the speculative interpretations of neighbouring regions discussed above, it is possible to refine existing paleogeographic models of the region during the Late Permian and Late Triassic, and include the basin-specific detail for the Irish Atlantic margin that was absent in previous regional syntheses.

The distribution of Late Permian salt of both the UK and Norwegian North Sea has been interpreted to be fault controlled, with salt-prone lithologies deposited in the hanging walls of active faults, while marginal carbonate and siliciclastic facies accumulated on basin margins and intra-basinal highs. The exact age of faulting remains ambiguous, with the Late Permian bathymetry either being inherited from Early Permian rifting, or representing syn-depositional extension in the Late Permian (e.g. McKie & Shannon, 2011; Jackson & Lewis, 2016; Jackson et al., 2019). Applying a similar model to the Slyne and Erris basins, the thicker salt-prone Zechstein Group in the Slyne Basin and the Southern Erris Sub-basin would be indicative of active Permian faulting, while the presence of thin marginal deposits in the Northern Erris Sub-basin suggests this area was a relative high with little active faulting. Therefore, the marine pathway connecting the Slyne Basin to the Boreal Ocean likely traversed an area other than the Erris Basin, an interpretation supported by the lack of Permian sediments in the north-eastern Irish Rockall Basin, the Donegal Basin and the Sea of the Hebrides Basin. The layers of salt interpreted in the Rónán Basin, the pre-Cretaceous 'conjugate margin' to the Erris Basin (Fig. 15A), might therefore indicate that the route of active Permian rifting may have been an anastomosing series of rifts extending northwards along the axis of a proto-Rockall and West of Shetland rift system, with remnants of these basins occupying the margins of the Rockall Basin after rifting and hyperextension in the Cretaceous (Fig. 16A). This may indicate that the framework for the present-day configuration of rift basins on the Irish Atlantic margin may have been established in-part during this period of Permian extension.

During the Late Triassic, the Northern Slyne and Southern Erris sub-basins may have also been the terminus for a seaway, this time stretching from the Tethys Ocean to the southwest. The Uilleann Halite Member in the Northern Slyne and Southern Erris sub-basins (Fig. 1, 8) likely represents the deposits of incursions of marine brines from the southwest. In neighbouring regions such as the Ulster Basin and the Irish Sea basins several discrete layers of halite are interpreted as successive marine flooding events into these regions (Jackson & Mulholland, 1993; Dunford et al., 2001; McKie, 2017). The Uilleann Halite Member might therefore represent the deposits of a more extensive marine incursion that extended beyond those found in the Irish Sea and North Channel region. The exact route of marine ingress is uncertain and likely obscured by Cretaceous and Cenozoic erosion, but may have come from the south, through the Celtic Sea and Porcupine basins (e.g. Scotese & Schettino, 2017), or from the north or east through the Donegal Basin or the Ulster-Larne Basin (e.g. Naylor, 1992). The paleogeography of the Late Triassic salt layers is distinct from the Late Permian as these marine incursions flood a predominantly arid lacustrine environment, represented by the thick red mudstones which dominate the majority of the Currach Formation (Fig. 8), which differs from the predominantly marine environment of the Zechstein Group deposits, represented by cleaner halite with few mudstone inclusions (Fig. 4). Additionally, the Triassic was a period of tectonic quiescence on the Irish Atlantic margin following Permian rifting (e.g. Tyrrell et al., 2007; Franklin et al., 2019) and Late Triassic sediments likely spilled out beyond the present-day basin boundaries (Fig. 16B), with their present-day distribution a product of preservation in post-Triassic rift basins.

7. Conclusions

Using a combination of 2D and 3D seismic, wireline, and core data, this study investigated the distribution of the salt in the Slyne and Erris basins and its influence on the structural evolution of these basins.

1. Two main salt-prone intervals are present in the Slyne and Erris basins. The Upper Permian Zechstein Group is salt prone throughout the Slyne Basin and in the Southern Erris Sub-basin, becoming dominated by carbonates and clastics in the Northern Erris Sub-basin. The Upper Triassic Uilleann Halite Member is developed in the Northern Slyne Basin and Southern Erris sub-basins.
2. Salt acts as a décollement and mechanically detaches distinct sections of stratigraphy within the Slyne and Erris basins. The Zechstein Group has the largest impact on basin development and is a regional décollement surface, with most syn-rift normal faults detached from the pre-Permian basement along this surface. The Uilleann Halite Member exerts similar controls on basin development where it is present.
3. Halokinesis occurred at several stages during the evolution of the Slyne and Erris basins. This includes extension in the Early Jurassic and the Late Jurassic, as well as post-rift reactivation during the Cretaceous and Cenozoic. This salt movement has created a variety of relatively immature salt-related structures throughout the Slyne and Erris basins, including salt pillows, rollers and reactive diapirs.
4. Where both salt successions are developed, the topography created by the Zechstein Group halokinesis influences the development of salt-related structures in the overlying Uilleann Halite Member, exemplified in the parallel salt pillow and salt wall pair observed in the Corrib structure. Outer-arc extension and gravitational collapse linked with the formation of the Zechstein Group salt pillows leads to the formation of Uilleann Halite salt rollers and walls. This kinematic interaction may serve as a framework for the structural evolution of similar structures in other basins with multiple stratigraphically discrete layers of salt.
5. An improved understanding of the distribution and composition of Permian and Triassic salt in the Slyne and Erris basins and in undrilled basins along the Irish Atlantic margin indicates that the framework of sedimentary basins along the Irish Atlantic margin may have been established as early as the Late Permian.

References

Alves, T.M., Moita, C., Sandnes, F., Cunha, T., Monteiro, J.H. & Pinheiro, L.M. 2006. Mesozoic-Cenozoic evolution of North Atlantic continental-slope basins: The Peniche basin, western Iberian margin. *AAPG Bulletin*, **90**, 31–60.

Ambassador 1962. Dowra No. 1 Well Report. Ambassador Irish Oil Company.

Amoco 1978. Well 19/5-1 Geological Completion Report. Amoco Ireland Exploration Company, compiled by Odell, R.T. & Thomas, I.W.

Amoco 1979. Wells 12/13-1 and 12/13-1A Geological Completion Report. Amoco Ireland Exploration Company, compiled by Odell, R.T. & Walker, D.

Anderson, H., Walsh, J.J. & Cooper, M.R. 2018. The development of a regional-scale intraplate strike-slip fault system; Alpine deformation in the north of Ireland. *Journal of Structural Geology*, **116**, 47–63.

Biancotto, F., Hardy, R.J.J., Jones, S.M., Brennan, D. & White, N.J. 2007. Estimating denudation from seismic velocities offshore NW Ireland. *Society of Exploration Geophysicists - 77th SEG International Exposition and Annual Meeting, SEG 2007*, 407–411.

BP 1979. Ireland, Porcupine Basin Well 26/22-1A Geological Completion Report. BP Petroleum Development Ltd. (Irish Branch), compiled by Dryden, G.J.

Britoil 1986. Eire Licence 1/82 evaluation of well 35/19-1. Britoil plc, compiled by Harvey, M. A. & Wild, J. L.

Brown, A.R. 2001. Calibrate yourself to your data! A vital first step in seismic interpretation. *Geophysical Prospecting*, **49**, 729–733.

Brown, A.R. 2011. *Interpretation of Three-Dimensional Seismic Data*. Society of Exploration Geophysicists & American Association of Petroleum Geologists.

Chapman, T.J. 1989. The Permian to Cretaceous structural evolution of the Western Approaches Basin (Melville sub-basin), UK. *Geological Society, London, Special Publications*, **44**, 177–200.

Chapman, T.J., Broks, T.M., Corcoran, D.V., Duncan, L.A. & Dancer, P.N. 1999. The structural evolution of the Erris Trough, offshore northwest Ireland , and implications for hydrocarbon generation. *Petroleum Geology of Northwest Europe: Proceedings of the 5th Conference*, 455–469.

Chew, D.M. & Stillman, C.J. 2009. Late Caledonian orogeny and magmatism. *In*: *The Geology of Ireland*. 143–173.

Coleman, A.J., Jackson, C.A.L. & Duffy, O.B. 2017. Balancing sub- and supra-salt strain in salt-influenced rifts: Implications for extension estimates. *Journal of Structural Geology*, **102**, 208–225.

Colin, J.-P., Ioannides, N.S. & Vining, B. 1992. Mesozoic stratigraphy of the Goban Spur, offshore south-west Ireland. *Marine and Petroleum Geology*, **9**, 527–541.

Cooper, M.R., Anderson, H., Walsh, J.J., Van Dam, C.L., Young, M.E., Earls, G. & Walker, A. 2012. Palaeogene Alpine tectonics and Icelandic plume-related magmatism and deformation in Northern Ireland. *Journal of the Geological Society*, **169**, 29–36.

Corcoran, D. V & Doré, A.G. 2002. Depressurization of hydrocarbon-bearing reservoirs in exhumed basin settings: evidence from Atlantic margin and borderland basins. *Exhumation of the North Atlantic Margin: Timing, Mechanisms and Implications for Petroleum Exploration*, **196**, 457–483.

Corcoran, D. V & Mecklenburgh, R. 2005. Exhumation of the Corrib Gas Field, Slyne Basin, offshore Ireland. *Petroleum Geoscience*, **11**, 239–256.

Corfield, S., Murphy, N. & Parker, S. 1999. The structural and stratigraphic framework of the Irish Rockall Trough. *Geological Society, London, Petroleum Geology Conference series*, **5**, 407–420.

Coward, M.P. 1995. Structural and tectonic setting of the Permo-Triassic basins of northwest Europe. *Geological Society, London, Special Publications*, **91**, 7–39.

Cunningham, G.A. & Shannon, P.M. 1997. The Erris Ridge: A major geological feature in the NW Irish Offshore Basins. *Journal of the Geological Society*, **154**, 503–508.

Croker, P.F. and Shannon, P.M. 1987. The evolution and hydrocarbon prospectivity of the Porcupine Basin, Offshore Ireland. *Petroleum Geology of Northwest Europe*, **3**, 633–642.

Dancer, P.N., Algar, S.T. & Wilson, I.R. 1999. Structural evolution of the Slyne Trough. *Petroleum Geology of Northwest Europe: Proceedings of the 5th Conference on the Petroleum Geology of Northwest Europe*, **1**, 445–454.

Dancer, P.N. & Pillar, N.W. 2001. Exploring in the Slyne Basin: a geophysical challenge. *The Petroleum Exploration of Ireland's Offshore Basins*, **188**, 209–222.

Dancer, P.N., Kenyon-Roberts, S.M., Downey, J.W., Baillie, J.M., Meadows, N.S. & Maguire, K. 2005. The Corrib gas field, offshore west of Ireland. *Geological Society, London, Petroleum Geology Conference series*, **6**, 1035–1046.

Deptuck, M.E. & Kendell, K.L. 2017. A Review of Mesozoic-Cenozoic Salt Tectonics Along the Scotian Margin, Eastern Canada. *In*: *Permo-Triassic Salt Provinces of Europe, North Africa and the Atlantic Margins*. Elsevier, 287–312.

Doré, A. 1991. The structural foundation and evolution of Mesozoic seaways between Europe and the Arctic. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **87**, 441–492.

Doré, A.G., Lundin, E.R., Jensen, L.N., Birkeland, O., Eliassen, P.E. & Fichler, C. 1999. Principal tectonic events in the evolution of the northwest European Atlantic margin. *Petroleum Geology of Northwest Europe: Proceedings of the 5th Conference*, 41–61.

Duffy, O.B., Gawthorpe, R.L., Docherty, M. & Brocklehurst, S.H. 2013. Mobile evaporite controls on the structural style and evolution of rift basins: Danish Central Graben, North Sea. *Basin Research*, **25**, 310–330.

Dunford, G.M., Dancer, P.N. & Long, K.D. 2001. Hydrocarbon potential of the Kish Bank Basin: integration within a regional model for the Greater Irish Sea Basin. *Geological Society, London, Special Publications*, **188**, 135–154.

Elf 1991. Final Well Report 202/18-1. Elf Enterprise Caledonia Ltd.

Enterprise 1996a. Well IRE 27/5-1 Geological Completion Report. Enterprise Oil plc, compiled by Rawlinson, A., Verlander, J., Scotchman, I. & Henderson, G.

Enterprise 1996b. IRE 18/20-1 Geological Completion Report. Enterprise Oil plc, compiled by O'Neill, N., Scotchman, I. & Dancer, N.

