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Second Annual PhD report

Tectonics and sedimentation in the Middle and Upper Jurassic succession of the northeast Porcupine Basin (offshore Ireland)

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Executive Summary

The Porcupine Basin, offshore Ireland, has been the subject of extensive hydrocarbon exploration since the mid 1970's, leading to a total of 30 exploration and appraisal wells and the acquisition of a considerable amount of 2D and 3D seismic data. Some discoveries, currently under re-appraisal, were made in the northeast part of the basin with the *Connemara* (Quadrant 26) and *Spanish Point* (Quadrant 35) oil accumulations hosted in Middle and Upper Jurassic sandstones. A number of studies showed that the Porcupine Basin developed in response of the northward propagation of the Atlantic rift system, with a main extensional phase during Late Jurassic to Early Cretaceous times. The aim of the PhD project is to better constrain the Mid and Late Jurassic of the north-eastern area of the Porcupine Basin, with a major focus on understanding the interplays between tectonic, sedimentation and erosion in the region.

In this study, petrophysical logs and 2D/3D seismic profiles, together with a significant number of biostratigraphic and core data, are used to constrain the Jurassic sedimentary response to the crustal extension at different scales (fault-block and regional). The Jurassic evolution of the Porcupine Basin can be divided in two distinct periods. The early succession corresponds is a Bathonian sequence, deposited in a fluvial-lacustrine environment directly above a Carboniferous sequence. It reflects a general base-level rise and has been controlled mainly by thermal subsidence and an irregular pre-Bathonian topography. In the Upper Jurassic, a number of erosional unconformities of broadly Oxfordian, Kimmeridgian and Portlandian/Volgian ages are well characterized throughout the study area. The top of the sequence is truncated by the Base Cretaceous Unconformity. These surfaces developed during different rift phases and bound three main sedimentary packages showing characteristic growth-faulting. At a broad scale, the deposition reflects a general sea-level rise, passing from a restricted marine environment to an open marine setting. It has been mainly controlled by intense syn-rift activity, which took place along N-S, NE-SW and mainly E-W fault-structures of different ages. In detail, these three extension phases are differently expressed from fault-block to fault-block and through the time, so that lateral variations within the packages are recognized from fault-block to fault-block, involving changes in facies, thickness and geometry. Thus, the development of the Upper Jurassic sequences suggests changes in the magnitude and timing of the deformation, leading to the separate development of contemporaneous rift-related sub-basins.

The second year of the PhD project focussed on **(a)** expanding, integrating and analysing the seismic and well data in the Quadrant 26 and 35 area (*Connemara* and *Spanish Point* oil accumulations), **(b)** identifying correlateable sedimentary packages based on an analysis of wireline log data, **(c)** carrying out seismic stratigraphic analysis of the Mid-Upper Jurassic syn-rift succession on selected profiles and **(d)** examining core photographs from Jurassic lithofacies in the Block 26/28 region.

1. Geological Introduction

The Porcupine Basin lies approximately 100 km west of Ireland [Fig. 1]. It underlies a large N-S trending bathymetric embayment within the European Atlantic Margin (EAM), in water depths ranging from 350m to more than 3000 m. The Porcupine Basin contains up to 10 km of strata of Late Paleozoic to Cenozoic age [*e.g.* Shannon, 1998; Naylor *et al.*, 2002; Naylor and Shannon, 2005] whose development is linked to the northward propagation of the Atlantic Rift system [*e.g.* Doré *et al.*, 1999; Spencer *et al.*, 1999; Spencer & MacTiernan, 2001; Naylor & Shannon, 1999 and 2005]. The geological evolution of the region developed in response to a series of rift events, interspersed with thermal subsidence phases and linked to local and regional magmatism [*e.g.* Sinclair *et al.*, 1994; Doré *et al.*, 1999; Williams *et al.*, 1999; Naylor & Shannon, 2005]. Palaeozoic and older tectonic structures exerted a strong influence on the tectono-stratigraphic evolution of the region [*e.g.* Doré *et al.*, 1999; Spencer and MacTiernan, 1999 and 2001; Spencer *et al.*, 1999; Naylor *et al.*, 1999 and 2002; Naylor & Shannon, 2005].

The north-eastern part of the basin, the study area of this PhD project, is located at the intersection of the N-S fault structures of the Main Porcupine domain with the NE-SW Slyne/North Porcupine structural trend [Fig. 1]. Jurassic and Early Cretaceous sediments in the basin were deposited in a multiphase rift setting characteristic of much of the Irish Atlantic Margin (IAM) [*e.g.* Croker & Shannon, 1987; MacDonald *et al.*, 1987; Sinclair *et al.*, 1994; Doré *et al.*, 1999; William *et al.*, 1999; Spencer & MacTiernan, 2001; Naylor & Shannon, 2005]. Sandstone of Middle and Upper Jurassic age are important reservoirs hosting petroleum accumulations and have been the focus of previous publications [*e.g.* Naylor, 1984 and 1996; Croker & Shannon, 1987; MacDonald *et al.*, 1987; Butterworth *et al.*, 1999; Shannon & Spencer, 1999; Spencer *et al.*, 1999; Shannon *et al.*, 2001; Spencer & MacTiernan, 2001]. Resting unconformably on Upper Carboniferous strata, Middle Jurassic strata were deposited in a fluvial-lacustrine setting [*e.g.* Croker & Shannon, 1987; MacDonald *et al.*, 1987; Sinclair *et al.*, 1994; Butterworth *et al.*, 1999] and pass upward to a restricted to open marine Late Jurassic strata that developed in a syn-rift setting.

The overarching aim of the PhD project is to define the interplay between tectonism, sedimentation and erosion within the Middle and Upper Jurassic succession of the NE part of the Porcupine Basin, with special emphasis on the areas of the *Connemara Oil Accumulation* (Quadrant 26) and *Spanish Point Accumulation* (Quadrant 35) [Fig. 2]. A series of horst and graben structures of Mesozoic age has been identified in the Porcupine Basin [Bulois & Shannon, 2006 and 2007]. In the study area, seismic lines correlated to well data showed that these structural features are composed of Carboniferous and Middle Jurassic successions, covered by an Upper Jurassic sequence and a thick Early Cretaceous succession. Moreover, on the basis of the seismic character, Bulois and Shannon [2006 and 2007] described several main stratigraphic sequences separated by different unconformities. The Base Cretaceous Unconformity (BCU) is the most pronounced of these and is recognised throughout the entire basin. The Portlandian/Volgian, Kimmeridgian and Oxfordian unconformities (respectively BPU, BKU and BOU for Base Portlandian, Kimmeridgian and Oxfordian unconformities) have also been recognised and correlated. While some of these unconformities can be correlated over some distance (*e.g.* BCU and TCU), there was still some uncertainty on the precise age of some of the other the Upper Jurassic sediments and unconformities due to poor biostratigraphic control.

The sedimentary thickness of the various packages is regionally variable. In the First Annual Report, Bulois & Shannon [2006] suggested that the extension could have evolved in a diffuse context and have been accompanied by strike-slip movements along some fault zones. They also suggested that extension took place along at least N-S and NE-SW structures and noted that the vertical displacement along the fault zone systems differs from one block to another.

This report describes the work carried out during the past year of the PhD (2006-2007), building on the results outlined in the First Annual Report [Bulois & Shannon, 2006]. The initial focus of the work was on the southern part of Quadrant 26 (*Connemara Oil Accumulation*), but it has now been extended southwards into Quadrant 35 (*Spanish Point Oil Accumulation*) where important geological features have been recognized.

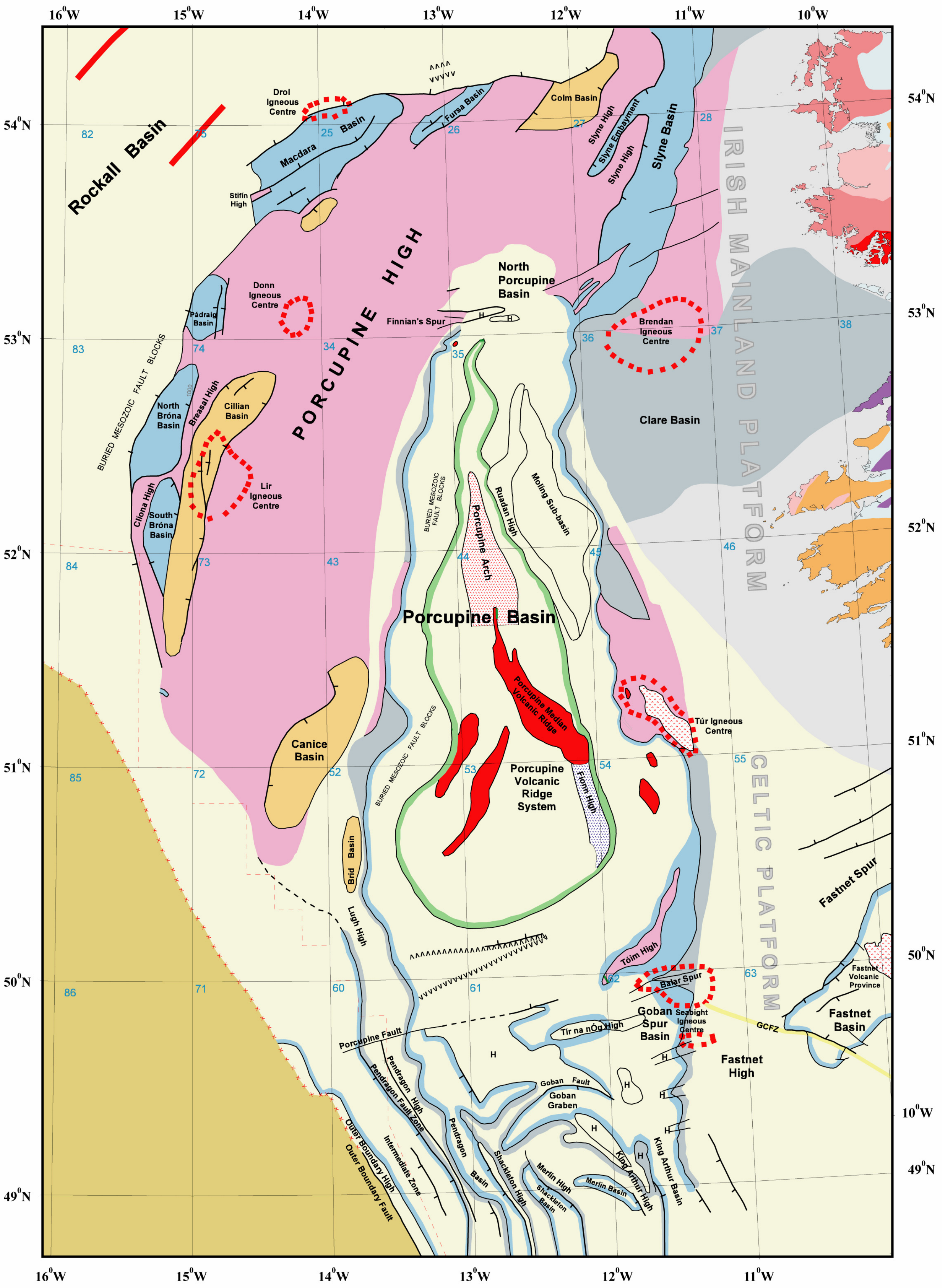


Fig. 1: **Structural map of the Porcupine Basin area.**
After Naylor *et al.* [2002]

2. Summary of Work:

The work of the second year of the PhD comprised the follows:

- Assembly of seismic and well data.
- Interpretation and correlation of wireline log data (including review of biostratigraphic data).
- Interpretation of 2D seismic data.
- Review of core photographs from the Upper Jurassic succession.
- Conference attendance.
- Training course in seismic data loading for the *Charisma* seismic interpretation package.

2.1 - Assembly of data base:
To date, a number of 2D seismic have been loaded (270 lines shot during the surveys BP85, IR80, HGSW93, PD93, CHEV96, OXYRL96, OXYRL97). We are awaiting delivery of 3D seismic data from Quadrant 26. Seismic data available in SEGY format is loaded on the *Charisma* machine. Paper copies of data where no SEGY format is available have been selected and will be provided by the *Petroleum Affairs Division* (PAD) in the near future. Well and core data have been digitised from paper copies available in house and from the PAD.

2.2 - Wireline correlations:
A preliminary correlation of the wells drilled in the 26/28 region was produced during the first year of the PhD. This was expanded and refined during the past year, with the addition of a number of key wells from Quadrants 26 and 35. Gamma ray and sonic logs were used to build the correlation. This enabled the identification of a number of lithofacies packages, which are correlated with confidence throughout the region. Relevant biostratigraphic data published in the literature and taken from well reports were interrogated and used to constrain the age of sediments and possible depositional environments.

2.3 - 2D seismic interpretation:
The data loading enabled to correlate some stratigraphic marker surfaces and seismic packages characterised during the well interpretation. The main unconformities defined during the first year of the PhD were studied in more detail, and work focussed on the Jurassic-Cretaceous. Work was carried out on the potential sub-basin architecture by constraining thickness and facies variations, as well as the identification of rift pulses. Seismic stratigraphic characteristics (*i.e.* onlap, downlap, offlap, *etc.*…) and seismic geometries provided constraints on the dynamics of the formation of the Porcupine Basin.

2.4 - Core description:
The *UCD Marine and Petroleum Geology Group* has assembled a database of core photographs from wells in the area. Digitisation of most of the photographs has taken place, together with core description and re-interpretation. This work is based on Prof. Shannon's and previous PhD studies, and has been carried out on the syn-rift Jurassic succession. It will move soon to the Middle Jurassic sedimentary succession. This work provides a basis for the identification of key lithostratigraphic features and assists with interpretation and assessment of the deposition environment. It helps to ground truth the wireline log correlations.

2.5 - Conferences and meeting:
Three conferences were attended during the past year. These were (1) *Exploring Atlantic Ireland 2006* in Dublin, (2) the annual *Irish Geological Research Meeting* (*IGRM*) in Coleraine and (3) the *INtegrated mapping FOr the substainable development of Ireland's MArine Resource* (*INFOMAR*) meeting in Dublin. A research poster was presented at the *IGRM* meeting. Meetings were held during the year with *Island Oil and Gas Ltd* staff and consultants (Niamh Redmond, Angela Melvin, Jim Mitchell and Brian Rumph) to discuss ideas and to view 2D and 3D seismic data.

2.6 – Training Course:
Schlumberger provided a training course in data loading on the *Charisma* seismic interpretation package in the *UCD School of Geological Sciences* in June 2007. This addressed one of the issues arising in the first year of the PhD, where a number of problems existed with the data loading on the *Charisma* package.

