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Exhumation in Irish sedimentary basins and implications for hydrocarbon exploration, offshore Ireland.

Volume 1

by

Dermot V. Corcoran

Thesis submitted in accordance with the requirements for the degree of Doctor of Philosophy

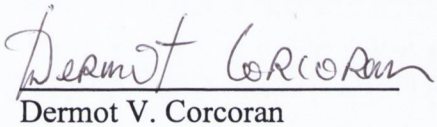
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Dermot V. Corcoran

Abstract

Exhumation, the removal of overburden resulting from the vertical displacement of rocks from maximum burial depth, occurs at both regional and local scales in offshore sedimentary basins and has important implications for the prospectivity of petroliferous basins. In these basins, issues to be addressed by the petroleum geologist include, the timing of thermal 'switch-off' of source rock units, the compactional and diagenetic constraints imposed by the maximum burial depth of reservoirs (prior to uplift), the physical and mechanical characteristics of cap-rocks during and post-exhumation, the structural evolution of traps and the hydrocarbon emplacement history. Central to addressing these issues is the geoscientist's ability to identify exhumation events, estimate their magnitude and deduce their timing.

In this study exhumation techniques are critically reviewed in the context of some of the exhumed offshore sedimentary basins peripheral to the Irish landmass. Vitrinite reflectance, apatite fission track analysis and sonic compaction data for specific wells have been combined with seismic and stratigraphic evidence to estimate the magnitude and timing of exhumation at a number of offshore locations. This analysis reveals a heterogeneous pattern (spatially and temporally) of exhumation which manifests both inter- and intra-basin variation. Exhumation analysis of a regional VR dataset indicates that average net exhumation (by basin) ranges from 0.8 kms to 3.7 kms for the sampled offshore basins as compared with an average net exhumation range of 3.6-4.5 kms for two onshore basins. Sonic compaction analysis for 8 wells in the Slyne Basin yields a mean net exhumation of 1.2 kms, with a range of 0.95-1.8 kms occurring within the basin.

The magnitude and timing of exhumation events have implications for the source, reservoir, seal and trapping elements of a petroleum system. Therefore exhumation must be considered when assigining risk factors used to estimate the probability of discovery for a prospect. Compared to a similar prospect in a 'continually subsiding basin', resource levels in in an exhumed prospect are generally lower.

Empirical observation indicates that hydrocarbon accumulations in exhumed basins of the Atlantic margin are commonly characterised by underfilled traps and hydrostatically pressured or modestly overpressured reservoirs. These observations are reviewed here in the context of the generic mechanisms by which top-seals leak, the properties of cap-rocks and the physical processes which occur during exhumation. *Syn-exhumation* top-seal efficiency (fluid retention capacity) is a major exploration risk in these exhumed basins, though *post-exhumation* top-seal integrity may be relatively high under certain conditions. Consequently, a further exploration risk factor in exhumed basin settings pertains to the limited hydrocarbon budget available post-regional uplift and the efficiency of the re-migration process.

The Carboniferous-Triassic petroleum system contains most of the undiscovered resources in the exhumed basins to the east, north and west of the island. The Corrib Gas Field, in the Slyne Basin, presents in microcosm some of the key challenges with respect to understanding the evolution of this petroleum system. Here, the post-Triassic overburden manifests a complex evolution with indications of flipped polarity, extensional, faulting on a crestal detachment structure during the Jurassic, succeeded by alternate episodes of burial and exhumation from the Early Cretaceous onwards. Compactional and thermal data supported by stratigraphic analysis and seismic interpretation indicate that kilometre scale (800-1700m) exhumation and erosion of the Jurassic overburden has occurred in the Corrib area during the early Cretaceous. A number of post-Aptian re-burial and exhumation events also occurred but are unlikely to have exceeded the earlier maximum burial of source, reservoir and seal rocks achieved during the Late Jurassic. Regional synthesis of the VR, AFT and stratigraphic data from the Irish inboard basins indicates that at least four phases of regional exhumation occurred in this area – during late Carboniferous-early Permian, early Cretaceous, early Palaeogene and late Palaeogene-Neogene, with some 'local' exhumation during Triassic-early Jurassic time, recorded by AFTA data from the southeast of the island.

This study confirms the importance of integrating constraints from seismic interpretation and regional stratigraphic data with estimates from the more indirect tectonic, thermal and compactional methods.

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DEDICATION

To my parents

(In memory of my Dad, but also for my Mum, who has never failed to remind me of unfinished business !)

and

To Yvonne, Cian, Orlaith & Meadhbh who made available that most precious of commodities – time !

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Chapter 1

Introduction, Aims and Geologic Setting

1.1 Introduction.

The petroleum exploration of Ireland's offshore basins is proving to be a tortuous affair. The facts speak for themselves: three decades of exploration, the drilling of 150 wildcat and appraisal wells, a yield of only 3 producing gas fields in the Celtic Sea Basin with a third commercial gas accumulation currently sanctioned for development in the Slyne Basin, and a number of oil and gas discoveries which have disappointed upon appraisal (Fig. 1.1). The details of this odyssey have been chronicled in a number of publications (Shannon *et al.* 2001; Naylor 1996; Croker & Shannon 1995), but the overriding (industry wide) impression is that a capital investment of, in excess of, €2 billion (cost of wells drilled in Irish offshore in money of today) has yielded very disappointing returns.

In any jurisdiction the intensity and longevity of the hydrocarbon exploration effort is influenced by a number of factors – oil price, fiscal incentives and technological advances being among the most important – but, it is hydrocarbon prospectivity/hydrocarbon resource potential that is the primary driver of exploration investment. The key elements of source, reservoir and trap/seal have long been recognized or postulated to be present in basins, offshore Ireland (Croker & Shannon 1995). However, it is the evolution of the petroleum systems within these basins that is less well understood in particular the impact on prospectivity of exhumation, in those basins with a multiphase exhumation history, has only recently become highlighted in the published literature (Doré *et al.* 2002b; Shannon *et al.* 2001). The implications of exhumation history for the petroleum geology of these offshore basins, is the central theme of this research work.

1.2 Aims

This thesis represents a compilation of work that has been carried out by the author at Trinity College Dublin and while working at Statoil Exploration (Ireland) Ltd. over the last 6-8 years. The research has four main objectives: firstly, it

endeavours to critically analyse the methodologies available for the assessment of exhumation in offshore basins; secondly, it aims to gather the disparate strands of evidence for the magnitude and timing of the main exhumation events in Ireland's offshore basins; thirdly, it aims to contribute to the assessment of exploration risk in exhumed basin settings, offshore Ireland; fourthly, it aims to outline an approach to top-seal assessment in exhumed basin settings; fifthly, as an example, it aims to present an integrated approach to the assessment of the magnitude and timing of exhumation of the Corrib Gas Field in the Slyne Basin.

This work utilizes a number of databases, some of which are partial or incomplete. A series of seismic lines/geoseismic sections have been compiled, from miscellaneous published sources and websites, for these offshore basins (Chapter 1). Access to digital sonic transit time, lithology and depth data for wells in the Slyne/Erris, Porcupine and Rockall basins was courtesy of Statoil Exploration (Ireland) Ltd (Chapter 3). A vitrinite reflectance (VR) database was compiled for 77 offshore wells courtesy of access to the geochemical reports for released wells, granted by the Petroleum Affairs Division (Department of Communications, Marine and Natural Resources, Dublin) (Chapter 4). New vitrinite reflectance (VR) data was generated by the author for well 42/21-1 in the Central Irish Sea Basin. New apatite fission track analyses (AFTA) were performed on wells 42/21-1 and 42/16-1, courtesy of Geotrack International Pty Ltd. and in collaboration with Dr. Paul Green (Chapter 5). The author also compiled a database of initial reservoir pressures (from miscellaneous published sources - for 160 Atlantic Margin and North Sea oil and gas fields). In addition, a database of formation pressures (Repeat Formation Tests [RFTs] and Drill-Stem Tests [DSTs]), formation integrity tests (FITs) and leak-off tests (LOTs), for basins offshore Ireland, were compiled by the author from well reports that were accessed courtesy of Statoil Exploration (Ireland) Ltd (Chapter 7).

The interpretation and results contained in Chapters 1, 3, 4, 6, 8 and 9 are entirely the work of this author. Chapters 2 and 7 are primarily the work of this author though these chapters, and partially Chapter 6 (Figures 6.1 & 6.2 are entirely the work of Dr. Doré) have benefited greatly from the results of collaborative effort with Dr. A.G. Doré of Statoil (UK) Ltd., arising out of this author's employment by

Statoil Exploration (Ireland) Ltd.. The AFTA results and interpretation, for wells 42/21-1 and 42/16-1, contained in Chapter 5, are entirely the work of Dr. Paul Green, although the regional context is provided by this author. A list of publications, pertaining to the research work undertaken in this thesis, is presented in Appendix 2.

1.3 Geological Setting

Ireland is almost encircled by a series of Mesozoic to Cenozoic sedimentary basins (Fig. 1.2). These basins can be categorized into two groups. The first group, which consists of the basins of Northern Ireland, the Irish Sea and Celtic Sea areas and the inboard basins of the Atlantic margin region (Slyne, Erris and Donegal basins), typically manifest an elongate morphology, are located in relatively shallow waters (<1000m) and commonly contain a truncated Cretaceous to Tertiary stratigraphic record. The second group, which is composed of the outboard basins of the Atlantic margin region (Goban Spur, Porcupine, Rockall and Hatton basins), are characterised by a more extensive surface area with relatively thicker Cretaceous and Tertiary successions, are lightly explored (excluding Porcupine Basin, only 3 wells drilled to date) and lie in relatively deeper waters.

It is generally recognised that at least part of the sediment fill in these offshore basins has been derived from periods of uplift and erosion of the Irish landmass and shelf regions (Naylor 1998; Jones *et al.* 2002; Allen *et al.* 2002). Onshore successions are dominated by thick sequences of Carboniferous sedimentary rocks which occur in the preserved remnants of Dinantian-Namurian basins, such as the Dublin, Clare, Munster and Northwest Carboniferous Basins (Strogen *et al.*, 1996; Croker, 1995, Philcox *et al.*, 1992) (Fig 1.2). Apart from an isolated outlier of Westphalian D sedimentary rocks in Co. Wexford (Clayton *et al.* 1986) and the Westphalian B succession of the Fintona Block in Co. Tyrone (Mitchell 1992), the youngest preserved Carboniferous successions onshore are of Westphalian A age (Sevastopulo 1981). Ireland is devoid of post-Palaeozoic rocks except for the northeastern part of the island and a few scattered outliers (Naylor 1992). Consequently, our understanding of the post Variscan geological evolution of the Irish landmass and its immediate environs is severely curtailed by the limited Mesozoic/Cenozoic onshore outcrop and the truncated stratigraphic record in many of the inboard basins.

Although the interpretation of the timing of exhumation from outcrops is non-unique, the proposition of extensive, post-Westphalian, exhumation of the Irish landmass and adjacent inboard regions is not generally disputed. In summary, there are 5 generic lines of evidence:

- the predominant, onshore, exposure of Palaeozoic (pre-Westphalian) and older rocks (Roberts 1989; Naylor 1992)
- present-day elevation of the Mourne and Slieve Gullion Tertiary granites, which were emplaced at depths of *c.* 3km in the crust (Gamble *et al.* 1999; Allen *et al.* 2002)
- present-day absence/partial absence of the predicted (McKenzie model) post-rift subsidence in the inboard basins (Brodie & White 1995)
- organic maturity levels (VR) of Carboniferous sections [both onshore and offshore] are generally higher than for Mesozoic-Cenozoic sections [offshore], for a given present-day burial depth (Fig. 1.3) (Corcoran & Clayton 2001)
- thermal history modelling of an extensive, onshore, apatite fission-track dataset indicates cumulative post-Triassic denudation in the range of 2-4 kms, although the magnitude of the exhumation varies both spatially and temporally in a complex pattern (Allen *et al.* 2002).

1.4 Onshore – stratigraphic evidence for timing of exhumation

The geological map of Ireland is a product of the cumulative (time-integrated) denudation of Ireland since late Palaeozoic time (Allen *et al.* 2002). Topographically the island is essentially saucer shaped, with a low elevation central area dominated by a Lower Carboniferous cover (occasionally breached by inliers of Devonian and older rocks) rimmed by generally higher elevation Devonian, Lower Palaeozoic and Dalradian sedimentary and meta-sedimentary rocks, Caledonian granites and pre-Dalradian gneisses (Fig 1.4).

Upper Carboniferous (Westphalian) rocks are restricted to a limited number of outcrop areas (Fig 1.5). Westphalian A (Langsettian) strata have been recorded in all of the Irish coalfields (Leinster, Slieveardagh, Crataloe, Kanturk, Coalisland) except for the Namurian Connaught/Arigna coalfield (Haughey & McArdle 1990) and appear to have been conformably overlain by a Westphalian B (Duckmantian) succession, at least in the Fintona Block, Co. Tyrone, where 1000

metres of an alluvial succession is preserved in the hanging wall of the Castle-Archdale Fault (Mitchell 1992). Sediments of Westphalian C (Bolsovian) age have not been recorded onshore Ireland, although they have been encountered in a number of offshore wells to the west of the island (Porcupine, Slyne, Erris, Donegal – Robeson *et al.* 1988) and to the east of the island (Kish Bank, Central Irish Sea basin), which suggests that they were likely to have been deposited onshore as well. The stratigraphic relationship between the Westphalian D and older sections (Borehole W80.5) is not observed in the Wexford outlier, though the Westphalian D strata contain recycled spores of Devonian to Westphalian A age (Clayton *et al.* 1986), suggesting a period of, at least local, uplift and erosion or that the sediments were derived from the rising Variscan foreland to the south. Reworked assemblages of Dinantian to Westphalian A age have also been reported from Kish Bank Well 33/22-1 (Naylor *et al.* 1993). Stephanian-Autunian rocks are not preserved onshore though they have been encountered offshore in the northern part of the Porcupine Basin where they are apparently conformable with the Westphalian successions (Fig 1.6).

In summary, the limited outcrop distribution does not provide any evidence of major angular discordance within the Westphalian succession. In contrast, Permian and Triassic successions rest with marked angular unconformity upon Westphalian and older rocks, at a number of onshore localities [Wexford, hanging wall, outlier – Permo-Trias rests upon Westphalian D to Dinantian rocks (Clayton *et al.* 1986); Coumaraglin valley, Co. Waterford, possible Triassic red clays overly Devonian rocks (Keely 1995); Kingscourt outlier – Permo-Trias rests upon folded Westphalian A and older rocks (Visscher 1971); onshore boreholes east of Lough Neagh, and in the Belfast Harbour area, all encountered Permian rocks resting unconformably upon Dinantian sediments or Lower Palaeozoic basement (Smith 1986)]. This picture is supported by the generalized cross-sections of George (1967) across County Antrim, which indicates a major angular discordance between the Triassic and Carboniferous successions (Fig 1.7)

In northeast Ireland an early Permian age is traditionally assigned to unfossiliferous red-beds that rest stratigraphically between the Upper Permian Magnesian Limestone and Dinantian or older rocks (Mitchell 1992). These red-beds are possibly the time equivalents of the Tatarian-Kazanian, Upper Rotliegend, sediments (*sensu* Glennie 1997b) described in the Southern Permian Basin, and the Appleby Group (*sensu* Jackson *et al.* 1997) of the East Irish Sea Basin, which is

consistent with the oldest K-Ar ages (268 +/- 6 Ma) reported by Forster & Warrington (1985) for the 'pre-Magnesian Limestone' volcanics encountered at the base of the Larne No. 2 Borehole. However, the absolute dating of these Permian sections is difficult due to time spans which are poorly constrained both radiometrically and biostratigraphically and the long-lived nature of the magmatic activity which occurred in the European-northwest African province during this period (Doblas *et al.* 1998; Glennie 1997b). Nevertheless, the onshore stratigraphic evidence points to the presence of a significant unconformity resulting from widespread exhumation (possibly a series of staggered pulses of uplift and erosion) during the early Permian period. This picture is confirmed by the few deep onshore boreholes in Northern Ireland which have penetrated pre-Permian rocks (Figs 1.6, 1.8) - Magilligan-1 borehole (onshore Rathlin Basin) encountered Permo-Triassic sediments resting unconformably upon a Namurian-Visean succession (Naylor 1992; Middleton *et al.* 2001); Belfast Harbour borehole (onshore Larne Basin) found a sequence of Dinantian carbonates beneath the Upper Permian Magnesian Limestone (Smith 1986; McCaffrey & McCann 1992); Langford Lodge and Ballyalton boreholes encountered Permian rocks resting unconformably upon Lower Palaeozoic basement (Manning *et al.* 1970; McCaffrey & McCann 1992; Maddox *et al.* 1997). Additional evidence for a major unconformity at the base of the Permian section is provided by the seismic section published by Illing & Griffith (1986) which shows strong erosional truncation at the base of the interpreted Permo-Triassic section (Fig 1.9)

Stratigraphically the Upper Permian Marls, in this area, are succeeded (with apparent conformity) by the Triassic Sherwood Sandstone (SSG) and evaporitic Mercia Mudstone (MMG) Groups which overstep the Permian successions onto the Highland Border Ridge and possibly southwards onto the Longford-Down Massif (Naylor 1992). However, published cross-sections (McCaffrey & McCann 1992; Maddox *et al.* 1997) suggest that the SSG and MMG succession thins, at least partially by erosional truncation, towards the southerly flanks of the Larne Basin (Fig 1.8). South of the Longford-Down Massif exposures of Triassic rocks are restricted to the Kingscourt area and possibly the Wexford outlier (240m of Killag Formation) where the absence of proven Permian strata in the immediate offshore wells suggests a Triassic age, although these rocks remain undated (Burnett *et al.* 1990; Naylor 1998). At Kingscourt, Visscher (1971) reported a conformable relationship between the Permian and Triassic successions with palynological assemblages of earliest Triassic,

Scythian, age (Kingscourt Sandstone Formation) directly overlying latest Permian, Thuringian, assemblages (Kingscourt Gypsum Formation).