Enterprise 2000a. Well IRE 18/25-2 Geological Completion Report. Enterprise Oil plc, compiled by Pay, M. & Geerlings, P.

Enterprise 2000b. Well IRE 18/20-3 Geological Completion Report. Enterprise Oil plc, compiled by Pay, M. & Geerlings, P.

Enterprise 2000c. Well IRE 18/20-4 Geological Completion Report. Enterprise Oil plc, compiled by Pay, M. & Geerlings, P.

Ferrer, O., Jackson, M.P.A., Roca, E. & Rubinat, M. 2012. Evolution of salt structures during extension and inversion of the Offshore Parentis Basin (Eastern Bay of Biscay). *Geological Society Special Publication*, **363**, 361–380.

Franklin, J., Tyrrell, S., Morton, A., Frei, D. & Mark, C. 2019. Triassic sand supply to the Slyne Basin, offshore western Ireland – new insights from a multi-proxy provenance approach. *Journal of the Geological Society*, **176**, 1120–1135.

Fugro. 1994. Field Report Irish Frontier Shallow Coring Project Blocks 19/13 and 27/24 Irish Sector Atlantic Ocean (Volume I).

Gardiner, P.R.R. & Visscher, H. 1971. Permian–Triassic Transition Sequence at Kingscourt, Ireland. *Nature Physical Science*, **229**, 209–210.

Gardiner, P.R.R. & McArdle, P. 1992. The geological setting of Permian gypsum and anhydrite deposits in the Kingscourt district, counties Cavan, Meath and Monaghan. *The Irish minerals industry*, 1980 – *1990,* 301-316

Gerlings, J., Hopper, J.R., Fyhn, M.B.W. & Frandsen, N. 2017. Mesozoic and older rift basins on the SE Greenland Shelf offshore Ammassalik. *Geological Society Special Publication*, **447**, 375–392.

Glennie, K.W., 1997. History of exploration in the southern North Sea. *Geological Society, London, Special Publications*, **123**, 5-16.

Grennan, E. 1992. The Glangevlin gypsum deposit, Co. Cavan. *The Irish minerals industry*, 1980 - *1990*, 317-325.

Hansen, T. H., Clausen, O. R., & Andresen, K. J. (in review) 2020. Thick- and thin-skinned basin inversion in the Danish Central Graben, North Sea – the role of deep evaporites and basement kinematics. *Solid Earth Discuss*. https://doi.org/10.5194/se-2020-127

Haughton, P., Praeg, D., Shannon, P., Harrington, G., Higgs, K., Amy, L., Tyrrell, S. & Morrissey, T. 2005. First results from shallow stratigraphic boreholes on the eastern flank of the Rockall Basin, offshore western Ireland. *Geological Society, London, Petroleum Geology Conference series*, **6**, 1077–1094.

Hitchen, K., Stoker, M.S., Evans, D. & Beddoe-Stephens, B. 1995. Permo-Triassic sedimentary and volcanic rocks in basins to the north and west of Scotland. *Geological Society, London, Special Publications*, **91**, 87–102.

Hudec, M.R. & Jackson, M.P.A. 2007. Terra infirma: Understanding salt tectonics. *Earth-Science Reviews*, **82**, 1–28.

Hutton, D.H.W. & Alsop, G.I. 1996. The Caledonian strike-swing and associated lineaments in NW Ireland and adjacent areas: sedimentation, deformation and igneous intrusion patterns. *Journal of the Geological Society*, **153**, 345–360.

Illing, L. V & Griffith, A.E. 1986. Gas Prospects in the 'Midland Valley' of Northern Ireland. *Geological Society, London, Special Publications*, **23**, 73–84.

Jackson, C.A.L. & Lewis, M.M. 2016. Structural style and evolution of a salt-influenced rift basin margin; the impact of variations in salt composition and the role of polyphase extension. *Basin Research*, **28**, 81–102.

Jackson, C.A.-L. & Stewart, S.A. 2017. Composition, Tectonics, and Hydrocarbon Significance of Zechstein Supergroup Salt on the United Kingdom and Norwegian Continental Shelves. *In*: *Permo-Triassic Salt Provinces of Europe, North Africa and the Atlantic Margins*. Elsevier, 175–201.

Jackson, C.A.L., Elliott, G.M., Royce-Rogers, E., Gawthorpe, R.L. & Aas, T.E. 2019. Salt thickness and composition influence rift structural style, northern North Sea, offshore Norway. *Basin Research*, **31**, 514–538.

Jackson, D.I. & Mulholland, P. 1993. Tectonic and stratigraphic aspects of the East Irish Sea Basin and adjacent areas: contrasts in their post-Carboniferous structural styles. *Geological Society, London, Petroleum Geology Conference series*, **4**, 791–808.

Jackson, M.P.A. & Vendeville, B.C. 1994. Regional extension as a geologic trigger for diapirism. *Geological Society of America Bulletin*, **106**, 57–73.

Jackson, M.P., & Hudec, M.R. 2017a. *Salt tectonics: Principles and practice*. Cambridge University Press. 62-75.

Jackson, M.P., & Hudec, M.R. 2017b. *Salt tectonics: Principles and practice*. Cambridge University Press. 256-303.

Jansa, L.F., Bujak, J.P. & Williams, G.L. 1980. Upper Triassic salt deposits of the western North Atlantic. *Canadian Journal of Earth Sciences*, **17**, 547–559.

Jolley, D.W. & Bell, B.R. 2002. The evolution of the North Atlantic Igneous Province and the opening of the NE Atlantic rift. *Geological Society, London, Special Publications*, **197**, 1–13.

Knott, S.D., Burchell, M.T., Jolley, E.J. & Fraser, A.J. 1993. Mesozoic to Cenozoic plate reconstructions of the North Atlantic and hydrocarbon plays of the Atlantic margins. *Petroleum Geology of Northwest Europe: Proceedings of the 4th Conference*, 953–974.

Le Breton, E., Cobbold, P.R. & Zanella, A. 2013. Cenozoic reactivation of the Great Glen Fault, Scotland: additional evidence and possible causes. *Journal of the Geological Society*, **170**, 403–415.

Lundin 2006. Well 13/12-1 Inishbeg Prospect End of Well Report. Lundin Britain Ltd., compiled by Craig, D. & Welding, P.

McCann, N. 1988. An Assessment of the Subsurface Geology between Magilligan Point and Fair Head, Northern Ireland. *Irish Journal of Earth Sciences*, **9**, 71–78.

McKie, T. & Shannon, P.M. 2011. Comment on ‘The Permian-Triassic transition and the onset of Mesozoic sedimentation at the northwestern peri Tethyan domain scale: Palaeogeographic maps and geodynamic implications’ by S. Bourquin, A. Bercovici, J. López-Gomez, J. B. Diez, J. Broutin, A. . *Palaeogeography, Palaeoclimatology, Palaeoecology*, **311**, 136–143.

McKie, T. 2017. Paleogeographic Evolution of Latest Permian and Triassic Salt Basins in Northwest Europe. *In*: *Permo-Triassic Salt Provinces of Europe, North Africa and the Atlantic Margins*. Elsevier, 159–173.

Merlin Energy Resources Consortium. 2020. The Standard Stratigraphic Nomenclature of Offshore Ireland: An Integrated Lithostratigraphic, Biostratigraphic and Sequence Stratigraphic Framework. Project Atlas. Petroleum Affairs Division, Department of the Environment, Climate and Communications, Special Publication **1/21**.

Naylor, D. & Shannon, P., 1982. Geology of offshore Ireland and west Britain.

Naylor, D., Shannon, P.M. and Murphy, N. 1999. *Irish Rockall Basin Region - a Standard Structural Nomenclature System*. Petroleum Affairs Division, Department of the Environment, Climate and Communications, Special Publication **1/99**.

Naylor, D. 1992. The post-Variscan history of Ireland. *Geological Society, London, Special Publications*, **62**, 255–275, https://doi.org/10.1144/GSL.SP.1992.062.01.21.

Naylor, D., Haughey, N., Clayton, G. & Graham, J.R. 1993. The Kish Bank Basin, offshore Ireland. *Petroleum Geology of Northwest Europe: Proceedings of the 4th Conference*, **4**, 845–855, https://doi.org/10.1144/0040845.

Pena dos Reis, R., Pimentel, N., Fainstein, R., Reis, M. & Rasmussen, B. 2017. Influence of Salt Diapirism on the Basin Architecture and Hydrocarbon Prospects of the Western Iberian Margin. *In*: *Permo-Triassic Salt Provinces of Europe, North Africa and the Atlantic Margins*. Elsevier, 313–329.

Petroleum Affairs Division. 2005. *Petroleum Systems Analysis of the Slyne, Erris and Donegal Basins Offshore Ireland - Digital Atlas*. Petroleum Affairs Division, Department of the Environment, Climate and Communications, Special Publications **1/05**.

Quinn, M.F., Smith, K. & Bulat, J. 2010. A Geological Interpretation of the Nearshore Area between Belfast Lough and Cushendun, Northern Ireland, Utilising a Newly Acquired 2D Seismic Dataset to Explore for Salt Layers for Possible Gas Storage within Man-Made Caverns*. British Geological Survey Commissioned Report CR/10/069*.

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

Ramos, A., Fernández, O., Muñoz, J.A. & Terrinha, P. 2017. Impact of basin structure and evaporite distribution on salt tectonics in the Algarve Basin, Southwest Iberian margin. *Marine and Petroleum Geology*, **88**, 961–984.

Robinson, K.W., Shannon, P.M. & Young, D.G.G. 1981. The Fastnet Basin: An Integrated Analysis. *In*: Illing, L. V. and Hobson, G. D. (eds) *Petroleum Geology of the Continental Shelf of North-West Europe*.

Rojo, L.A., Cardozo, N., Escalona, A. & Koyi, H. 2019. Structural style and evolution of the Nordkapp Basin, Norwegian Barents Sea. *AAPG Bulletin*, **103**, 2177–2217.

Schiffer, C., Doré, A.G., Foulger, G.R., Franke, D., Geoffroy, L., Gernigon, L., Holdsworth, R.E., Kusznir, N., Lundin, E., McCaffrey, K., Peace, A.L., Petersen, K.D., Phillips, T.B., Stephenson, R., Stoker, M.S. & Welford J.K. 2019. Structural inheritance in the North Atlantic. *Earth-Science Reviews*, 102975.

Scotchman, I.C., Doré, A.G. & Spencer, A.M. 2018. Petroleum systems and results of exploration on the Atlantic margins of the UK, Faroes & Ireland: what have we learnt? *Geological Society, London, Petroleum Geology Conference series*, **8**, 187–197, https://doi.org/10.1144/PGC8.14.

Scotese, C.R. & Schettino, A. 2017. Late Permian-Early Jurassic Paleogeography of Western Tethys and the World. *In*: *Permo-Triassic Salt Provinces of Europe, North Africa and the Atlantic Margins*. Elsevier, 57–95.

Shannon, P.M. 1991. Tectonic framework and petroleum potential of the Celtic Sea, Ireland. *First Break*, **9**, https://doi.org/10.3997/1365-2397.1991006.

Shannon, P.M. & Naylor, D. 1998. An assessment of Irish offshore basins and petroleum plays. *Journal of Petroleum Geology*, **21**, 125–152.

Shell 2009. IRE 12/2-1 West Dooish Exploration Well End of Well Report – Volume 2 Subsurface Section. Shell E&P Ireland Ltd.

Statoil 2004. Well 19/11-1 & 1A Final Well Report. Statoil Exploration (Ireland) Ltd., compiled by Hofsøy, R., Skagen, J., Mortensen, H. & Conroy, J.

StatoilHydro 2009. Well 19/8-1 Cashel Prospect End of Well Report. Statoil Exploration (Ireland) Ltd., compiled by MacTiernan, B., Kleppa, S., Hunnes, O., Sigve-Selnes, K. & Igbineweka, O.J.

Stewart, S.A., Harvey, M.J., Otto, S.C. & Weston, P.J. 1996. Influence of salt on fault geometry: examples from the UK salt basins. *Geological Society, London, Special Publications*, **100**, 175–202.

Stewart, S.A. 2007. Salt tectonics in the North Sea Basin: a structural style template for seismic interpreters. *Geological Society, London, Special Publications*, **272**, 361–396.

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

Štolfová, K. & Shannon, P.M. 2009. Permo-Triassic development from Ireland to Norway: basin architecture and regional controls. *Geological Journal*, **44**, 652–676.