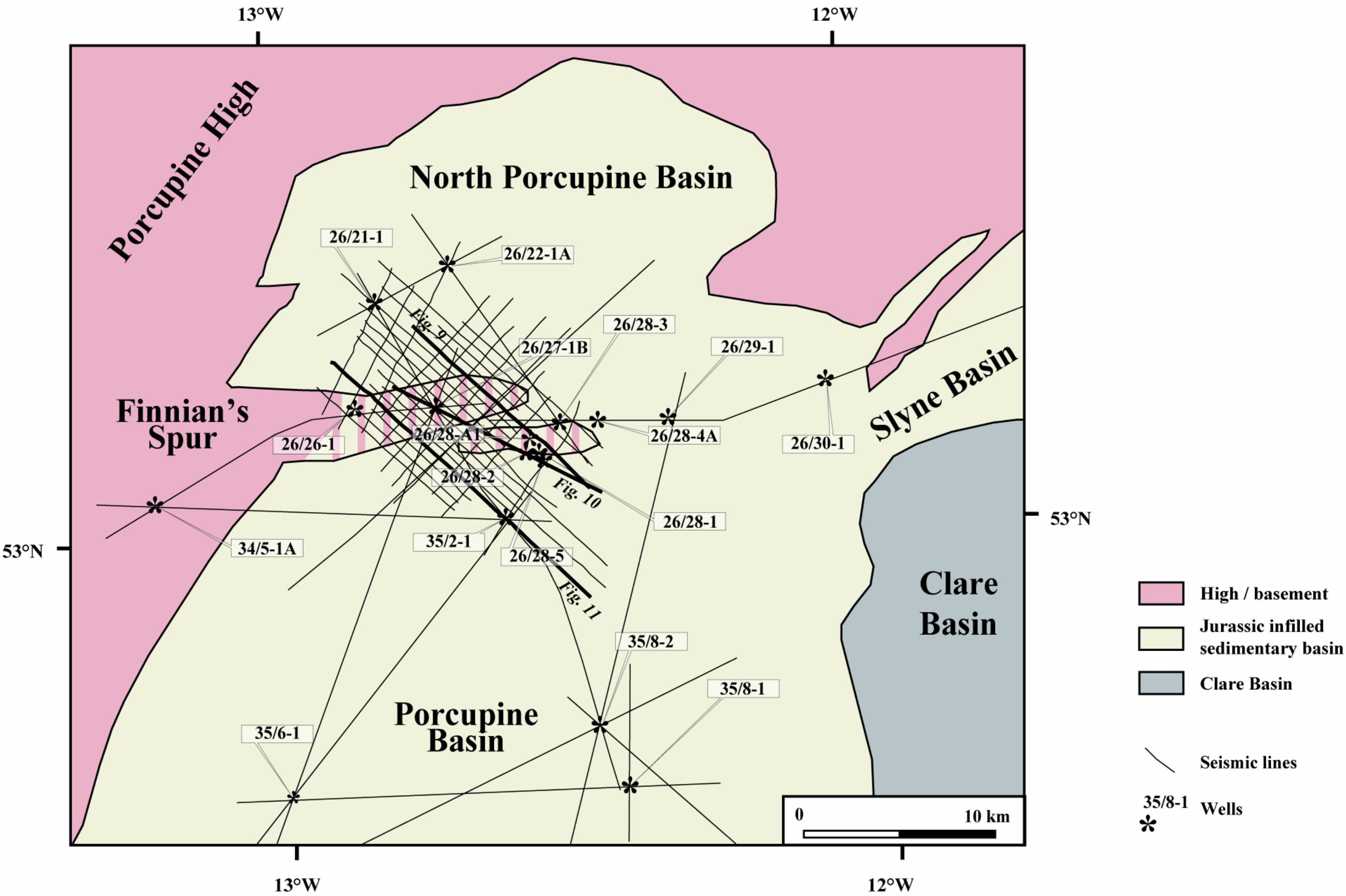


Fig. 2: **Position map of the wells and seismic data analysed in this study.**

3. Wireline log correlation and core analysis:

This focussed on the lithofacies description and analysis of the Jurassic succession. Initial correlation focussed on Block 26/28 (*Connemara Oil Accumulation*) where there has been a significant amount of data [Fig. 2]. It then progressed to the surrounded fault-blocks of the Quadrant 26, as well as to Quadrant 35 [Fig. 4 and 5].

Croker & Shannon [1987] proposed the first correlations for wells drilled in the Porcupine Basin and described the Jurassic sedimentary succession at a broad scale. Sinclair *et al.* [1994] and Williams *et al.* [1999] published regional correlation for the Jurassic succession and proposed a model of the structural evolution of the basin by distinguishing, at a regional scale, individual deposition phases. The First Annual Report [Bulois & Shannon, 2006] proposed some correlations, mainly based on the paleontological indices described in well reports. However, it appeared that there were some discrepancies in the age of the sediments, especially depending on the species used for the study. This uncertainty was probably compounded by reworking of sediments and faunal/floral species.

In the First Annual Report [Bulois & Shannon, 2006], we showed that a number of correlateable unconformities can be recognized on well and seismic data [Fig. 3]. These unconformities (especially Base Cretaceous Unconformity [BCU] and Top Carboniferous Unconformity [TCU]) can be used to define the Jurassic succession. Work during the past year shows that lithofacies characteristics defined by using both gamma ray and sonic logs, can be correlated at a regional scale [Fig. 4 and 5]. Four main packages have been identified. These formations are controlled by regional events (*e.g.* tectonism, thermal subsidence, marine/terrestrial environment, sea level fluctuation, clastic input). On a detailed scale, biostratigraphic elements are also used to define the age of the sediments as well as the deposition environment.

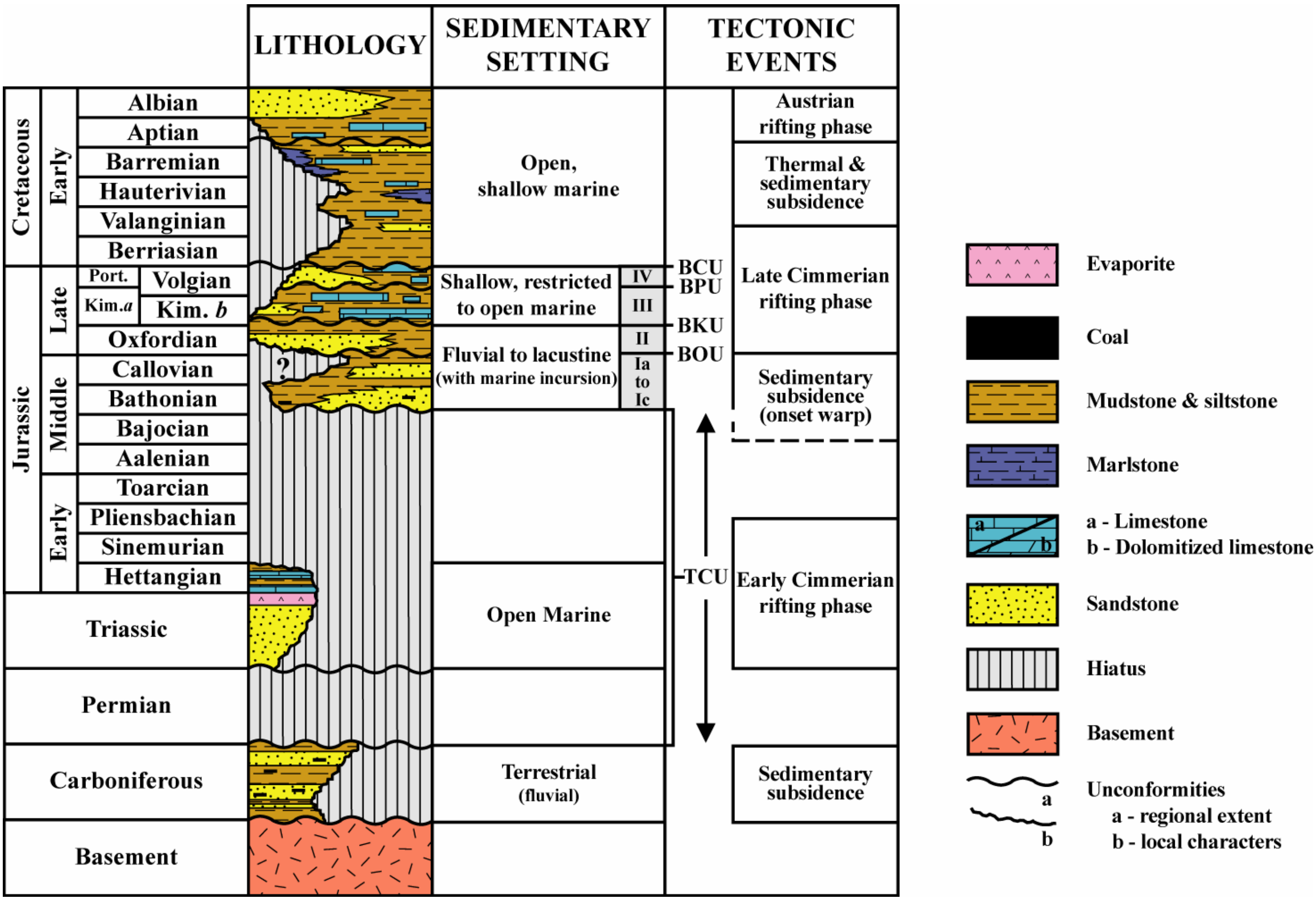


Fig. 3: **general geologic evolution of the NE Porcupine Basin, from wells and seismic data.**

3.1 - Wireline log correlations:

Figures 4 and 5 show wireline log correlations of wells drilled in the northern area of the Porcupine Basin. They are based on a lithofacies interpretation from gamma ray and sonic logs and are supported by cuttings and occasional cores. Furthermore, some biostratigraphic data [Tab. 1] have been used in order to constrain the ages and the nature of the depositional systems in the specific area of the Block 26/28. Some in-house 2D and 3D seismic data (provided by *Island Oil & Gas Ltd*) were examined in order to help to constrain the correlations.

3.1.a – Correlateable surfaces:

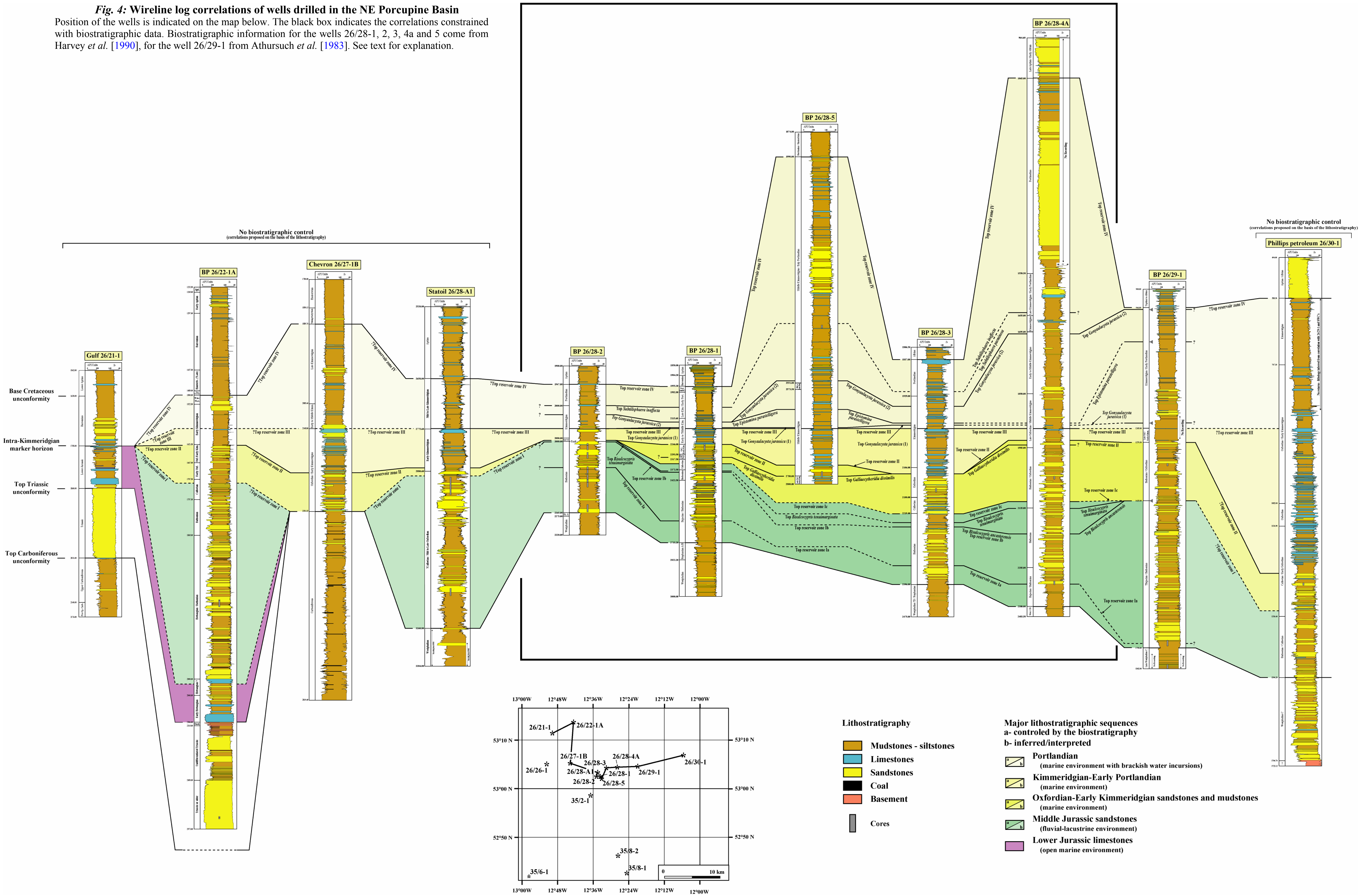
The wireline log correlations, supported by core and seismic data enabled the definition of four characteristic sequences. Jurassic sequences are bounded by major unconformities at Top Carboniferous and Base Cretaceous levels. Moreover, some other unconformities within the Jurassic succession have been described, but are hard to identify on the wireline data.

- **First order unconformities:**

  As shown in the First Annual Report [Bulois & Shannon, 2006], the BCU is well constrained by wireline log response. The variation of Lower Cretaceous biostratigraphic markers shows that an important erosion phase took place over the Porcupine Basin in a heterogeneous manner. As a result, Berriasian to Aptian sediments have been locally preserved [Fig. 4 and 5]. Similarly, the TCU seems to run throughout the study area [Fig. 4]. Stephanian A and/or B to Westphalian strata have been recovered in wells, indicating that the Middle Jurassic deposition has been influenced by the residual Carboniferous topography.

Fig. 4: **Wireline log correlations of wells drilled in the NE Porcupine Basin**

Position of the wells is indicated on the map below. The black box indicates the correlations constrained with biostratigraphic data. Biostratigraphic information for the wells 26/28-1, 2, 3, 4a and 5 come from Harvey *et al.* [1990], for the well 26/29-1 from Athursuch *et al.* [1983]. See text for explanation.



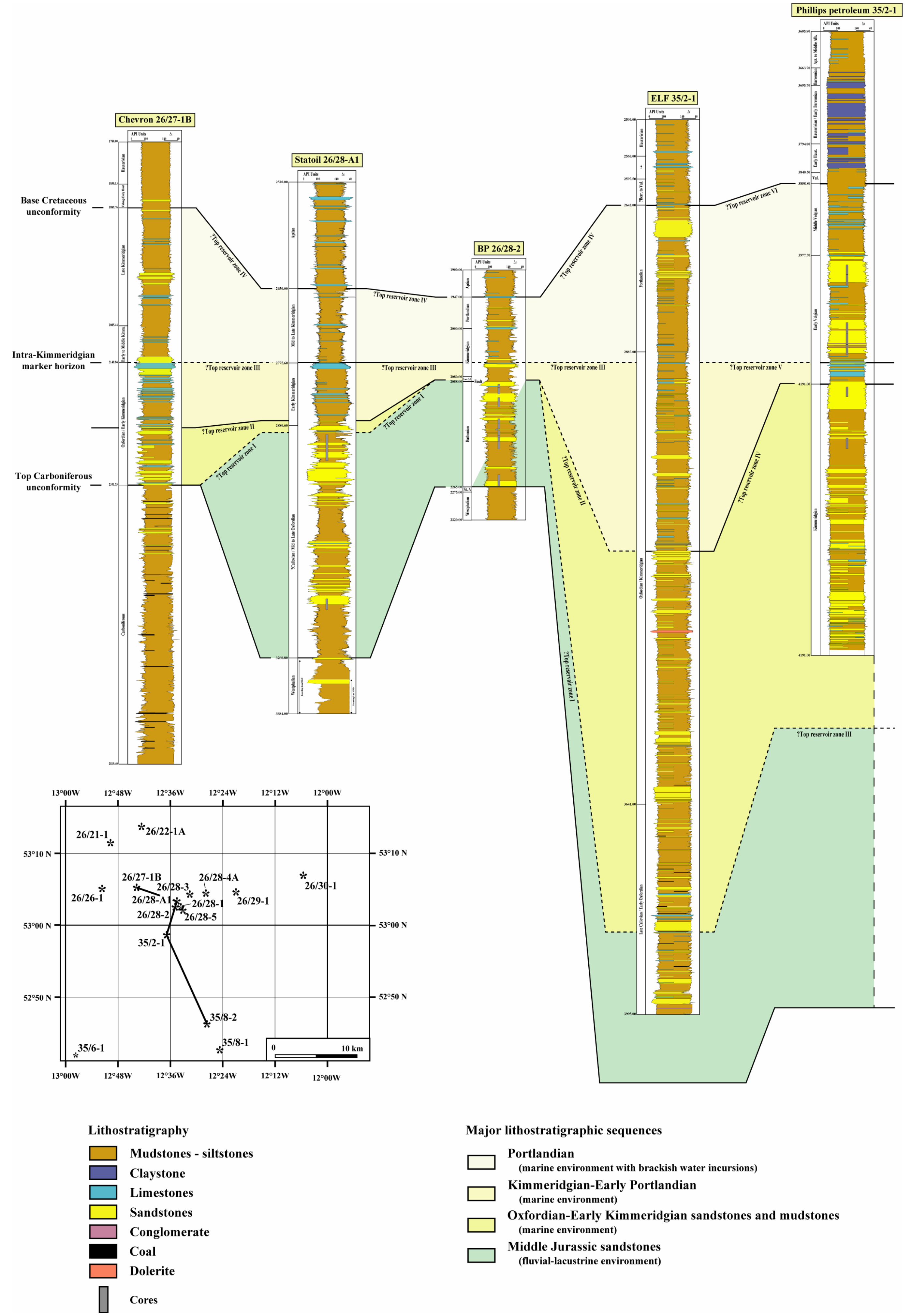


***Fig. 5:* Wireline log correlations of wells drilled in the *Connemara* and *Spanish Point* oil accumulations**

The wireline correlations are based on the recognition of the lithostratigraphic packages identified in some of the wells drilled in the Block 26/28 [fig. 4]. Position of the wells is indicated on the map. See text for explanation.