Onshore in Northern Ireland the MMG section is stratigraphically overlain by a marine basinal succession of Rhaetic to Liassic age (observed along the foreshore at Larne – Parnell *et al.* 1992). Subsequent denudational episodes have resulted in a patchy present-day distribution of Liassic rocks, with a maximum of 250m of Hettangian to Pliensbachian mudstones and minor limestones preserved in the area of the Port More borehole (Wilson 1981; Shelton 1997). Liassic fossils were also reported from drift boulders at Ballycastle Co. Antrim (Wilson 1972) and at Kill O'-the-Grange in Co. Dublin (Broughan *et al.* 1989). However, *in-situ*, representative strata of Late Pliensbachian to early Cenomanian age (approximately 100 Ma of geologic time) have not been preserved onshore save for two palaeo-karst fill deposits encountered at Cloyne, Co. Cork (Bajocian-Bathonian lacustrine clays – Higgs & Beese 1986) and at Piltown, Co. Kilkenny (Late Jurassic to Early Cretaceous lacustrine/paralic clays – Higgs & Jones 1998) (Fig 1.10). This severely truncated stratigraphic record suggests either a long-lived, post Pliensbachian, depositional hiatus occurred across the island or that one or a series of exhumation events punctuated the island's Liassic to Early Cretaceous subsidence history. The presence of Mesozoic sediments within karstified Tournasian limestones at Cloyne and Piltown indicates that an active karst system may have been developed, at least close to the southern coastline, as early as Bajocian times, though, the actual solution collapse that ensured preservation may not have occurred until the Tertiary era.

The earliest Cretaceous rocks recorded onshore are of Cenomanian age. Along the northeastern coastline at Murlough Bay and Ballintoy Harbour exposures of Santonian to early Maastrichtian Chalk (Ulster White Limestone) are underlain by a thin (<1 metre at Ballintoy) basal facies (Hibernian Greensand Formation) of Santonian age, which includes glauconitic sandstone and Dalradian, Triassic and Liassic pebbles (Fletcher 1997; Parnell *et al.* 1992) (Fig 1.10). South of the Highland Border Ridge, the lower part of the Hibernian Greensand Formation (Cenomanian age) is preserved with approximately 10 metres of the formation encountered at Cottonmount Quarry, Mallusk, resting unconformably upon Liassic (Biffa, Cottonmount Environmental Statement, 2003). A number of minor hiatuses occur in the Hibernian Greensands Formation and in the lower part of the Ulster White Limestone Formation (Turonian sediments are unknown in the region), but these

'interruptions' can be viewed in the context of a punctuated but progressive Santonian to Maastrichtian transgression of the pre-existing topography (Naylor 1992). The thickest preserved section of Ulster White Limestone in outcrop is 120 metres in the Ballycastle area of the Rathlin Trough, although in excess of 146 metres (base not reached) were encountered in the Aughrimderg borehole in the Lough Neagh-Larne Basin (Fletcher 1977). However, Cope (1997) has suggested that complete successions of Chalk could have obtained thicknesses of at least 200-300 metres in the more basinal settings, at least in the Irish Sea area.

Away from this northeast corner of the island a single occurrence of Late Cretaceous Chalk has been recorded at Ballydeanlea, Co. Kerry, in a small outlier which has been preserved courtesy of the solution collapse of a karstic cavern in Dinantian limestones (Walsh 1966) (Fig 1.10). This Chalk Breccia, which is encased in Namurian shale bedrock, has also been interpreted as representing deposition at the foot of an active submarine fault scarp during the Campanian (Evans & Clayton 1998). At this location, the upper surface of the chalk is covered by a thin veneer of recent soils and alluvium but in NE Ireland a spectacular unconformity is observed between Palaeocene basalts of the Antrim Lava Group and the underlying Santonian to Maastrichtian chalks (Ulster White Limestone). Up to 15 metres of relief can be observed on this palaeokarst surface. This observation, together with the frequent alignment of pinnacles, dolines and cave passages along pre-existing joints, suggests that the chalk in Northern Ireland was a well cemented, low porosity, limestone prior to fracturing during early Palaeocene exhumation and the subsequent emplacement of the basalts (Simms 1998). Detailed investigation of the chalk-basalt stratigraphic relationships (Lyle & Preston 1993) suggest that the eruption of basalt commenced in north Antrim with uplift and denudation of the chalk increasing to the south. The maximum original thickness of the lava flows is unknown, due to post Palaeocene erosion, but up to 780 metres of Antrim Lava Group succession was encountered in the Langford Lodge borehole (McCaffrey & McCann 1992). Palynological correlations suggest that these lavas were predominantly erupted in two main pulses at 58 Ma (Lower Basalt Formation) and 55 Ma (Upper Basalt Formation) with up to 15 metres of bauxitic and lateritic soils and other sediments deposited in the Interbasaltic period, together with, locally, some tholeiitic lava flows (Anderton 2000). High resolution aeromagnetic data has facilitated the offshore mapping, in the northern Irish Sea region,

of NW-SE trending Palaeogene dyke swarms which have been identified onshore in the Carlingford-Slieve Gullion area (Fig 1.10; see also Fig 1.11 below). These swarms can be traced through the Isle of Man, the East Irish Sea Basin and onshore to Anglesey where outcrop samples have yielded Ar-Ar emplacement ages of 63-61 Ma (Horak *et al.* 1998).

Although the present-day near surface bedrock of Co. Antrim is dominated by the Antrim Lava Group, regional evidence indicates a far from passive post-Palaeocene history (Fig 1.10). For example, immediately to the south of the Lough Neagh –Larne Basin SHRIMP U-Pb crystallization dates of *c.* 56 Ma for the Mourne and Slieve Gullion granites indicates contemporaneous intrusion and suggests that *c.* 3kms of unroofing has occurred in this area of the Longford-Down Massif, since the Palaeocene (Gamble *et al.* 1999; Allen *et al.* 2002). In addition a patchwork of geomorphological observations throughout the island, (summarised in Mitchell 1976), provide evidence for post-Palaeogene fault activity [e.g offset of Palaeogene dyke at Killary Harbour, Co. Galway; ~500 metre offset of karstified Carboniferous limestone surface at Ben Bulbin, Co. Sligo; ~600 metre offset of basal Carboniferous conglomerate at Maumtrasna, Co. Mayo; preservation of roof-rock to Caledonian Leinster Granite at elevation of 1000 metres O.D. at Lugnaquilla, Co. Wicklow].

There are a number of lines of evidence which indicate that post-Palaeocene (Antrim Lava Group) subsidence has occurred, at least in the northeast of the island. At Kingscourt, basalts of presumed Palaeocene age, have been emplaced upon an erosion surface which consists of a karstified Permian gypsum deposit. (Simms 1998). The preservation of these 'rotted' basalts and the underlying soft gypsum deposits, can only have occurred as a result of burial beneath a post-Palaeocene cover. Further north, apparent extensional reactivation of major basin bounding fault systems has resulted in the preservation of a sequence of interbedded basalt weathering products, pyroclastics and lacustrine deposits at Ballymoney (Rathlin Basin) and at Lough Neagh (Lough Neagh-Larne Basin) where the succession is overlain by up to 350 metres of Upper Oligocene, siliclastic and lignite-rich, strata (Lough Neagh Group) in the Washing Bay borehole (Wilkinson *et al.* 1980; Mitchell 1980). The basal succession, which is only found proximal to faults, has been assigned a possible Eocene age by Parnell *et al.* (1989) though Shelton (1997) has argued that the basalt weathering products are Upper Oligocene in age. Boreholes drilled at a distance

from the faults have encountered the Upper Oligocene (Lough Neagh Group) resting unconformably upon fresh unweathered Palaeocene basalt – representing a time gap of in excess of 25 Ma.

Elsewhere on the island isolated pockets of Neogene sediments have been preserved primarily due to a karstified Carboniferous limestone bedrock (Fig 1.10). These occurrences (which include the following – Oligocene non-marine clays at Ballymacadam, Co. Tipperrary; limonitic breccias of presumed Tertiary age near Listry, Co. Kerry; Upper Pliocene dark, non-marine, clays at Hollymount, Co. Carlow; Upper Pliocene-Pleistocene non-marine sands at Poulnahallia, Co. Galway; silica clay and chert of inferred Tertiary age at Ballygaddy, Co. Offaly; clays of probable Tertiary age at Tullyallen and Drybridge, Co. Louth and at Ballyellin, Co. Carlow; redeposited sulphide ores containing Tertiary plant fossil at Tynagh, Co. Galway) have been summarized by Davies (1970), Mitchell (1980), Naylor (1992) and Allen *et al.* (2002). Mio-Pliocene deposits are unknown in the northeast (Shelton 1997) which suggests that a significant hiatus or erosional unconformity was developed in the area during the 20 Ma Neogene period. In the Lough Neagh area, a locally folded Upper Oligocene clay succession (which subcrops the Quaternary) has been interpreted as evidence of Miocene compressional inversion (George 1967; Roberts 1989).

The subaerial emplacement of the Palaeocene lavas onto an irregular karstified chalk landscape, the presence of interbasaltic laterite horizons, and the predominance of non-marine deposits in the Tertiary stratigraphic record, suggests that Ireland was above sea level for much of the Tertiary era. The current elevation of these deposits (up to 100m O.D at Ballymacadam) and the evidence of active late Tertiary faulting in northeastern and western Ireland (George 1967; Badley 2001) suggest that the present-day Irish landscape is primarily of Neogene origin. This landscape has been modified subsequently by glacial erosion during the Quaternary ice ages which itself has driven further erosion through isostatic rebound post removal of the ice load. Evidence of ongoing isostatic readjustment of shorelines (in response to removal of the ice load) is provided by the raised beach cliffs in the footwall of the Ballintoy Harbour Fault, where sea caves are preserved 5-10 metres above present-day sea level (Lyle 2003).

1.5 Offshore – stratigraphic evidence for timing of exhumation

In the offshore arena, a more complete, though still truncated, Carboniferous to Tertiary stratigraphic record is observed in Ireland's inboard basins (Fig 1.2). The degree of truncation varies, from the almost total absence of 'post-rift' Cretaceous and Tertiary sediments in the Irish Sea basins to the condensed 'post-rift' record in the northern Slyne and Erris basins, which can be compared with the almost continuous 'post-rift' sedimentary record in the 'outboard' Porcupine and Rockall depocentres. Nevertheless the preserved stratigraphy in the inboard basins provides a patchwork of evidence, which helps to constrain the timing of exhumation events which have affected the Irish landmass and shelf regions. A brief 'clockwise' resume is offered here of the seismic and stratigraphic evidence for major unconformities and exhumation events in these inboard basins.

Lough Indaal Basin & Rathlin Basin

The Lough Indaal and Rathlin basins consist of two, NE-SW trending, half-graben structures of opposite polarity, with the shallow ramp margins of both basins separated by the Dalradian 'Middle Bank' high (Fig 1.11). In the Lough Indaal Basin, seismic interpretation indicates a present-day basin fill of up to 2500m of Permo-Triassic sediments which onlap the Middle Bank high to the south (Fyfe *et al.* 1993). A major unconformity is interpreted at the base of this Permo-Triassic section, but it is not known if Late Palaeozoic rocks have been preserved beneath this unconformity. BGS shallow boreholes (75/41, 75/43 & 75/44) drilled in the northeast of the Lough Indaal Basin have proven the presence of Liassic mudstones, which subcrop Quaternary sediments but rest conformably upon Rhaetic sediments of the Penarth Group. The thickest preserved section of Liassic sediments is in the hanging wall of the basin-bounding fault (Fig 1.11). It is not known if younger Jurassic, Cretaceous or Tertiary sediments are preserved in this hanging wall area (Fig 1.12).

Similarily, a preserved basin fill, dominated by Permo-Triassic sediments, of *c.* 3000m, has been postulated for the Rathlin Basin. These sediments extend north-west of the Foyle Fault and onlap the Middle Bank high (Fig 1.11). The onshore Port More borehole, which is drilled in the hanging wall of the Tow Valley Fault, encountered 249m of Liassic sediments overlying a Permo-Triassic succession of 1129m (Wilson & Manning 1978). The youngest preserved Liassic sediments in this

borehole are Early Pliensbachian in age, although the entire Liassic section, at this location, has been faulted and distrupted by a number of Palaeogene igneous intrusions. The Liassic is unconformably overlain by 91m of the Late Cretaceous Ulster White Limestone Formation, which in turn is unconformably overlain by 76m of the Early Palaeogene, Lower Basalt Formation (Wilson & Manning, 1978). Seismic interpretation suggests the presence of up to 1000m of Carboniferous sediments along the southeastern margin of the Rathlin Basin, with progressive truncation of this section, beneath the Saalian unconformity, towards the northwestern ramp margin (Fig 1.13). This interpretation is supported by the evidence from the Magilligan-1 borehole, drilled onshore along the northern ramp margin, where Triassic (Sherwood Sandstone Group) sediments rest unconformably upon a Namurian to Visean section.

In summary, the punctuated stratigraphic record, for the Lough Indaal and Rathlin basins, indicates at least four periods of extensive exhumation have occurred in this area – constrained to the Late Carboniferous-Early Permian, Early Pliensbachian-Santonian, Early Maastrichtian-Late Palaeocene, Middle Eocene-Recent.

North Channel Basin

The North Channel Basin consists of two sub-basins, which are separated by the offshore extension of the NE-SW trending Southern Uplands Fault Zone (SUFZ) (Fig 1.11). The southern, Portpatrick sub-basin, is narrow and elongate in a NNW-SSE direction, is bounded to the east by the Portpatrick Fault, and is composed of a series of tilted fault blocks with easterly dipping polarity. The northern sub-basin has a NE-SW orientation, is essentially an offshore extension of the Lough Neagh-Larne Basin and is characterised by westerly dipping fault blocks of opposite polarity to the Portpatrick sub-basin (Maddox *et al.* 1997).

Carboniferous strata have not yet been encountered by drilling in the North Channel Basin, but in excess of 3000m of Permo-Triassic sediments are estimated to have been preserved in both the Larne and Portpatrick sub-basins (Maddox *et al.* 1997). The outcrop of Westphalian A and B successions in Co. Tyrone (Mitchell 1992), the presence of reworked Namurian-Westphalian miospores in Triassic mudstones of the Palace Army Barracks borehole southeast of Belfast (Naylor & Clayton 2000) and the evidence from seismic data of a major angular unconformity at the base of the Permian section, in both the onshore and offshore Larne Basin (Shelton

1997), all point to a major phase of exhumation during the Late Carboniferous-Early Permian period (Fig 1.14).

Seismic interpretation indicates that post-Triassic sediments are absent from the North Channel Basin, with Quaternary-Recent sediments resting unconformably upon the Mercia Mudstone Group (Fig 1.15). However, in the immediate onshore area, there has been a patchy preservation of Rhaetic and Liassic successions, with 50m of Liassic sediments encountered in the Larne-1 borehole, resting conformably upon the underlying MMG sediments, and 250m of Liassic preserved at the Port More borehole (see above). Middle Jurassic to Tertiary sediments are not preserved in the North Channel Basin, so the timing of post Pliensbachian exhumation events can only be constrained by reference to the stratigraphic record in the onshore Lough Neagh-Larne Basin. Here, Cenomanian to Early Maastrichtian Hibernian Greensand and Ulster White Limestone Formations rest with angular discordance upon Liassic and older rocks (McCaffrey & McCann 1992). Other major unconformities are also observed, at the base of the subaerially erupted lavas of the Palaeocene Antrim Lava Group, at the base of the succession of mixed pyroclastics and lacustrine sediments of the Lough Neagh Group, and at the base of the Quaternary-Recent sediments.

Peel Basin

The Peel Basin consists of a faulted NE-SW trending half-graben structure with dip polarity to the northwest (Fig 1.11). It is separated from the NE-SW trending Solway Basin by an extension southwards of the Galloway Ridge. The basin fill consists dominantly of Permo-Triassic sediments, which are unconformably overlain by Quaternary-Recent sediments (Fig 1.16). Newman (1999) has reported that 52m of Rhaetic to Hettangian claystones were encountered, beneath the Quaternary cover, in well UK111/29-1 and that a thin Liassic outlier may be present over the central and southwestern part of the basin. A major unconformity also exists at the base of the Permo-Triassic sequence – with both exploration wells (UK111/25-1A and 111/29-1) finding Permian sediments resting upon Dinantian carbonates (Floodpage *et al.* 2001). This unconformity is readily identified on seismic by the termination/erosion of pre-Permian fault planes and the dramatic angular discordance between the Permo-Triassic bedding and the seismic reflectors in the underlying Carboniferous or older section (Fig

1.16a). A comparison of the seismic lines orthogonal to the Peel Basin and the Solway Basin (Fig 1.16b) suggests that Namurian-Stephanian sediments may have been preserved on the southern flanks of both basins, but have been removed from the basin centres via basin inversion and erosion during a phase of Variscan compression.