Steel, R.J. & Wilson, A.C. 1975. Sedimentation and tectonism (?Permo-Triassic) on the margin of the North Minch Basin. *Journal of the Geological Society*, **131**, 183–200.

Swiecicki, T., Wilcockson, P., Canham, A., Whelan, G. & Homann, H. 1995. Dating, correlation and stratigraphy of the Triassic sediments in the West Shetlands area. *Geological Society Special Publication*, **91**, 57–85.

Tate, M.P. & Dobson, M.R. 1989. Late Permian to early Mesozoic rifting and sedimentation offshore NW Ireland. *Marine and Petroleum Geology*, **6**, 49–59.

Texaco 1978. Well 13/3-1 Final Geological Report. Texaco Ireland Ltd., compiled by Stuart, I.A.

Thomson, A. & McWilliam, A. 2001. The structural style and evolution of the Bróna Basin. *Geological Society, London, Special Publications*, **188**, 401–410.

Trueblood, S. and Morton, N. 1991. Comparative Sequence Stratigraphy and Structural Styles of the Slyne Trough and Hebrides Basin. *Journal of the Geological Society*, **148**, 197–201, https://doi.org/10.1144/gsjgs.148.1.0197.

Trueblood, S. 1992. Petroleum geology of the Slyne Trough and adjacent basins. *Geological Society Special Publication*, 315–326.

Tyrrell, S., Haughton, P.D.W. & Daly, J.S. 2007. Drainage reorganization during breakup of Pangea revealed by in-situ Pb isotopic analysis of detrital K-feldspar. *Geology*, **35**, 971–974.

Tyrrell, S., Souders, A.K., Haughton, P.D.W., Daly, J.S. & Shannon, P.M. 2010. Sedimentology, sandstone provenance and palaeodrainage on the eastern Rockall Basin margin: evidence from the Pb isotopic composition of detrital K-feldspar. *Geological Society, London, Petroleum Geology Conference series*, **7**, 937–952.

Van Hoorn, B. 1987. The south Celtic Sea/Bristol Channel Basin: origin, deformation and inversion history. *Tectonophysics*, **137**, https://doi.org/10.1016/0040-1951(87)90325-8.

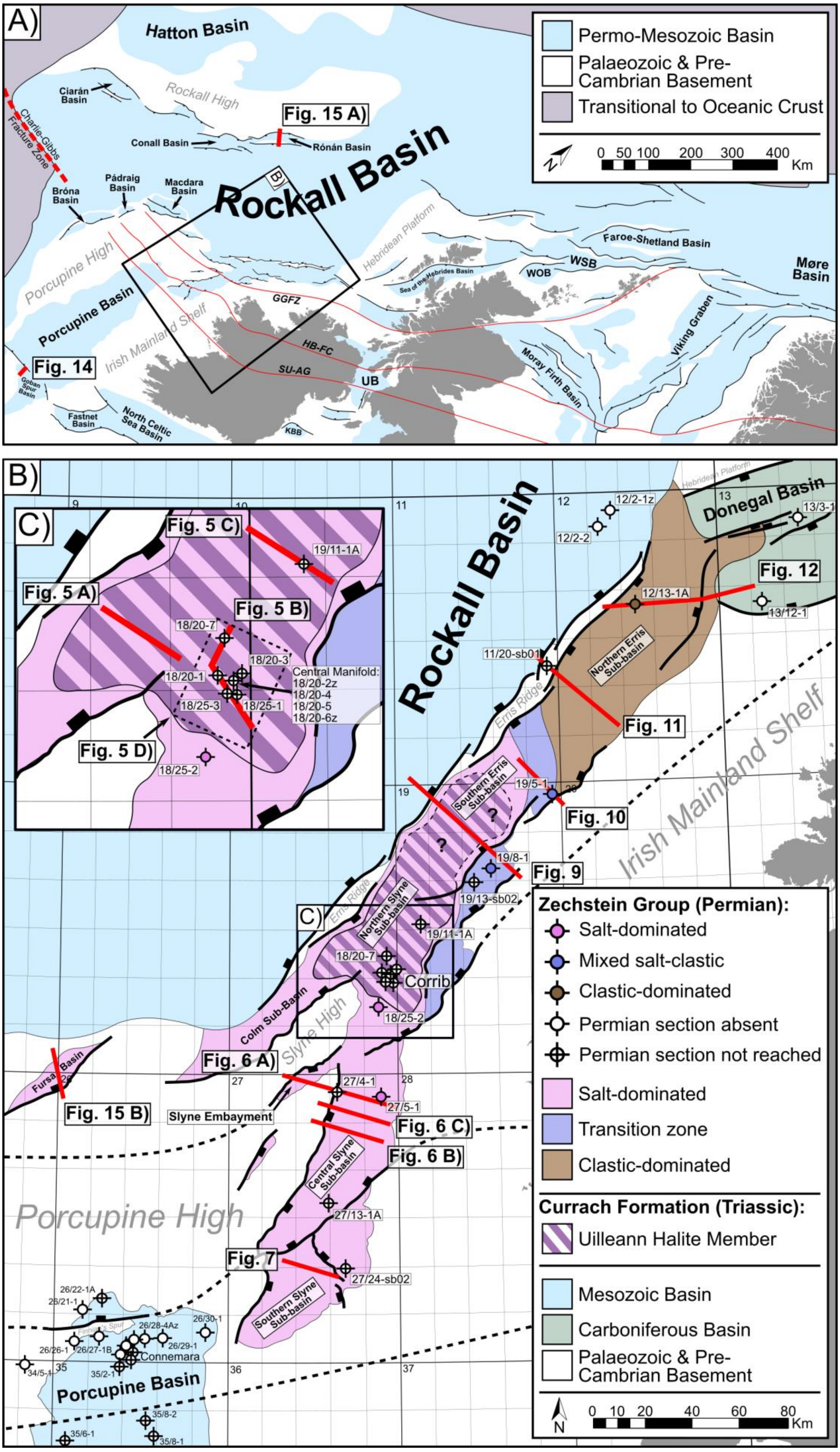
Walsh, A., Knag, G., Morris, M., Quinquis, H., Tricker, P., Bird, C. & Bower, S. 1999. Petroleum geology of the Irish Rockall Trough – a frontier challenge. *Petroleum Geology of Northwest Europe: Proceedings of the 5th Conference*, 433–444.

Wilson, R.C.L., Hiscott, R.N., Willis, M.G. & Gradstein, F.M. 1989. The Lusitanian Basin of west-central Portugal: Mesozoic and Tertiary tectonic, stratigraphic, and subsidence history. *Extensional tectonics and stratigraphy of the North Atlantic margins*, 341–361.

Withjack, M.O. & Callaway, S. 2000. Active normal faulting beneath a salt layer: An experimental study of deformation patterns in the cover sequence. *AAPG Bulletin*, **84**, 627–651.

Zamora, G., Fleming, M. & Gallastegui, J. 2017. Salt Tectonics Within the Offshore Asturian Basin. *In*: *Permo-Triassic Salt Provinces of Europe, North Africa and the Atlantic Margins*. Elsevier, 353–368.

Figure Captions



A)
Hatton Basin
Rockall High
Ciarán Basin
Fig. 15 A)
Conall Basin
Rónán Basin
Charlie-Gibbs Fracture Zone
Rockall Basin
Bróna Basin
Pádraig Basin
Macdara Basin
B)
Porcupine High
Hebridean Platform
Faroe-Shetland Basin
WSB
WOB
Møre Basin
Sea of the Hebrides Basin
Porcupine Basin
GGFZ
Irish Mainland Shelf
HB-FC
SU-AG
UB
Viking Graben
Moray Firth Basin
Fig. 14
Goban Spur Basin
Fastnet Basin
North Celtic Sea Basin
KBB
Permo-Mesozoic Basin
Palaeozoic & Pre-Cambrian Basement
Transitional to Oceanic Crust
0 50 100 200 300 400 Km
B)
C)
Fig. 5 C)
19/11-1A
Fig. 5 A)
Fig. 5 B)
18/20-7
18/20-3
18/20-1
Central Manifold: 18/20-2z 18/20-4 18/20-5 18/20-6z
18/25-3
18/25-1
Fig. 5 D)
18/25-2
Rockall Basin
Hebridean Platform
Donegal Basin
12/2-1z
12/2-2
13/3-1
Fig. 12
12/13-1A
13/12-1
11/20-sb01
Northern Erris Sub-basin
Erris Ridge
Fig. 11
Irish Mainland Shelf
Southern Erris Sub-basin
19/5-1
Fig. 10
19/8-1
Fig. 9
19/13-sb02
Northern Slyne Sub-basin
19/11-1A
18/20-7
Corrib
18/25-2
Colm Sub-Basin
Slyne High
Fursa Basin
Fig. 15 B)
Fig. 6 A)
27/4-1
27/5-1
Slyne Embayment
Fig. 6 C)
Fig. 6 B)
Central Slyne Sub-basin
Porcupine High
27/13-1A
Fig. 7
27/24-sb02
Southern Slyne Sub-basin
26/22-1A
26/21-1
26/30-1
26/28-4Az
26/26-1
26/27-1B
26/29-1
Connemara
34/5-1
35/2-1
Porcupine Basin
35/8-2
35/6-1
35/8-1
Zechstein Group (Permian):
Salt-dominated
Mixed salt-clastic
Clastic-dominated
Permian section absent
Permian section not reached
Salt-dominated
Transition zone
Clastic-dominated
Currach Formation (Triassic):
Uilleann Halite Member
Mesozoic Basin
Carboniferous Basin
Palaeozoic & Pre-Cambrian Basement
0 10 20 40 60 80 Km

Figure 1: A) *Map showing the location of the study area and other Permo-Mesozoic basins along the north-western European Atlantic margin, adapted from Doré et al. (1999) and Naylor et al. (1999). Caledonian structural lineaments which segment the basins are highlighted in red.* ***Abbreviations:*** *GGFZ – Great Glen Fault Zone; HB-FC – Highland Boundary-Fair Head-Clew Bay Lineament; KBB – Kish Bank Basin; SU-AG – Southern Uplands-Antrim-Galway Lineament; UB – Ulster Basin; WOB – West Orkney Basin; WSB – West Shetland Basin.* ***B)*** *Map showing the distribution of Permian and Triassic salt throughout the Slyne and Erris basins and neighbouring basins. Faults are displayed at Top Permian offset.* ***C)*** *Map showing distribution of salt in the Northern Slyne Sub-basin.*