Table 1: Reservoir zones and simplified associated biostratigraphy in the wells of Block 26/28 (after Harvey _et al._ , 1990)

Stages	Zones	microfossil assemblages	Deposition environments	
Bathonian	**Zone Ia**	Rich microfossil assemblages, with microfaunas and palynofloras impoverished	Alluvial	**Fluvial / Lacustrine**
	Zone Ib	Significant abundances of bissacate pollen _Cerebropollenites mesozoicus_ _Callialasporites dampieri, minus, microvelatus, turbatus_ Low abundance of pteridophyte spores _Deltoidospora_ spp. _Densoisporites velatus_	Fluvial / Lacustine	
	Zones Ib - Ic	Freshwater alga _Botryococcus_ spp. together with freshwater microplankton High abundance of plant articles Abundance of freshwater ostracods _Darwinula_ spp. _Bisulcocypris tenuimarginata_ * , _ancasterensis_ *	Swamp / Lacustine	
Upper Oxfordian	**Zone II**	Evidence of dinocysts and ostracods in the Oxfordian _Rosenkrantzi_ amonite zone _Occisycysta balia_ Evidence of non-marine/marine oastracods _Galliaecytheridia dissimilis_ * _Darwinula_ spp. Some evidences of freshwater to brackish charophyte oogonia	Coastal plain to restricted marine	**Marine restricted (close to the shore) to shallow marine**
Upper Oxfordian to Lower Kimmeridgian	**Zone III**	Rich in palynofloras and microplankton _Gonyaulacysta jurassica_ * _Systematophora_ spp. _Leptodinium subtile_ _Lithodinia/Sentusidium_ plexus _Histiophora/Epiplosphaera_ plexus _Scriniodinium crystallinum_ Small gasteropods, foraminifera and oestracods	Shallow marine	
Upper Oxfordian to Lower Kimmeridgian	**Zones II - III** (similarities)	Significant abundance of gymnosperm pollen _Callialasporites_ spp. _Cerebropollenites mesozoicus_ _Perinopollenites elatoides_ Low to high abundance of pteridophyte spores Variable abundance and diversity of microfaunas	Coastal plain to shallow marine	
Lower / Late ?Kimmeridgian to Middle Volgian	**Zone IV**	Evidence of dinocysts in the Middle Volgian _Okusensis_ - _Rotunda_ and lower Kimmeridgian ammonite zones _Muderongia_ sp., _Valensiella_ & _Epiplosphaera_ spp. Very high abundance in microplankton (dominant) _Rhynchodiniopsis cladophora_ _Glossodinium dimorphum_ _Systematophora_ _Cribroperidinium_ _Sentusidinium_ Rich in diverse marine palynofloras _Subtilisphaera inafecta_ * , _paeminosa_ * _Gonyaulacysta jurassica*, dangeardii_ _Pterospermella aureolata_ _Ctenidodinium chondrum_ Significant abundance in gymnosperm pollen _Callialasporites_ spp. _Perinopollenites elatoides_ _Cerebropollenites mesozoicus_ _Classopolis torosus_ Significant abundance in abraded plant cuticles and structured humic plant debris Significant abundance of microfaunas _Eoguttulina_ spp. _Epistomina parastelligera_ * _Lenticulina muenteri_ Ophiouroid ossicles Echinoid spines Fish teeth Glomospira spp. Gasteropods	**Open marine**	

* indicates the species which are plotted on Figure 4

- **Second order unconformities:**

Other unconformities have been defined by analysing some reprocessed 2D and 3D seismic lines. In particular, an intra-Kimmeridgian reflector (probably of Mid-Kimmeridgian age) can be followed regionally and is interpreted to represent a major flooding surface. This probably corresponds to the initiation of a major rift phase.

Furthermore, the top of a sandy sequence of Oxfordian to Early Kimmeridgian age can be mapped on the reprocessed seismic data. The top of this sequence is marked by an erosion surface, which may correspond to the uplift preceding the Late Jurassic rifting phase in the basin (*i.e.* the BOU defined by Bulois & Shannon [2006]). The uncertainty on the age could be the result of a variable erosion phase, expressed by the remobilisation of the sediments in some places and the deposition in others. As a result, an irregular surface was created and tends to be flatten with prolonged erosion.

3.1.b – Jurassic sedimentary sequences:

The Jurassic succession, of variable thickness largely due to Early Cretaceous erosion, is bounded by the TCU and the BCU. Four main Jurassic sequences (named Zone I to Zone IV) have been recognized on the basis of their lithofacies characteristics as well as some characteristic biostratigraphic markers used to define their ages [Fig. 4].

- **Zone I (Bathonian):**

Middle Jurassic (?Bajocian to Bathonian) strata (*i.e.* Zone I) were encountered in most of the wells, with the exception of the well 26/28-5 in the *Connemara Oil Accumulation* and in the Quadrant 35 further South, as the wells were not drilled deep enough. In general, the sequence is composed of an alternation of thick sandy beds and muddy material deposited in a continental setting. Conglomerates have also been recorded toward the base of the sequence. A number of coarse to fine grained sandy beds shows slump structures and small channels associated with cross-laminations [Fig. 6]. These features suggest a medium to low energy fluvial system.

In detail, two main depositional phases can be distinguished on the basis of the occurrence and thickness of the sandstone strata. The base of the sequence is generally composed of thick (5 to 10 m) sandstone layers whereas, at the top of the sequence, thinner layers are generally recorded. The general fining-upward sequence was probably controlled by rising base level. Thus, a high energy braided system is suggested toward the base of the sequence, whereas the top of the sequence indicate a lower-energy system typical of a meandering river domain. Calcrete deposition has also been described in some of the well reports, testifying to a shallow lake domain or a very low-energy river system with water level variations. Overall, the river system tended to lose energy over the Middle Jurassic, in parallel with the installation of a lake in the south.

In Block 26/28, biostratigraphy data [Athersuch *et al.*, 1983; Harvey *et al.*, 1990] were used to constrain in more detail the depositional evolution through the Middle Jurassic. Three subzones (Ia to Ic) [Tab. 1] were defined, and the general picture is probably similar to a fluvial/alluvial system evolving in close proximity to a lake domain [Tab. 1]. Zone Ia is a mud-dominated alluvial plain, with probable sub-aerial exposure. It passes upward to a more distal environment with the development of low-medium energy fluvial channels and, down to the South, to the installation of an early lake, or at least, swamp domain [Fig. 6b]. The lacustrine transgression continued during the entire deposition of the Zone Ic, which is mainly composed of lacustrine mudstone, with periodic coarse sediment incursions.

In the North Porcupine Basin, well 26/22-1A penetrated a similar sandstone-mudstone succession associated with thin coals, deposited at the same level as the Bathonian sediments of Block 26/28. Core 2 recovered coarse grain sandstones, overlying by siltstone and thin mudstone deposits, suggesting an alluvial plain passing to a higher-energy fluvial environment. However, coal might be related either to a reorganisation of the drainage system or a change in base level (*i.e.* infilling(s) of old, unused or dying river meanders; floodplains-related with close proximity of abundant shallow lakes, or maybe associated with a delta plain setting), suggesting then a lower-energy system than further south, in the Porcupine Basin.

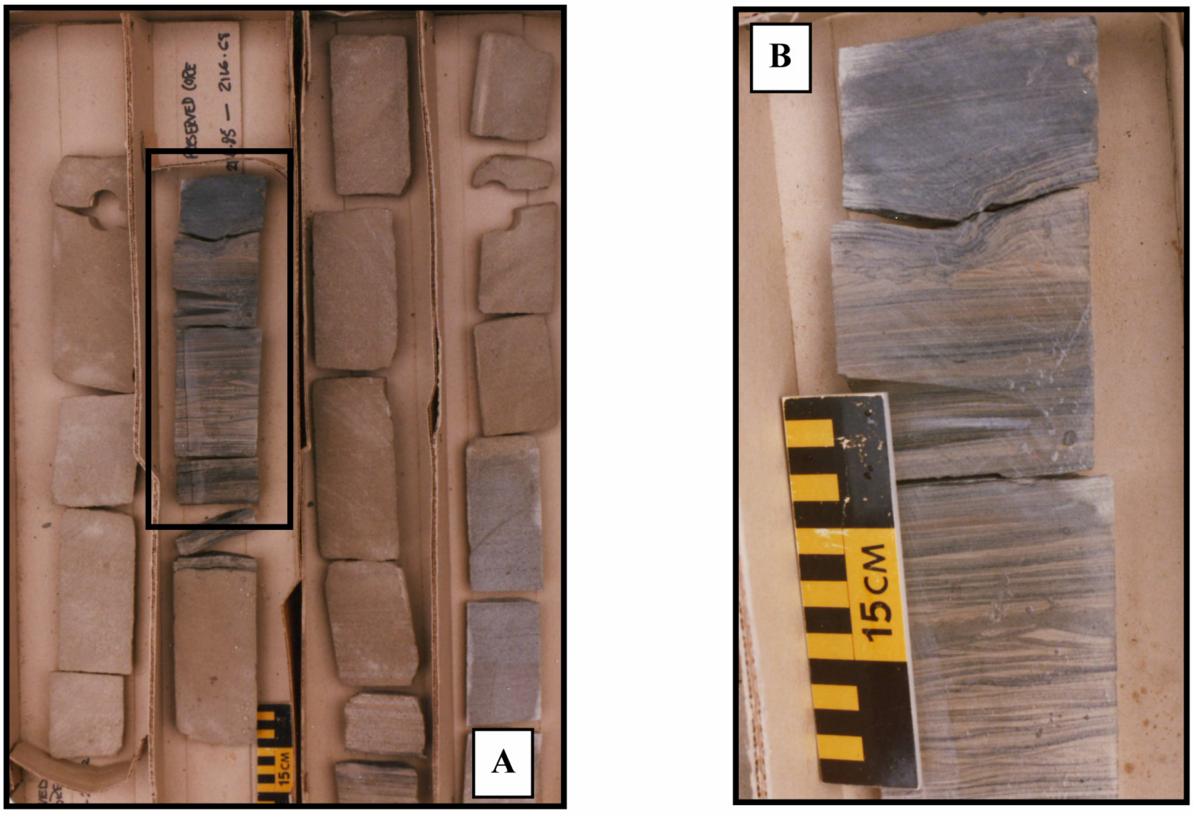


Fig. 6: **Example of typical facies and associated sedimentary structures of the Bathonian unit recovered in core 4 of the well 26/28-2 (zone I)**

A- core photograph representing the alternation sandstone / laminated sandstone in the depth interval 2116.68-2120.01 m (boxes 3 and 4). The black box represents the location of the photograph 5B. ***B-*** Detailed core photograph shows slump strucures, small channels and ripples in laminated sandstones at the depth of 2116.85 m.

Variations in the thickness of the Middle Jurassic succession [Tab. 2], suggest that deposition was driven mainly by the accommodation of sedimentation space available during this period (*i.e.* subsidence of the basin floor) and the paleo-topography. In other words, the lateral variation is thought to result from a passive infilling driven by the creation of Late-Triassic/Early Jurassic half-graben (well 26/28-1 and 26/28-4A), combined elsewhere with a subsequent differential erosion phase acting on these fault blocks during the Late Bathonian to Callovian time, and potentially during the very Early Oxfordian time.

- **Zone II (Oxfordian-Early Kimmeridgian):**

Recognized in most of the wells, Zone II is composed of Oxfordian to Early Kimmeridgian strata, consisting in sandstones of variable thickness, intercalated with siltstones and mudstones [Fig 4 and 5]. Occurrences of limestone material (?mostly calcrete) are also characteristic of this sequence. The

Table 2: **depths in meters of the Jurassic reservoir zones in Block 26/28 (*after* Harvey *et al.* , 1990)**

	26/28-1	26/28-2	26/28-3	26/28-4A	26/28-5	Age
Zone IV	1955	1947	1837	1065	1990	Midle Volgian
Relative thickness	*213*	*103*	*172*	*767*	*673*	Lower Kimmeridgian
Zone III	2168	2050	2009	1832	2663	Upper Oxfordian
Relative thickness	*78*	*38*	*123*	*136*	*90*	Kimmeridgian
Zone II	2246	-	2132	1968	2753	Oxfordian
Relative thickness	*94*		*87*	*151*	*> 57*	
Zone Ic	2340	-	2219	2119	-	
Relative thickness	*42*		*31*	*80*		
Zone Ib	2382	2088	2250	2199	-	Bathonian
Relative thickness	*241*	*65*	*118*	*125*		
Zone Ia	2623	2153	2368	2324	-	
Relative thickness	*112*	*112*	*28*	*56*		

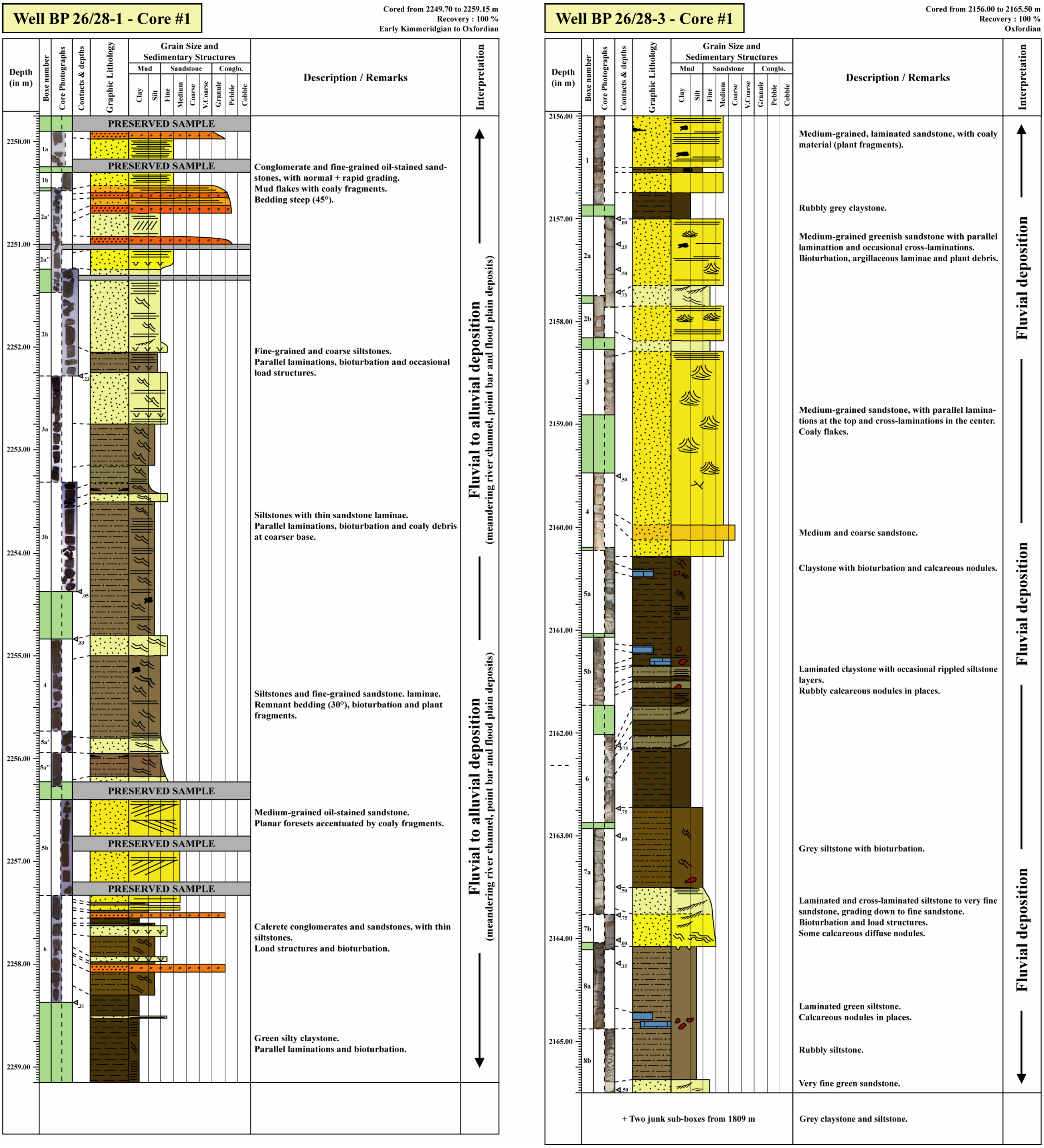


Fig. 7: **description of cores drilled in the Zone II (Upper Oxfordian to Early Kimmeridgian).**
The core log are based on photographs interpretation, supported by core description made by P.M. Shannon. Position of the wells is indicated on figure 2. Core position in the vertical sedimentary succession can be seen on figure 4.

succession is interpreted as a coastal/estuarine plain in most of the area. However, in detail, biostratigraphic data suggests a non-marine basal portion becoming marine for the rest of the sequence. There is a variable abundance of freshwater to brackish species, such as *Galliaecytheridia dissimilis* recovered in various wells [Tab. 1 and Fig. 4], indicating a depositional environment relatively closed to the shore. Thus, a fluvial system probably drained the entire area into a freshwater to brackish lake, with periodic connection(s) to marine water.