Jurassic (post Hettangian), Cretaceous and Tertiary sediments have not been preserved in the Peel Basin, so the stratigraphic record offers few constraints with respect to the timing of Mesozoic and Cenozoic exhumation events. However, SHRIMP U-Pb dates for the Mourne and Slieve Gullion granites, which were intruded into the Longford-Down Massif to the northwest of the Peel Basin, indicate that significant unroofing (up to 3000m) of this area has occurred since 56 Ma (Gamble *et al.* 1999; Allen *et al.* 2002).

Kish Bank Basin

The Kish Bank Basin is an elongate NE-SW trending half-graben structure developed in the hanging wall of the Lambay-Dalkey Fault (Fig 1.17). The basin is bounded to the SW by the NW-SE trending Bray Fault and is bisected by a major NW-SE trending dextral strike-slip fault, the Codling Fault, which causes an apparent net dextral offset of the basin margin of between 4 km (Dobson & Whittington 1979) and 9 km (Dunford *et al.* 2001). Of the four wells drilled in the basin to date only one, well 33/22-1, has penetrated pre-Permian sediments. This well encountered, beneath a Quaternary cover, a Westphalian B-D section resting unconformably upon chloritic slates of Cambrian age. The extent of missing section from the top of the Carboniferous succession in this well is unclear as the upper 114m is unfossiliferous and can be interpreted as Stephanian or Westphalian D in age (Naylor *et al.* 1993). However, seismic interpretation indicates that local erosion has occurred, in the Kish Bank Basin, at the Saalian unconformity (Fig 1.18).

The preserved post-Palaeozoic stratigraphy of the Kish Bank Basin is dominated by a Permo-Triassic succession. In well 33/17-1, Tertiary sediments (Pliocene or older) rest unconformably upon the Triassic Mercia Mudstone Group (Naylor *et al.* 1993). Seismic interpretation indicates that the MMG is conformably overlain by a marine Liassic section (Dobson & Whittington 1979). Jenner (1981) estimated a maximum of 300 m of preserved Jurassic section, but Broughan *et al.* (1989) suggested that up to 2,700 m of Liassic sediments are preserved in the hanging

wall of the Bray Fault. Seismic interpretation presented in Dunford *et al.* (2001) also indicates the possibility of a Liassic outlier in the hanging wall of the Lambay Fault (Fig 1.19). A major unconformity exists between the Liassic and the overlying Tertiary sediments. Regional considerations suggest that the oldest Tertiary sediments in the Kish Bank Basin may be of Oligocene age (Jackson *et al.* 1995), although a Pliocene or older date has been assigned to the Tertiary sediments in well 33/21-1. Erosional truncation is observed on seismic at the Base Tertiary unconformity and clearly dates the folding of the hanging wall, inversion, anticline, drilled by well 33/21-1, as pre-Pliocene in age (Fig 1.19).

Central Irish Sea Basin

The Central Irish Sea Basin is a narrow, elongate NE-SW trending half-graben system with alternating polarities of dip towards the SE and NW. It extends from the Caernarfon Bay Basin in the NE to the Wexford outlier in the SW (Fig 1.20). To the south, the basin is bounded by the offshore extension of St. Tudwal's Arch which is bisected and dextrally offset by the SE extension of the Codling Fault Zone. Significant N-S trending faults are also observed in the Central Irish Sea Basin (Maddox *et al.* 1995; Maingarm *et al.* 1999; Izatt *et al.* 2001).

The stratigraphic record indicates a major hiatus at two levels in the Central Irish Sea Basin. In wells 42/12-1, 42/12-2 and 42/16-1, Triassic sediments of the Sherwood Sandstone Group rest unconformably upon sediments of Westphalian D-Stephanian age indicating widespread uplift, non-deposition and possible erosion during the Permian. In well 42/17-1, there is a faulted contact between the Triassic Mercia Mudstone Group and the underlying Westphalian D section. In this well, a conformable 64 m thick section of Hettangian-Sinemurian siltstones and claystones was encountered in the hanging wall of this fault and is unconformably overlain by Quaternary sediments. The presence of more extensive Liassic outliers, along the hanging walls of basin margin faults, have been inferred from seismic data (Corcoran & Clayton 1999; Izatt *et al.* 2001), which is consistent with the observations from other Irish Sea basins where a major phase of uplift and erosion is post-Liassic in age.

Cretaceous sediments have not been recorded in the Central Irish Sea Basin. Late Triassic, MMG sediments, subcrop the base of the Quaternary section over much of Central Irish Sea area. The present day basin manifests an anticlinal

morphology, which has probably been accentuated by NW-SE directed compressional basin inversion during the Tertiary (Fig 1.21). Maingarm *et al.* (1999) reported Tertiary sediments in well 42/8-1 and seismic evidence suggests that Tertiary sediments are locally preserved in the hanging wall of some basin-bounding faults. The interpreted onlap in a basinward direction of ?Eocene – Oligocene sequences onto the Mercia Mudstone Group in the NW of the basin (Fig. 4 from Maingarm *et al.* 1999) suggests that Tertiary compressional inversion (*sensu* Roberts 1989) had at least been initiated by Late Eocene-Oligocene time (Fig 1.22). This Palaeogene section is in turn truncated by a mid-Miocene to early Pleistocene erosional event (Figs 1.21, 1.22).

St. George's Channel - Cardigan Bay Basin

The St. George's Channel-Cardigan Bay Basin is a NE-SW trending half-graben system located between Pembrokeshire and SE Ireland (Figs 1.20). This half-graben system is compartmentalised by a number of NW-SE trending fault zones, including the Sticklepath-Lustleigh and Codling Faults which mark the limits of the St. George's Channel Basin to the SW and NE respectively. Consequently, a transtensional pull-apart origin has been inferred for the St. George's Channel Basin, due to its location at a releasing stepover in the Codling-Sticklepath-Lustleigh strike slip system (Turner 1997). Post-Carboniferous sediment thickness is estimated to have reached some 12,000m in the basin centre, including *c.* 2500m of Liassic sediments and a substantial, *c.*1500m, Tertiary section (Welch & Turner 2000). To the SW of the Codling Fault Zone, thick (up to 10,000m in the basin centre) Mesozoic strata in the hanging wall of the St. George's Fault are folded into an open synform which has been truncated at the Base Tertiary unconformity (Fig 1.23; see also Fig. 11 in Tucker & Arter 1987). Combined sediment loading and fault movement in this area has resulted in the emplacement of a linear salt wall along the St. George's Fault (Dimitropoulos & Donato 1993).

The stratigraphic record provides evidence for at least three phases of exhumation in the St. George's Channel-Cardigan Bay Basin. In well 103/2-1, Triassic sediments rest unconformably on coal measures of Westphalian D age (Barr *et al.* 1981; Musgrove *et al* 1995). In the North Celtic Sea and St. George's Channel-Cardigan Bay basins, an extended period of post-Variscan peneplanation is indicated by the absence of

Permian rocks and the limited distribution of the Early Triassic Sherwood Sandstone Group (Musgrove *et al.* 1995).

A second phase of regional exhumation is indicated by the limited preservation of Cretaceous sediments in the area north of the Variscan Front (Fig 1.20; Tappin *et al* 1994). In general, the Tertiary succession rests with marked unconformity upon strata of Late Jurassic/older age indicating a period of basin-scale exhumation which is post Late Jurassic in age (Fig 1.23). In excess of 1,500 m of Eocene and younger Tertiary sediments are preserved in the hanging wall of the St. George's Fault (Tappin *et al.* 1994). Detailed seismic interpretation and structural analysis by Williams *et al.* (2005) has resolved two major inversion episodes in the Late Cretaceous and Neogene with a possible third minor phase during the Eocene (Fig 1.24). No deposits of mid-Miocene to early Pleistocene have been encountered in the St. George's Channel-Cardigan Bay Basin suggesting a period of widespread exhumation at this time (Dobson & Whittington, 1987). Peneplanation of the Palaeogene and early Neogene topography by the Base Quaternary unconformity is clearly observed on a number of seismic lines in this area (Figs 1.23, 1.24).

North Celtic Sea – Fastnet Basin

The North Celtic Sea Basin (NCSB) and Fastnet Basin (FB) form part of a complex of Mesozoic extensional basins developed in the Celtic Sea area during the early development of the North Atlantic (Fig 1.25; Ziegler, 1982). The NCSB is bounded by a series of Palaeozoic ridges and platforms and contains a thick Triassic to Cretaceous sedimentary fill. Rifting episodes occurred during the Triassic, Late Jurassic and Early Cretaceous (Rowell 1995), but post-rift subsidence was terminated by phases of regional exhumation and tectonic inversion during the Cenozoic. A major unconformity is present at the base of the Mesozoic succession in both the NCSB and FB, with Triassic sediments resting unconformably upon a folded and thrusted Variscan basement composed of Early Namurian and Dinantian (Culm Facies) or older rocks (Gardiner & Sheridan, 1981). Permian sediments are absent from the NCSB and FB and the Early Triassic Sherwood Sandstone Group (SSG) appears to have been deposited in an intermontane setting, where palaeotopography was controlled by the end Carboniferous thrust belt morphology (Fig 1.26; Musgrove *et al.* 1995). The SSG is conformably overlain by the locally saliferous Mercia Mudstone Group (MMG)

and these Triassic continental sediments are succeeded by up to 2500m of Lower to Middle Jurassic marine carbonates and shales with occasional thin sandstones. The overlying Late Jurassic, syn-rift, succession consists of fluvial, deltaic and shallow marine sandstones, mudstones and limestones.

During the Middle Jurassic to Middle Cretaceous, pulsed rifting and tectonism, arising from regional plate reorganization, may have resulted in depositional hiatus or the local, syn-rift, development of erosional unconformities (Mid-Cimmerian, Late-Cimmerian and Aptian unconformities) (Petrie *et al.* 1989; Rowell 1995). For example, in the NCSB during the Late Jurassic, erosion of footwall blocks towards the basin margins occurred (Fig 1.27), though within the main depocentres of the NCSB, the uppermost Jurassic and lowermost Cretaceous sediments are interpreted to be conformable. Continental and paralic sediments of the Lower Cretaceous Wealden Group are succeeded by marine sandstones and shales of the Greensand Group which are in turn conformably overlain by a Cenomanian to Maastrichtian chalk succession. Restored isopachs suggest that up to 1000-1400m of chalk accumulated along the axis of the NCSB, prior to Tertiary exhumation episodes (Murdoch *et al.* 1995). This exhumation has resulted in the present-day subcrop of Cretaceous chalk at the sea floor in the centre of the NCSB (Fig 1.28), and the complete removal of Cretaceous sediments towards the northeast, in the St. George's Channel-Cardigan Bay Basin (Fig 1.24). Two Cenozoic erosional events have been documented - regional uplift during the Palaeocene (Eocene-Oligocene sediments rest unconformably upon Cretaceous chalk over much of the NCSB) and tectonic inversion characterised by basin doming and fault reversal during the Oligo-Miocene (Eocene-Oligocene sediments have been deformed with the chalk during the post-Oligocene inversion and eroded prior to deposition of Plio-Pleistocene sediments – Fig 1.28), with net exhumation in excess of 1100m interpreted in the northeast of the basin (Murdoch *et al.* 1995).

Middle or Upper Jurassic sediments are encountered in only two wells (56/26-1 and 63/8-1) in the Fastnet Basin (Fig 1.25). The evidence from these wells suggests that a minor hiatus exists between the Toarcian marine shales and the overlying Bajocian and Bathonian shales and sandstones. However, the emplacement of igneous intrusives in the centre of the FB during the Bajocian and to the west in the Goban Spur basin, during the Bathonian-Callovian (Caston *et al.* 1981; Cook 1987) suggests potential for more widespread regional erosion during this Middle Jurassic

period. A more pronounced hiatus is present between the Bathonian and Kimmeridgian successions and a major erosional unconformity occurs at the base of the Cretaceous succession, with continental Wealden sediments of Valanginian to Late Barremian age overstepping the eroded Jurassic topography (Fig 1.29). Lower Cretaceous, paralic to marine, sandstones and shales of the Greensand Formation rest with minor unconformity upon the Wealden section, but conformably underly a Cenomanian to Early Maastrichtian chalk succession. Regional exhumation and erosion occurred during the early Palaeogene as all of the wells in the Fastnet Basin have encountered Mid Eocene-Oligocene limestones and shales, or younger sediments, resting unconformably upon Campanian-Early Maastrichtian chalk. Seismic evidence suggests that local Oligo-Miocene compressional inversion has occurred in the area of wells 63/8-1 and 63/4-1, where Miocene sediments rest directly upon Lower Cretaceous sediments (Robinson *et al.* 1981).

South Celtic Sea, Bristol Channel & Cockburn Basin

The South Celtic Sea (SCSB) and Bristol Channel (BCB) basins, are separated from the FB and NCSB, to the north, by the Palaeozoic cored Labadie Bank and Pembroke Ridge. These basins are bounded to the south by the Cornubian Platform, which contains the relatively shallow Cockburn Basin (CB) (Fig 1.25). The boundary between the SCSB and the BCB is defined by the southern extension of the Waterford Lineament (Fig 1.25; van Hoorn, 1987). A number of phases of exhumation can be inferred from the stratigraphic record in these basins.

A major angular unconformity is interpreted at the base of the Mesozoic succession in the SCSB (Fig 1.30). Locally, an undated (Permian? age) wedge of sediment is observed on seismic beneath this unconformity, but preservation is restricted to a minor half-graben close to the northwest margin of the CB (Fig 1.31). Late Carboniferous-Early Permian volcanics have been encountered by drilling in the Melville sub-basin, to the south, but the absence of strong reflectivity suggests that volcanics may not be present in the CB wedge (Smith 1995). Above the Base Mesozoic unconformity a typical Triassic succession is developed in these basins, with a thin relatively sand poor SSG succession, overlain by an evaporite rich MMG succession. Subsequent mobilization of these Triassic halite beds has resulted in the development of salt pillows within the BCB and SCSB. The MMG is conformably overlain by marls

and limestones of the Penarth Group, which are in turn succeeded by marine shelf limestones of the Lower Jurassic.

Middle Jurassic successions, though well developed in the BCB, are poorly preserved in the SCSB (Fig 1.30; Petrie *et al.* 1989). Upper Jurassic strata are generally thin or absent from the CB, SCSB and BCB basins, indicating an extensive phase of uplift and erosion during the Late Jurassic-Early Cretaceous (Fig 1.29). For example, well 93/2-1 encountered Wealden sediments of Barremian to Aptian age, resting unconformably on Bathonian rocks. Up to 500m of Wealden sediments are preserved in the SCSB, with this succession, for the most part, conformably overlain by marine sandstones and shales (Greensand and Gault) of mid-Albian to Cenomanian age (Weighell, 1980). Up to a 1000m of Upper Cretaceous sediment is preserved in these basins (Tappin *et al.* 1994). Thickness variations, within the Upper Cretaceous chalk section, are locally due to syndepositional pillowing of the Triassic halites followed by progressive regional exhumation towards the east where an extensive phase of Palaeogene uplift and erosion may have been induced by the emplacement of the Lundy igneous complex during the early Eocene (Harland *et al.* 1989; Thorpe *et al.* 1990). Although poorly developed and largely restricted to the south of the Cockburn Basin, up to 500m of mid-Eocene to late Oligocene sediments are preserved in the SCSB, where they have been subsequently folded by a phase of Oligo-Miocene compressional inversion (Fig 1.32). This structuration has been peneplaned by erosion at the Base Quaternary unconformity.

Slyne-Erris Basins

The Slyne-Erris Basin (SEB) is a narrow, elongate, NE-SW trending basin system located approximately 60 kms off the coast of Mayo and Donegal. It consists of a series of asymmetric half-grabens separated by cross-cutting transfer zones (Fig 1.33). These basins have experienced a multiphase rifting and inversion history although the preserved basin morphology is primarily the result of Middle-Late Jurassic rifting (Dancer *et al.* 1999; Chapman *et al.* 1999). Four wells (12/13-1a, 18/25-2, 19/5-1 and 27/5-1) in the basin have drilled pre-Mesozoic successions and all have encountered a major unconformity at the base of a Late Permian, Zechstein, sequence. The age of the Upper Palaeozoic strata which subcrop this unconformity varies from Westphalian C (well 19/5-1) to Late Devonian (12/13-1a)

(Robeson *et al.* 1988). This contrasts with the preservation of Stephanian sediments to the south, in a number of wells in the North Porcupine area, and suggests a strong tectonic control on the preservation of the basin fill during Late Carboniferous-Early Permian exhumation (see Fig 1.6).

A striking characteristic of the Slyne Basin is the severely truncated Mesozoic and Cenozoic stratigraphic record, with an almost complete absence of post-rift (Jurassic rift) sediments. Cretaceous sediments are absent from the central and southern Slyne Basin area, where a thin cover of Late Miocene or younger sediments rests unconformably on syn-rift sediments of Late Bajocian to Bathonian age (Fig 1.34). In the northern Slyne Basin (at least locally in the Corrib area – see Chapter 8) a thin blanket of Albian marine sediments rest directly upon an eroded Middle and Upper Jurassic succession (Fig 1.35). However, in the northerly Erris Basin, more than 1 km of Cretaceous strata are locally preserved, including an almost continuous, conformable, Late Ryazanian-Maastrichtian succession (969m thick) in well 12/13-1a, which sits unconformably upon Rhaetic sediments at this location (Fig 1.36). To the southwest, in well 19/5-1, this Cretaceous succession has been completely eroded, and Late Miocene sediments sit directly upon the Early Sinemurian. A minor hiatus is present at the base of the Tertiary section in well 12/13-1a with a relatively condensed Danian, Late Palaeocene and Eocene succession resting upon Maastrichtian chalk (Chapman *et al.* 1999). This is in contrast to the Corrib area of the Slyne Basin (see Chapter 8) where Eocene volcanics, which have yielded K/Ar dates of 40-43 Ma, rest unconformably upon the Early Maastrichtian chalk. A major hiatus in the stratigraphic record is also observed at the top of this volcanic section as it is unconformably overlain in the Corrib area by Late Miocene to Recent sediments.