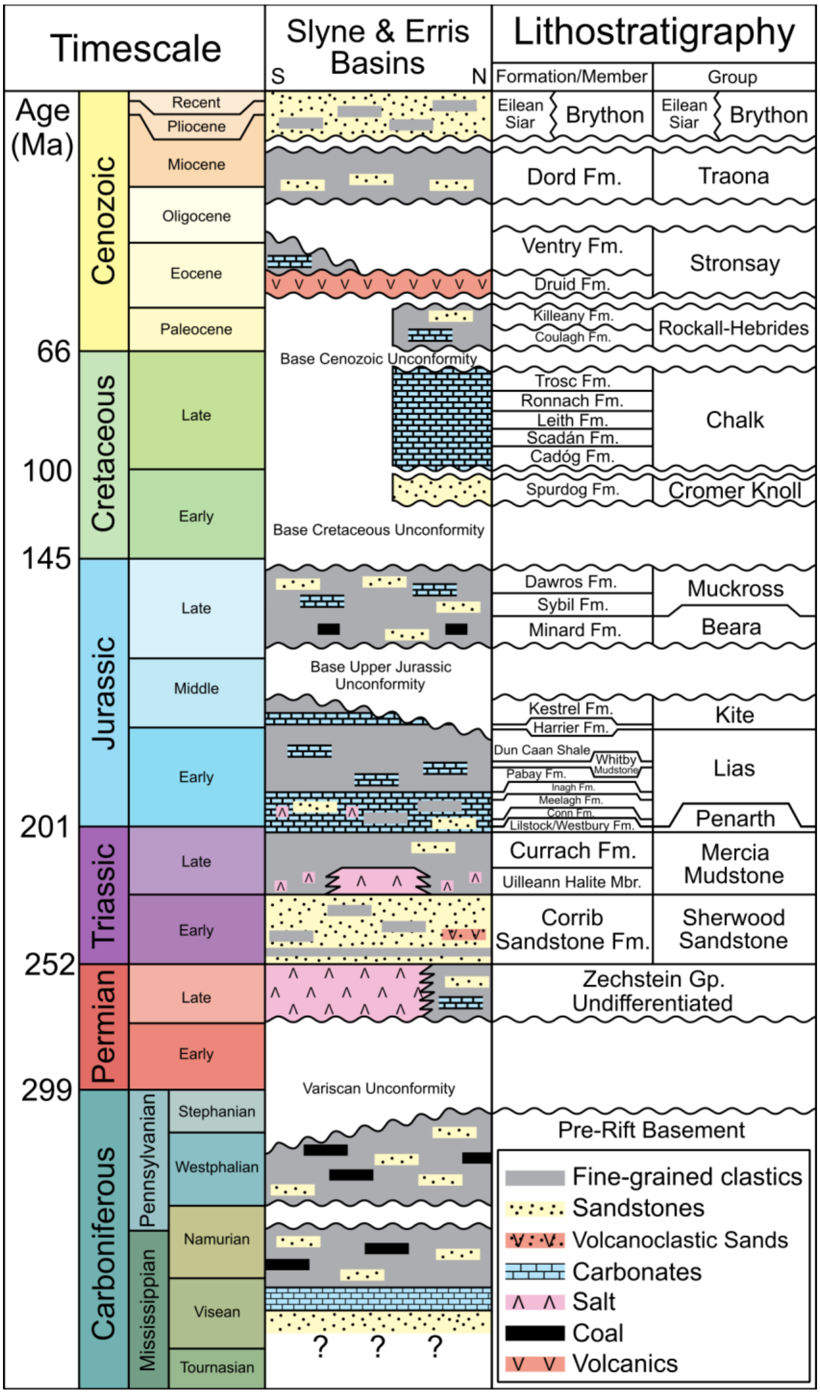


Figure 2: *Simplified chronostratigraphic chart for the Slyne and Erris basins. Lithostratigraphic nomenclature adapted from Merlin Energy Resources Consortium (2020).*

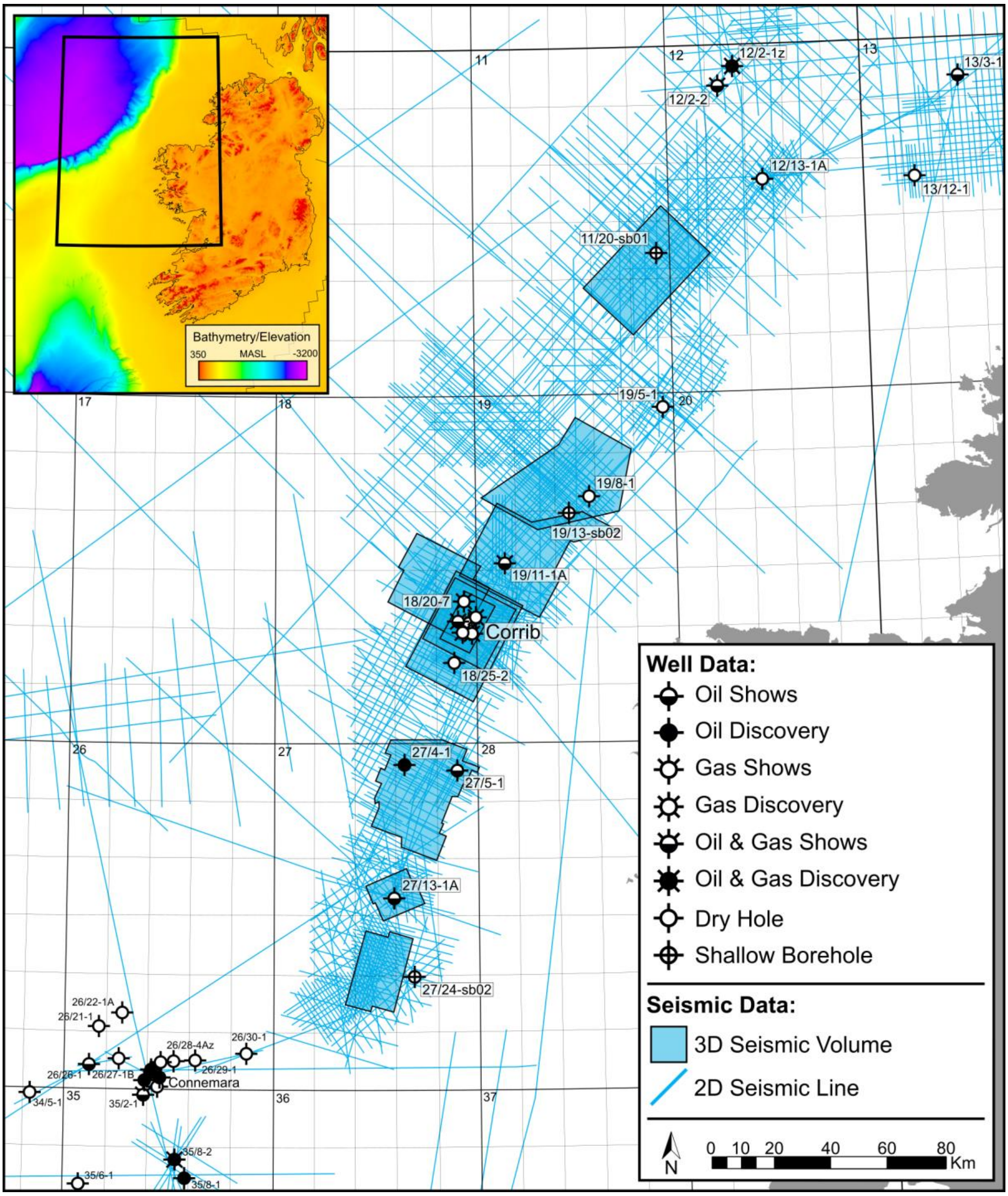


Figure 3: *Map showing study area and datasets used.* ***Inset Map:*** *Bathymetry of the study area.*

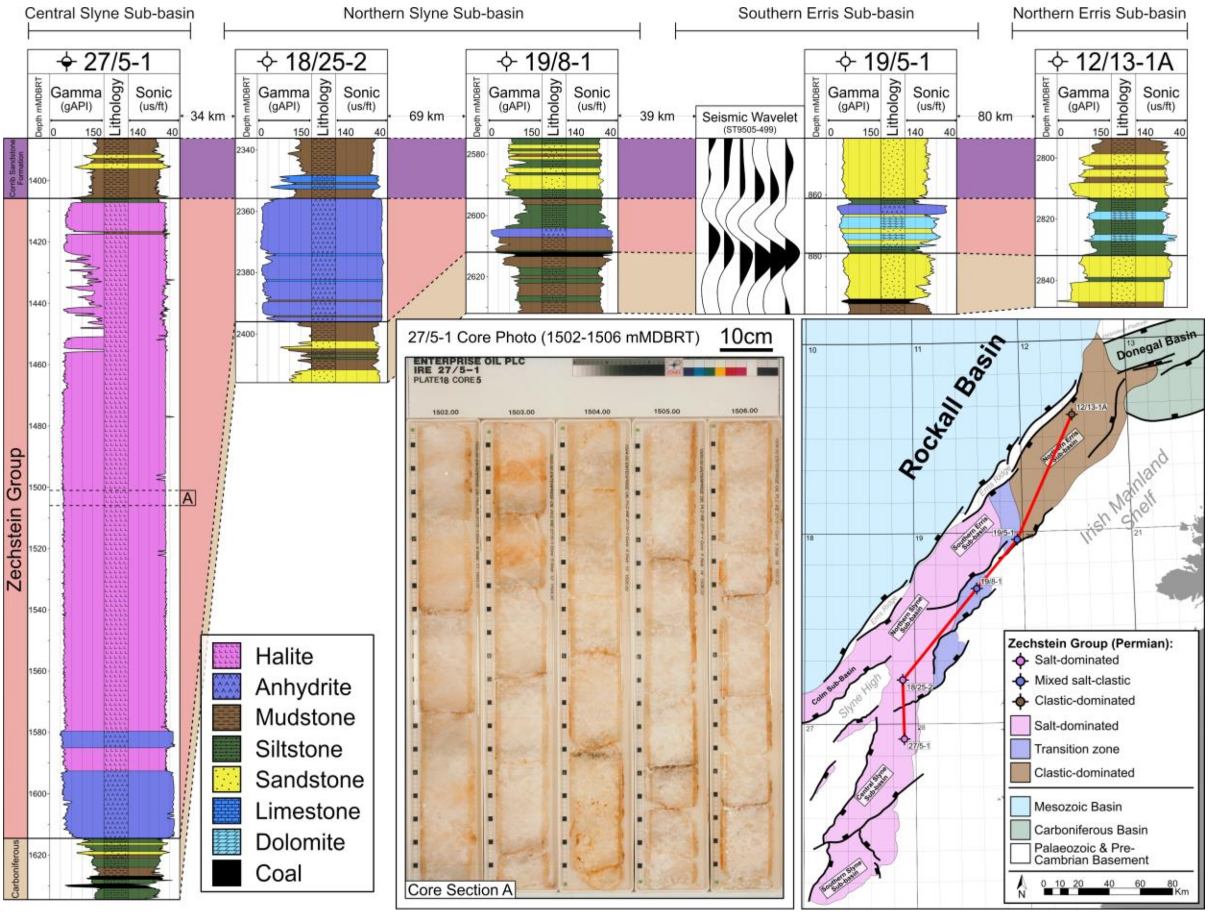


Figure 4: *Lithological well correlation of the Zechstein Group through the Slyne and Erris basins. Correlation is flattened to the top of the Zechstein Group.* ***Inset:*** *Select core photos from the 27/5-1 well in the central Slyne Basin, showing the massive, crystalline, halite-prone Zechstein Group.*