A number of cores penetrated Zone II, especially in the Block 26/28 area [Fig. 7]. In the north of the area (core 1 of BP 26/28-3 well), an assemblage of thick laminated claystones and siltstones with cross-laminated sandstones testify to a clear fluvial deposition environment, whereas marine fossils are less abundant, or even absent. Further south (core 1 of BP 26/28-1 well), the succession tends to show a more alluvial character, with meandering river channels, point bar and flood plain deposits, suggesting thus a lower energy domain. Occasional marine incursions in this area are also possible. A similar configuration has been observed in core 2 of BP 26/28-5 well. The bottom part is mud dominated with planar lamination and load structures. In some places, there are some well developed limestone beds, which tend to be restricted to calcareous flakes in others. Fine grained sandy materials have also been recorded and show some characteristic ripples and sometimes some occasional cross-laminations. Overall, this suggests a distal floodplain. The top of the core recovered thick medium-grained sandstones with conglomerates in some places. These show occasional planar laminations, sometimes some cross-laminations and erosive bases, so that this overall sequence is interpreted to have been deposited in a more in-channel fluvial environment.

Similarities of sedimentary features in other wells show that Zone II extends clearly toward the east (wells 26/29-1 and 26/30-1) and the north-west (wells 26/28-A1, 26/27-1B and 26/22-1A) of the study area. The thickness is very variable [*e.g.* Tab. 2], suggesting that the deposition has been mainly driven by pre-existing (i.e. Middle Jurassic) topography. Furthermore, the Callovian sediments are probably absent over the most of Quadrant 26, as well as in wells 35/2-1 and 35/8-2. This suggests a localised to regional hiatus in sedimentation, and is thought to be a consequence of an early discreet rifting phase. This took place during the Oxfordian and has been succeeded by a marine transgression. Clastic pulses show an unstable sedimentary domain, with readjustment of deposition accordingly to the topography together with the tectonics.

In the southern part of the basin [Fig. 5], the occurrence of sandstones is more prevalent. Well reports also describe reworking of Upper Westphalian material at the base of the well 35/2-1. This indicates that well 35/2-1 was drilled closed to the edge of the Jurassic Porcupine Basin, where there was exposure of Carboniferous strata. Assuming that the deposition is also fault-related in this area, tectonics helped to preserve by subsidence the sequence, whose the thickness can reach more than 750 m. Thus, fault movements in this area have been probably more important (*i.e.* vertical displacements) and led to the development of different depocentres. Further south, in the 35/8-2 area [Fig. 5], the thickness has decreased to 400 m. The clastic input in this area is higher than in the northern part of the basin. Well reports interpreted that succession as a very shallow marine depositional environment.

- **Zone III (Kimmeridgian):**

* Zone III, mostly of Kimmeridgian age, shows a similar setting throughout Quadrant 26 [Fig 4]. It is composed of thin siltstone-mudstone layers intercalated with characteristic limestone and dolomites layers, thicker and better developed than in Zone II. Figure 4 shows that the bottom of the sequence can be correlated throughout the entire area as it represents the end of thick clastic deposits. Similarly, the top of the sequence is marked by characteristic limestone layers, locally well developed or which can be followed as a strong reflector on 3D seismic data (*e.g.* in the Block 26/28). Occasional sandstones also developed throughout the area [Fig. 4 and 5], but the clastic pattern increases toward the north at the expense of limestone layers. It also appears that limestone layers are more prevalent toward the east of Quadrant 26, suggesting a deepening of the basin during the deposition. Thus, the whole sequence shows a marginal depositional setting and has been deposited under transgressive marine conditions. Micropaleontological data [Tab. 1] suggest some restricted marine conditions in most of Block 26/28, but slightly more marine than for Zone II situated underneath.

The sedimentary sequence in Quadrant 35 is different [Fig. 5], indicating a drastically different depositional environment than the north. Well 35/2-1 shows rare limestones with sandstone in beds developed extensively. Well reports indicate important reworking events over the Kimmeridgian period, supporting thus a rift episode through the Kimmeridgian for this area. In well 35/8-2, massive sandstones have been cored. They display a range of sedimentological features that indicate turbiditic deposition, which might have extended through the Zone IV. Thus the depositional environment is inferred to represent a submarine fan or slope, developed at the edge of an actively faulted basin.

Although the boundaries are unclear from place to place, the systematic difference in thickness, both in quadrants 26 and 35, indicates the formation of local depocentres. The sedimentary sequence recovered in the wells suggests a rapid deepening of the basin, as a result of an active Kimmeridgian rifting phase. It is suggested that fault movements controlled most of the marine transgression over the area and so, most of the sedimentation. Thus, Zone III is thought to be related to a major rifting phase which occurred during the Upper Jurassic. The rifting phase resulted in a marine transgression, probably in a regional manner as testified by the erosive base and the rapid change in the sedimentation between the Zones III and IV. Differential extensional movements along the faults may have led to the formation of local sub-basins.

- **Zone IV (Portlandian/Volgian):**

The final phase of deposition, consisting in Zone IV, took place especially during Portlandian/Volgian times, and perhaps since the Lower Kimmeridgian in some places. In the absence of correlation with the 3D dataset, the distinction from the underneath Zone III is based on the limestone signature as layers are thinner. Overall, the sequence is composed of thick mudstone and thin limestone strata, deposited in response to a rising sea-level throughout the Porcupine. The lower part of the succession is mudstone-dominated, indicating a low energy, deep environment of deposition with possible local deltaic deposits. A number of very thick sandstone layers developed in some areas [Fig. 4]. Interpreted as submarine fans, they reflect a rift-related deepening of the basin floor. Thus, the sandy layers can be related to differential erosion which occurred during rift pulses. Biostratigraphic data indicate an open marine environment with isolated brackish water incursions [Tab. 1].

The Portlandian/Volgian succession displays a dramatic thickness variation, probably as a result of the Early Cretaceous erosion (*i.e.* BCU) which truncates the upper part of the sequence. The effect of the BCU is also accentuated by the development of thick sandy units (e.g. 26/28-4A and 26/28-5). Sinclair *et al.* [1994] showed that the onset of block rotation was synchronous with a Late Kimmeridgian influx of coarse siliclastic debris in both alluvial and submarine fans. A similar association has been previously reported [Croker & Shannon, 1987; MacDonald *et al.*, 1987; Moore, 1992; Shannon, 1998]. Here, the late Jurassic sedimentation is thought to have been driven by tectonic subsidence of, first, submerged areas and, second, the whole domain. The variation in thickness has then been accentuated by the early fault-block architecture which tends to individualize sub-basins.

3.2 – Geological evolution:

Overall, two main mega-sequences can be identified and correlated through the region. The Middle Jurassic succession was deposited in response to a fluvial system, with north-south flow mainly driven by an earliest topography and a subsiding basin floor. The Upper Jurassic succession is characterised by an important phase of tectonism [Fig. 3], resulting in the development of various sedimentary environments developed in a regional sea-level rising. At a smaller scale, these two sequences are well developed in the Block 26/28 area [Fig. 2], and well constrained by biostratigraphic data. However, the basin architecture seems to be complex. The variation of thickness in the different zones [Tab. 2] suggests ***(1)*** the pre-existing Middle-Jurassic topography played an important role into the basin infilling and ***(2)*** the preserved Upper Jurassic deposition is a result of the combination of differential extension phases along several normal fault systems and the expression of the BCU. This has led to the development of sub-basins, evolving in a response to geological events of regional scale. Figure 8 presents a geological model of the Block 26/28 area for the Jurassic, based on the correlations presented in this report [Fig. 4] and constrained by biostratigraphic data [Tab. 1].

3.2.a - Discussion on the ages:

As a number of previous studies, the previous correlations [Bulois & Shannon, 2006] indicated a number of discrepancies in the ages from one well to another. A common hypothesis suggested suggested that biostratigraphic data were not reliable, particularly for reworking of older material into the Mesozoic (*e.g.* Carboniferous or younger) succession has been described in various wells [Athersuch *et al.*, 1982; Smith & Higgs, 2001], and published correlations showed a number of inconsistencies in the Jurassic column. However, Harvey *et al.* [1990] proposed a number of correlateable species over the Block 26/28 of the Porcupine Basin. There were reviewed as part of the present study, and the ages given by the well reports can be reviewed as follow:

- **Zone I:**

The Middle Jurassic succession is considered to be mostly of Bathonian age. A possible Callovian age has been given to some strata in the well reports [Fig. 3] but, as Harvey *et al.* [1990] noted, non-marine Callovian strata are regionally rare. Similarly, they concluded that miospores reflect an age no older than Bajocian. They reviewed a number of palynological species, and concluded that zones I to III are entirely non-marine throughout the study area. Freshwater ostracods such as *Bisulcocypris spp* (*B. tenuimarginata* and *B. ancasterensis*) have been plotted here as correlateable markers and are characteristic of strata developed during the Bathonian. *Darwinula spp.* have also been recorded in abundance, but do not represent correlateable markers as they have been also identified in Zone IV suspected of Oxfordian age.

- **Zones II and III:**

Zones II and III are thought to be of Oxfordian to Lower Kimmeridgian age. As indicated by Harvey *et al.* [1990], no positive micropalaeontological or palynological evidence is encountered to indicate the occurrence of Callovian to middle Oxfordian sediments. Various correlative microfaunal markers have been identified, but are very variable in abundance. In Zone IV, *Galliacytheridia dissimilis* are often associated with non-marine oestracods such as *Darwinula spp*, testifying to a slow and localised marine transgression with freshwater incursions. Other occasional microfossils occurrences support this interpretation. Nevertheless, the top of *G. dissimilis* should indicate an age no older than Upper Oxfordian but has been identified in strata of Kimmeridgian [Fig. 4], so that part of Zone IV is thought to contain some reworked material. Zone III is richer in palynofloras and microplankton of Upper Oxfordian to Lower Kimmeridgian ages, such as the correlative marker *Gonyaulacista jurassica*. They indicate a strictly marine depositional environment.

- **Zones IV:**

The various wells recovered a rich and diverse marine palynofloral assemblage with the exception of the sand unit were the species become severely reduced. Zone IV shows an abundance of microplankton whose youngest date is middle Volgian. However, another correlateable level of *G. jurassica* has been proposed by Harvey *et al.* [1990] and indicates that the base of Zone IV is of Kimmeridgian age. Similarly, other characteristic palynofloras such as *Subtilispharea inaffecta* and *Subtilisphaera paeminosa* enable the identification of Kimmeridgian sediments in some wells. A significant abundance of marine microfaunas such as *Epistomina parastelligera* are of correlateable value [Fig. 4]. Although most of species show a characteristic marine environment, there is also a characteristic assemblage of freshwater/quasi-marine oestracods in the well 26/28-5, which reflects an increase of freshwater in the basin.

It appears that the ages, given by the biostratigraphic data, are robustly constrained over the study area and fit well with the lithostratigraphic packages previously identified. However, some complications can be anticipated in the Portlandian/Volgian succession where some species are mixed with others evolving in different environments. Thus, the rifting phase(s) might have played an important role in the reworking microfauna.

3.2-b: Deposition model:

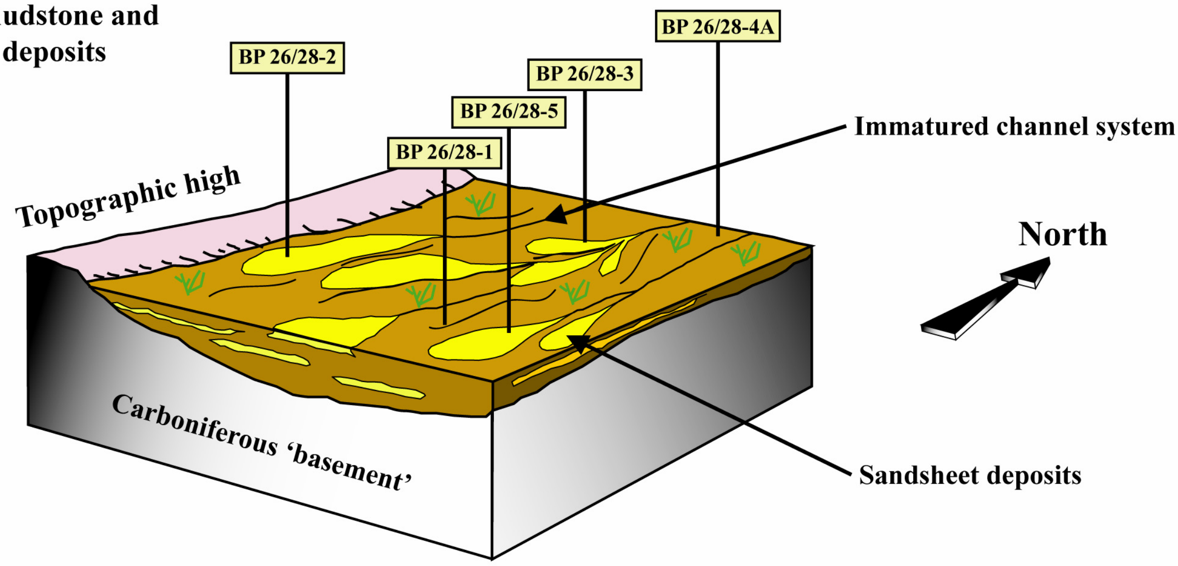
Figure 8 represents a geologic model of the Jurassic Porcupine Basin, for the specific area of Block 26/28. It is based on the correlations proposed on Figure 4 and is supported by the biostratigraphic data described above. Two main periods can be distinguished:

- **Middle Jurassic succession (Zone I):**

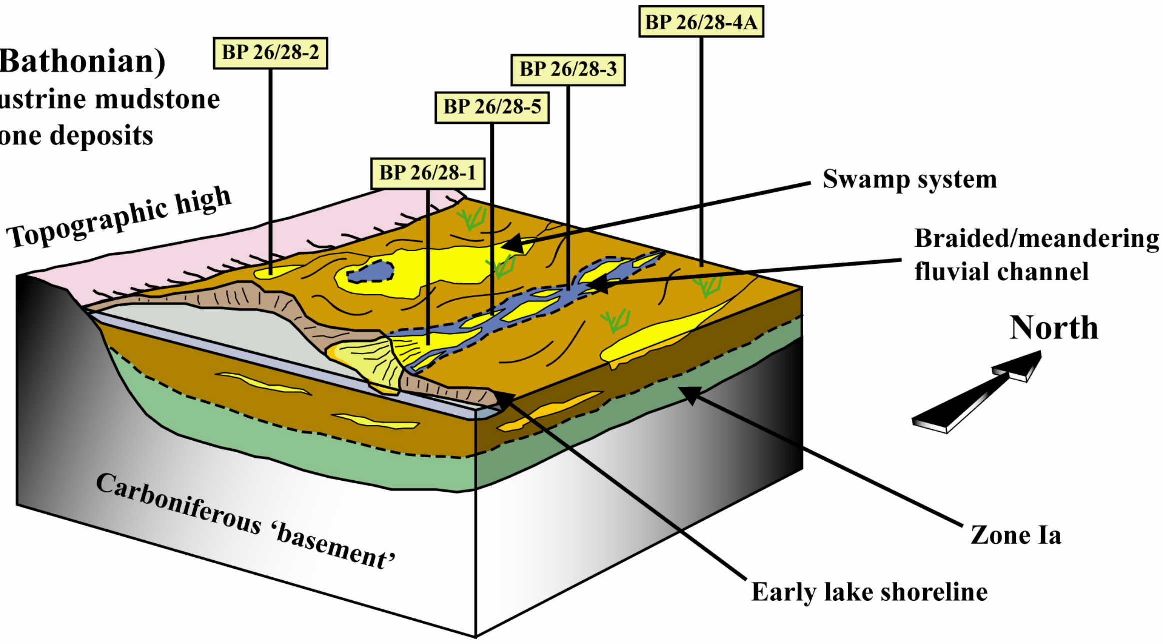
The Middle Jurassic strata (Zone I, divided in subzones Ia to Ic) were deposited during the Bathonian, in a terrestrial environment corresponding in general to meandering and/or braided channels, which tend to

Fig. 8 (next pages): **Schematic evolution of the Jurassic Period in the Block 26/28 of the Porcupine Basin.**
A- Evolution for the Bathonian succession (subzones Ia to Ic), showing a thermal subsiding basin and the development of associated sedimentary deposits. ***B-*** evolution for the Oxfordian to Portlandian/Volgian succession (zones IV to VI), showing sedimentary depositional processes in a rifted basin. These reconstructions are based on the well correlation presented in figure 4 and are constrained by occasional cores and biostratigraphic data (mostly from Harvey *et al.* [1990]). See text for explanation.

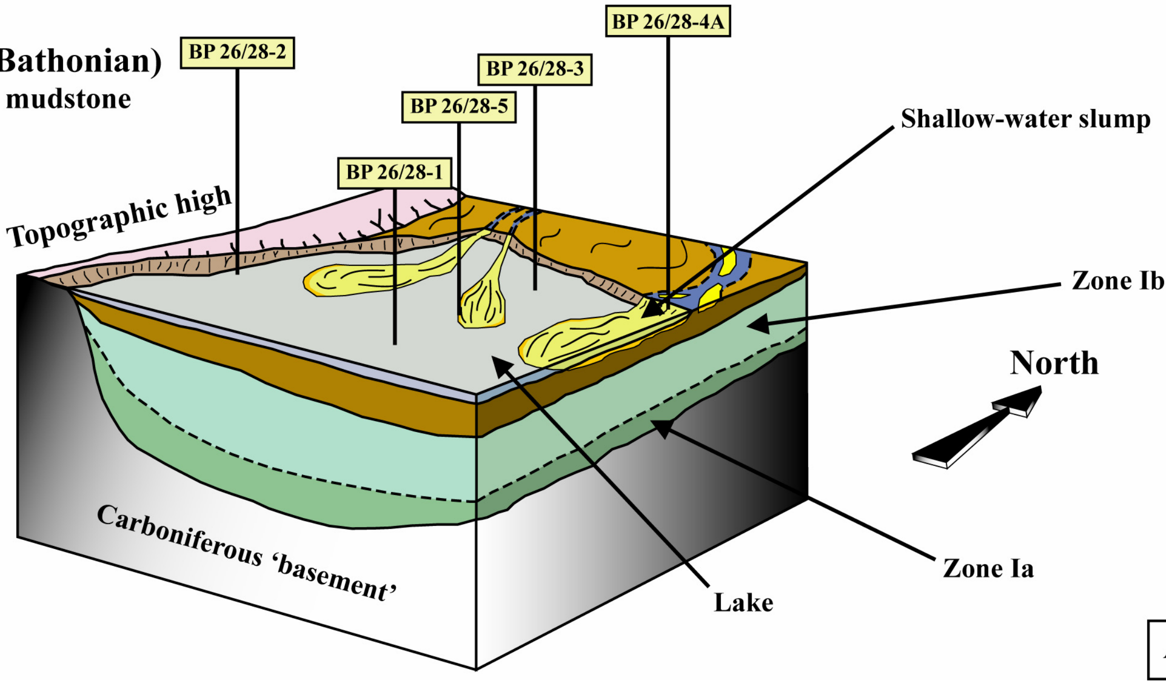
Zone Ia (Bathonian)
Alluvial mudstone and sandstone deposits



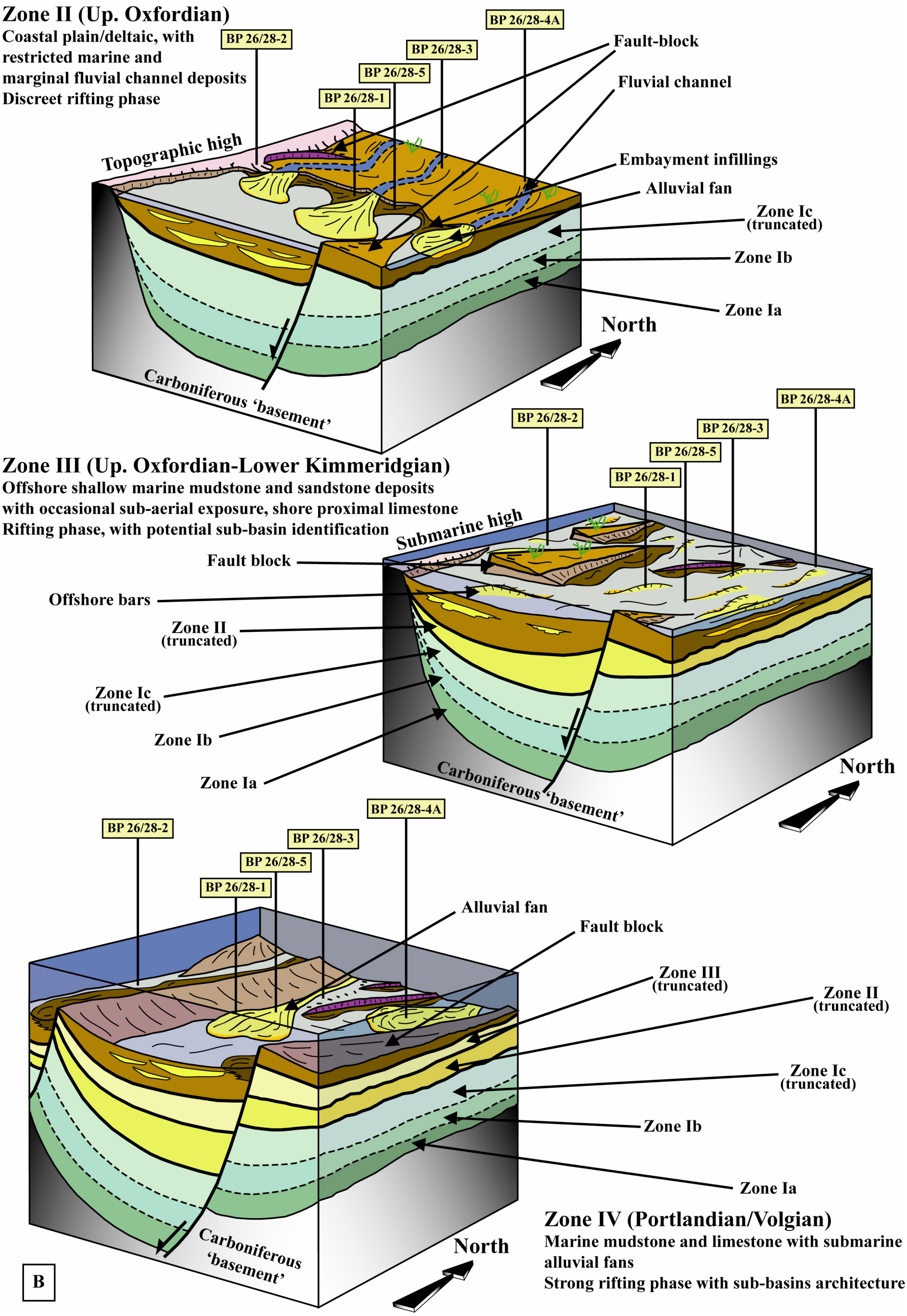
Zone Ib (Bathonian)
Fluvial-lacustrine mudstone and sandstone deposits



Zone Ic (Bathonian)
Lacustrine mudstone deposits



A


Zone II (Up. Oxfordian)
Coastal plain/deltaic, with restricted marine and marginal fluvial channel deposits
Discreet rifting phase
BP 26/28-2
BP 26/28-4A
BP 26/28-3
BP 26/28-5
BP 26/28-1
Fault-block
Fluvial channel
Topographic high
Embayment infillings
Alluvial fan
Zone Ic (truncated)
Zone Ib
Zone Ia
North
Carboniferous 'basement'
Zone III (Up. Oxfordian-Lower Kimmeridgian)
Offshore shallow marine mudstone and sandstone deposits with occasional sub-aerial exposure, shore proximal limestone
Rifting phase, with potential sub-basin identification
BP 26/28-4A
BP 26/28-2
BP 26/28-3
BP 26/28-5
BP 26/28-1
Submarine high
Fault block
Offshore bars
Zone II (truncated)
Zone Ic (truncated)
Zone Ib
Zone Ia
North
Carboniferous 'basement'
BP 26/28-4A
BP 26/28-2
BP 26/28-3
BP 26/28-5
BP 26/28-1
Alluvial fan
Fault block
Zone III (truncated)
Zone II (truncated)
Zone Ic (truncated)
Zone Ib
Zone Ia
Zone IV (Portlandian/Volgian)
Marine mudstone and limestone with submarine alluvial fans
Strong rifting phase with sub-basins architecture
North
Carboniferous 'basement'
B

disappear toward the top the sequence to give place to a lacustrine domain. The three subzones are mainly composed of thick sandy sequences intercalated with mudstones. At the base, sandy deposits show some sandsheet characteristics, mainly in the subzone Ia, and potentially subzone Ib. At the top, some shallow-water slump (possibly turbiditic) indicates a change in sedimentary transport and deposition. Thus, toward the top of the sequence (part of zones II and III), the depositional environment shows a clear invasion of fresh water, resulting progressively in the communication with a fresh-water lake [Fig. 8a]. This general pattern is correlated with biostratigraphic data [Tab. 1].

The model presented here assumes that the Block 26/28 area was a localized depositional basin during the Bathonian. The sedimentary thickness varies laterally, with a main depocentre in the central part and a thinner sequence in proximity of the edge of the basin. Such a geometry would be expected due to the downward warping of the basin floor, either under the load of the sedimentary column or the thermal cooling and contraction of the continental crust from earliest rift phases (*i.e.* sedimentary subsidence *vs* thermal subsidence) [*e.g.* Croker & Shannon, 1987; Sinclair *et al.*, 1994; Doré *et al.*, 1999]. Furthermore, the development of local calcrete in the central part of the basin (wells 26/28-1 and 26/28-3) indicates the formation of proto-soils. Therefore, the basin subsidence is thought to be more rapid in a way toward the centre of the basin and enabled the development of a proto-lake which tend to be well developed toward the end of the Bathonian. Moreover, the deposition is probably controlled by the earliest topography of the basin floor, consisting in Triassic to Early Jurassic fault-blocks. The erosion of these fault-blocks nourished partially the sedimentary deposition, driven by a N-S river system. Thus, the Middle Jurassic sedimentation results from the interplay between sediment supply (clastic influx) and the accommodation space.

- **Upper Jurassic succession (zones II to IV):**

The Upper Jurassic succession (*i.e.* deposition of zones II to IV) is characterised by an important phase of tectonism [Fig. 3]. It results in the development of a broad range of sedimentary environments, passing from brackish waters toward a marine setting as a response to a regional sea-level rise [Tab. 1 and Fig. 8]. The base of the sequence, Zone II, was deposited during the Oxfordian to Early Kimmeridgian. It is sandy-dominated, with thin mudstone layers, and interpreted as a coastal plain deposit. Biostratigraphic information shows a stronger influence of marine waters than the underlying zone, but was dominated by non-marine species. Thus, a first marine transgression, localised in appearance, took place during the Oxfordian. It was probably driven by a slow and localised early rifting phase, but most of the sedimentary control, both in terms of nature and thickness, is probably due to the topography of the basin floor (*i.e.* Middle Jurassic topography and the erosion phase during the Callovian). Similar processes occurred schematically for the deposition of zones III and IV.

Thick mudstone-siltstones layers associated with characteristic limestones, occasionally dolomitized, developed during the Upper Oxfordian to Lower Kimmeridgian (Zone III), and maybe even until Middle Kimmeridgian in some places. The development of Zone III is related to a marginal marine environment and testifies to a general deepening of the basin. During this period, individualization of fault-blocks probably led to a localized sub-basin depositional architecture.

A similar configuration continued during the Portlandian/Volgian (Zone IV), with some complications in places with the development of thick submarine fan systems (well 26/28-4A and 26/28-5). The clastic inputs are thought to be the result of erosion phases related to rift pulses. Sub-basins were filled in by a marine sedimentary sequence, in response of a generalized sea-level rise.