In summary, the stratigraphic record in the Slyne-Erris Basin points to the development of major unconformities in response to exhumation episodes which are constrained to the Late Carboniferous-Early Permian, Late Jurassic-Early Cretaceous, Late Cretaceous-Early Palaeogene, Late Palaeogene-Late Miocene. However, the magnitude of exhumation and erosion, associated with these unconformities, varies spatially throughout the Slyne/Erris area due to the overprinting of multiple phases of regional exhumation and local inversion episodes. These exhumation events include: rift-related footwall uplift events caused by extension during the Middle-Late Jurassic and Aptian rift phases; massive, kilometer scale, uplift

and erosion along the western margin of the basin due to rifting of the Rockall Basin during the Late Jurassic-Early Cretaceous (Fig 1.37; Chapman *et al.* 1999), transient uplift associated with mantle hot-spot activity during the Early Cretaceous and Early Eocene (Jones *et al.* 2001); regional uplift during the Palaeogene possibly associated with igneous underplating (Clift & Turner, 1998); and local inversion-related uplift during the Oligo-Miocene (Dancer *at al.* 1999).

Donegal Basin

The northwest shelf area, offshore Donegal, is dominated by a series of NE-SW trending grabens and half-grabens sandwiched between the Precambrian basement ridges of the Outer Hebridies Platform and the Islay-Donegal Platform (Fig 1.33). The presence of Mesozoic and early Cenozoic sediments in the basin remains to be proven. The single well drilled in the basin to date, well 13/3-1, encountered Miocene?/Pleistocene-Recent sediments resting directly upon a section of Westphalian D-Stephanian age. However, in the south of the Donegal Basin, Dobson & Whittington (1992) have interpreted a thicker sedimentary section from seismic data and shallow boreholes, with the possible presence of in excess of 2500m of Permo-Triassic to Middle Jurassic basin fill. A seismic section presented in Allsop & Stevens (2002) clearly indicates the erosion of hundreds of metres of Jurassic? section at the Miocene unconformity (Fig 1.38). However, at least one major pre-Tertiary erosional event can be inferred from nearby well data. Evidence from well UK132/15-1, which encountered Barremian-Aptian sediments resting unconformably upon Precambrian granite, indicates that erosion progressed to deep crustal levels during the Early Cretaceous, due to massive footwall uplift on the flanks of the Rockall Basin, prior to post rift thermal subsidence (Musgrove & Mitchner 1996). Studies by Stoker (2002) and others, of Neogene sedimentation patterns along the NE Atlantic margin, have identified an early Pliocene unconformity as representing the onset of a late Neogene exhumation episode in NW Britain.

In summary, the single well (13/3-1) drilled in the Donegal Basin indicates a long lived stratigraphic break occupying most of Mesozoic and Tertiary time. However, seismic evidence from the south of the basin suggests that Mesozoic successions were deposited but have been eroded during subsequent Mesozoic and Cenozoic episodes of denudation.

1.6 Regional tectono-stratigraphic context of Irish basins

Although these Irish basins (described above) vary in morphology and basin fill they form a sub-set of Norwegian, Faeroese, British, Irish and Iberian basins which are related to the evolution of the northwest European Atlantic margin. This evolution is primarily the story of the break-up of the Permo-Triassic, Pangaean, supercontinent which had been assembled, in part through Variscan collision, during the late Carboniferous-early Permian time and the coalescence of a southwards propagating 'Arctic' rift and a northward propagating 'Atlantic' rift to form the North Atlantic Ocean. This margin has experienced a prolonged extensional history (spanning *c.* 350 Ma) with episodes of extension documented during the Carboniferous, Permo-Triassic, Middle-Late Jurassic, Early Cretaceous, middle Cretaceous and latest Cretaceous-Early Eocene periods (Doré *et al.*, 1999; Roberts *et al.* 1999; Johnston *et al.* 2001). Although North Atlantic seafloor spreading (between Newfoundland and Iberia) was initiated during Aptian times, the final break-up of Pangaea did not occur (in the Norwegian-Greenland Sea) until the earliest Eocene (*c.* 53 Ma) (Lundin & Doré 2005).

In general terms this extensional history has resulted in the formation of two broad bands of Late Palaeozoic to Cenozoic sedimentary basins along the northwest European Atlantic Margin – a series of inboard basins, which are typically sediment filled (with little bathymetric expression), located along the eastern margins of the continental shelf and a series of larger (typically underfilled with sediment) outboard basins, which underly the main bathymetric embayments along the margin (e.g. South Porcupine, Rockall, Faroe-Shetland, Møre and Vøring basins) (Spencer *et al.* 1999; Shannon *et al.* 2001; Shannon *et al.* 2005). The Porcupine Basin has characteristics of both the inboard and outboard basins (Shannon *et al.* 2005).

The inboard basins, which generally manifest a narrow, N-S to NE-SW trending, elongate morphology with structurally segmented depocentres, include the Irish Sea, Celtic Sea, Slyne, Erris, Donegal, Lough Indaal, Rathlin, Hebrides, West Shetland and Halten Terrace basins. The morphology and distribution of Carboniferous basins in the offshore area is poorly understood. Both extensional and strike-slip, pull-apart, episodes (in an overall, Variscan, foreland basin setting) have been proposed to account for the variable carbonate and clastic successions observed in these basins (Roberts *et al.* 1999; Strogen *et al.* 1996). However, the (preserved) Mesozoic sedimentary fill in these inboard basins reflects the deposition of thick

continental sequences in response to Permo-Triassic rifting and subsidence (*c.* 5 kms of Triassic sediments deposited in the East Irish Sea Basin – Jackson *et al.* 1997) followed by the deposition of marine and deltaic successions (in most of these basins) in response to early Jurassic subsidence and middle-late Jurassic rifting. In contrast, the outboard basins are dominated by thick, mainly clastic, successions of Cretaceous and Tertiary age, which overlie locally preserved early Mesozoic and late Palaeozoic sediments. This tectono-stratigraphic configuration reflects the generally basinwards-stepping (westwards-stepping) rift pattern through time, which has resulted in the overprinting of a complex network of Jurassic and older basins by a continuous chain of deep, NE-SW trending Cretaceous-Cenozoic basins (Lundin & Doré 1997). This present-day basin configuration has been interpreted by Doré *et al.* (1999) to represent changes in extensional style and a progressive clockwise rotation in extension direction through time – from mosaic-like fragmentation of Pangea during the Permo-Triassic, to systematic E-W extension during the Late Jurassic to dominantly NW-SE extension during the Early Cretaceous.

The prolonged extensional history of the northwest European Atlantic Margin has been punctuated by a number of episodes of regional exhumation and compressional inversion between late Palaeozoic and Neogene time. These episodes include - Variscan inversion of early Carboniferous extensional basins during the closure of the Rheic ocean (Fraser & Gawthorpe 1990; Chadwick *et al.* 1993); regional early Cretaceous exhumation in the Irish Sea, south Celtic Sea, Wessex and Slyne basins related to incipient Atlantic rifting and sea-floor spreading in the Bay of Biscay (Kammerling 1979; McMahon & Turner 1998; Green *et al.* 2001; Holford *et al.* 2005a; Corcoran & Mecklenburgh 2005; Holford *et al.* 2005b); a combination of regional epeirogenic uplift and inversion during the early Palaeogene in the Irish Sea basins and North Celtic Basin in response to the initiation of the Iceland plume, with associated magmatic underplating (Brodie & White 1995; Smallwood & White 2002), and Laramide compression (Murdoch *et al.* 1995); Palaeogene-Neogene intra-plate compression associated with Alpine lithospheric shortening and ridge push from North Atlantic sea floor spreading which has resulted in the generation of large scale, multiphase, Cenozoic inversion structures through the Hatton, Rockall, Faroe-Shetland, Møre and Vøring basins (Boldreel & Andersen 1993; Doré & Lundin 1996; Doré *et al.* 1999; Hitchen 2004; Johnson *et al.* 2005) together with localized inversion structures in

the Irish Sea, Celtic Sea, Lough Neagh-Larne and Slyne basins (George 1967; Dancer *et al.* 1999; Williams *et al.* 2005; Holford *et al.* 2005a); Neogene regional exhumation of onshore Norway, Scotland, Faeroe Islands, Svalbard and Barents Sea Basin triggered by intraplate compressive stress (Cloetingh *et al.* 1990) but magnified by changes to a wetter climate (during the Neogene) and ultimately glacial erosion and isostatic readjustment during the Pleistocene (Japsen & Chalmers 2000; Doré *et al.* 1999).

1.7 Summary/conclusions from stratigraphic evidence

Analysis of the onshore evidence and the preserved stratigraphic record in the offshore basins indicates that the Irish landmass and shelf regions have been affected by a number of pervasive exhumation events, which can be constrained to selected time periods in geological history (Fig 1.39). At least five, potentially regional, exhumation episodes are interpreted to have occurred - a Late Carboniferous to Early Permian event, a Late Jurassic to Early Cretaceous event, an early Palaeogene event, a Late Palaeogene event and a Neogene episode. Other unconformities are present in these basins but the majority of these unconformities relate to local, relatively minor tectonism and relative sea level changes. However, a pervasive Middle Jurassic (Mid Cimmerian) exhumation event may also have affected the Irish shelf and landmass region, although evidence for Mid Cimmerian uplift and erosion is somewhat tenuous in the inboard basins, due to merging of Mesozoic and Cenozoic unconformities. For example in the North Celtic Sea and Fastnet Basins non-marine coastal plain Oxfordian and Kimmeridgian sediments sit unconformably on early to mid-Jurassic marine shelf muds or calcareous sandstones. Regional seismic data, from the North Porcupine area, shows some evidence of angular truncation at this unconformity (MacDonald *et al.* 1985), but this surface is more commonly characterized by a strong high amplitude reflection, without erosional truncation (Scotchman & Thomas 1995; Chapman *et al.* 1999).

Unconformities are also recognized in the outboard (non-exhumed) basins of the Porcupine and Rockall region which, by definition, contain relatively continuous and complete post-rift (Jurassic rift) successions. However, only in the Porcupine Basin has sufficient drilling occurred to elucidate the Mesozoic stratigraphic record. A number of unconformities are recognized in the basin including

the Base Cretaceous (Late Cimmerian) unconformity, which has long been recognized on seismic as a major regional unconformity (Croker & Klemperer 1989). This unconformity marks the cessation of Late Jurassic rifting and the erosional truncation of subcropping pre-rift and syn-rift sequences below. However, little uplift and erosion is observed at this unconformity, in the centre of the basin. No significant stratigraphic breaks are recognized in the basin centre wells, between the early Cretaceous and Late Tertiary, although there is evidence from the basin margin wells of stratigraphic breaks during the Aptian and Late Palaeocene (Tate 1993; Jones *et al.* 2001).

There are clearly a number of different forces which, when convolved with falls in eustatic sea-level, contribute to the temporal and spatial pattern of exhumation which can be deduced from the stratigraphic record. Study of these forces is beyond the scope of this thesis, suffice to state here that genetic classification of the driving forces for exhumation indicates three potential origins – compressional, thermal and isostatic, although there are many published variations on each theme. For example proposed mechanisms for regional, Palaeogene-Neogene, exhumation in northwest Europe include:

1. Compressional reactivation of extensional crustal detachments causing inversion of pre-existing basins (Hillis, 1992).
2. Backward transmission of compressive forces from the leading edge of an underthrusted foreland plate to invert remote basins, such as the Southern North Sea, carried upon the underthrust plate (Lowell, 1995).
3. Episodic changes in intraplate stress fields resulting from mechanical coupling of geodynamic processes at plate boundaries and deformations in plate interiors – in particular flexural deflections of the lithosphere in northwest European basins may account for 'paired' areas of accelerated subsidence and exhumation during the Late Neogene (Cloetingh & Kooi, 1992).
4. Non coaxial inversion of the St. George's Channel Basin during the Neogene, with coeval transpression and transtension focused at discrete bends and stepovers on the basin-bounding faults (Williams *et al.* 2005).
5. Presence of a local, Palaeogene, mantle hotspot beneath the East Irish Sea Basin (Cope 1994). Presence of Late Carboniferous-Early Permian, Panangean, mantle plume beneath northwest Europe (Doblas *et al.* 1998).

6. Regional igneous underplating of the NE Atlantic margin, along a NNE-SSW axis, related to the Icelandic plume (Brodie & White, 1995; Clift & Turner, 1998).
7. Glacio-isostatic response due to deglaciation and to sedimentary unloading resulting from erosion caused by glacial processes (Riis & Fjeldskaar, 1992; Doré & Jensen, 1996).

Variations in basin setting, structural style, exhumation magnitude, and the spatial and temporal distribution of exhumation in the Irish landmass and shelf regions suggests that all of these mechanisms have contributed, at some time in geological history, to the denudation of the area.

Chapter 2

A review of techniques for the estimation of magnitude and timing of exhumation in offshore basins

2.1 Introduction and definition of exhumation

Exhumation describes the removal of overburden material by any means from a basin or other terrane such that previously buried rocks are exposed at the earth's surface (Table 2.1; Doré *et al.*, 2002a). As a generic term it has been used to describe both the return of deep-seated lower-crustal/mantle rocks to the Earth's surface (Ring *et al.*, 1999) and the removal of sediment by erosion from basins at shallow crustal levels. Exhumation is a global process that occurs in a range of geological settings – from mountain belts (such as the major collisional orogens of the Caledonides, Appalachians/Hercynides, Alpine, Andean and Himalayan belts) to offshore basins, and at a variety of scales – ranging from the *c.* 80 kms of exhumation that has been estimated for the Western Gneiss Region of the Norwegian Caledonides (where eclogites, once deeply buried within the lithosphere, are now at outcrop) (Milnes *et al.* 1997), to the more modest levels (generally <5 kms) of exhumation which have been documented in the non-orogenic Late Palaeozoic to Cenozoic basins of the North Atlantic Margin (Doré *et al.*, 2002). Whereas thermochronology, geomorphology, structural geology and petrology, are the main tools used to estimate the timing and magnitude of exhumation in orogenic settings an alternative toolkit is appropriate for the assessment of exhumation in offshore sedimentary basins. This review draws heavily upon the wealth of studies dedicated to exhumation in the petroliferous basins of NW Europe but is primarily focused on a critique of the techniques that have been used to quantify exhumation in the basins peripheral to the Irish landmass.

A wide variety of techniques are now available to help quantify the magnitude and timing of exhumation in offshore sedimentary basins (Skagen, 1992; Doré *et al.*, 2002a). Methodologies employed in the offshore arena generally utilise local 'point' measurements of rock displacement with respect to tectonic (e.g subsidence curves), thermal (e.g vitrinite reflectance, fission track analysis),

compactional (e.g core porosity, sonic velocity) or stratigraphic (e.g section correlation, seismic section subcrop analysis) frames of reference. Some additional techniques such as geomorphological analysis (Lidmar-Bergstrøm & Naslund, 2002) and cosmogenic nuclide interpretation (Stroeven *et al.*, 2002) have been used to assess the exhumation of onshore sedimentary successions, but have no direct application in offshore basins – although they can provide useful constraints on the interpretation of exhumation via onshore-offshore correlations (Japsen *et al.* 2002). Mass balance computation of eroded and deposited sediment volumes (Jones *et al.* 2001; Jones *et al.*, 2002) can illustrate general points about the exhumation/burial history of a basin (and hence about its prospectivity) but is less applicable to "point" measurements, for example at a well location or prospect. In all cases, large uncertainty is associated with estimates from individual techniques, as confirmed by the discrepancies between estimates of exhumation derived from different methods at a given location (Skagen, 1992; Nyland *et al.*, 1992; Hillis, 1995; Cope, 1997; Japsen & Bidstrup 1999; Ware & Turner, 2002). The aim of this review is to critically assess the available techniques for the assessment of exhumation in offshore sedimentary basins. These techniques are illustrated and appraised by reference to basins in NW Europe, in particular the exhumed Irish sedimentary basins.

One issue with respect to the exhumation of rock columns is the broad lexicon of terms (uplift, surface uplift, crustal uplift, uplift of rocks, inversion, exhumation, erosion, denudation) that has developed in this field of study (Table 2.1) (for discussion see England & Molnar, 1990; Doré *et al.*, 2002a). Some of these terms have lacked formal definition and have been used interchangeably, often resulting in confusion, in part because of the different 'scale' of focus of various research groups. As highlighted by England and Molnar (1990) "a displacement is only defined when both the object displaced and the frame of reference are specified". This study is primarily concerned with the local (at the scale of hydrocarbon traps offshore Ireland, normally less than 300 km^2) or 'point' vertical displacement of rocks, from maximum burial depth, relative to the present-day seabed (offshore basins) or ground level (onshore basins). In many cases these local or point measurements cannot differentiate between displacement due to local fault related inversion and displacement due to regional exhumation (Turner & Williams 2004). As a result, inferences are difficult to make from individual measurements with respect to i) the driving force of this

displacement (compressional, thermal or isostatic), ii) its longevity (permanent versus transient), or iii) the potential impact of changes in eustatic sea-level throughout the Mesozoic and Cenozoic eras. The term, *surface uplift* is retained to describe uplift of the Earth's surface (averaged over an area of c. 10^3-10^4 km^2) with respect to mean sea-level (geoid) whereas *crustal uplift* is used to describe vertical displacement of the rock column with respect to the same datum. For example, the Cenozoic of the northwest European continental shelf is characterized by widespread evidence of *crustal uplift* which has been interpreted from mapped regional patterns of exhumation estimates derived from subsidence curves (Brodie & White 1995; Rowley & White 1998), vitrinite reflectance profiles (Corcoran & Clayton 2001; Argent *et al.* 2002), apatite fission track analysis (Green *et al.* 1999; Green *et al.* 2001), shale compaction trends (Hillis *et al.* 1994; Ware & Turner 2002; Japsen *et al.* 2002) and stratigraphic reconstruction (Holliday 1993; Cope 1997).