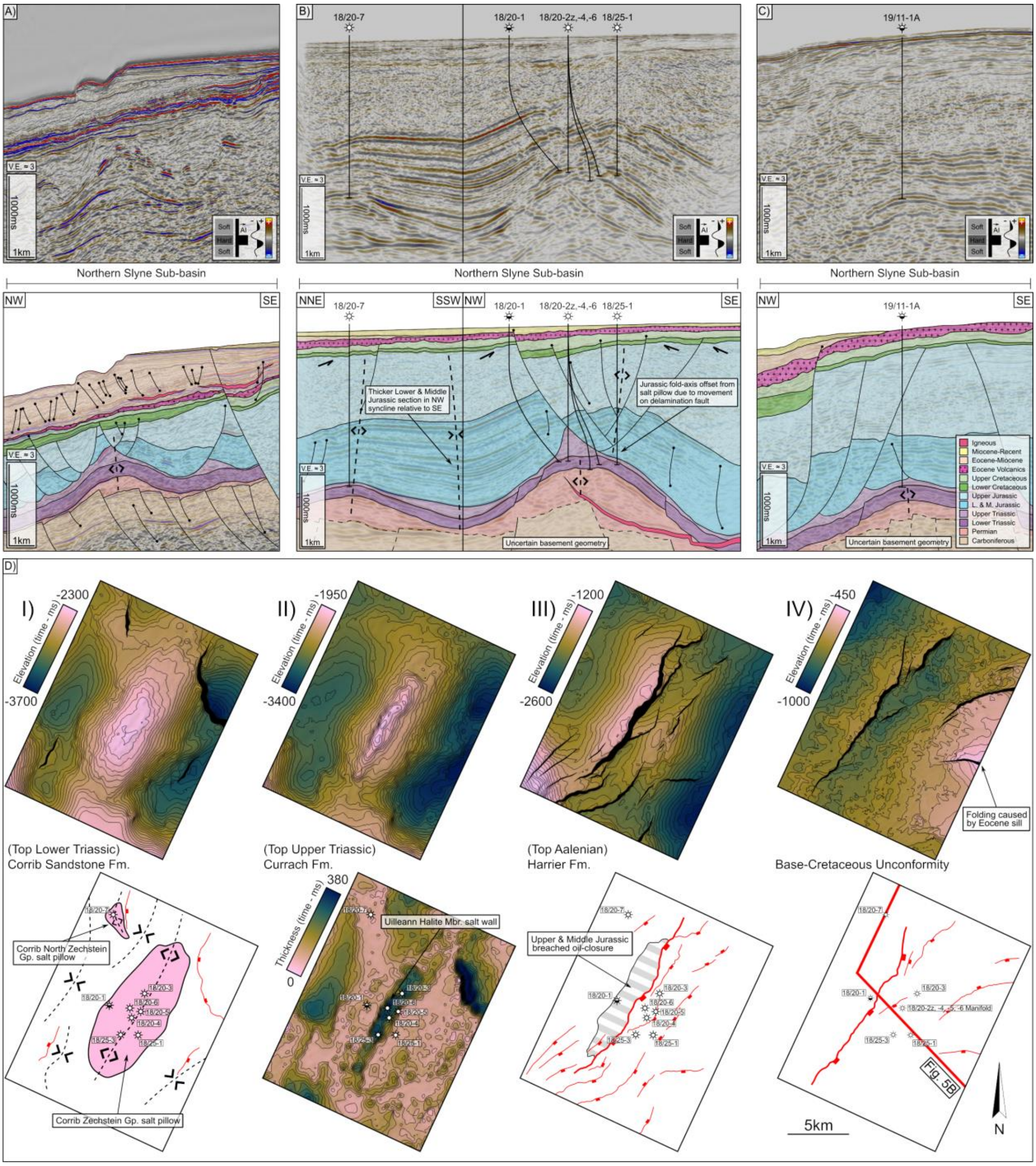


__Figure 5:__ Seismic sections from the northern Slyne Basin. See figure 1 for locations. ***A)*** *Inline 1600 from the 2018 Inishkea Reprocessed 3D seismic volume and accompanying geoseismic section. A Zechstein Group salt pillow folds the Corrib Sandstone Formation, with delamination faults soling out in the Uilleann Halite Member of the Currach Formation above the crest of the fold.* ***B)*** *Arbitrary line from the 2013-01 (13SH3D) 3D seismic volume and accompanying geoseismic interpretation. Two salt-cored folds are visible, one containing the 18/20-7 'Corrib North' gas discovery, and the other containing the Corrib gas field. A major eastward-dipping delamination fault is developed in the Jurassic section above the crest of the Corrib structure, soling out above a small salt diapir within the Uilleann Halite Member, with a faulted rollover*

formed in the hanging-wall of this fault. Well name 18/20-2z, -4, -6 indicates the location of the subsea manifold for three distinct wells. ***C)*** *Arbitrary line from the 2001/01 3D seismic volume and accompanying geoseismic section. The salt-cored fold tested by the 19/11-1A well is shown, with minor delamination faults forming above, soling out in the Uilleann Halite Member The steep westward dip along the western edge of the structure demonstrates the influence of post-rift thermal subsidence in the Rockall Basin.* ***D) I)*** *Time-structure map of the top Corrib Sandstone Formation and accompanying map (below) showing Zechstein Group salt pillows.* ***II)*** *Time-structure map of the top Currach Formation and accompanying TWTT thickness map (below) of the Currach Formation.* ***III)*** *Time-structure map of the Top Harrier Formation and accompanying fault map (below) with the maximum structural closure in the hanging-wall highlighted (the extent of the residual column encountered in well 18/20-1 is uncertain).* ***IV)*** *Time-structure map of the Base-Cretaceous Unconformity and accompanying fault map (below).*

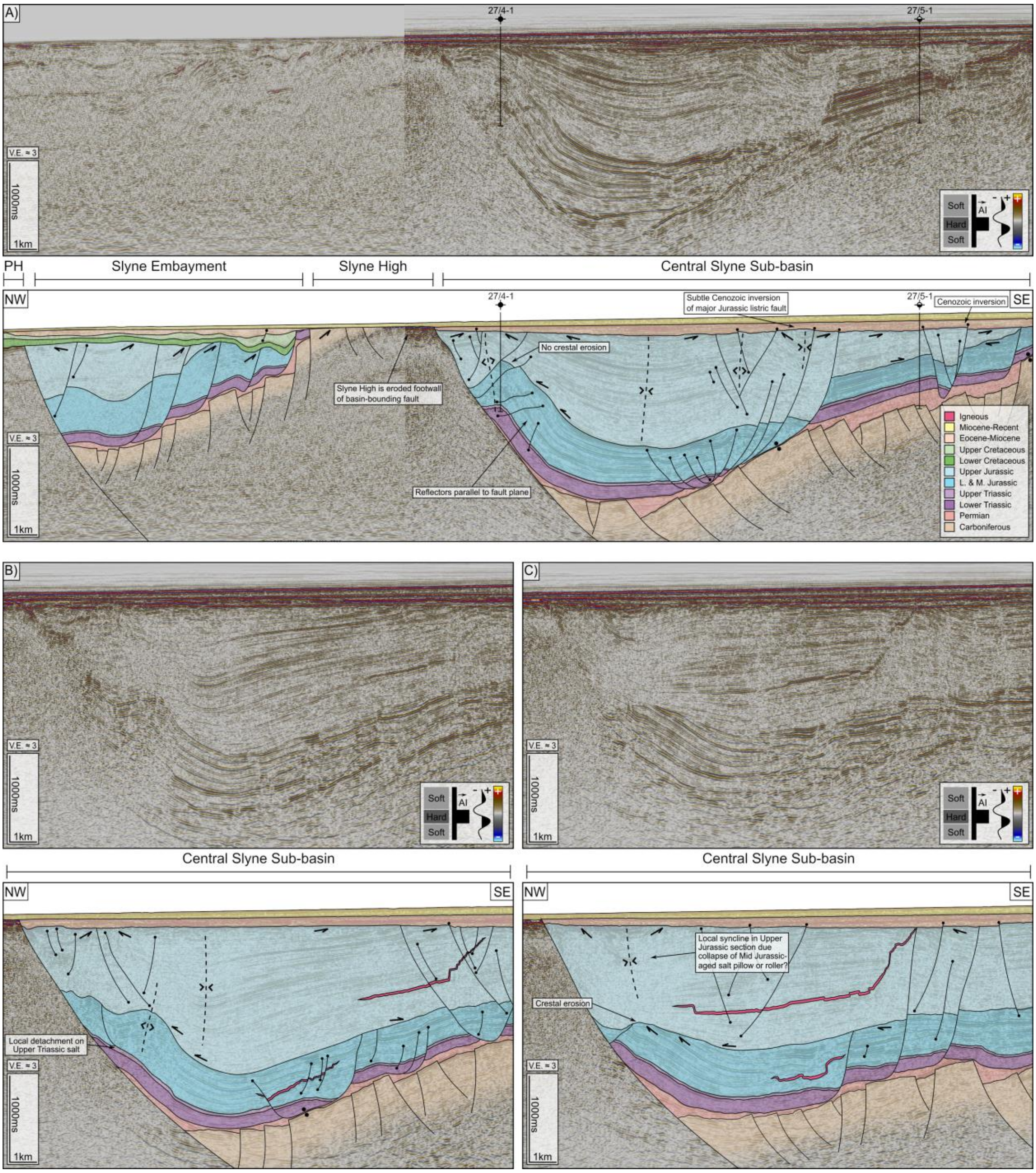


Figure 6: *Seismic sections from the central Slyne Basin. See figure 1 for seismic line locations.* ***A)*** *Composite seismic section of 2D seismic line E96IE09-28 and inline 2740 from the 2000/08 (E00IE09) 3D seismic volume with accompanying seismic interpretation.* ***Abbreviations:*** *PH – Porcupine High* ***B)*** *Inline 1790 from the 2000/08 (E00IE09) 3D seismic volume with accompanying seismic interpretation.* ***C)*** *Inline 2040 from the 2000/08 (E00IE09) 3D seismic volume with accompanying seismic interpretation.*

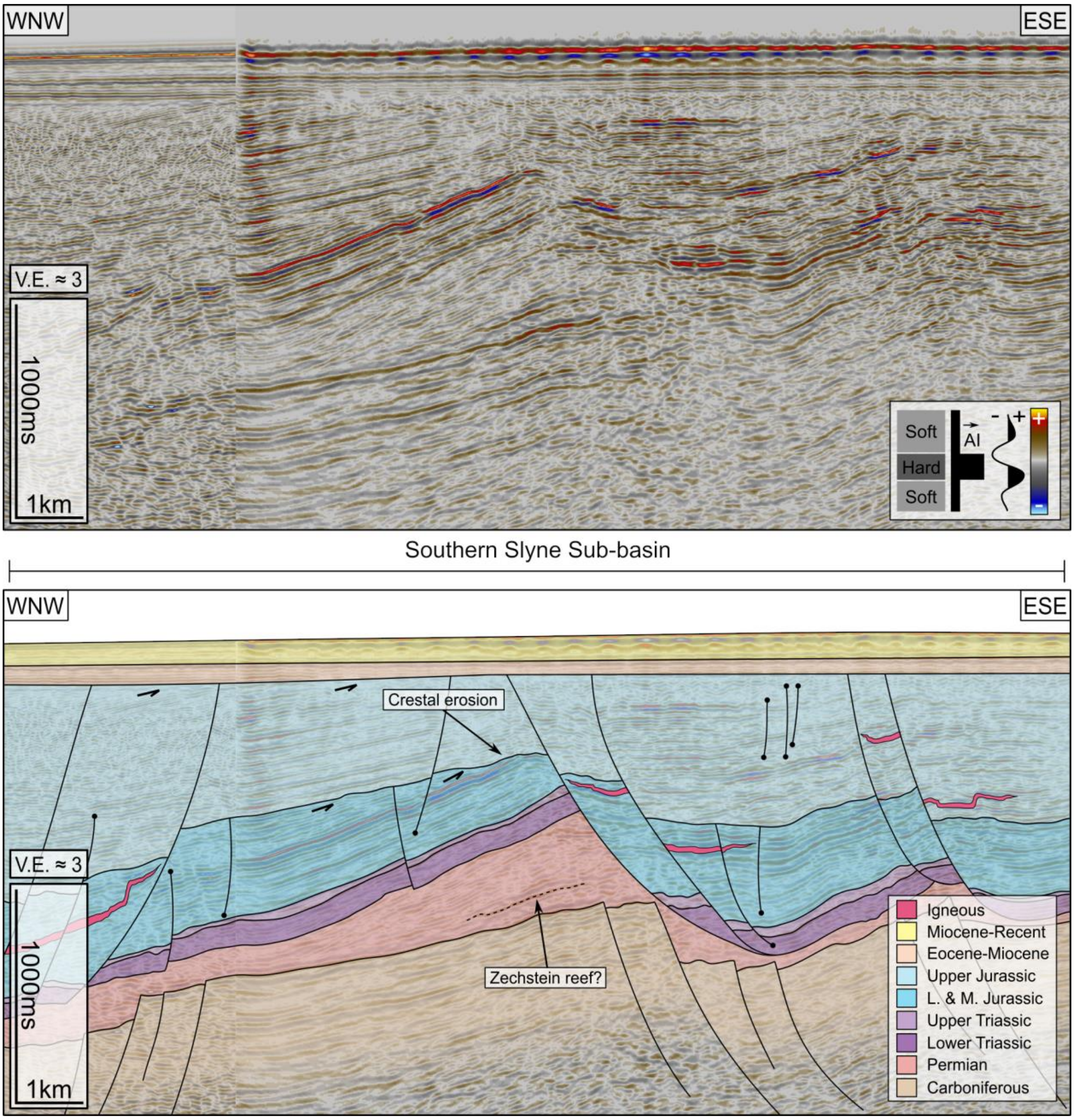


Figure 7: *Composite seismic section of 2D seismic line TK25-95-32 and crossline 3163 from the 2010/01 (SL103D) 3D seismic volume, with accompanying geoseismic interpretation. The Middle and Lower Jurassic section is severely eroded on the crest of the fault block cored by the large salt roller, with a thicker section preserved in the hanging-wall. See figure 1 for seismic line location.*