3.3 – Conclusions:

Four sedimentary zones have been correlated regionally, based on an analysis of the wireline response, as well as the sedimentary features and the biostratigraphy species recovered in occasional cores and cuttings [Fig. 4 and 5]. They show a progressive evolution from a terrestrial deposition toward an open marine sedimentation. The scales of these zones, over several km, indicate major sedimentary controls of regional extent [Fig. 3]. The Bathonian sedimentary succession reflects a base-level rise, probably due to thermal subsidence. The Upper Jurassic sedimentation was controlled by extensional faults in a marine transgression setting. However, in details, factors of secondary order complicated the geological evolution of the Porcupine Basin. Thus, the Bathonian deposition was controlled by the earlier topography of the basin floor (*i.e.* ?pre-Middle Jurassic)

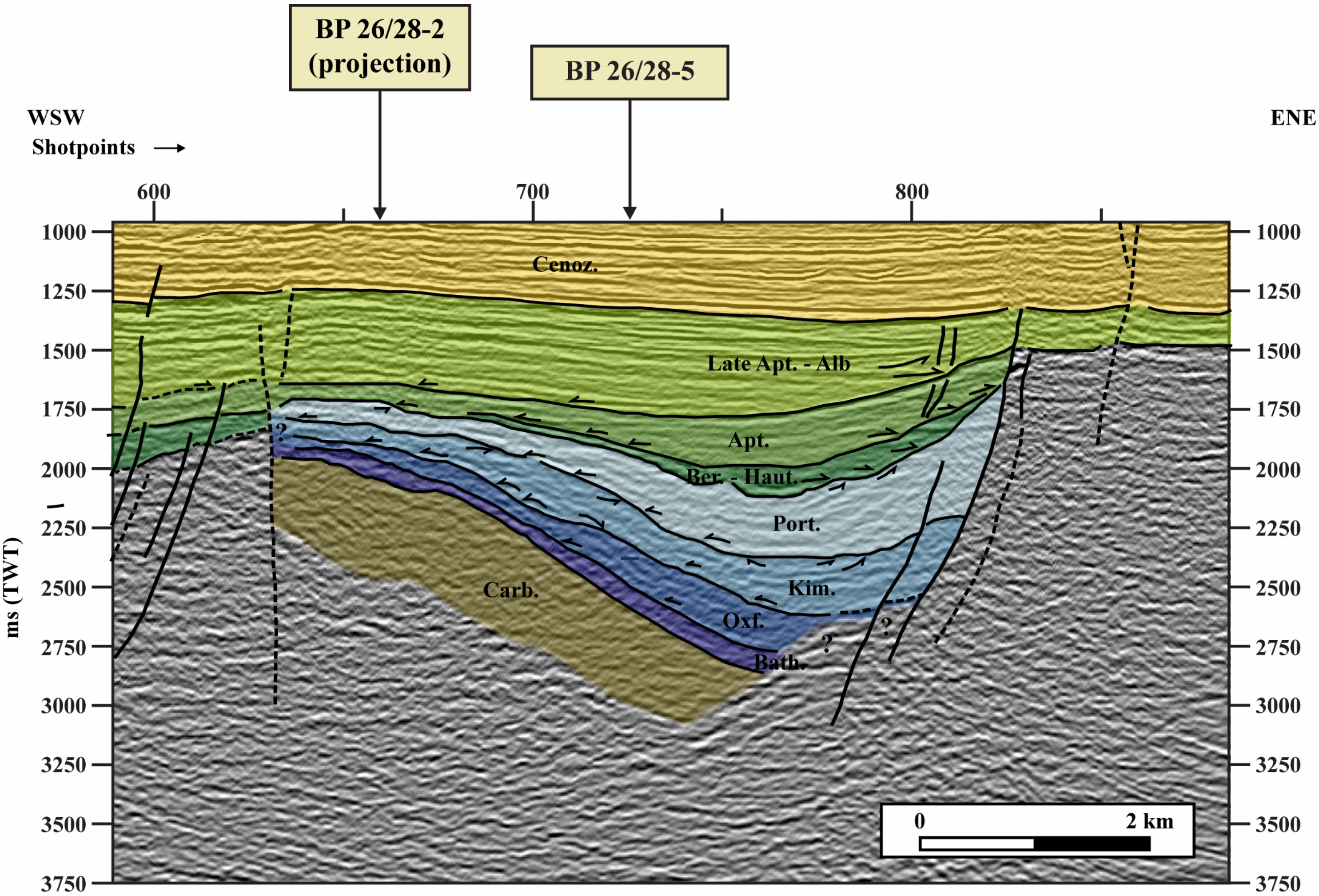


Fig. 9: **geometry of the main unconformities in the Block 26/28**

whereas, during the Upper Jurassic, the marine transgression was forced by localization of diachronic extension phases along specific fault zones. As a result, the sedimentary succession differs from place to place, in terms of thickness and sometimes lithofacies. At a smaller scale, the southern part of the basin has experienced such variations, as shown for the Block 26/28 area [Fig. 8]. Rift tectonics led to the development of individual sedimentary sub-basins. However, in the absence of high resolution biostratigraphic data, we are still unable to constrain properly the ages of the geological processes at the scale of the whole study area, so that depositional settings could more complicated than described above [Fig. 8].

This evolutionary scenario is consistent with the seismic interpretation (see below), which showed a number of unconformities in the Upper Jurassic succession (respectively Oxfordian, Kimmeridgian and Portlandian) [Fig. 3 and 9].

4. Seismic record and tectonic features in the northern part of the Porcupine Basin:

Several Carboniferous to Recent seismo-stratigraphic packages were broadly described in the First Annual Report [Bulois & Shannon, 2006]. Five to six of them corresponded to the Mid- to Upper Jurassic succession, deposited in response of regional active tectonism. In several places, a number of unconformities has been recognized and suggest that the Porcupine Basin developed in response to several Jurassic rift episodes. During the past year, the analysis of new 2D seismic data enabled a better understanding of the geology at regional and local scales. Four seismo-stratigraphic packages are identified and correspond to the lithological correlations described above [Fig. 9]. They are separated by a number of, associated with characteristic growth-faulting. Three main rifting events, of Oxfordian, Kimmeridgian and Portlandian/Volgian ages, are suggested.

4.1 – Description of the Jurassic sedimentary column:

The analysis of the seismic lines shot during the surveys IR80 and PW93 [Fig. 2] enable the recognition of several seismo-stratigraphic packages from fault-block to fault-block within the Quadrant 26 and further south. Figure 9 represents a typical rotated fault block in the *Connemara Oil Accumulation*. The Mid to Upper Jurassic succession is composed of 4 packages, deposited in response to the geological processes described above. In a general way, the Bathonian succession does not show any growth faulting in contrast to the Oxfordian, Kimmeridgian and Portlandian/Volgian sequences. A number of unconformities, the BOU, BKU and BPU, are well identified and are thought to be related to discrete rift events of similar ages. However, there are a number of differences from fault-block to fault-block, indicating that the geological evolution of the basin is probably complex. The following description is specifically focussed on the Jurassic succession, both in the North Porcupine Basin and the north-eastern Porcupine Basin.

4.1.a – Middle Jurassic:

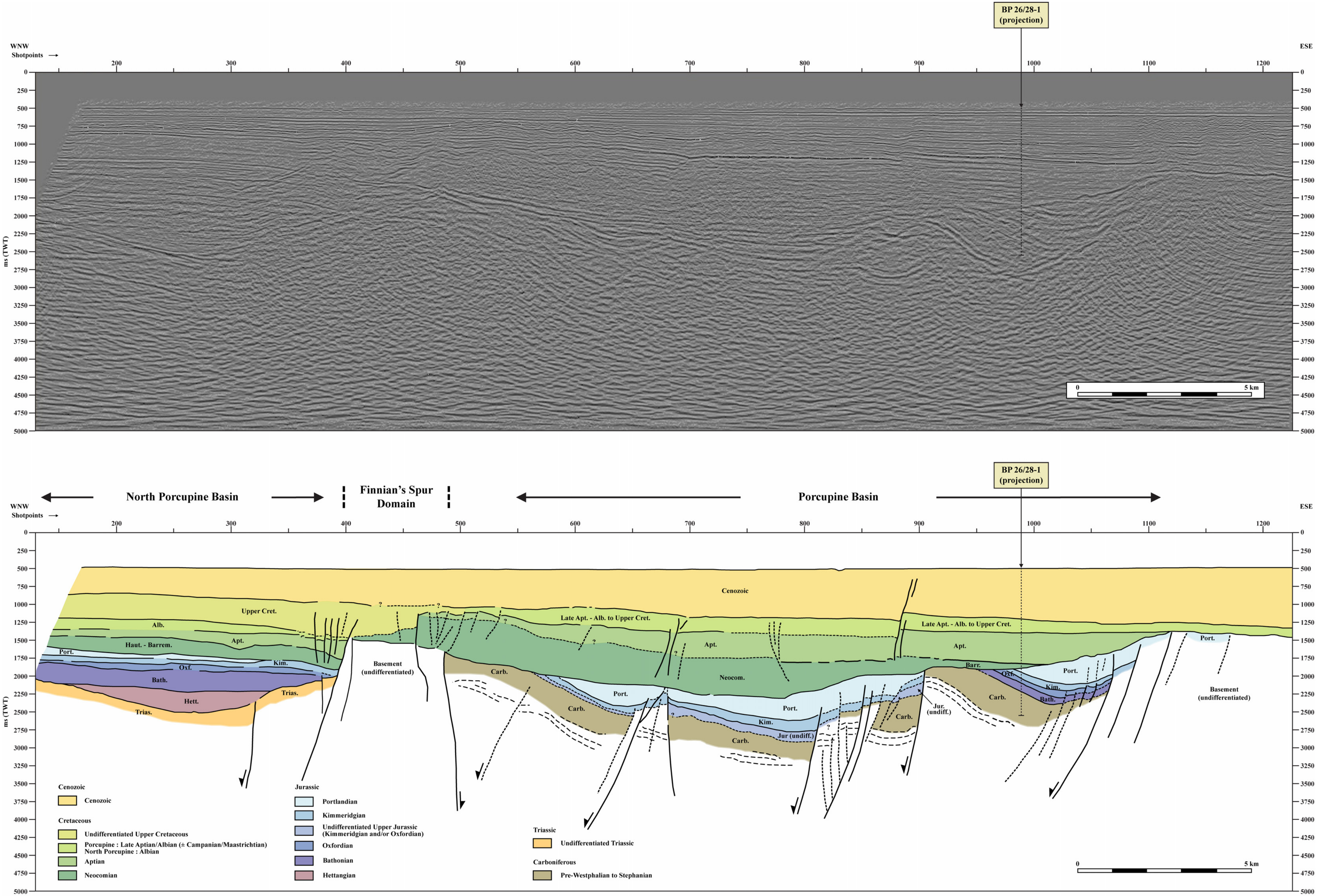
Middle Jurassic strata have been encountered throughout the northern part of the Porcupine Basin. In some areas, such as 26/28-1 and 2 [Fig. 10 and 11], they clearly overlie the Carboniferous strata. In others, like in the 26/27-1B area [Fig. 11], Middle Jurassic strata are absent, indicating thus either a non-deposition (edge of the Middle Jurassic Porcupine Basin) or an erosion phase during an early Late Jurassic rifting. Nevertheless, the absence of well control, together with the generally poor quality of the seismic response beneath 2750 ms TWT and the lack of difference in the seismic signature for these specific formations with the underlying Carboniferous succession, makes the occurrence of Middle Jurassic strata difficult to identify in the central part of Quadrant 26 [Fig 10 and 11]. In the North Porcupine Basin, Middle Jurassic strata are deposited unconformably on Hettangian and Triassic sediments [Fig 10]. They occur as homogenous layers which tend to thin toward the edge of the basin. These are consistent with an onset warp tectonic setting [Fig. 3]. Middle Jurassic strata are most likely of Bathonian age, although older sediments may occur locally above the Carboniferous-Early Jurassic topography. The Bathonian seismic package generally shows some strong sub-parallel, continuous reflectors of different amplitudes, together with some transparent (*i.e.* non-reflective) continuous zones, both in the North Porcupine and the Porcupine basins [Fig. 10 and 11]. Potential onlaps on the underlying Carboniferous strata can be seen in the Porcupine Basin [Fig 10 and 11], but the geological boundary between Carboniferous and Middle Jurassic strata is clearer as the top of the Carboniferous succession is markedly truncated by an early to Middle Jurassic sub-aerial erosion phase (*i.e.* TCU). In the 35/2-1 area [Fig. 12], Bathonian strata shows a similar seismic patterns.

The Bathonian strata are much thicker in the North Porcupine Basin than in the south of the Quadrant 26 [Fig 10 and 11]. This might imply a sub-basin architecture during the Middle Jurassic period, with two basins (*i.e.* North Porcupine and Porcupine) separated by the Finnian's Spur domain [Fig. 1]. Figure 12 shows a similar configuration of the Bathonian. The Bathonian strata are clearly bounded by a late Middle Jurassic to Early Oxfordian erosion surface (*i.e.* BOU), which may be the result of an Early Oxfordian rifting event. If the Middle Jurassic sediments were deposited in a gradual, but episodic transgression on a low relief, the thickness recorded is also a combination of the late peneplanation by the Early Oxfordian rifting (*i.e.* development of the BOU).

4.1.b – Late Jurassic:

At least three phases of rifting can be defined in the Porcupine Basin during the Jurassic period (Oxfordian, Kimmeridgian and Portlandian/Volgian), resulting in unconformities [*e.g.* Fig. 9]. The last Portlandian/Volgian unconformity is recognized everywhere in the study area as the most important rifting event, and is clearly associated with growth-faulting in most of the fault-blocks. The Oxfordian and Kimmeridgian unconformities are harder to distinguish and seem to correspond to more localized rifting events. Thus, figures 10 to 12 indicate that the record of these extensional events have been differentially recorded from fault-blocks to fault-blocks, as a result of various ages in growth-faulting.

Fig. 10 (next page): **Seismic line IR80-09 (Block 26/28 - Porcupine Basin).**
Arrows represent the throw direction along the major normal faults identified during the seismic interpretation. Position of the seismic section is indicated on Figure 2.


BP 26/28-1
(projection)
WNW
Shotpoints →
ESE
200
300
400
500
600
700
800
900
1000
1100
1200
ms (TWT)
0
5 km
North Porcupine Basin
Finnian's Spur
Domain
Porcupine Basin
Cenozoic
Upper Cret.
Alb.
Apt.
Haut. - Barrem.
Port.
Kim.
Oxf.
Bath.
Hett.
Trias.
Basement
(undifferentiated)
Late Apt. - Alb. to Upper Cret.
Neocom.
Carb.
Kim.
Jur (undiff.)
Barr.
Jur.
(undiff.)
Cenozoic
Cenozoic
Cretaceous
Undifferentiated Upper Cretaceous
Porcupine : Late Aptian/Albian (± Campanian/Maastrichtian)
North Porcupine : Albian
Aptian
Neocomian
Jurassic
Portlandian
Kimmeridgian
Undifferentiated Upper Jurassic
(Kimmeridgian and/or Oxfordian)
Oxfordian
Bathonian
Hettangian
Triassic
Undifferentiated Triassic
Carboniferous
Pre-Westphalian to Stephanian

- **Oxfordian:**

Oxfordian strata rest unconformably on Bathonian strata. They generally show some strong continuous reflectors which are onlapping Bathonian sediments, and are truncated by a probably Kimmeridgian age erosional surface (identified as the BKU) [Fig. 9].

The development of Oxfordian strata is associated with localized fault-block individualization. As a result, thicknesses vary from one fault-controlled sub-basin to the next. Figure 12 shows a typical variation of the thickness within the Oxfordian succession, with a 100 to 150 ms TWT thickness into the northwest passing to 40 to 50 ms TWT in the 35/2 area. In the 26/28 area [Fig. 10 and 11], approximately 50 ms TWT of Oxfordian strata have been recorded. Oxfordian strata can range from absent to depocentres containing up to 550 ms TWT in some fault-blocks.

In Block 26/28, evidence of growth-faulting is seen, especially toward the top of the Oxfordian succession. This indicates that the deposition took place in a discreet rifting phase throughout the study area. However, the extensional deposition setting of the Oxfordian is not identified everywhere, implying that fault-block creation resulted in a localized activity. Consequently, the development of the depocentres seems to be more important at the base of the hanging walls of contemporaneous fault structures. Oxfordian extension is clear toward the eastern part of the Porcupine Basin, with the development of sedimentary well-nourished fault-blocks [Fig. 12].