From the perspective of the petroleum explorationist *net exhumation* (*net uplift* - *sensu* Doré & Jensen 1996) - the difference between the present-day burial depth of a reference unit (source, reservoir or seal) and its maximum burial depth prior to exhumation – is the parameter of most interest (Fig. 2.1). This arises because, irrespective of the number of unconformities in a stratigraphic succession, maximum burial depth (when coincident with maximum compaction and temperature exposure) is a key control on the maturation, compaction and diagenetic state of source, reservoir and seal rocks and consequently, has important implications for the hydrocarbon prospectivity of a basin (Jensen & Schmidt 1993; Doré *et al.* 2002b). *Gross exhumation* (or total exhumation) describes the magnitude of erosion which must have occurred at a particular unconformity prior to post-exhumation re-burial. Although, the term *exhumation* is rarely associated with quantitative measures in the literature (Doré *et al.*, 2002a), in this paper *exhumation* is the preferred descriptor to clearly differentiate these 'intra-basin' local or point measurements (displacements relative to a dynamic datum e.g. seabed) from 'uplift' measurements (displacements relative to a static datum e.g. geoid) which *sensu stricto* pertain to regional lithospheric and plate scale tectonic processes.

2.2 Why measuring exhumation is important

Exhumation events, involving erosion and removal of overburden, and in some cases surface uplift, can have profound effects on the evolution of sedimentary basins and the hydrocarbon systems they contain. Consequently, quantification of the magnitude and timing of these exhumation events has direct economic importance, in terms of our understanding of petroleum systems and prospectivity in exhumed basins. Furthermore, it offers some critical insights to other geological issues such as the evolution of passive margins, the role of mantle plumes, evidence for underplating, isostatic readjustment, glacial erosion etc.

With respect to petroleum geology, empirical observation suggests that the application of conventional resource assessment and risk evaluation methodologies to exhumed basins may result in the overestimation of the undiscovered resource potential for these basins. Realization early in the exploration programme that a basin has been exhumed gives rise to a different approach to hydrocarbon exploration and can help to constrain resource and risk prediction (Doré *et al.* 2002b). Nyland *et al.* (1992) and Doré & Jensen (1996) were among the first to highlight the impact of exhumation on petroleum systems. MacGregor (1995b) noted that exhumed petroliferous basins were characterised by concentrated field size distributions (most of basin reserves in one large field) as opposed to the more typical dispersed distributions (<25% basin reserves in largest fields) of 'continually subsiding' basins. He also indicated that the mechanism of exhumation may be important, in terms of petroleum resource preservation, suggesting that regional uplifts of compressional origin may be more destructive of a basin's petroleum system than uplifts of isostatic or thermal origin. A systematic and comprehensive review of the implications of exhumation for prospect assessment and risking has been provided by Doré *et al.* (2002b).

Although there is a complex interplay between the timing and magnitude of an exhumation event and the evolutionary status of a petroleum system, some generalizations can be made with respect to the effects of exhumation. In summary the negative effects of exhumation include:

- A limited hydrocarbon budget is available to charge traps as a result of the 'switch-off' of source rock maturation during exhumation.

- Generally, higher levels of reservoir diagenesis (with respect to present day burial) prevail and this can impact the net-to-gross ratio, porosity, water saturation and recovery factor for exhumed reservoirs.
- A reduced probability of effective top-seal exists in exhumed basins, except where highly ductile seals are present.
- A predominance of gas over oil is observed due to the liberation of methane from oil, formation water and coal induced by pressure release during exhumation.

The potential positive effects of exhumation for hydrocarbon resources include:

- Local re-deposition of erosional products which may give rise to an isolated working hydrocarbon kitchen.
- Development of fracture permeability in tight reservoirs as a result of a changing stress regime during exhumation.
- Introduction of a light oil budget due to retrograde condensate drop-out caused by pressure reduction during uplift and re-migration of hydrocarbons to shallower reservoirs
- Ex-solution of methane from formation waters, due to decreasing solubility as temperature and pressure reduces during uplift, offers an alternative mechanism for charging gas accumulations.

2.3 Irish landmass and offshore basins – an exhumation laboratory

The post Variscan evolution of NW Europe is characterized by a pattern of diachronous rifting and subsidence punctuated by repeated episodes of exhumation which have resulted from rift-shoulder uplift, hotspot activity, compressional inversion, eustatic sea-level change, glaciation and isostatic readjustment. A legacy of this evolution is the Irish landmass which is encircled by a series of Mesozoic to Cenozoic sedimentary basins (Fig. 2.2). These basins are

categorized into two groups. The first group, which consists of the basins of Northern Ireland, the Irish Sea and Celtic Sea areas and the inboard basins of the Atlantic margin region (Slyne, Erris and Donegal basins), typically manifest an elongate morphology, are located in relatively shallow waters (<1000m) and commonly contain a truncated Cretaceous to Tertiary stratigraphic record. The second group, which is composed of the outboard basins of the Atlantic margin region (Goban Spur, Porcupine, Rockall and Hatton basins), are characterised by a more extensive surface area with thicker Cretaceous and Tertiary successions, and they lie in deeper waters.

Although Ireland is devoid of post-Palaeozoic rocks, except for the northeastern part of the island and a few scattered outliers, it is generally recognised that at least part of the sediment fill in these offshore basins has been derived from periods of uplift and erosion of the Irish landmass and shelf regions (Naylor 1998; Jones *et al.* 2002; Allen *et al.* 2002). A consequence of the paucity of Mesozoic/Cenozoic onshore outcrop and the truncated stratigraphic record in many of the inboard basins is that direct study of the post Variscan (late Carboniferous/early Permian) geological evolution of the Irish landmass and its immediate environs is severely curtailed. As a result geoscientists have turned to indirect interpretation methods (such as techniques for the assessment of exhumation) augmented by observations from outcrops, to help constrain the Mesozoic and Cenozoic history of the area.

While the interpretation of the timing of exhumation from outcrops is non-unique, the proposition of extensive, post-Westphalian, exhumation of the Irish landmass and adjacent inboard regions is not generally disputed. The five generic lines of evidence for this exhumation have been summarized in Chapter 1, section 1.3.

2.4 Techniques for assessment of exhumation.

The principles governing the estimation of magnitude and timing of exhumation in offshore basins, with respect to four generic frames of reference (tectonic, thermal, compactional and stratigraphic) are now outlined. A summary critique is also presented for individual methodologies. The diversity of published estimates of exhumation for individual wells from Irish offshore basins is summarized in Table 2.2 and a

comparison of exhumation estimates derived from different methods is presented in Table 2.3 for wells in the East Irish Sea Basin (EISB).

2.4.1 Tectonic based techniques

A framework for the assessment of exhumation in offshore basins is provided by the lithospheric stretching model of McKenzie (1978), which predicts an initial synrift (fault related) subsidence followed by an exponentially decreasing post-rift (thermal) subsidence. This model facilitates the calculation of theoretical subsidence curves (for a given stretching factor β) which can then be compared with observed tectonic subsidence histories derived from the backstripping and unloading of sediment columns encountered in wells. Deviations of the observed from the predicted subsidence curves can be used, in some cases, to estimate the magnitude and timing of exhumation. Vertical displacement (exhumation) is measured with respect to the theoretically predicted tectonic (basement) subsidence curve.

The general methodology for the computation of the magnitude of exhumation at any given well location involves a number of steps (Fig. 2.3). Firstly, water-loaded basement subsidence curves are computed from available well-log data (or from pseudo-well points where geologic age-depth pairs and other data can be retrieved from seismic interpretation) using standard backstripping and decompaction techniques (Allen & Allen 1990). As great uncertainty is attached to estimates of palaeo-water depth the tectonic subsidence is normally expressed as a series of error bars through time, representing the minimum and maximum estimates of water depth at the time of deposition (Clift & Turner 1998). Secondly, forward modelled theoretical subsidence curves (based upon assumed β, uniform extension and finite duration of rifting – Jarvis & McKenzie (1980)) are then fitted to the backstripped subsidence data. The stretching factor β can be independently rationalised from regional seismic data via summation of fault heaves across the syn-rift normal faults or from estimates of the post-rift crustal thickness. Where the modelled tectonic subsidence is greater than the observed subsidence at any time along the curve, a phase of uplift is interpreted and in the case of sub-aerial exposure and erosion an estimate of the magnitude of exhumation can be derived (Fig. 2.3).

Rowley & White (1998) have refined this methodology, for the important case of a regionally exhumed basin (i.e. basin-scale exhumation, as opposed to local fault-block scale exhumation), where the post-rift rock record is partially or completely missing. In this scenario, inverse modelling of water-loaded subsidence curves derived from backstripping of the remnant (mainly syn-rift) stratigraphy yields information about strain rate, stretching factor β, and the timing and duration of rifting. These parameters are then used to forward model the post-rift thermal phase of subsidence (how much thermal subsidence should have occurred), followed by the conversion of water loaded subsidence into sediment loaded curves and the computation of the missing section (magnitude of exhumation), which is given by:

$$S = E\,([\rho_a-\rho_w]/[\rho_a-\rho_s]) \qquad \text{Rowley \& White (1998)} \qquad (1)$$

Where S = minimum estimate of exhumation; E = water-loaded component of tectonic thermal subsidence; ρ_a = asthenosphere density; ρ_w = seawater density; ρ_s = sediment density.

A 2D approach is also commonly used for the modelling of lithospheric extension and subsidence (Kusznir *et al.* 1995; Roberts *et al.* 1998). This approach attributes flexural strength to the lithosphere so that lithospheric loads are distributed regionally and compensated for via flexural isostasy rather than via local (Airy) isostasy, as favoured in the 1D approach. Although there is some agreement that the differences between flexural and local isostatic models during backstripping may be minimal (if flexural strength of lithosphere is low or if the associated loads are long wavelength – Tate *et al.* 1993; Baxter *et al.* 2001) the relative merits of the 1D vs 2D backstripping analysis have been widely debated in the literature (e.g. White 1990; Roberts *et al.* 1998).

The advantages of the tectonic framework for the study of exhumation in offshore basins, relative to other techniques, is that it provides additional insights, into thermal and mechanical processes of lithospheric stretching, basin evolution and uplift, that are fundamental to hydrocarbon exploration in extensional tectonic regimes. In contrast to thermal and compactional methodologies, the tectonic approach can yield

estimates of *gross exhumation* for unconformities that are at their maximum burial depth present-day (compare Fig. 12 Corcoran & Clayton 2001 with Fig. 7 Jones *et al.* 2001). Limitations of tectonic based techniques include:

1. McKenzie-type lithospheric stretching models provide a valid framework for the assessment of exhumation in intracratonic rift basins but clearly are not applicable where basins are developed due to flexure or strike-slip deformation. The McKenzie type models may even be less applicable as a baseline (for the assessment of exhumation) in some passive margins, where non-uniform extension or depth-dependent stretching has occurred (Steckler *et al.* 1988). Also, the McKenzie model assumes instantaneous rifting when, in fact, this is often invalid and will lead to significant departures in the prognosed relative thicknesses of the synrift and postrift successions, where protracted rifting has occurred (e.g. St. George's Channel Basin – Welch & Turner 2000). Examples of areas where probable depth-dependent stretching has a radical influence on the uplift-subsidence pattern include the Porcupine Basin, offshore Ireland (Baxter *et al.*, 2001) and the Vøring Basin margin, offshore Norway (Roberts *et al.*, 1997). Furthermore, in basins where exhumation has been triggered by igneous underplating or plume activity, the shape of the subsequent cooling (subsidence) curve may be effected by other factors such as the shape of the underlying asthenospheric thermal anomaly (Clift & Turner 1998; Jones *et al.* 2001).
2. The accuracy of water-loaded tectonic subsidence curves is dependent upon the quality and quantity of the available palaeobathymetric data (Roberts *et al.* 1998). As a result robust palaeo-water depth estimates are critical to the identification and quantification of exhumation from subsidence analysis.
3. Where syn-rift strata have been removed from footwall blocks (common location of exploration wells) 1-D subsidence analysis can result in anomalously low estimates of β which in turn results in minimum estimates for exhumation.
4. In the case of permanent uplift (where post rift succession has been completely removed) the Rowley & White (1998) methodology assumes that the remnant stratigraphy represents the final rift phase in the evolution of the basin and that no subsequent stretching events have occurred. For example, in the case of the

East Irish Sea Basin this assumption may be invalid as the evidence from the adjacent St. George's Channel Basin (where a more complete Mesozoic to Cenozoic stratigraphic record is preserved) suggests that episodic pulses of rifting occurred over a *c.* 120 My period during the Triassic-Jurassic (Welch & Turner 2000).

5. Although early Cenozoic exhumation along the northeast Atlantic margin is associated with extensive vulcanism and dyke emplacement, the thermal models derived from subsidence modelling in these basins tend to overestimate peak heatflows compared to values derived from vitrinite reflectance and fission track sources (Clift & Turner 1998; Green *et al.* 1999).

2.4.2 Thermal history-based techniques

Thermal history based techniques provide information about the movement of rocks relative to a thermal frame of reference by utilizing the general principle that sedimentary rocks are heated as they are buried and cool as they are exhumed. In a vertical succession of rocks, a peak palaeotemperature profile interpreted from vitrinite reflectance (VR), apatite fission-track (AFT) analysis, fluid inclusion data (or any palaeo-thermal indicator) can be used to estimate the palaeogeothermal gradient for that succession (at peak palaeotemperature exposure) and, by extrapolation to an assumed palaeo-surface temperature, the magnitude of exhumation at that location (Fig.2.4). AFT analysis also provides a direct estimate of the timing of exhumation (cooling from maximum palaeotemperature) – (Green *et al.* 2002) but, in some cases, stratigraphic relationships can also be used to constrain timing (Evans & Clayton 1998; Corcoran & Clayton 1999). Furthermore, the style of the peak palaeotemperature profile may allow selection of appropriate profiles for exhumation analysis by identifying successions that have been heated by conductive, rather than advective, processes (Bray *et al.* 1992; Duddy *et al.* 1994).

The general approach to the assessment of exhumation at an offshore well location involves a number of steps (Fig. 2.4). Firstly, using appropriate sampling and analytical procedures, a vertical series of samples are collected, processed and

analysed for the relevant palaeo-thermal (VR, AFT, etc.) indicators to derive a peak palaeotemperature versus depth profile for that well location.

In the case of VR (R_o%), kerogen concentrate, isolated from composite cuttings or a core sample, is embedded in an epoxy resin mount which is then polished to a flat shiny surface. Measurements are made, from this surface, of the percentage of incident light (usually at a wavelength of 546 nm) reflected from vitrinite particles under oil immersion (Stach *et al.* 1982). Ideally, reflectance measurement on 100 vitrinite particles is desirable for each polished kerogen preparation. However, in practice, fewer determinations may be made (due to paucity of vitrinite in the sample, etc.) and R_o histograms are used to identify the primary vitrinite population and detemine R_m (mean random vitrinite reflectance) for each sample. This parameter R_m % is then translated to an absolute palaeotemperature value (peak palaeotemperature for that sample and depth) using a number of published empirically based or kinetic schemes (Barker & Pawliewicz 1986; Barker 1988; Burnham & Sweeney 1989; Barker & Goldstein 1990; Sweeney & Burnham 1990).

In the case of AFT analysis, apatite grains, which are isolated from the sample using conventional processing and separation techniques, are mounted in epoxy resin on glass slides and are then polished and etched to reveal the fossil fission-tracks which are normally between 10 to 20 μm in length. As fission-track density is proportional to elapsed geological time and uranium content, the method relies upon the constant relative abundance of $^{235}U/^{238}U$ to compute a fission track age for the apatite grain. Uranium concentration is computed by using the External Detector Method (EDM), where the spontaneous tracks (caused by the spontaneous fission of ^{238}U) are counted in the apatite grain itself and induced tracks (due to induced fission of ^{235}U) are generated and counted in the external detector (usually muscovite of low uranium content) (Andriessen 1995). Consequently, fission track analysis results in the measurement of two parameters – number of fission-tracks (from which fission-track age is derived – Hurford & Green 1983) and distribution of fission-track lengths (from which temperature history is elucidated – Laslett *et al.* 1987). A detailed knowledge of the kinetics of the fission-track annealing process and formal statistical procedures have been used to develop forward modelling programs which can simulate fission-track age and track length distributions consistent with input time-temperature pathways (Green *et al.* 1989). As chlorine (Cl) content has an impact on the fission-track annealing kinetics in apatite, the modelling procedure

attempts to match fission-track age and length distributions for both the entire sample and for the individual apatite grains (within the sample) binned into discrete wt% Cl intervals. By comparing the model data with the measured age and track length distributions (Fig. 2.5), estimates of maximum palaeotemperature can be interpreted for up to three palaeo-thermal episodes (Green *et al.* 2001; Green *et al.* 2002). As there is a lack of constraints on low-temperature (below 60°C, corresponding to burial of less than 2 kms) history from AFTA, supplementary insights can be provided by low-temperature thermochronometry such as the (U-Th)/He dating of apatite (Huuse 2002). This system which is based on the accumulation and diffusive loss of Helium produced by alpha decay of Uranium and Thorium impurities within apatite grains (Farley, 2000), offers potential for improved resolution in the timing of cooling events and independent estimation of maximum palaeotemperatures between 50-80°C.