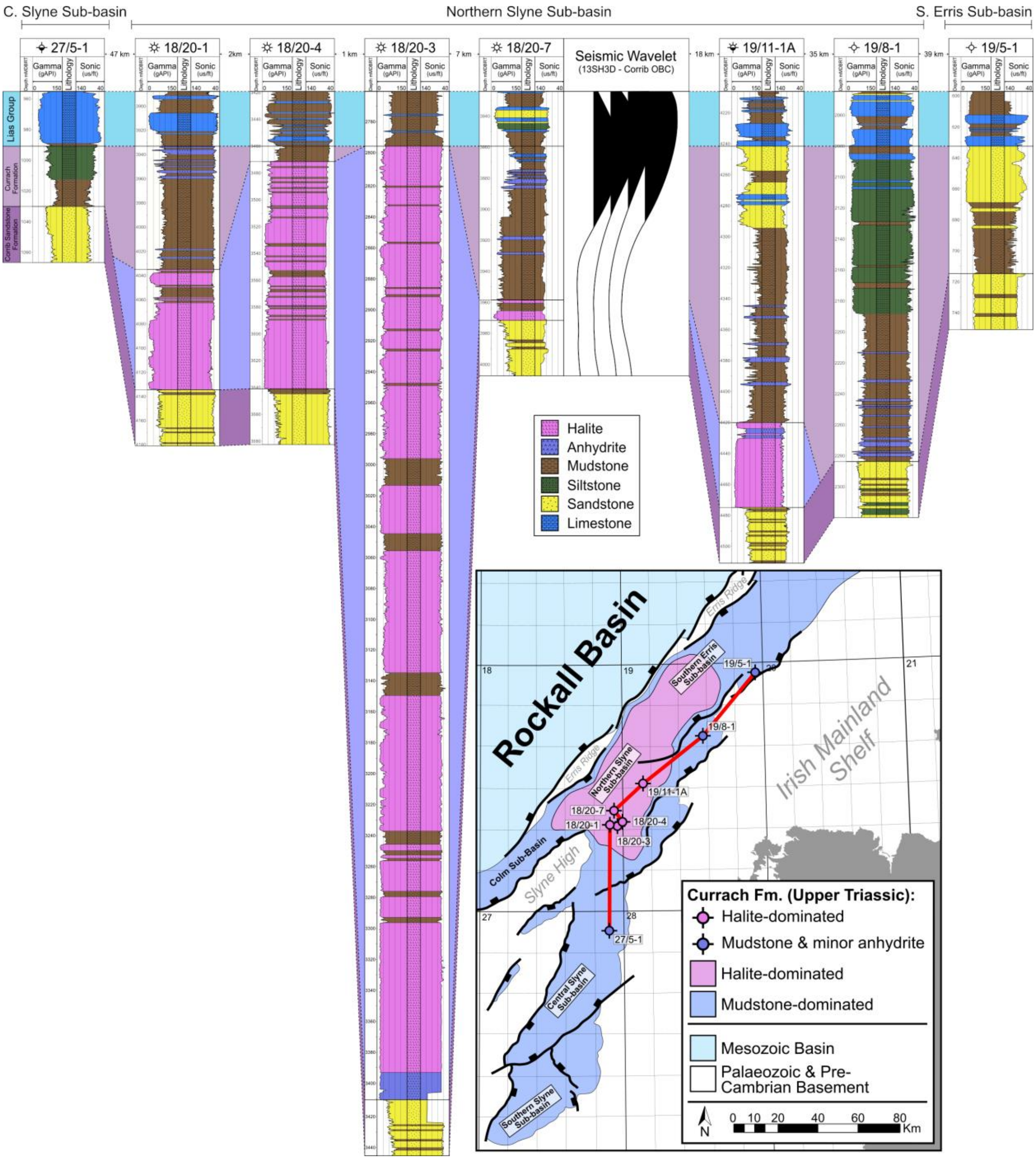


Figure 8: *Lithological correlation of the Currach Formation and Uilleann Halite Member of select wells through the Slyne and Erris basins. Correlation is flattened to the top of the Currach Formation. Well 18/20-3 penetrates the salt wall above the Corrib salt-cored fold.*

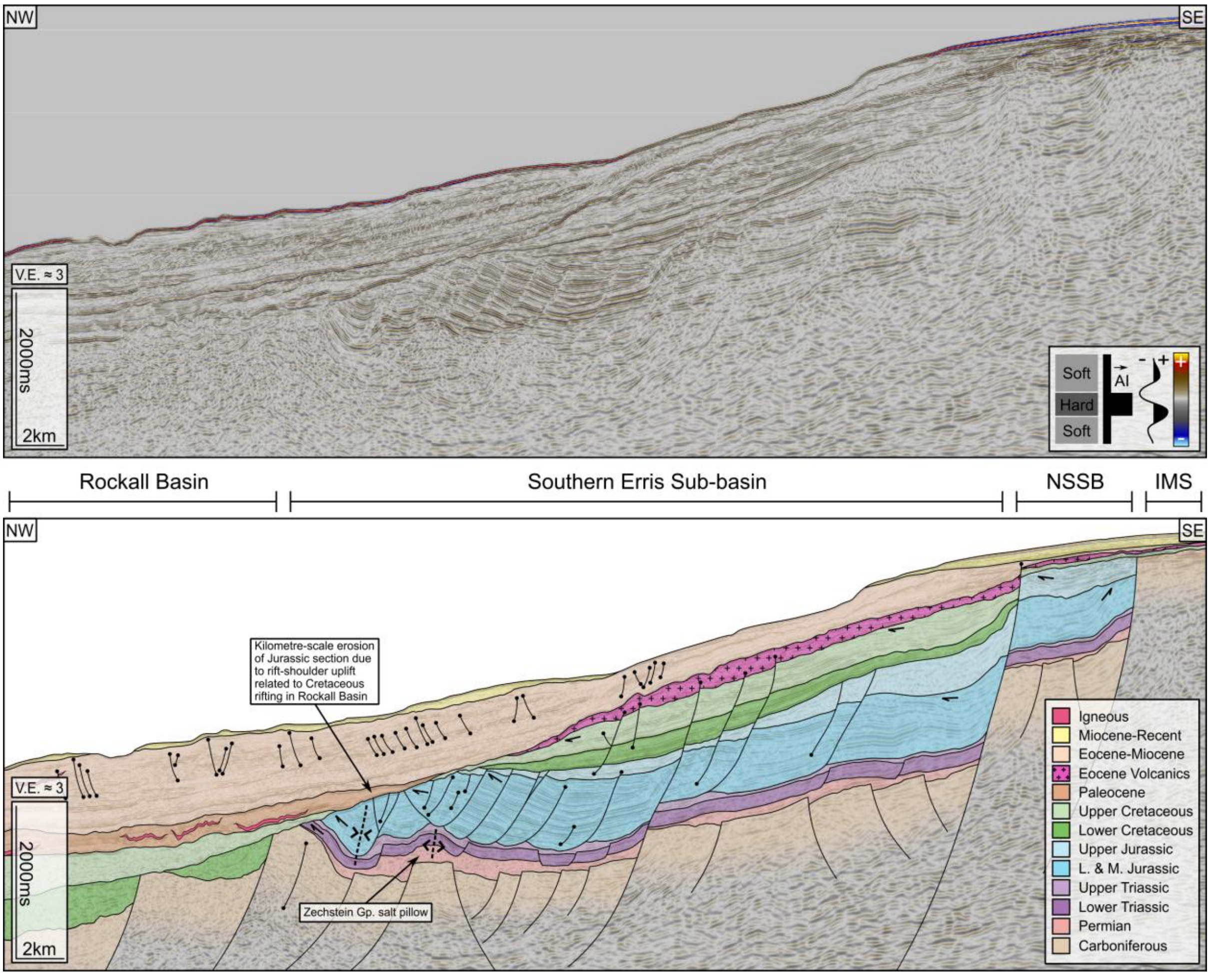


Figure 9: *2D seismic line ERM07-6000 and accompanying geoseismic section. The Jurassic section in the southern Erris Basin is dominated by tightly spaced, westward-dipping listric faults which detach on the Uilleann Halite Member. There is also a Zechstein salt pillow evident near the western margin of the basin. Stratigraphy in the Rockall Basin is constrained through correlation with the 12/2-1 and 12/2-2 wells to the NE. See figure 1 for seismic line location.* ***Abbreviations:*** *IMS – Irish Mainland Shelf; NSSB – Northern Slyne Sub-basin.*

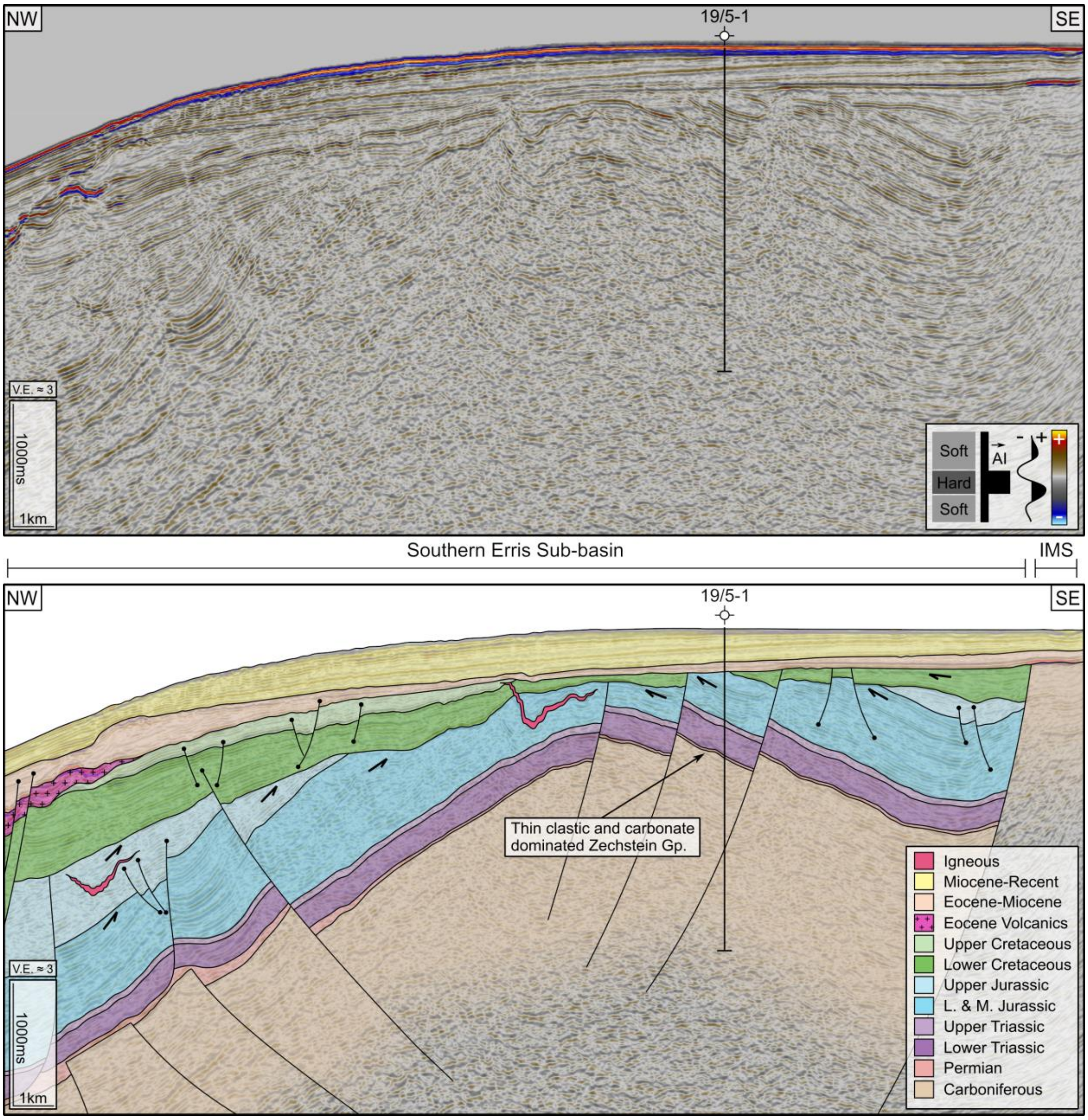


Figure 10: *2D seismic line ST9505-449 and accompanying geoseismic section. The proportion of salt in the Zechstein Group increase north-westwards. Faults on the eastern side of the section hard link through the Zechstein Group, while on the western side faults are mechanically detached above and below the Zechstein Group salt. See figure 1 for seismic line location.* ***Abbreviations:*** *IMS – Irish Mainland Shelf.*