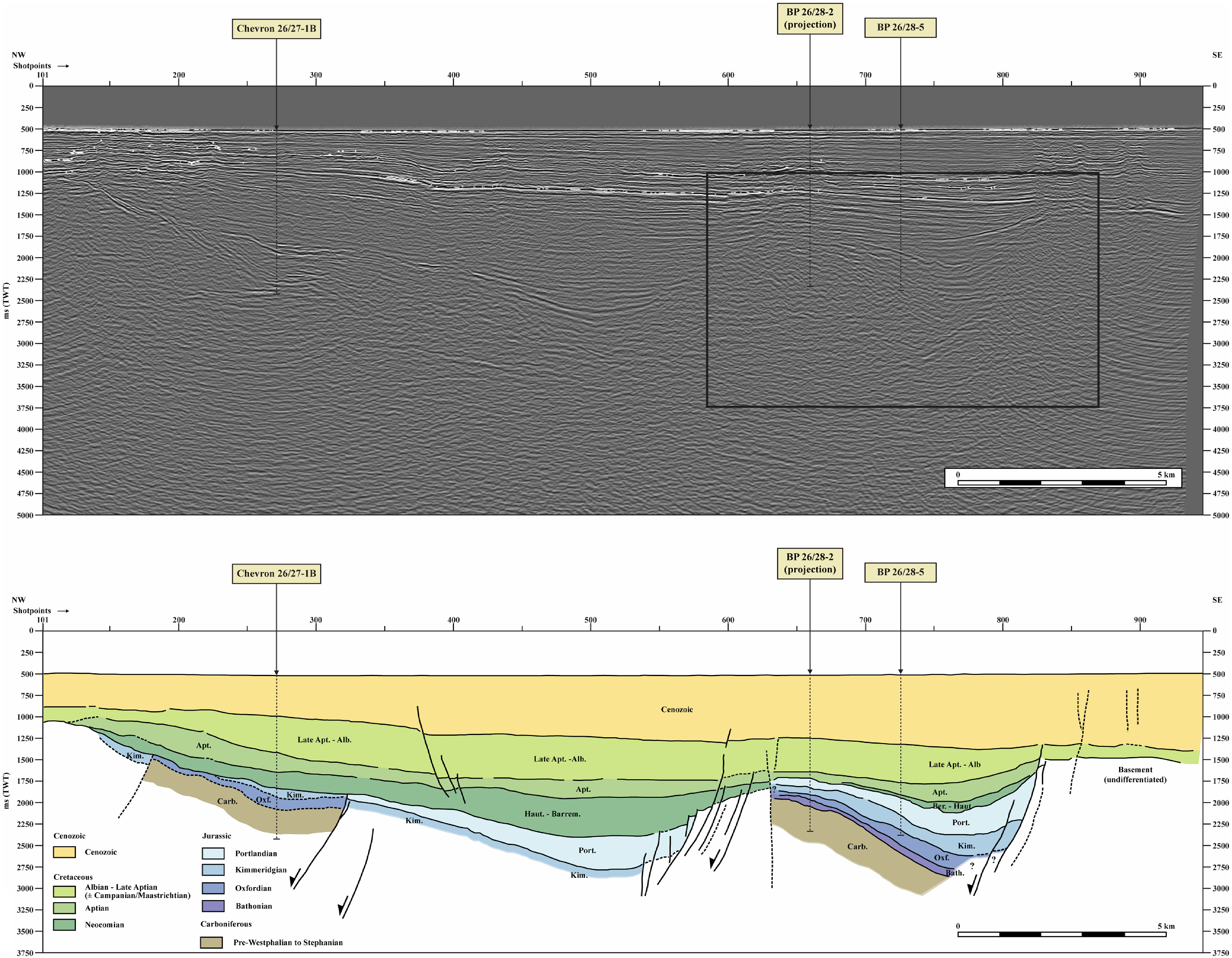
Oxfordian deposition in quadrants 26 and 35 took place in an early sub-basin setting, with deepening of the basin floor along active fault structures and potential flooding of local highs at the end of the Oxfordian.

- **Kimmeridgian:**

Kimmeridgian strata are well developed throughout the whole study area. The upper boundary is marked by the BPU, which is defined by truncation of the reflectors. Some strong, continuous reflectors occur within the succession, and are either onlapping or downlapping on the BKU [Fig. 10 and 11]. They locally show with more chaotic to transparent seismic facies. The Kimmeridgian thickness varies from less than 50 ms TWT into the north of Block 26/28 [Fig. 11] to more than 200 ms TWT in well 35/2-1 area [Fig. 12]. At a regional scale, a general thinning can be seen from east to west within the Kimmeridgian. This implies an uplifted margin in the northwest of the study area at that specific period. Several authors [*e.g.* Croker & Shannon, 1987; MacDonald *et al.*, 1987; Sinclair *et al.*, 1994] also indicated that the northwest edge of the basin was uplifted during this period. Moreover, typical growth-faulting characterises the Kimmeridgian sedimentary succession, which indicates a continuation of the earlier extension. However, the magnitude of growth-faulting seems to vary from one fault-block to the next, as a result of fault movement combined with the BPU erosion phase. In consequence, the incidence of fault structures might have been erased by later erosion, implying a kind of 'fault remobilisation effect' (underlined by transparent seismic facies). Specifically, the presence of the BPU at the top of the sequence testifies to an important truncation event which clearly differs from place to place.

Figure 12 shows that most of the Kimmeridgian sequence was controlled by active faulting, especially toward the northwest of the Block 35/2. If it is particularly clear within the western fault-blocks, it is harder to identify in the adjacent ones toward the east, and only minor growth-faulting has been recognized. In Block 26/28 [Fig. 10 and 11], the deposition is more clearly localized within particular fault-blocks, and sometimes only at the top of the Kimmeridgian sequence. Small extension is thus identified in the central half-graben and might be totally absent in some fault-blocks. However, the lateral variation of the Kimmeridgian succession is harder to identify, as if there has been either a smaller rate deposition or a remobilisation/erosion of sediments during the Portlandian (*i.e.* BPU) or later (*i.e.* BCU). In the well 26/27-1B area [Fig. 11], the Kimmeridgian succession has been partially eroded, probably by the Portlandian erosion phase (*i.e.* BPU) and then by the Early Cretaceous erosion phase (*i.e.* BCU). According to the well correlations, the early Kimmeridgian succession was deposited

Fig. 11 (next page): **Seismic line PW93-316 (Block 26/28 - Porcupine Basin).**
Arrows represent the throw direction along the major normal faults identified during the seismic interpretation. Position of the seismic section is indicated on Figure 2. Black box indicates the position of Figure 9.



Chevron 26/27-1B
BP 26/28-2 (projection)
BP 26/28-5
NW
SE
Shotpoints
101
200
300
400
500
600
700
800
900
ms (TWT)
0
5 km
Cenozoic
Late Apt. - Alb.
Late Apt. -Alb.
Late Apt. - Alb
Apt.
Kim.
Carb.
Oxf.
Haut. - Barrem.
Port.
Ber. - Haut
Bath.
Basement (undifferentiated)
Cenozoic
Cenozoic
Cretaceous
Albian - Late Aptian (± Campanian/Maastrichtian)
Aptian
Neocomian
Jurassic
Portlandian
Kimmeridgian
Oxfordian
Bathonian
Carboniferous
Pre-Westphalian to Stephanian

in a restricted marine environment (Zone III) (*Cf.* paragraph 3.1.b). The transition from Zone II to Zone III during the Middle Kimmeridgian corresponds to a strong deepening of the basin floor as a response of fault activity. However, the thickness of Kimmeridgian strata varies laterally from fault-block to fault-block [Tab. 2, Fig. 10 and 11]. Fault activity is therefore seen as having a major control on Kimmeridgian deposition, so that the marine transgression is as a consequence of the basin floor deepening. The depocentres location is mainly controlled by the fault-block development.

Therefore, a sub-basin architecture is suggested for the Kimmeridgian period, in order to explain the difference in the sedimentary record. This has led to the accentuation of the Oxfordian extension in some places (west of the margin) or to proper individualization of rifted sub-basins in others.

- **Portlandian/Volgian:**

The Portlandian strata have been recorded extensively throughout the study area, and most of the fault-blocks show a thick succession of 250 to 500 ms TWT in the depocentres. They clearly onlap underlying strata, which are mostly of Kimmeridgian age [Fig. 9]. The top of the sequence is cut by the BCU which has extensively eroded the Portlandian/Volgian sediments. Figures 9 to 12 show that the succession is characterised by strong and continuous reflectors, which show different dips within different fault blocks. Although it is hard to distinguish a real change in the seismic character, the amplitude of the reflectors seems to vary laterally, within and between fault blocks. Accordingly to the wireline correlation, there is no major difference in the nature of the sedimentary infill, with the exception of locally sandy packages.

Interestingly, the displacement along faults for this period differs from the Kimmeridgian and Oxfordian times, where deformation was restricted to a few extensional fault systems. The Portlandian/Volgian sequence shows clear growth-faulting on its whole thickness. The Portlandian/Volgian tectonic activity is thought to represent the main period of rift activity of the Late Jurassic. The Early Cretaceous erosion phase has been insufficient to mask the displacement along fault systems, even if it has removed partially some of the succession.

Some fault-blocks, such as in the central part of Block 26/28 [Fig. 10], have been divided in two sub-basins during the Portlandian. Moreover, some extensional perched basins might have developed very locally on the eastern edge of the Porcupine Basin [Fig. 10]. The development of thick submarine fans are the result of local extensional phases (*e.g.* wells 26/28-4A and 26/28-5) and express local discrete rift pulses inside the Portlandian/Volgian period. On the eastern edge of the Porcupine Basin, basement uplift is clear (*e.g.* blocks 26/29 and 26/30) and continued until the Late Aptian with individualization of substantial high zones. Seismic analysis shows that the deformation continued during the Early Cretaceous, controlling clearly the Neocomian deposition in the Block 26/28. Probable minor extensional activity along localized fault systems is linked to an Early Aptian rifting phase.

The development of angular unconformities [Fig. 9] does not show a local pattern, as proposed by Sinclair *et al.* [1994], meaning that the fault-blocks floor subsided on their entire part. This also implies a regional pattern (*i.e.* several km of extension), with several fault zones active at the same time. Nevertheless, the sedimentary record is different from a fault-block to another, as the movement along the faults is different (*i.e.* control on the sedimentary thickness and different dips and even sedimentary occurrence). For the Portlandian succession, alluvial fans development is thought to be related to erosion phases with sediment sourced either from the top of surrounded fault blocks or coming from the uplifted margin of the Porcupine Basin. Thus, the Upper Jurassic architecture of the Porcupine Basin probably corresponds to an individualisation of sub-basins whose the sedimentary infilling has been made in a similar way, in response of regional events such as sea-level rise. The tectonic subsidence has been the principal cause of the sedimentation and has been much faster over the Portlandian/Volgian period in the Block 26/28 area.

4.1.c – Discussion:

Figure 13 shows a simple schematic model of the evolution of the Porcupine Basin for the Jurassic period, based on the observations from the present study. It is also supported by publications of other workers [*e.g.* Sinclair *et al.*, 1994; Williams *et al.*, 1999]. Four main phases of deposition can be recognized and correspond broadly to the major zones defined previously during the wireline log correlations.

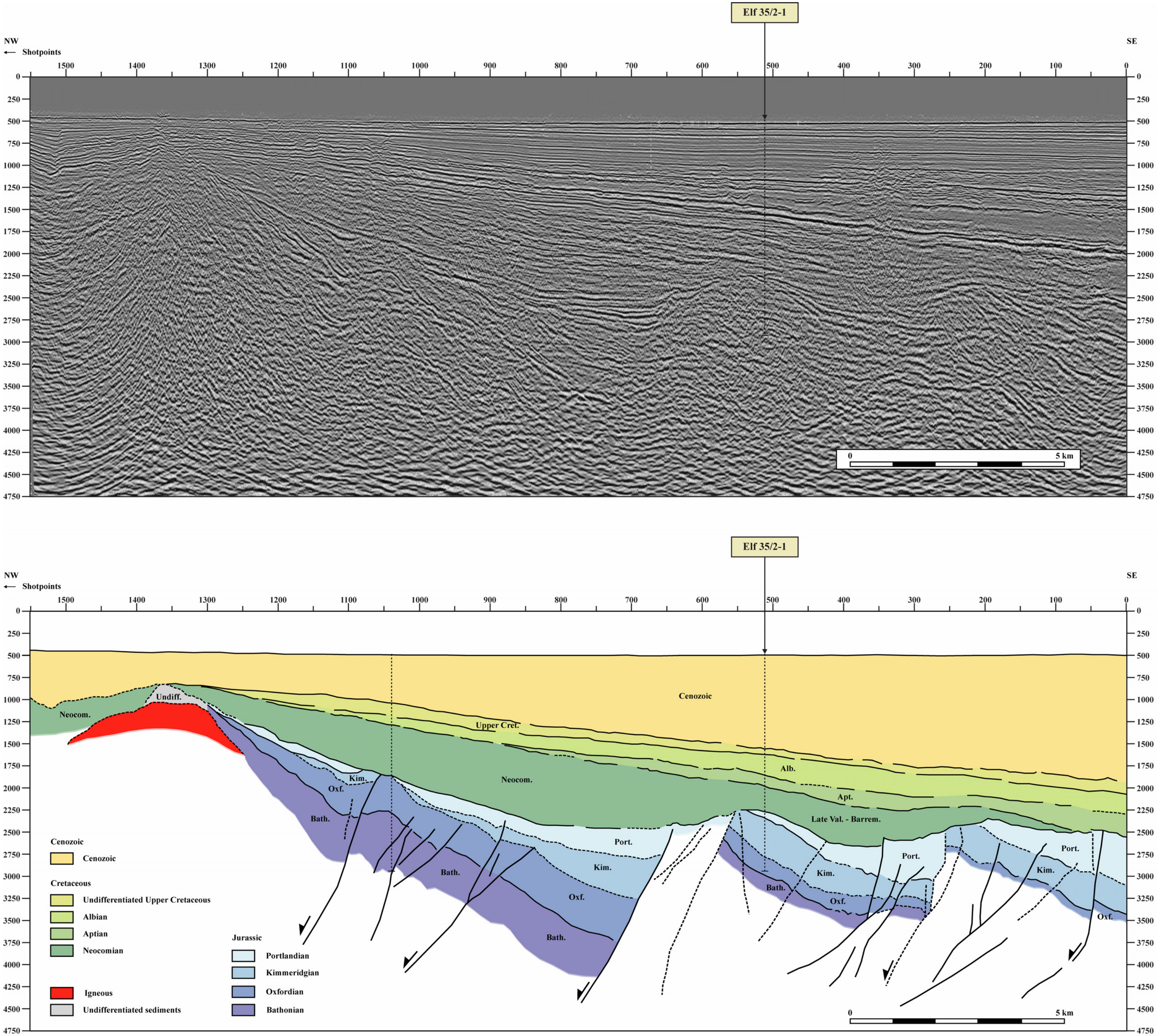


Fig. 12: **Seismic line IR80-27 (blocks 26/28 and 35/2 – Porcupine Basin)**
Arrows represent the throw direction along the major normal faults identified during the seismic interpretation. Position of the seismic section is indicated on Figure 2.

- **Bathonian (onset warp – deposition of Zone I):**

The Middle Jurassic succession, mostly of Bathonian age, corresponds to the development of fluvial to lacustrine deposits in an onset warp rift setting. As described on figure 8a, a major deposition phase took place during the Bathonian. However, several authors [*e.g.* Croker & Shannon, 1987; MacDonald *et al.*, 1987; Croker and Klemperer, 1989; Sinclair *et al.*, 1994] suggested that this continental sedimentary setting was transgressed in the Late Oxfordian. In the Block 26/28, the Bathonian succession has been clearly eroded by the BOU and that particular erosional surface can be mapped on most of the seismic lines used for this project. Moreover, well correlation [Fig. 4 and 5] indicated that similar lithostratigraphic packages can be followed in most of the wells, and are typically of Bathonian age. The presence of similar thickness in these lithofacies in structurally isolated blocks indicates that this unit was deposited before the Oxfordian rift phase. Regional uplift in the Porcupine Basin probably occurred at that stage, resulting in sub-aerial exposure of the whole study area and a lake of sedimentation. The Finnian's Spur domain has played the role of a barrier, explaining the differences between the North Porcupine and Porcupine basins.

- **Oxfordian (first Late Cimmerian rifting phase – deposition of Zone II):**

The Oxfordian strata deposited most likely in an estuarine environment, with evidence of a restricted marine transgression which took place in response to a localized rifting phase. Growth-faulting has been clearly identified on the eastern margin of the Porcupine Basin [Fig. 13], in two well identified rotated fault-blocks. Small, precursor extensional faulting has also been identified along some fault zones in the well 35/2 area whereas fault-movement is harder to identify in Block 26/28 and further northwest. In Block 26/28, Oxfordian extension is difficult to identify but is suspected to have taken place along particular fault systems. This localised tectonism led to the development of sub-basins in the study area. Zones where the sediments are thin may have undergone sub-aerial exposure. In most places, the highstand of the Oxfordian marine transgression has been enough to inundate topographic highs and crest of rotated fault-blocks. In some areas, such as in Block 26/28, the marine transgression has been delayed as a result of an uplifted margin.

- **Kimmeridgian (second Late Cimmerian rifting phase – deposition of Zone III):**

The Kimmeridgian strata suggest an important deepening of the whole Porcupine Basin, probably in response to an important rift phase which took place along most of the fault zones. As described previously, Kimmeridgian sediments have been deposited in a shallow marine environment following the Oxfordian transgression. They correspond to Zone III, which has been recognized in the whole area [Fig. 4 and 5]. The base of the Kimmeridgian sequence shows some similarities with the Oxfordian sediments, and is thought to belong to this particular unit (*i.e.* deposits of Zone II). As a result, the deepening of the Porcupine Basin took place probably during the Early to Middle Kimmeridgian. Associated subsidence seems to vary from fault-block to fault-block, suggesting localized depocentres.