Many other palaeo-thermal indicators, both organic (e.g. Thermal Alteration Index, TAI, and Spore Colour Index, SCI) and inorganic (e.g. homogenization temperatures from fluid inclusions, illite crystallinity correlated to VR) have the potential to yield a peak palaeotemperature versus depth profile. However, although published conversions to equivalent VR values exist for these indicators (Hood *et al.* 1975; Héroux *et al.* 1979) considerable uncertainty may be introduced, *inter alia*, due to variations in response times to heating by the individual maturation indices (Robinson *et al.* 1987).

Once the palaeotemperature versus depth profile has been established for a given well location a palaeogeothermal gradient (or multiple, segmented, gradients) can be interpreted and simple graphical construction can be used to estimate the magnitude of exhumation at an unconformity (Fig. 2.6). However, this methodology relies critically on certain key assumptions: i) that the palaeo-thermal imprint is primarily the result of conductive heating due to depth of burial and has not been affected by advective heating processes; ii) that the thermal conductivity of removed and preserved sections are similar; and iii) that the appropriate palaeo-surface temperature has been selected (Green *et al.* 2002).

The graphical construct of Bray *et al.* (1992) (presented by Green *et al.* 2002) offers the appropriate thermal framework for the assessment of exhumation at an unconformity and circumvents some of the pitfalls associated with the use of the semilog plot (VR versus depth) advocated by Dow (1977). To avoid confusion, temperature and palaeotemperature measurements should be displayed with respect to seabed (for offshore well; ground level for onshore well) and not TVDKB (True Vertical Depth below Kelly Bushing) as, in the offshore environment, seabed is the appropriate datum for the extrapolation to a palaeo-surface temperature (see Fig. 2.6). The earlier graphical construct of Dow (1977) has been adopted by a number of workers (e.g. Horstman 1984; Unomah & Ekweozor 1993). This method uses the vertical depth separation (on a VR versus depth semi-log plot) between the VR gradient value immediately above an unconformity and the intercept of the pre-unconformity VR gradient segment extrapolated to the same VR value, as an estimate of the amount of eroded section (Fig. 2.7). As highlighted by Katz *et al.* (1988) this construct is flawed as it does not take account of the reduced graphical separation (on a semi-log plot) resulting from increased absolute VR values, nor does it account for the actual 'annealing' of the VR profile discontinuity with increasing re-burial. In contrast, the Green *et al.* (2002) approach uses only the pre-unconformity palaeotemperature segment (independent of 'annealing' process) and an assumed palaeo-surface temperature to determine the magnitude of exhumation at an unconformity.

One of the main advantages of a thermal framework approach to the assessment of exhumation is the widespread availability of palaeo-thermal indicators which provide insights into basin evolution that are not available from inspection of the remnant rock record (for example, palaeo-thermal indicators may yield information with respect to palaeo-geothermal gradients which can be used to estimate the magnitude of missing section, independent of stratigraphic evidence). VR is widely used in the oil industry to define potential areas of oil and gas generation in a basin and is the primary indicator of organic maturation recorded in wells offshore Ireland (Corcoran & Clayton 2001). AFT analysis has been extensively applied in exhumed offshore basins (Floodpage *et al.* 2001; Green *et al.* 2001) and to deduce the fission-track cooling chronologies of the onshore rock record (Allen *et al.* 2002). A further advantage is that, in the absence of a post-unconformity rock record, AFT analysis can provide a direct estimate of the timing of exhumation from the derived fission track age.

There are a number of pitfalls and sources of uncertainty with respect to the use of a thermal framework approach (VR and AFT) to estimate the magnitude of exhumation:

1. Non-linear palaeotemperature profiles (i.e. bell shaped profiles, dog-leg profiles, or profiles with negative palaeogeothermal gradients – in the absence of local igneous intrusions or large scale variations in thermal conductivity) cannot be used to estimate the magnitude of exhumation at a given well location (Duddy *et al.* 1998). These profiles clearly derive from transient thermal effects caused by emplacement of molten magma and/or hydrothermal fluid flow, both of which can result in the distortion of conductive heat distribution in a basin (Wycherley *et al.* 2003).
2. Palaeo-thermal indicators such as VR and AFT are dominated by maximum palaeotemperatures and do not preserve information on thermal events that occurred prior to the achievement of peak palaeotemperatures. Complete annealing of fission-tracks in apatite generally occurs in the 110-120°C range so AFTs cannot store information on exhumation (cooling) events that occurred prior to the most recent episode of 'complete annealing' of tracks (Andriessen 1995).
3. Translation of VR values into absolute palaeotemperatures can introduce systematic errors in the estimation of palaeogeothermal gradients and consequently, the magnitude of exhumation (Green *et al.* 2002). Although the kinetic model (EASY%R_o algorithm) of Sweeney & Burnham (1990) is widely accepted as the most accurate VR to temperature translation method, within the range of organic maturity associated with oil and gas generation, other empirically based translation schemes are also used over wider maturity ranges (e.g Barker & Pawliewicz 1986; Barker 1988; Barker & Goldstein 1990). In general, the use of these empirically based VR to palaeotemperature translation schemes will produce higher palaeogeothermal gradients and lower estimates of exhumation relative to the Sweeney & Burnham model (see Fig. 3 of Green *et al.* 2002 and Fig. 8 of Corcoran & Clayton 2001).
4. An underlying assumption of thermal history techniques is that the measured palaeo-thermal profiles represent the distribution of temperature with depth

immediately prior to exhumation. In highly stretched basins and for old (especially syn-rift) stratigraphy, the palaeo-thermal indicators may represent maximum palaeotemperatures attained early in basin history (due to heat-flow pulse from rifting) and not subsequently exceeded (Allen *et al.* 1998).

5. The thermal method assumes that the palaeotemperature-depth profile is linear through the preserved section and that the palaeogeothermal gradient can be linearly extrapolated through the removed section to the assumed palaeo-surface temperature. This assumption is valid only in cases where the thermal conductivity of the removed and preserved sections is identical although Green *et al.* (2002) report that in practice the assumption of linearity (of palaeogeothermal gradients) has yielded reliable results.
6. Offsets in VR (palaeotemperature) profiles have many causes. Some of these can be attributed to geological factors such as faulting, lithological (thermal conductivity) variations or changes in organic provenance. Some result from the limitations of the VR sampling and analytical techniques, such as the deficiencies of cuttings samples and maceral misidentification, which can result in low reproducibility of identical datasets (Fig. 2.8) (Dembicki 1984).
7. A number of workers have proposed that retardation of vitrinite reflectance commonly arises in overpressured sedimentary sequences (Hao & Chen 1992; McTavish 1998; Carr 2000). The general effect of VR retardation is to decrease the computed palaeogeothermal gradient and violate the assumptions underlying an estimate of exhumation.
8. Likewise, the suppression of vitrinite reflectance (deviations of VR profile towards lower values of R_m%) can result from the presence of hydrogen-rich vitrinites. Consequently, variations in the chemical composition of vitrinite, between well locations, may lead to invalid comparison of VR gradients and associated exhumation estimates (Price & Barker 1985; Goodarzi *et al.* 1994).
9. Complex present-day temperature and palaeotemperature distributions are anticipated in the proximity of mobile halite layers. For example, the high thermal conductivity of salt may result in the derivation of an anomalously high palaeogeothermal gradient for a well drilled on a salt dome-supported anticline and, consequently, a spurious estimate for the magnitude of exhumation will result at that location (Archard *et al.* 1998).

2.4.3 Compaction-based techniques

Compaction is the reduction in sediment volume which occurs during burial and is the result of mechanical and thermochemical processes (Magara 1976; Sclater & Christie 1990; Bulat & Stoker 1987). It is generally expressed by the reduction in porosity with burial depth (more correctly expressed as porosity variation with effective stress - Hubbert & Rubey 1959; Waples & Couples 1998), which has long been thought to follow an exponential curve of the form

$$\phi = \phi_0 e^{-by} \qquad \text{(Athy 1930; Hedberg 1936)} \qquad (2)$$

where ϕ is the porosity at depth y, ϕ_0 is the original porosity at depositional surface and b is the lithology-dependent compaction coefficient which determines the slope of the ϕ-depth curve. Although some porosity 'rebound' can occur during exhumation (through recovery of elastic component of deformation when effective stress is reduced), a large number of laboratory tests and empirical observations confirm that sediment compaction is largely irreversible (Luo & Vasseur 1995; Giles *et al.* 1998). This observation, together with the fundamental assumption that the relevant stratigraphic units in the basin have experienced equilibrium compaction (i.e. compaction under hydrostatic conditions) with burial, forms the basis of compaction-based techniques for the assessment of exhumation.

The general methodology to compute an absolute estimate of the magnitude of exhumation at any given well location involves two steps (Fig. 2.9). Firstly, a plot of porosity (or some proxy thereof) versus depth for a given rock unit must be established from the 'normally buried' unexhumed successions in the basin – the reference curve. A reliable porosity-depth trend (reference curve) requires a large number of porosity measurements distributed over a wide depth range, from samples that are at their maximum burial depth present-day (Giles *et al.* 1998). Porosity-depth curves can be generated from direct porosity measurements on core plugs retrieved from a wellbore or from *in-situ* porosity/density or sonic measurements from wireline logs. Secondly, a porosity-depth curve (usually based on sonic transit time versus depth) is established for individual well locations and compared with the reference curve. Stratigraphic units that are shallower than their maximum burial-depth will have anomalously low porosity

(low transit time) with respect to present-day burial depth. The displacement, along the depth axis, of the observed porosity values or compaction (ϕ-depth) trend from the 'normal' unexhumed trend yields an estimate of *net exhumation* for that well location (Fig. 2.9). Maximum burial depth (B_{max}) can be computed for the section by adding the net exhumation (E_N) to the present-day burial depth ($B_{present\text{-}day}$)

$$B_{max} = E_N + B_{present\text{-}day} \qquad (3)$$

Net exhumation (E_N) will equal total or gross exhumation (E_G) only in the case where the erosional unconformity is at the seabed or present-day ground level. Where post-exhumational burial (B_E) has occurred, gross exhumation will be given by

$$E_G = E_N + B_E \qquad \text{(Menpes \& Hillis 1995).} \qquad (4)$$

A number of variations in methodology have evolved based upon the compaction parameter studied, approaches to selection of the normal compaction reference curve for an area and optimization of curve fitting techniques. The most direct method involves the plotting of measured core-porosity from individual wells vs. depth for a particular lithostratigraphic (clastic reservoir) unit (Fig. 2.10). In the example of Fig. 2.10, using the Triassic of basins west of Ireland, *net exhumation* at each well location is estimated from the displacement of the measured porosity values from a reference curve constructed, in this case, from a mixed empirical (North Sea Tertiary reservoirs) and theoretical (Sclater & Christie compaction curve) input. The significant spread in measured porosity values for any given burial depth suggests facies and diagenetic controls on porosity distribution in the Sherwood Sandstone reservoir are significant.

The widespread availability of sonic logs in offshore wells has rendered the sonic interval transit time or interval velocity parameter the most popular method for the estimation of exhumation from compaction trends. Where lithology is known Δt (interval transit time, or the reciprocal, interval velocity) may be used as a proxy for porosity courtesy of the Wylie time-average equation:

$$\Delta t_{log} = \Delta t_{ma}\,(1\text{-}\phi) + \phi \Delta t_f \qquad \text{(Wyllie } et\ al.\text{ 1956)} \qquad (5)$$

where ϕ is porosity, Δt_{log}, Δt_{ma} *and* Δt_f are, respectively, the sonic log, rock matrix and pore fluid interval transit times. Typically, an exponential curve of the form

$$\Delta t = \Delta t_0 \exp^{(-by)} \quad \text{(Magara 1976)} \qquad (6)$$

is fitted through a log derived Δt (interval transit time) versus depth plot, preferably for a single lithofacies or stratigraphic unit. Curve fitting can be constrained by the imposition of simple boundary conditions which refines the functional relationship between sonic transit time and depth to:

$$\Delta t = \Delta t_0 \exp^{(-by)} + c \text{ (Heasler \& Kharitonova 1996)} \qquad (7)$$

where $\Delta t_0 =$ 591 μsec./m (approximate sonic transit time in sediments at depositional surface) and c is the asymptote of the Δt vs. depth curve, where ϕ approaches zero (also known as shift constant for curve fitting); c typically ranges from 128 to 223 μsec./m - range of rock matrix transit times from dolomites to shales.

Heasler & Kharitonova (1996) logarithimically transformed this expression to a linear equation

$$\ln(\Delta t - c) = \ln \Delta t_0 - by \qquad (8)$$

to facilitate standard least squares fitting techniques. Curve-fitting, to the logarithimically transformed transit time vs. depth data, can be optimized by adjusting the shift constant (c) to minimize average absolute value and root mean square errors. The best-fit transit time vs. depth curve is extrapolated above the erosion surface (unconformity, ground level or seabed) to the upper boundary condition (approximate transit time of uncompacted sediment at original depositional surface – 180 μsec./ft [591 μsec./m]). Magara (1976) and Heasler & Kharitonova (1996) used the vertical displacement, along the depth axis, of the original depositional surface from the present surface to yield the amount of erosion or *net exhumation* (Fig. 2.11).

An alternative approach was pursued by Ware & Turner (2002) who adopted a generic unexhumed compaction curve ('supercurve') for the EISB by averaging normalized transit time vs. depth curves for the four most complete Mercia Mudstone

successions in their database (Fig. 2.12). The difference between the 'super curve' and each measured transit time datapoint gives a single exhumation estimate, the mean value of which yields mean *net exhumation* (apparent mean total exhumation of Ware & Turner 2002) for that well location. The validity of this 'supercurve' as a compaction baseline for Triassic shales in the EISB is difficult to assess. However, comparison with the southern North Sea 'Brockelschiefer Shale' curve of Marie (1975) (see Fig. 5 of Ware & Turner (2002)) indicates that the 'supercurve' is shallower (shifted towards the surface and consequently predicting less erosion) than the 'Brockelschiefer' curve which itself is thought to underestimate exhumation in the southern North Sea (see below).

Japsen *et al.* (2002) have suggested that the functional form of the transit time-depth relationship represented by Eq. (7) may be applied to marine shales dominated by smectite/illite but is inappropriate for kaolinite rich shales or heterolites of continental origin like the Triassic Bunter Shale. Furthermore, Japsen (1998) has shown that realistic compaction trend baselines are best achieved through evaluating physical models for a given lithology and not via an arbitrary choice of mathematical functions and regression parameters. The advantage of a significant well database and good stratigraphic control has allowed Japsen (1999) and Japsen (1998) to adopt a more refined methodology to accommodate burial anomalies associated with lithological variations and overpressuring in the formulation of normal velocity-depth baselines for Cretaceous and Tertiary sediments in the North Sea basin. Analysis of 845 wells in the North Sea Basin by Japsen (1998) indicates that description of the normal velocity-depth trend for chalk is best accommodated by a series of linear segments rather than a single mathematical function.

In contrast to the Ware & Turner (2002) 'supercurve' approach, a Corcoran & Mecklenburgh (2005) study of exhumation in the Slyne Basin, utilizes actual measured transit time data from adjacent basins (Rockall and Porcupine basins) to establish a 'normal shale compaction' reference curve for the assessment of exhumation in the Corrib gas field area of the Slyne Basin. This reference curve was established by selecting five deep wells in the Porcupine and Rockall basins (with TDs from 9,000-18,000 ft below seabed), with extensive Cenozoic and Mesozoic shale sections, which are at their maximum burial depth present-day (Fig. 2.13a). This reference curve was assumed to represent the form of the unexhumed compaction curve for shaley sediments

in the Slyne Basin. Estimates of exhumation were achieved by comparing this curve with the transit time data for the preserved Jurassic shales in each of the Corrib wells. The difference between the depth of the (Porcupine and Rockall) derived 'normal compaction reference trend' and the depth of each measured transit time point in an exhumed (Corrib) well yields a single estimate of *net exhumation.* Histograms and standard descriptive statistics were then used to illustrate the distribution of *net exhumation* estimates and determine the *mean net exhumation* estimate for each well (Fig. 2.13b).

The methodologies employed by Ware & Turner (2002), and Corcoran & Mecklenburgh (2005) offer alternative approaches to the definition of the baseline normal compaction curve in an area affected by regional exhumation. Earlier studies (Marie 1975; Glennie & Boegner 1981) of the Southern North Sea basin utilized plots of mid-point depth versus interval velocity, for the Early Triassic Bunter Shale formation, to estimate exhumation along the Sole Pit inversion axis, relative to wells removed from the inversion axis (incorrectly assumed to have zero exhumation). Bulat & Stoker (1987), also working in the SNS basin, plotted interval velocity versus mid point depth for a range of stratigraphic intervals and cross-plotted exhumation results derived from different parts of the stratigraphy as a check on consistency. However, Japsen (2000) has highlighted that cross-plotting implicitly assumes simultaneous maximum burial of both units and fails to recognize that individual stratigraphic units may have experienced different levels of erosion at different times. The author supports his argument by proposing a geological model, which invokes a pre-Chalk erosional event (late Jurassic-late Cretaceous) age along the Sole Pit axis, to account for differences in the burial anomalies for the Chalk and Bunter units in this area - outside of the Sole Pit inversion axis the burial anomalies for the Chalk and Bunter units are close to identical suggesting that maximum burial, prior to Neogene exhumation, was coincident in time for these areas.