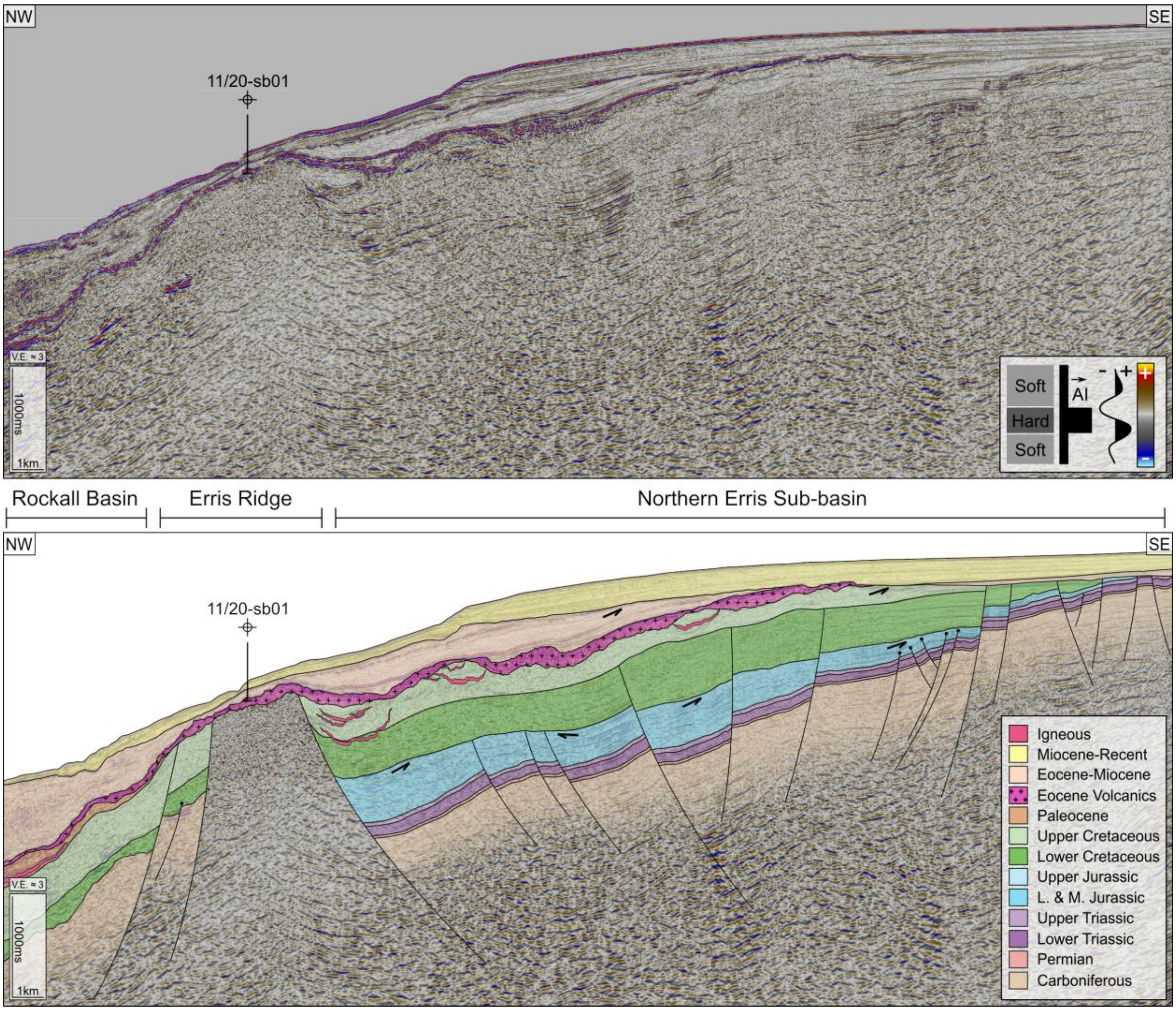


Figure 11: *2D seismic line PH98GPO133-027 and accompanying geoseismic section. The northern Erris Basin dips westwards into the bounding fault along the margin of the Erris Ridge, with a significantly reduced Mesozoic section preserved beneath the Base-Cretaceous Unconformity. There is little evidence of salt-related structures in this part of the basin. Eocene lavas cause significant degradation of image quality. See figure 1 for seismic line location.*

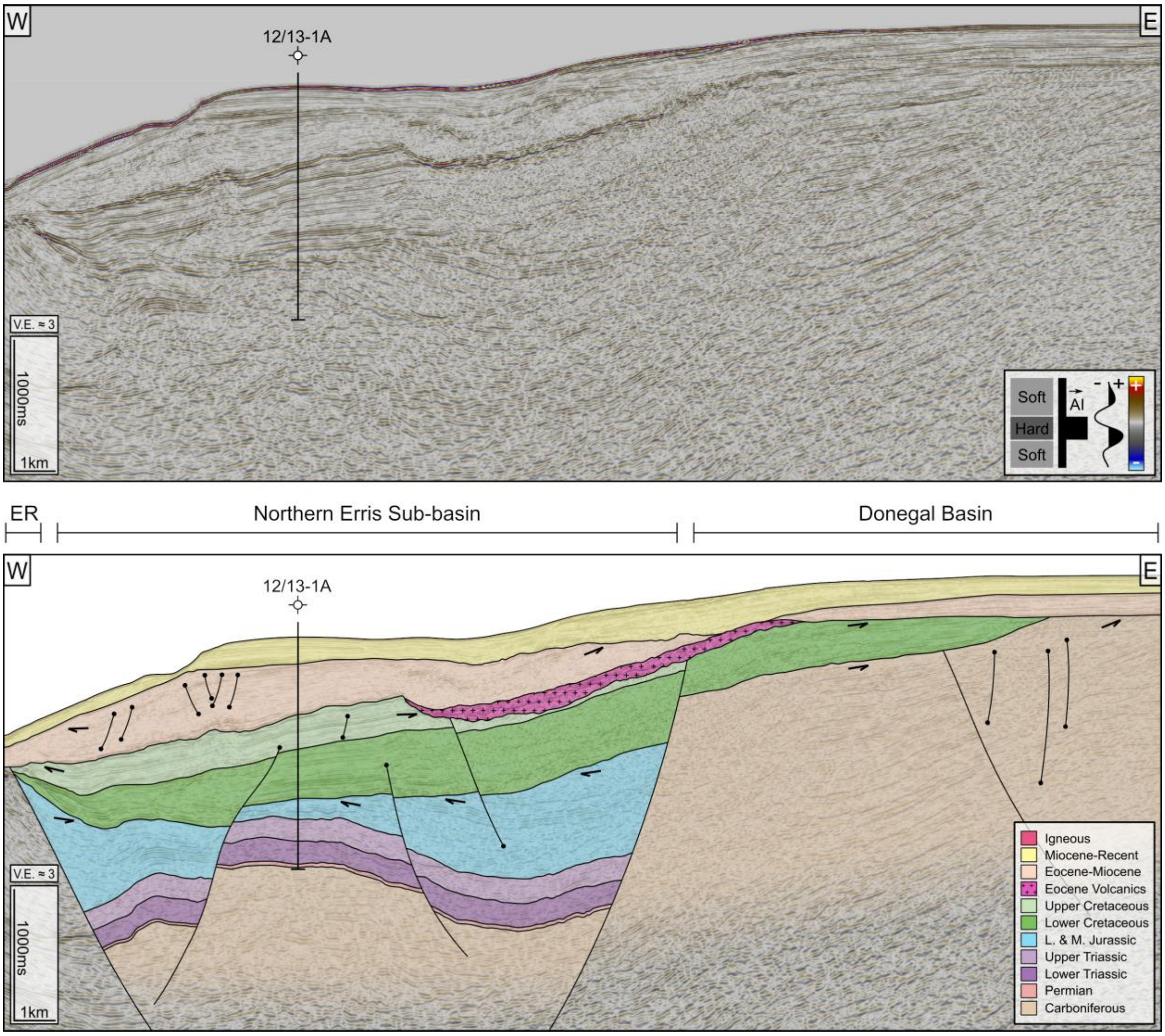


Figure 12: *2D seismic line DBS99-304 and accompanying geoseismic section. Here the northern Erris Basin is bounded by the Erris Ridge to the northwest and the Palaeozoic Donegal Basin to the northeast, with a significantly reduced Mesozoic section preserved beneath the BCU. There is little evidence of salt-related structures in this part of the basin. See figure 1 for seismic line location.* ***Abbreviations:*** *ER – Erris Ridge.*

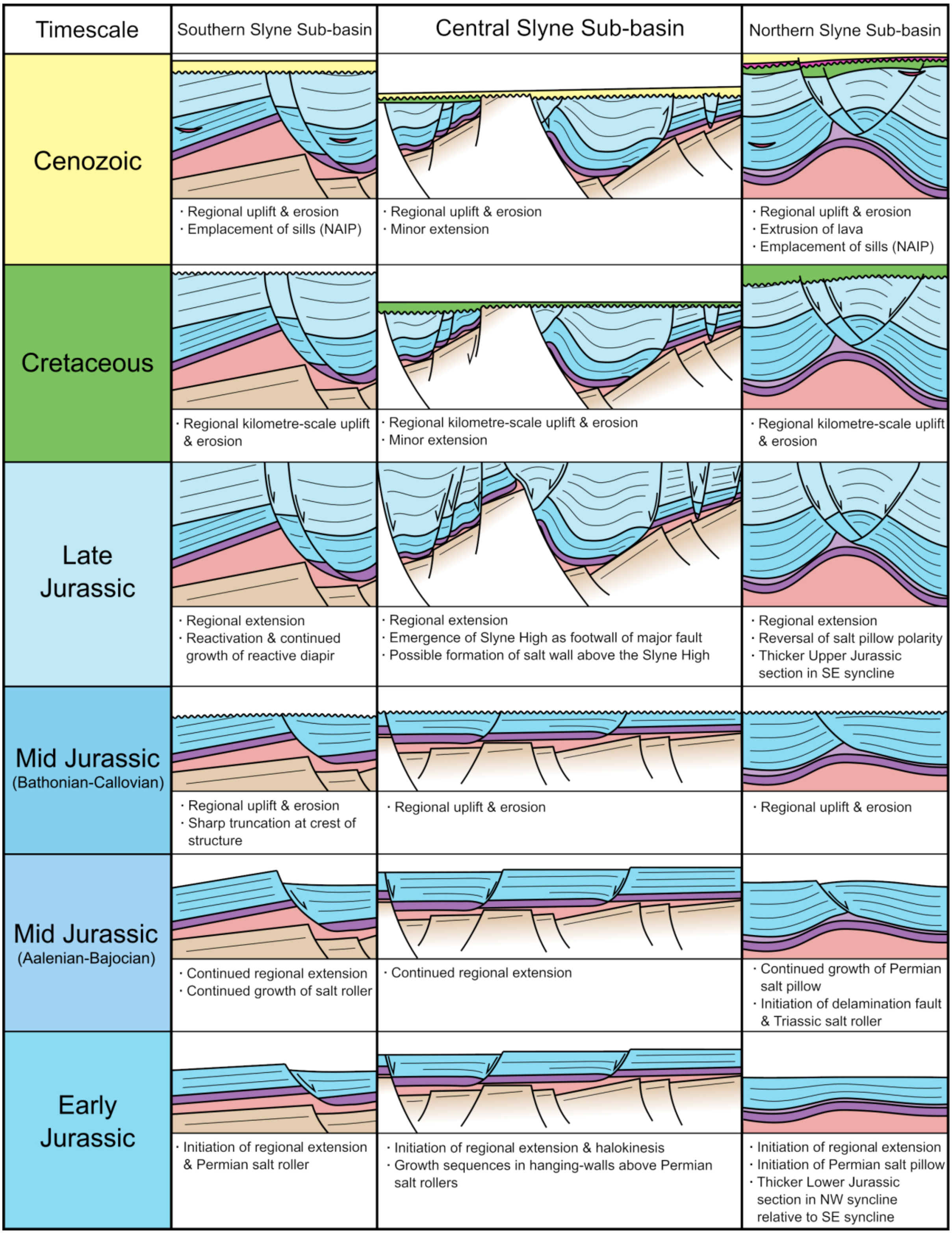


Figure 13: *Schematic evolutionary model for the formation of different salt-related structures discussed in this study highlighting their multiphase structural evolution. Seismic lines through the structures illustrated in the Southern, Central and Northern Slyne sub-basins are shown in Fig. 6, 7A and 8B respectively.* ***Abbreviations:*** *NAIP – North Atlantic Igneous Province.*