Kimmeridgian strata show well defined growth-faulting in most of the fault-blocks. However, the magnitude of fault displacement seems to differ from one fault-block to another, indicating that tectonism has been localised to particular places. As a result, Kimmeridgian thickness varies from one fault-block to the next.

Occurrence of major growth-faulting has been clearly identified in the Block 26/30, whereas it varies from fault-block to fault-block in Quadrant 35 [Fig. 12], and seems to be restricted to the top of the sequence in the Block 26/28 area [Fig. 10 and 11]. Thus, the specific observation of early growth-faulting in the Block 26/30, which has been delayed in the other fault-blocks further west, implies to consider a proper sub-basin architecture (already initiated during the Oxfordian times). The only difference with the previous extension phase consist in a reg of the faulting to the whole area at the end of the Kimmeridgian, implying thus an acceleration of tectonic subsidence and late inundation to most of the fault-blocks.

- **Portlandian/Volgian (third Late Cimmerian rifting phase – deposition of the zone IV):**

Block rotation clearly took place during the Portlandian/Volgian period (also referred as Tithonian phase in the literature). It resulted in fault-blocks individualisation in the whole Porcupine Basin, with various displacements along the fault structures. Although the Early Cretaceous erosion phase is thought to have a regional impact on the preserved sedimentary thickness, the Portlandian/Volgian faulting

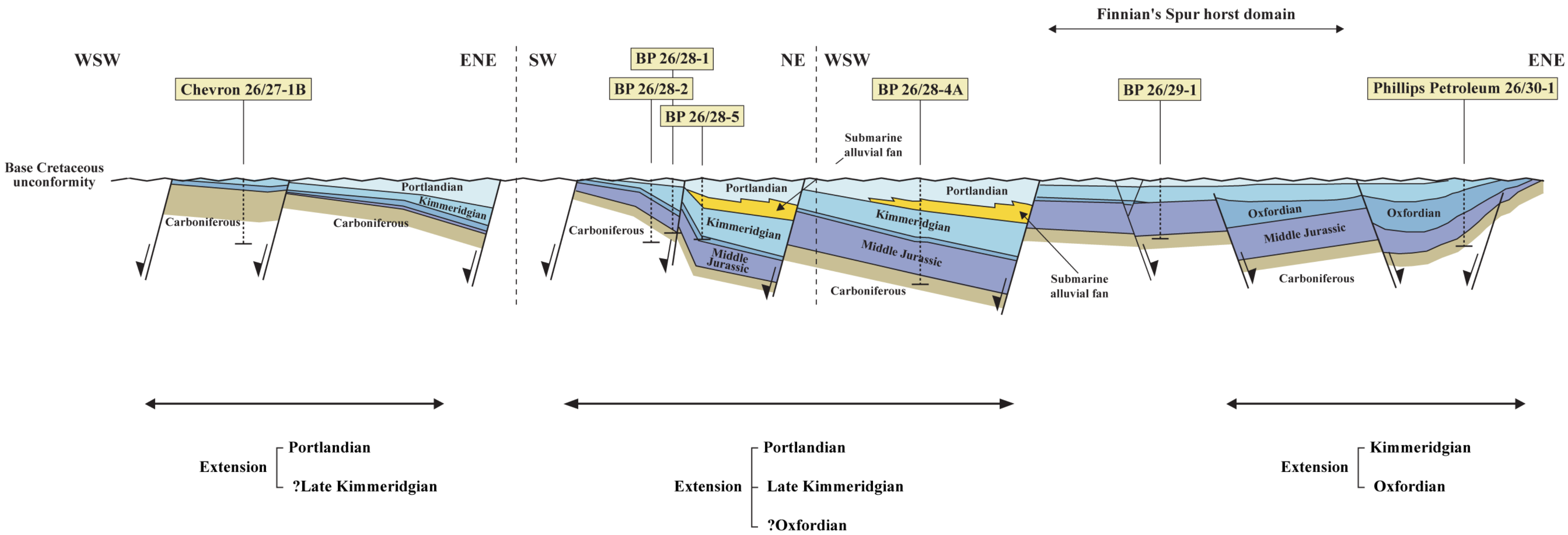


Fig 13 : **2D geological evolution of the Jurassic Porcupine Basin**

The correlations are based on the lithostratigraphic packages identified previously [Fig. 4 and 5]. Position of the wells is indicated on figure 2.

contributed in a major change in the sedimentation . Therefore, the Portlandian/Volgian sedimentary succession has been deposited in response to the rifting and a subsequent marine transgression.

Minor tectonism has been identified on the eastern margin of the Quadrant 26 region but this area is thought to have been uplifted at the end of the Portlandian, probably in response of the early tectonic movements initiating the Cretaceous rifting (*i.e.* development of the BCU). On the other hand, extension has been widespread in most of the blocks 26/27, 28 and 29 as well as the Quadrant 35. Sinclair *et al.* [1994] suggested that the flooding of the basin and part of the margins was accompanied by a broadening of the subsidence. They also suggested that the tectonic subsidence of the fault-blocks during this specific period was accompanied by a thermal anomaly uplift event, re-exposing the basin margin to sub-aerial/submarine erosion and the development of clastic bodies such as the submarine fans identified in the wells 26/28-4A and 26/28-5. The Portlandian/Volgian extension was discontinuous and at least two well defined rift pulses can be identified.

Location of extension along specific fault system led to a different geometry of the layers from fault-block to fault-block (*i.e.* change in dip). Thus, tectonism was a major control on sedimentation, which appears to be fairly heterogeneous from the east to the west (*i.e.* limestone occurrence), even if continuous lithostratigraphic packages have been recognized over a scale of several kilometres.

The Jurassic evolution of the Porcupine Basin is a result of a multiphase rifting, implying some fault-block sedimentary compartmentalization though the time. Migration of the rifting since the Oxfordian is quite obvious. It began in the North Porcupine Basin area, and then on the eastern part of the Porcupine Basin, before becoming regionally developed during the Late Kimmeridgian and particularly the Portlandian. This specific location of the deformation through the time led to the development of interlinked fault-blocks, and especially to a sub-basin architecture. The recognition of similar lithostratigraphy at a local and regional scale implies common regional processes in the deposition, together with more local event. As noticed by Sinclair *et al.* [1994], the geological evolution of the Porcupine Basin is a result of several subsidence phases, thought to be due, first to the sedimentary loading (i.e. Bathonian) and to the tectonics (i.e. Oxfordian, Kimmeridgian and Portlandian/Volgian).

The interpretation which is proposed here differs from published models in several respects, especially regarding the timing of the rifting phases and associated geological events. First of all, it is unclear that Callovian strata exist in the study area [Fig. 4], so that Middle Jurassic sediments are probably restricted to the single Bathonian period. As a result, the development of the BOU shows the first rifting record, represented by an early uplift phase in the area. This event may have begun at the end of the Callovian, and had a significant importance to enable remobilisation of most of the younger sediments deposited in both the North Porcupine and the Porcupine basins.

Sinclair *et al.* [1994] and Williams *et al.* [1999] proposed that the first thermal subsidence [Fig 3] occurred during the latest Oxfordian through the Kimmeridgian, and was not accompanied by significant fault-growth. However, Oxfordian and Kimmeridgian extension events, even if located in the same fault-blocks, are thought to be well separated, leading to the development of the BKU. In the Porcupine Basin, subsidence varies from fault-block to fault-block, so that the apparent thickness differs. Moreover, the increase in subsidence during the Kimmeridgian resulted in flooding of the area, with the exception of high fault block and basement crests. Marine sub-basins developed differentially in such setting and have been filled in by sedimentary deposits of Zone III.

A third, more obvious and well defined, rifting phase developed over the study area during the Portlandian/Volgian period. As noted by Sinclair *et al.* [1994], significant growth-faulting and erosion of uplifted areas began since the Late Kimmeridgian, and non-deposition and erosion are testify by the well developed BPU. Significant rift pulses have been recorded over this specific period. The highstand of the Portlandian marine transgression has flooded the basin margins during this period and may have enabled the development and individualization of perched basins [Fig. 10]. Therefore, it suggests a maximum in the marine transgression, implying an important subsidence over the study area. However, this maximum in subsidence has been tightly linked with the tectonics inside the Porcupine Basin, so that it has not occurred, in a synchronous way. Sinclair *et al.* [1994] and Williams *et al.* [1999] also suggested this hypothesis, but at a regional scale. The Jurassic Porcupine Basin therefore probably developed different rifted sub-basins during the Portlandian/Volgian period.

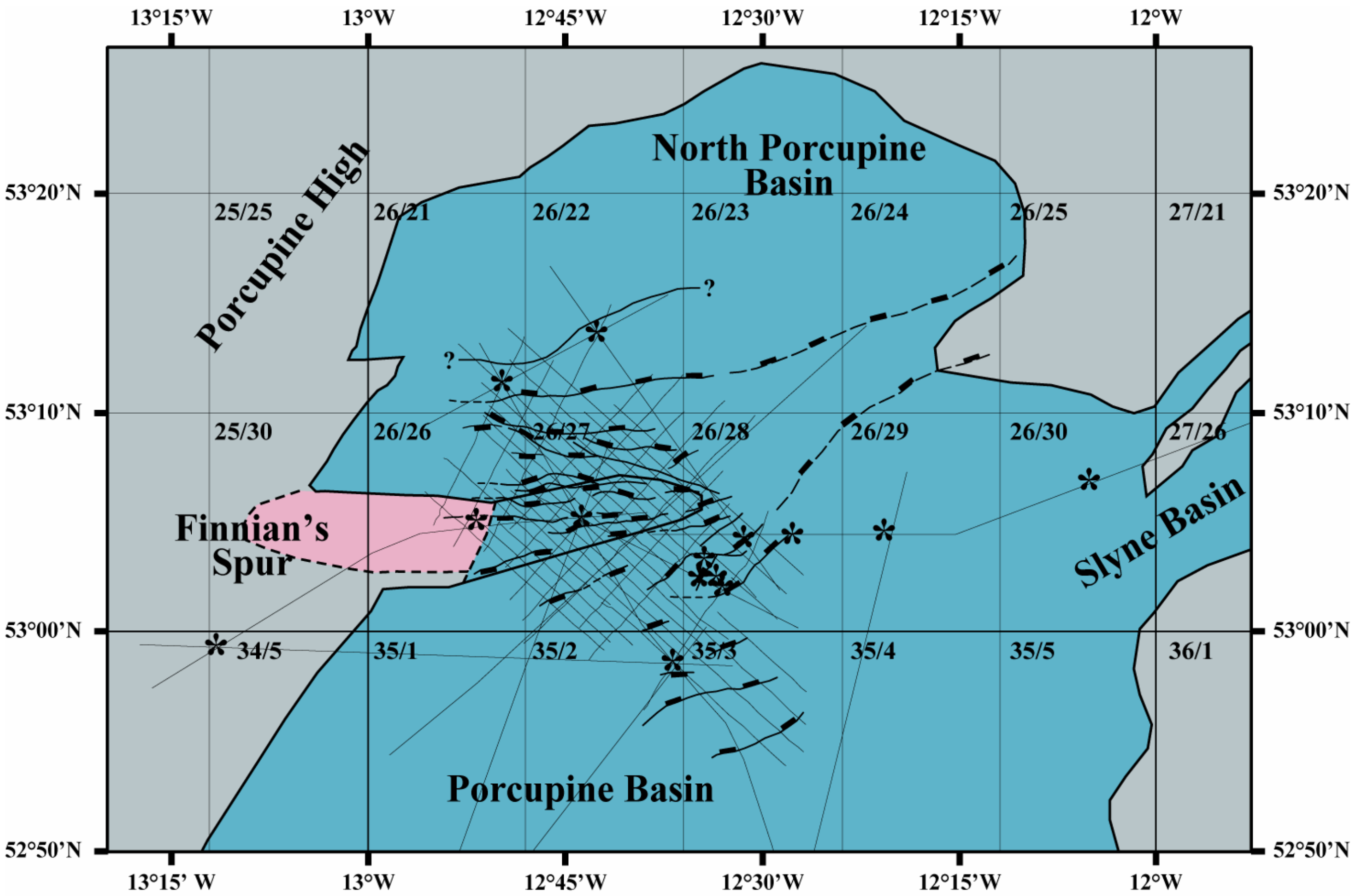


Fig. 14: **Base Cretaceous subcrop map.**

Tectonic features are based on the analysis of seismic lines (narrow lines). Stars indicate well, whose the position is on Figure 2. The pink colour indicates the part of Finnian's Spur without Jurassic cover. The grey colour indicates Upper Paleozoic terrains.

4.2 – Structural response to the rifting:

Presented here as a work in progress, figure 14 shows a map of the fault-systems at the base of the Cretaceous strata in the region of blocks 26/26, 27 & 28 and 35/2 & 3. This map is based on a review of the 2D seismic surveys IR80, NWI-91 and PW93, which were shot at the intersection between the Porcupine region and the Slyne-Erris Basin [Fig. 1]. As a result, the structures are expected to show a different pattern in their orientation, with at least well defined N-S and NE-SW directions, as it has been broadly recognized in the literature [*e.g.* Naylor & Shannon, 1982; Croker & Shannon, 1987; Doré *et al.*, 1997 and 1999; Spencer & MacTiernan, 2001; Naylor *et al.*, 2002 and 2005].

It appears that the fault-structures are lying along a significant NE-SW direction in the southwest of Block 26/28, whereas in the central/north-western part, an E-W orientation is well identified. However, it seems to turn toward the northeast in the middle part of the Block 26/28 and run in parallel of the other structures further south. This general pattern reminds the direction of the major NE-SW fault zone lying at the south of the Slyne Basin [Fig. 1], implying a continuity of this fault-zone into the North Porcupine and Porcupine basins to connect the E-W oriented Finnian's Spur domain.

These particular orientations are consistent with fault structures described previously in the literature [*e.g.* Naylor *et al.*, 1999 and 2002; Naylor & Shannon, 2005]. It has been widely recognized that the dominant direction of the extensional stress was W-E to WNW-ESE throughout the Jurassic rifting phase [*e.g.* Sinclair *et al.*, 1994; Doré *et al.*; 1999]. Thus, E-W structures should present minor extensional faulting, to show a real strike-slip motion.Interestingly, seismic lines show that the Finnian's Spur domain has been active during the Jurassic rifting and played an important role in the separation of the North Porcupine Basin from the Porcupine Basin further south. If it explains the difference in the signature of the sedimentary sequences identified previously, growth-faulting on each side of this features have been identified for the Upper Jurassic succession. Thus, strike-slip fault is most likely suggested here.

In the Porcupine Basin, the Jurassic strata are generally less extensive than the Cretaceous, as they have been constrained by the main basin-bounding faults and extended locally on basement highs [Fig. 9 to 12]. A number of horst and graben have been identified in the study area. In general, the half-graben are bounded by a major normal fault which shows displacement of various ages. Block faulting appears to have exercised an increasing influence on sedimentation since the Kimmeridgian, the Oxfordian fault movement being restricted to particular fault-blocks on the eastern margin. Subsidence from fault-block to fault-block appears to be different, and led to variation in the thickness of stratigraphic units.

5. Future plans:

The major tasks and objectives of the coming months are as follow:

- Acquire and load further seismic data surveys (both 2D and 3D), to be obtained soon from PAD. These data will provide a much better coverage to understand the structural orientations and the response of the sedimentary processes.
- Continue detailed seismic mapping of the Jurassic interval to constrain the zones identified on the wireline log correlation. The regional unconformities will be mapped, in order to constrain the tectonic activity.
- Carry out detailed analysis of seismic facies.
- Examine key cores and carry out detailed petrography on selected zones in order to constrain the depositional and diagenetic history of the succession.
- Constrain the movement, age and subsidence rate along the major fault systems, in order to constrain the model of the geological evolution described above.
- Present results of the study at the Annual General Meeting of the British Sedimentological Research Group at the University of Birmingham (December 2007).
- Present results of the study at the Irish Geological Research Group Meeting to be held at UCD in February 2008.
- Start work on the preparation of a paper to be submitted for publication to a peer-reviewed international journal.

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