Similar methodology to that of Bulat & Stoker (1987) has also been reported for studies in the Inner Moray Firth (Hillis *et al.* 1994), in the Celtic Sea/South-Western Approaches (Hillis 1991; Menpes & Hillis 1995) and in the Southern North Sea/East Midlands Shelf (Hillis 1993). In these studies the lower bound of the velocity *vs.* depth distribution (higher bound of transit *vs.* depth) was assumed to represent the normal compaction reference curve. Smith *et al.* (1994) questioned the selected reference curve

of Hillis (1993) for the Chalk Group, Southern North Sea Basin, and suggested that the results derived by using this reference curve (as opposed to the Sclater & Christie 1980 curve for North Sea chalks) overestimated exhumation by up to 550m.

Another compaction-based method which has been used to estimate exhumation utilises a drilling parameter, rate of penetration (ROP), as a proxy for the porosity vs. depth trend in a wellbore (Skagen 1992; Nyland *et al.* 1992). When drilling in hydrostatically pressured shales, ROP normally decreases with depth as the shales become more compact. Because other drilling parameters also affect ROP, a 'corrected' drilling rate called the *dc*-exponent is first established:

$$dc\text{-exponent} = [\log(R/60N)]/[\log(12W/10^6D)] \quad \text{(Dickey 1992)} \quad (9)$$

where R = ROP in feet/hour; N = rotary speed in revolutions per minute; W= weight on bit in pounds; D = wellbore diameter in inches.

A *dc*-exponent reference curve is established for the compaction of normally pressured shales *vs.* depth. By comparing the computed *dc*-exponents, from actual drilling progress, with this reference curve on a linear scale, an estimate of net exhumation is obtained from the extrapolation of the computed *dc*-exponent line to the depth axis. Although the *dc* exponent method is widely used by drilling engineers for the prediction of undercompaction (overpressuring), its application to the estimation of overcompaction and exhumation by geologists is not yet widespread.

The advantages of compaction methods for the study of exhumation in offshore basins are the widespread availability of sonic logs and independence from rock sample collection, processing and associated pitfalls. For example, sonic (or density) logs through a shale section are *in situ* measurements of shale velocity (or density) and have reduced susceptibility to distortions from transient heating relative to thermally based methods. In addition, sonic velocity based methods have potential as pre-drill predictors, of the magnitude of exhumation, in areas where high-resolution seismic velocity data is available. Limitations of compaction-based techniques include:

1. The relationship between compressional velocity and porosity depends critically on lithology (Mavko *et al.* 1998), so that the underlying assumption of the sonic interval transit time method, that log measured transit time can be used as a proxy for porosity via the Wyllie time-average equation, is invalid in many cases. In fact, Raymer et al. (1980) suggest that this assumption is only reliable for consolidated sandstones over a limited porosity range of 25-30%.
2. Stratigraphic units must exhibit a consistent relationship between depth and compaction if they are to be of use in exhumation analysis. The absence of a consistent relationship suggests that the compaction trend is obscured by the 'data noise' of lithological variation, diagenetic imprint and other factors.
3. Unreliability in establishing the baseline compaction trend (reference curve) for a basin or rock unit is a key limitation, particularily in basins where pervasive regional exhumation has occurred. Existing methodologies which utilize statistical manipulation to establish a reference curve lack support from physical models and in some cases assume that a heterolithic sedimentary sequence can be described by a single average compaction coefficient. In particular, the methodology of Heasler & Kharitonova (1996) and Ware & Turner (2002) assumes that the functional form of the transit time-depth relationship is known *a priori*, but this is not the case in the basins studied by these authors.
4. Exhumation may be underestimated if the compaction process is partially reversed due to poroelastic rebound (pore dilation and microfracturing) caused by the removal of the overburden load (Japsen 2002).
5. Caution must be exercised when interpreting compaction-derived exhumation estimates in basins containing mobile salt layers (Archard *et al.* 1998). Sonic velocity trends established in the carapace to a mobile salt-layer may contain a component of halokinetically induced exhumation, which is not relevant to the pre-salt stratigraphic units.
6. In hydrostatically pressured extensional basins both effective stress and temperature increase with burial depth, so it is generally uncertain when compactional or thermal processes are responsible for observed increase in velocity (decrease in transit time). The sonic velocity method assumes that mechanical compaction is the dominant control on porosity loss through burial. While this assumption may be correct for argillaceous sediments (Magara 1978) and for clastic sediment burial depths of 2-3 kms (80°C isotherm), beneath this

depth range chemical diagenesis increases and thermochemical compaction becomes the main driver of porosity loss (Bjørkum *et al.* 2001). However, increased compaction due to thermal processes, at this depth range will also be strongly influenced by mineralogical composition.

7. Even in basins where extensive well control is available the selection of the reference succession is problematic, as ideally it should represent a relatively homogeneous formation (in terms of mineralogy, cementation and acoustic properties), represent an extensive depth range (single wells usually have a limited depth range for a given formation) and represent a hydrostatically pressured 'normal compaction' trend for that stratigraphic unit (Japsen 1998).

2.4.4 Stratigraphic correlation-based techniques

Present-day outcrop distribution provides a snapshot of the time-integrated denudational history of an area (Allen *et al.* 2002). As a result, basic stratigraphic techniques of unconformity identification, section correlation, extrapolation and restoration can offer a cogent rationale for estimating the timing and magnitude of exhumation. In the offshore, the application of basic seismic-stratigraphic interpretation can offer additional constraints with respect to exhumation estimates. For example, in the eastern Inner Moray Firth, the seabed subcrop pattern of the Upper Cretaceous-Tertiary sediments allowed McQuillan *et al.* (1982) and Barr (1985) to postulate from seismic horizon geometries that at least 650m of Lower Cretaceous-Tertiary section had been removed from the western part of the basin. Holliday (1993) was among the first to contest the initial estimates (derived from apatite fission track analysis) for *c.* 3000m of Cenozoic exhumation in northern England, on the basis of the stratigraphic constraints offered by the preserved Mesozoic successions in adjacent basins.

A large volume of literature has also been published on the Cretaceous to Recent topographic evolution of Scandinavia and its relationship to the well constrained subsidence and fill of the North Sea, Mid-Norway and Barents Sea basins (Riis 1996;

Overeem *et al.* 2001). For example in the North Sea Basin, the Cenozoic to recent denudational morphology and exhumation history of southern Norway has been constrained from detailed seismo-stratigraphic and sedimentary facies mapping, patterns of clinoform breakpoint migration, and palaeogeographical compilations linked to eustatic sea-level changes (Huuse 2002). Onshore-offshore correlations, pre-Quaternary subcrop patterns and bedrock landforms, combined with changes in sediment transport directions in the eastern North Sea, during the late Cenozoic, have been used to identify two phases of Neogene exhumation of the South Swedish dome and adjacent offshore Skagerrak-Kattegat Platform area (Japsen *et al.* 2002). A mass balance approach (comparing the volume of material eroded from a hinterland to the volume deposited in adjacent basins) has also been used to derive first-pass estimates of exhumation of onshore areas (see for example Jones *et al.*, 2002, on volumetric redistribution around the North Atlantic margins which they attribute to exhumation resulting from the Iceland plume). This technique can also be used to constrain exhumation of offshore basins where these areas have been submerged subsequent to denudation (see for example Eidvin *et al.* 1993 on the Barents Sea, off northern Norway). Mass balance calculations, however, provide only the crudest estimate of exhumation; large errors are inevitable due to input to a basin from multiple provenances, to long distance transport of sediments away from adjacent depocentres, to solution losses and to erroneous density assumptions. Such calculations are mainly useful to derive a picture of basin-scale exhumation but offer little insight into exhumation at a specific point (e.g. a well) in the basin.

The stratigraphic approach to the quantification of exhumation at an unconformity involves the identification of the maximum preserved section (or preferably the correlative conformable succession) beneath the unconformity – the reference section. A minimum estimate of *exhumation* (erosion) is then determined for a particular well location, by comparing the thickness of the equivalent stratigraphic unit encountered in the well with the preserved isopach in the reference section (Fig. 2.14). Similarily, where seismic data are available, and sub-unconformity truncation patterns are present a minimum estimate of exhumation across a particular structure can be obtained, subject to appropriate assumptions with respect to rock velocities (Fig. 2.15).

Onshore and offshore Mesozoic outcrop patterns have been used to infer regional, early Cenozoic, exhumation centered on the Irish Sea area (Holliday 1993; Cope 1994; Brodie & White 1995). Subsequently, Cope (1997) used detailed stratigraphic arguments, based upon the matching of extrapolated outcrop and subcrop sections around the Irish Sea area with the amount of cover lost, to invoke the presence of exhumation during the Early Cretaceous ('Late Cimmerian event'), in addition to the early Cenozoic event. Murdoch *et al.* (1995) generated restored Cretaceous Chalk isopachs as part of an integrated study to quantify the magnitude and timing of exhumation in the North Celtic Sea area and estimated that up to 1100m of Cenozoic exhumation had occurred towards the basin centre.

The advantages of the stratigraphic approach to estimate exhumation in offshore areas include the widespread use of well stratigraphic correlation and seismic data in offshore basins, and the fact that this method can be utilized even if the unconformity is today at its maximum burial depth. Detailed stratigraphic correlation, to identify the youngest rocks preserved beneath the unconformity, and the oldest preserved above, can offer the most precise direct evidence of the timing of exhumation.

Limitations of the stratigraphic approach are:

1. Where epeirogenic (see Table 1) uplift and denudation has occurred, quantification of exhumation is difficult as entire stratigraphic intervals may have been removed by erosion. In such cases only a minimum estimate of exhumation is possible by comparison with the reference section.

2. Where the original depositional thickness of an eroded stratigraphic unit varies, regional isopach and seismic facies mapping of this unit is required to establish the basin trend, so that this variation in isopach can be factored into exhumation estimates derived via this unit (Murdoch *et al.* 1995).

2.5 Comparison of exhumation estimates – Irish offshore basins

Comparison of exhumation estimates derived from different methods, illustrated using wells drilled in basins offshore Ireland

Systematic comparison, on an individual well basis, of exhumation estimates made with respect to the four frames of reference (tectonic, thermal, compactional, stratigraphic), has proved difficult, as few published studies have embraced all four methodologies. However, a medley of published estimates of magnitude and timing is available for wells from Irish offshore basins and these data for 69 individual wells, summarized in Table 2.2, allow some comparisons to be made. Discrepancies between individual estimates arise for many reasons even where measurements are made with respect to the same reference frame. For example, VR data is usually retrieved from mudrocks whereas sedimentary apatite grains (used in AFT analysis) are primarily collected from sandstones, which given their contrasting permeabilities will inevitably lead to discrepancies resulting from exposure to different thermal fluxes within the same stratigraphic column.

2.5.1 Celtic Sea Basins

This comparative dataset (Table 2.2) is dominated by exhumation estimates from the Celtic Sea area where Murdoch *et al.* (1995) employed a multidisciplinary approach (44 wells) to assess the magnitude and timing of Tertiary uplift events and their impact on the maturity of the Jurassic source rocks in the North Celtic Sea Basin. An understanding of the magnitude and timing of Cenozoic exhumation in this particular offshore basin is facilitated by the extensive well database, the relatively monotonous Cenomanian to Maastrichtian chalk successions, the preservation of Eocene-Oligocene clastics beneath the Pleistocene unconformity, and the opportunity to restore the chalk and Tertiary isopachs based upon interval velocity trends established for the preserved chalk sections. In map view (see Fig. 14 from Murdoch *et al.* 1995) the distribution of exhumation estimates indicates a NE-SW trending, basin-centred, anticlinal flexure which suggests at least a component of compressional reactivation and shortening of this formerly extensional basin.

Estimates of net exhumation derived from the chalk compaction (sonic transit time) methodology of Menpes & Hillis (1995) can be compared with the net exhumation estimates derived from the Murdoch *et al.* (1995) multidisciplinary approach, for 6 wells (48/19-1, 49/9-1, 49/9-2, 49/14-3, 50/6-1, 50/12-2 – Table 2.2). This comparison indicates that the net exhumation estimates of Menpes & Hillis (1995) are consistently higher than the, stratigraphically constrained, net exhumation estimates of Murdoch *et al.* (1995). This suggests some systematic bias in the selection of the 'normal compaction trend' (Menpes & Hillis trend too deep) for the Upper Cretaceous chalk interval but illustrates how a multivariate approach to estimating exhumation can in some cases provide a first order control on the accuracy of estimates using a single methodology.

2.5.2 Kish Bank, Central Irish Sea and St. George's Channel basins

In areas where the post-rift record is severely attenuated (e.g. by erosion), estimating the magnitude and timing of exhumation is difficult when more than one phase of uplift has occurred. This limitation is clearly demonstrated in the Irish offshore. The relatively consistent picture that emerges from the Murdoch *et al.* (1995) study of the Celtic Sea Basin is in strong contrast to the broad range in estimates of the magnitude and timing of exhumation at well locations in the Kish Bank, Central Irish Sea and St. George's Channel basins (Table 2.2). For example, Jenner (1981) argued that 3000m of uplift and erosion was required to explain the observed levels of thermal maturity of the Westphalian sediments in well 33/22-1 (Kish Bank Basin) whereas the VR interpretations (more extensive dataset) of Naylor *et al.* (1993) and Corcoran & Clayton (1999) indicate net exhumation of less than half this magnitude. Naylor *et al.* (1993) suggest that stratigraphic constraints dictate a post-Liassic timing for this exhumation event, in contrast to the Early Permian exhumation event proposed by Corcoran & Clayton (1999) on grounds of stratigraphy and regional palaeogeothermal gradients. Unpublished shale velocity analyses, referred to in Dunford *et al.* (2001), offer exhumation estimates of 1500m (33/21-1), 960m (33/22-1), 875m (33/17-2A) and 350m (33/17-1) for the four wells in the Kish Bank Basin, although these estimates are quoted as being 500-1000m less than the magnitude of the Palaeogene and younger exhumation events identified by the (unpublished) AFTA data for three of these wells. In this case, the higher estimates from AFTA (a lower palaeogeothermal gradient

translates into higher exhumation estimate) may be interpreted as indicating hydrothermal fluid flow within the permeable Sherwood Sandstone Group (majority of apatite grains recovered from this unit), resulting from regional dyke emplacement during the Palaeocene.

In the Central Irish Sea Basin (wells 42/16-1, 42/17-1, 42/21-1) tectonic, thermal and stratigraphic methods have been used to estimate exhumation. Although there is some agreement between the estimates for well 42/17-1 (1900m post-Sinemurian exhumation from the VR interpretation of Corcoran & Clayton (1999) versus 2080m of early Cretaceous exhumation interpreted from sonic transit time data by Williams *et al.* 2005), there is a large scatter in the estimates of both the magnitude and timing of exhumation for wells 42/12-1 and 42/16-1. AFTA data indicates that both of these well locations have experienced a multi-phase exhumation history (Duncan *et al.* 1998; Green *et al.* 2001), with episodes of exhumation identified in the early-middle Cretaceous, Early Tertiary and Late Tertiary. So, for well 42/16-1, the Williams *et al.* (2005) estimate of 2240m (based on compaction trends of Triassic Mercia Mudstone Group shales) can only be compared with the Green *et al.* (2001) estimate of 2975m (based on AFTA & VR samples from Triassic and Carboniferous sediments) for the early Cretaceous exhumation event – the largest magnitude event of the three events identified by AFTA. The transit time/velocity method cannot distinguish between the different exhumation episodes, but indicates the net amount of section removed since maximum burial, which in this case occurred prior to the early Cretaceous event.

Estimates from tectonic and thermal methods are available for a single well, 42/21-1, in the St. George's Channel Basin (Table 2.2). Good agreement exists between thermal estimates (1600m - Corcoran & Clayton (1999) versus 1500m – Green *et al.* 2001) for the main phase of exhumation and there is broad consensus with respect to the timing of this episode (Palaeogene), with an additional event (Late Tertiary) resolved by AFTA data (Green *et al.* 2001). Discrepencies between the estimates derived from tectonic modelling (600m – Welch & Turner (2000) versus in excess of 2000m – Allen *et al.* (1998)) may result from differences in rift history employed by these authors. The Welch and Turner (2000) model invoked a protracted Triassic-Jurassic rift history over 120 My to model the observed subsidence, whereas the Allen *et al.* (1998) model

involved two discrete phases of stretching in the Triassic separated by 40 My. Insights gained from seismic interpretation in the St. George's Channel Basin has allowed Williams *et al.* (2005) to highlight multiple causes and timings for the observed exhumation in this basin, to better understand inter-well variations in the magnitude of the exhumation, and, importantly to describe differences in the contribution of inversion to exhumation within the same basin, attributable to strain partitioning along major bounding faults. This is a key observation that is likely to apply to other basins that are both exhumed and inverted.