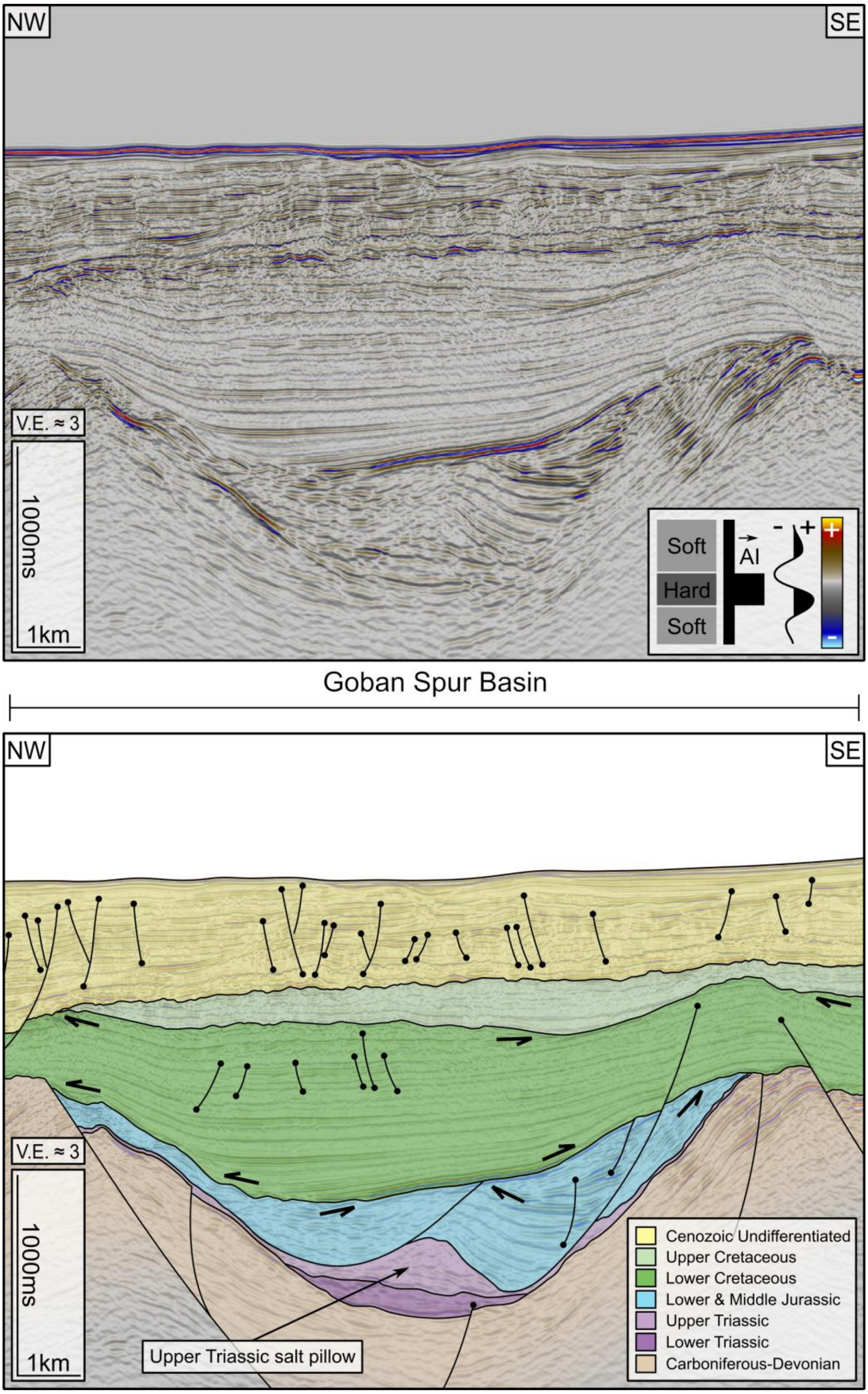


Figure 14: *Part of 2D seismic line PAD13-044M and accompanying geoseismic section. A distinct décollement surface is observed beneath the Base-Cretaceous Unconformity. An Upper Triassic salt pillow is also observed in this section.*

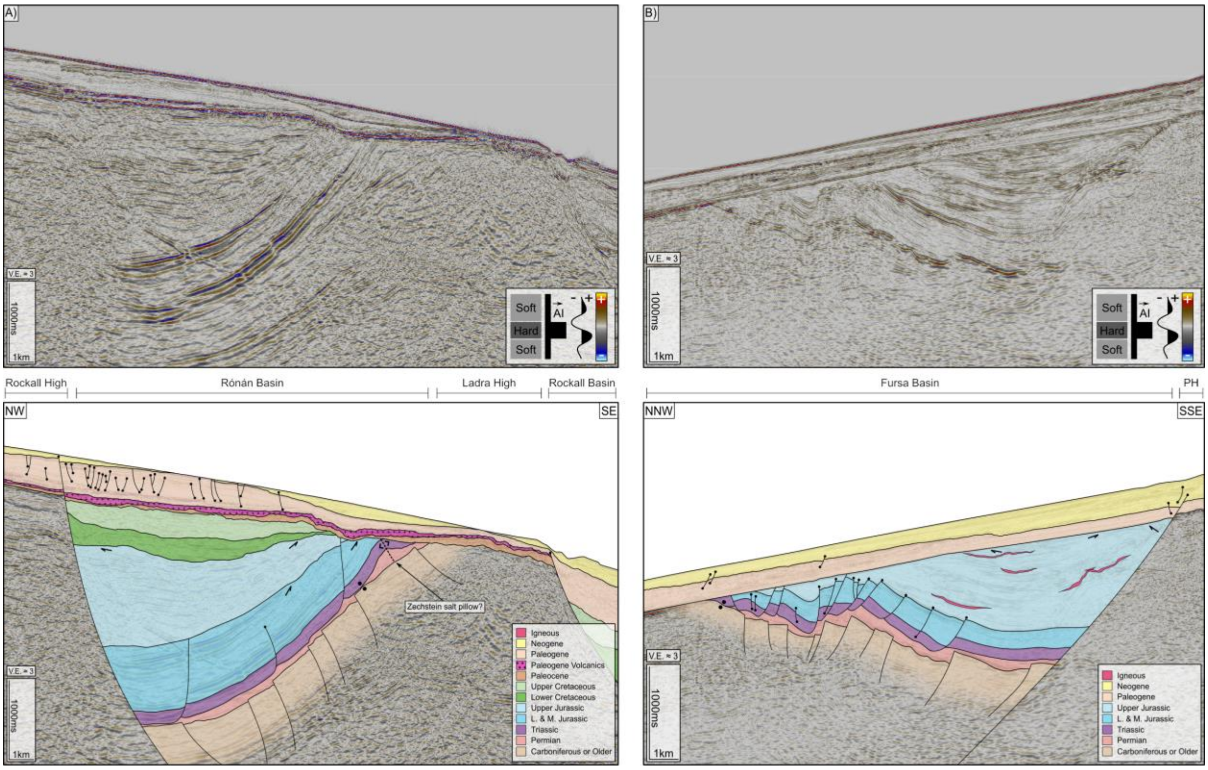


Figure 15: A) *Part of 2D seismic line WRM96-107 and accompanying geoseismic section. The Rónán Basin is located on the 'conjugate margin' of the Erris Basin on the north-western margin of the Rockall Basin.* ***B)*** *Part of 2D seismic line IR11040 and accompanying geoseismic section. A distinct décollement surface is interpreted in the Fursa Basin between the bright top-basement reflector and the overlying Mesozoic section.* ***Abbreviations:*** *PH – Porcupine High.* ***Note:*** *As the Rónán and Fursa basins are currently undrilled, these interpretations are speculative.*

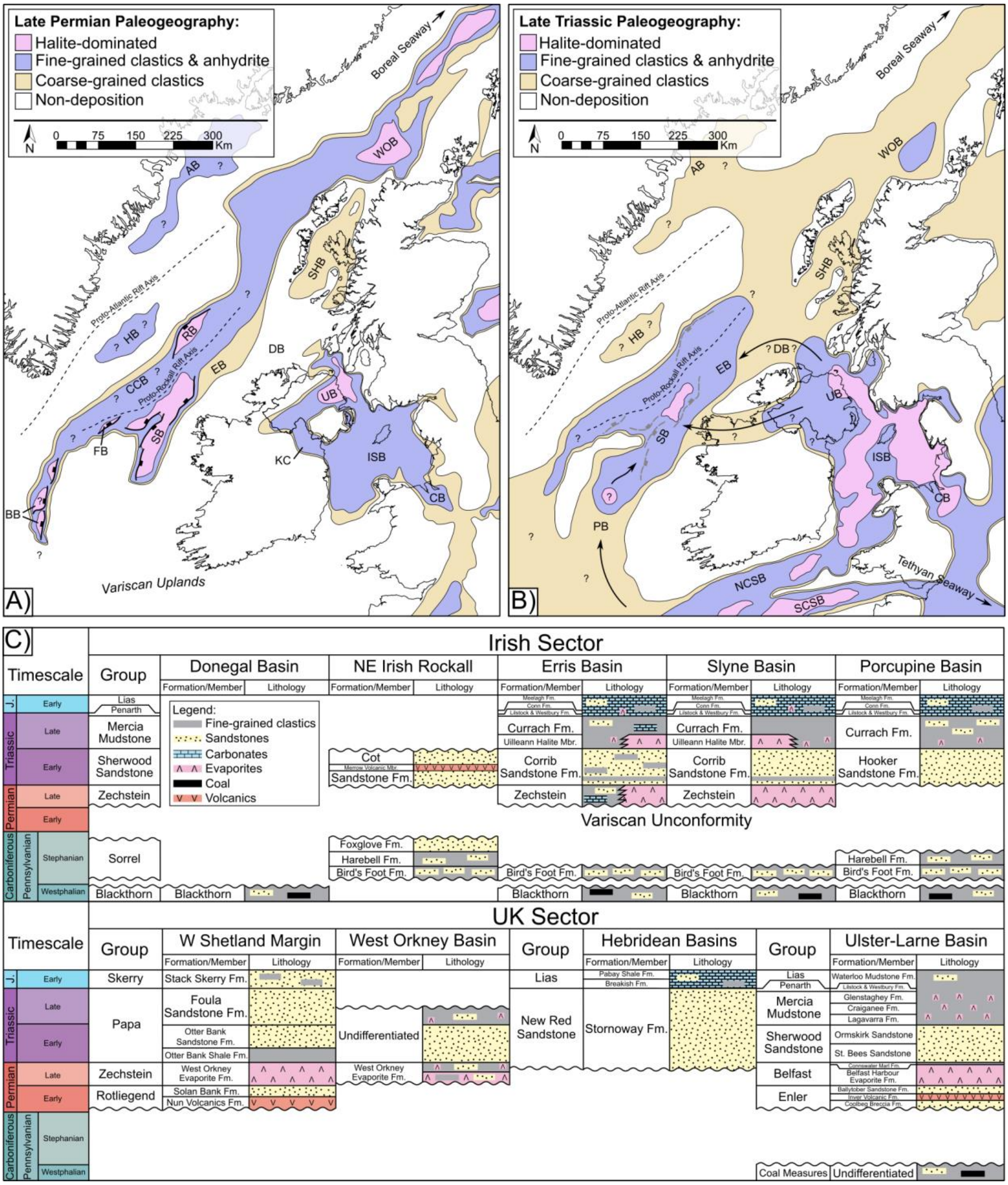


***Figure 16: A)** Schematic Late Permian paleogeographic map of the Irish Atlantic margin and neighbouring regions showing the route of marine ingress from the Boreal Ocean to the Slyne and Erris basins. **B)** Schematic Late Triassic paleogeographic map of the Irish Atlantic margin and neighbouring regions showing three potential routes of marine ingress from the Tethys Ocean to the Slyne and Erris basins. UK sector, Irish Sea and Celtic Sea basins adapted from McKie, 2017. Greenland basins adapted from Gerlings et al., 2017. **C)** Simplified stratigraphic columns of the Upper Pennsylvanian to Lower Jurassic sections from several basins surrounding the study area, showing the broad distribution and composition of Permo-Triassic*

rocks. Irish sector adapted from Merlin Energy Resources Consortium (2020), UK sector adapted from Stoker et al. (2017), Ulster-Larne Basin adapted from Quinn et al. (2010). ***Abbreviations:*** *AB – Ammassalik Basin; BB – Bróna basins; CB – Cheshire Basin; EB – Erris Basin; FB – Fursa Basin; HB – Hatton Basin; ISB – Irish Sea basins; KC – Kingscourt; NCSB – North Celtic Sea Basin; PB – Porcupine Basin; RB – Rónán Basin; SB – Slyne Basin; SCSB – South Celtic Sea Basin; SHB – Sea of the Hebrides Basin; UB – Ulster Basin; WOB – West Orkney Basin.*