2.5.3 Porcupine Basin

Exhumation studies within the Porcupine Basin have been generally confined to wells drilled along the northern and eastern margins of the basin. The Mesozoic and Cenozoic evolution of this basin is broadly characterised by rifting during the Jurassic followed by Cretaceous and Cenozoic post-rift subsidence. Tectonic modelling by Jones *et al.* (2001) indicates that this subsidence history was punctuated by two phases of transient regional uplift, of the northern and eastern flanks, during the Early Cretaceous (200-700m) and Early Eocene (300-600m). Although these transient uplift episodes are observed in the Jones *et al.* (2001) subsidence models for wells 35/8-2 and 35/19-1 they are not preserved by the VR thermal framework – (see Table 2.2 and Fig. 12 of Corcoran & Clayton (2001) which show no discontinuity in the palaeotemperature profiles throughout the Cretaceous and Cenozoic sections of these wells) – presumably due to "annealing" of the VR profiles through post-exhumation reburial (an example of how tectonic modelling can, in some cases, discriminate effects that have been obscured in the thermal record due to subsequent reburial). However, a significant earlier discontinuity is observed in VR profiles at the base of the Mesozoic section in wells (26/28-1, 26/28-2, 35/15-1, 36/16-1) along the northern and eastern margins (Robeson *et al.* 1988; Corcoran & Clayton 2001). Estimate of the magnitude of this pre Middle Jurassic exhumation event range from 1000-2100m (Table 2.2). Evidence from fission-track data (McCulloch 1993) and stratigraphy confirm that the Mesozoic-Cenozoic sections (in wells 26/28-1 and 26/28-2) are at peak temperature exposure present day, whereas the sub-unconformity Carboniferous section had previously experienced higher temperatures – most likely, prior to a Late Carboniferous-Early Permian exhumation event (Corcoran & Clayton 2001).

2.5.4 Slyne/Erris Basins

In the Slyne/Erris basins thermal, compaction and stratigraphic methods have been used to estimate exhumation in seven wells. A sonic transit time compaction study of Jurassic shales in the northern part of the Slyne Basin (Corrib Gas Field wells – 18/20-1; 18/20-2; 18/20-3, 18/20-4, 18/25-1) has yielded a tight cluster of gross exhumation estimates (range 1277-1632m – Table 2.2) for these five wells. In contrast, the estimates from thermal techniques (for the three wells that have VR data) demonstrate a wider range (927-1705m), with the largest discrepancy between the sonic and VR estimates occurring in well 18/20-2 (estimates of 1498m and 927m respectively), where palaeo-temperature distributions may be locally effected by the presence of a 770m halite diapir at the base of the Jurassic section. To the south of the Corrib Field area (Fig. 2.2), exhumation estimates have been derived for well 27/13-1 from a plethora of techniques including geochemical biomarker indices (Scotchman & Thomas 1995). This well penetrated a Miocene-Quaternary cover unconformably overlying a thick (>2 km), succession of Bathonian-Rhaetian sediments. In this well the estimates from thermal techniques are consistently higher by 540-1200m than estimates reported from other methods (Table 2.2). These discrepancies may be at least partially accounted for by 'distortion' of the thermal reference frame due to advective thermal fluxes in permeable Middle Jurassic sandstones caused by dyke emplacement during the Palaeogene. In the Erris Basin well 19/5-1, estimates from thermal techniques (3600m and 3500-4000m), measured in the Carboniferous (Dinantian-Westphalian C) section and reported in Chapman *et al.* (1999) and Robeson *et al.* (1988) respectively, are in broad agreement both with respect to timing and magnitude. However, in spite of this consensus view, stratigraphic constraints indicate that this interpretation would have required the deposition of an anomalously thick succession (an additional 3500-4000m) of Late Carboniferous (Westphalian C-Stephanian) sediments prior to uplift and erosion during the early Permian.

2.5.5 East Irish Sea Basin

The East Irish Sea Basin (EISB) is a preserved remnant of a late Palaeozoic to early Mesozoic extensional basin system (Knipe *et al.* 1993). Subsequent uplift and denudation has removed most of the post-Triassic cover, which has resulted

in a remnant stratigraphic column consisting of Triassic, with occasional small outliers of Liassic, subcropping Pleistocene-Recent sediments. This truncated rock record makes exhumation techniques of critical importance in understanding the post-Triassic burial and uplift history of this basin. Although there is broad agreement that kilometer scale (1-3 kms) exhumation has occurred, reconciliation of exhumation estimates, by different authors using differing methodologies, can be problematic. For example, a southwards increase in exhumation determined from sonic velocity analyses contradicts the denudation trends derived from AFT studies, which show a southward decrease in exhumation (Green *et al.* 1997; Ware & Turner 2002).

A comparison of published Cenozoic exhumation estimates for wells in the EISB is presented in Table 2.3. Gross exhumation (E_G) estimates of Rowley & White (1998) and Ware & Turner (2002), derived from tectonic, thermal and compactional techniques, are compared with the stratigraphical arguments of Cope (1997). The 'lost cover' reconstruction of Cope (1997) is primarily based upon palaeogeographical considerations and extrapolations from the remnant land and submarine outcrops and subcrops within and peripheral to the EISB. His speculative estimates (Table 2.3) of depositional thicknesses must be viewed in the context of the internal basin and block structural morphology and evolution of the EISB. This gives rise to two important caveats – i) that basinal successions are likely to have been significantly thicker than successions on elevated blocks (for example Cope (1997) estimates that basinal successions within the EISB probably contained 1400-1800m of Jurassic rocks, whereas the interbasinal swells may have accumulated as little as 500m of Jurassic sediments); ii) that erosional episodes during the Jurassic and Cretaceous may have significantly reduced the total thicknesses accumulated up to that point.

A broad spectrum of exhumation estimates, derived from thermal and compaction data, has been produced for the EISB by different workers. For example, Hardman *et al.* (1993), using the Dow (1977) method to interpret an extensive VR dataset for the basin, suggest variation in exhumation from 300-3000m, whereas Roberts (1989) estimated an average 2000m of exhumation from VR data. Estimates from sonic velocity data include the 1200-1500m of Colter & Barr (1975) and the 2000m of Colter (1978) for well 110/3-2. Considerable variation in gross exhumation is estimated for individual wells (e.g. for well 110/20-1, estimates of 900m, 2280m and 1401m have been derived from tectonic, thermal and compaction techniques

respectively – Table 2.3) highlighting the uncertainty associated with estimates from individual techniques.

The exhumation estimates computed from sonic velocity data (Ware & Turner 2002) are generally, though not consistently, lower than the estimates derived from subsidence modelling, and are consistently lower than the estimates derived from the Rowley & White (1998) modelling of VR data (Table 2.3) – although the opposite relationship between thermal and compaction estimates is suggested for the EISB by Fig. 8 of Cowan *et al.* (1999). Rowley & White (1998) concluded that their exhumation estimates from tectonic modelling were broadly in agreement with the fission track-derived exhumation estimates for the same area (2700-3200m of Lewis *et al.* 1992; 1500-2000m of Green *et al.* 1997). As suggested by Ware & Turner (2002), the systematically higher estimates of exhumation derived from thermal history methods, in the EISB, may be strong evidence of the influence of hydrothermal fluid flow on palaeotemperature profiles.

Work on this basin, in particular, clearly shows how a complex exhumation history can provide the explanation for widely differing exhumation estimates derived from different techniques. For example, Holford *et al.* (2005a) present a palaeotemperature-depth plot for well 110/20-1, derived from AFT and VR data, which indicates that this well (and probably the entire EISB) has experienced a complex thermal and exhumation history, with at least four distinct cooling episodes since late Carboniferous times. The AFT data provides evidence for three palaeo-thermal events with separate phases of cooling, during the early Cretaceous, early Palaeogene and Neogene. However, the style (low to negative palaeogeothermal gradient) of the early Palaeogene palaeotemperature profile suggests that hydrothermal or advective heating was dominant during the early Palaeogene at this location. Furthermore, the palaeotemperatures indicated by the VR data, from the Westphalian section of this well, are 20-40°C higher than the early Cretaceous and early Palaeogene palaeotemperatures derived from the AFT data, suggesting a cooling event, prior to the early Cretaceous, most likely relating to Late Carboniferous/Early Permian exhumation.

2.6 Discussion and conclusions

Quantification of the timing and magnitude of exhumation is of critical importance to the understanding of petroleum systems in exhumed basin settings. A holistic approach is recommended as all four generic methodologies documented here (tectonic, thermal, compaction and stratigraphic) potentially offer insights with respect to the exhumation 'problem' in offshore basins. Large uncertainty is associated with estimates from individual techniques. Tectonic-based techniques, such as subsidence analysis, are largely dependent on crustal models (e.g. McKenzie 1978), and may therefore be inappropriate to use in terrains where such models do not apply or require modification. Thermal techniques (e.g. AFT, VR) may be of limited use, with respect to estimation of exhumation, where advective heating has occurred, due to the resulting non-linear palaeogeothermal gradients. However, in basins dominated by conductive heat-flow processes thermal techniques can offer reliable, independent, information with respect to both the magnitude and timing of exhumation events. In basins where more than one phase of uplift has occurred, this is a particular advantage as complex exhumation histories generally cannot be resolved via compaction-based or tectonic-based methodologies. Compaction-based techniques (e.g. sonic transit time) can suffer from such factors as unreliability in establishing a baseline compaction curve, overpressured sections and variability in the mineralogy of the measured section but offer potential as pre-drill predictors of exhumation magnitude where reliable seismic velocity information is available.

Where convergence of the estimates from the different techniques occurs, more reliable values for the magnitude of exhumation can be achieved. Regional stratigraphic correlation, palaeogeographic analysis and extrapolation of sub-unconformity erosional truncation patterns on seismic data, offer critical 'sense' checks on exhumation estimates derived from other techniques. These stratigraphic insights may be particularly important where exhumation at a given point in a basin has multiple causes – for example, in the case where local tectonic inversion is superimposed upon epeirogenicic uplift on a basin scale. One recent study which highlights the advantage of adopting a, multi-disclipinary approach is that of Williams *et al.* (2005), who used a combination of seismic interpretation and exhumation proxies to deconvolve the

superimposed contributions of tectonic inversion and regional epeirogenic uplift to exhumation in the St. George's Channel Basin.

A review of the offshore basins peripheral to Ireland supports these assertions, and highlights the inherent difficulty in using individual exhumation techniques in isolation. Even in the best-case scenarios, discrepancies exist between estimates made via contrasting frames of reference. However, an understanding of the geological factors that govern the validity of the various methods helps to rationalise some of these discrepancies and results in a more appropriate tool selection. For example, in order to distinguish between different episodes in a multi-phase tectonic history, AFT data is required as number of fission tracks and distribution of track lengths are the only measureable parameters which can yield the information on maximum palaeotemperature and timing of cooling necessary to resolve multiple exhumation episodes (Green *et al.* 2002). In contrast, estimates from compaction data yield little information on exhumation history but can indicate the net amount of section removed since maximum burial. Velocity-based estimates of exhumation offer the best opportunity for pre-drill exhumation prediction, in areas where reliable seismic stacking velocities are available. In basins characterised by significant post-exhumation subsidence, the tectonic approach has the important advantage of retaining a record of exhumation events, which have been obliterated from the compactional and thermal record through post-exhumation burial and heating.

Cross-referencing estimates of timing and magnitude between different methods (e.g. subsidence modelling, AFT, VR and sonic velocity analyses) is an essential step in reducing uncertainty in the exhumation estimate, but assessing stratigraphic and seismic evidence together with these proxies is a critical factor in validating an exhumation estimate. On the other hand, where systematic divergence occurs between exhumation estimates from different techniques, this discrepancy itself may provide a valuable insight into the geological history of the basin – as shown, for example, in the Slyne-Erris and East Irish Sea Basin, where consistently higher exhumation estimates from thermal indicators are probably locally indicative of igneous and hydrothermal activity.

Chapter 3

Sonic transit time technique - estimation of magnitude of exhumation, Slyne Basin, offshore Ireland.

3.1 Introduction.

The well database for the Slyne Basin, offshore Ireland, consists of four exploration wells, five appraisal wells (Corrib Field) and one shallow borehole (BH 2A) (Fig. 3.1; Table 3.1). Extended sonic logs are available for eight of these wells. In this study, the sonic interval transit time parameter has been used to compare compaction trends in the Slyne Basin with a generic compaction trend for the Porcupine and Rockall basins. A modified version of the sonic transit schemes of Magara (1976), Heasler & Kharitonova (1996) and Ware & Turner (2002) has been developed to estimate the magnitude of exhumation at these eight well locations in the Slyne Basin. The theory and generalized methodology, for the assessment of exhumation from sonic transit time, has been outlined in Chapter 2 (Section 2.4.3). The primary difference in the methodology presented here is that the 'normal compaction reference curve' has been developed from shale transit time data recorded in 5 deep wells in the adjacent Rockall and Porcupine basins where basin evolution is characterized by relatively continual subsidence (Table 3.1).

3.2 Procedure – Data Editing.

The following procedure has been utilized in this study. Firstly, digital sonic transit time, lithology and depth data have been copied from Statoil's database into an EXCEL spreadsheet for the 8 Slyne Basin and 5 Rockall & Porcupine Basin wells listed in Table 3.1. All depths were adjusted to sub-seabed depths (in feet) – the compactional frame of reference. All wells were edited for logging artefacts (e.g. sonic data recorded through casing, between 1833-2403mBRT, in well 18/20-2 was removed due to poor quality) and filtered to remove the transit time data for 'non-shale' lithologic sections such as chalk, volcanics, halite, carbonates and major sandstone intervals. This filtering was achieved courtesy of Statoil's lithology encoding and customization of the auto-filtering routine in EXCEL. In addition, spot checks of the filtered data were performed

by visual inspection of the operator's completion log for each of the wells. Extensive overpressured shale sections have not been identified in the Slyne Basin wells. Regional evidence suggests that the Jurassic section in this basin is hydrostatically pressured although some mild overpressure may be present in the organically rich Sinemurian to Toarcian shale sections. [Actual state of pressure in shales is usually not measured but is inferred from RFT (Repeat Formation Test) data acquired in interbedded reservoir sections.] The resulting filtered data, for the 8 Slyne Basin wells, is compared with the unedited and unfiltered data for each well in Figures 3.2 to 3.11.

For these Slyne Basin wells the main objective of the filtering process was to isolate the sonic transit time vs depth data for shales within the Jurassic successions. In this study, these Jurassic shales are modelled as a singular compactional unit, bounded above by a major erosional unconformity (Base Cretaceous-Mid Miocene Unconformity) and below by Late Triassic (Mercia Mudstone Group) and Permian sequences, containing mobile and diapiric halite units (see Chapter 1). These intervals have the potential to act as décollements, resulting in local differential uplift above and below these detachment layers, and can result in complex compaction profiles. For example, in the area of a salt dome significant exhumation of the carapace may occur without any change in the vertical displacement of the pre-halite section, relative to seabed. Consequently, prior to exhumation analysis, all Cretaceous, Tertiary and pre-Jurassic data have been removed from the dataset for the 8 Slyne Basin wells, with the exception of well 27/5-1 where limited Jurassic shale sections were encountered. In this well, shales in the Upper Triassic Mercia Mudstone Group and at the base of the Lower Triassic Sherwood Sandstone Group have also been incorporated in the exhumation analysis for this well (Figs 3.8-3.10). No halite was encountered in the Mercia Mudstone Group in well 27/5-1, which suggests that the Triassic and Jurassic section can be modelled as a singular compactional unit at this location.

In this study the 'normal compaction reference curve' has been established by selecting 5 deep wells (approx. 9,000-18,000 ft below seabed), with extensive shale sections, from the Rockall and Porcupine basins. Although some of these well locations may have experienced a phase of transient uplift during the Early Cretaceous and again in the Early Eocene (Jones *et al.* 2001), the Mesozoic and Cenozoic sections, in all 5 wells, are at their maximum burial depth present-day. The

selection of these wells is rationalized by the opportunity they offer to examine the compaction behaviour of Jurassic, Cretaceous and Tertiary shales over a large depth range, which incorporates the maximum burial depth of the Jurassic successions in the Slyne Basin. These wells have been individually edited (Fig. 3.12 – 3.16), as per the procedure for the Slyne Basin wells, prior to amalgamation of the 5 wells to establish the 'normal compaction reference curve' (Fig. 3.17).

Overpressured shale sections have been inferred from the available RFT data (Palaeocene in 35/18-1) and 'drilling mud weight' data (Lower Cretaceous-Upper Jurassic in 35/19-1) and have been removed from the 'normal compaction' dataset prior to curve fitting. Clear evidence for overpressuring, towards the base of the 35/19-1 well, is provided by the sonic transit time data - anomalously high transit times are observed in the shaley section below 15,000 feet sub-seabed (Fig. 3.18) suggesting anomalously high shale porosities due to overpressuring at this location.

The data editing process has endeavoured to isolate the 'shaley' sections in the 5 Rockall and Porcupine wells and in the Jurassic sections of the 8 Slyne Basin wells. The horizontal scatter in the sonic data points (in μsec/ft) gives an indication of the residual lithologic variation in these 'shaley' sections and also provides a qualitative assessment of the noise in the data. This residual scatter observed in this study appears to be less than the scatter observed in the published data of Heasler & Kharitonova (1996) [Tertiary sands and shales – Bighorn Basin, Wyoming] and similar to the scatter in the data of Ware & Turner (2002) [Triassic Mercia Mudstone Group shales - East Irish Sea Basin].

3.3 Procedure - EXCEL Manipulation

This study follows the fundamental assumption of Heasler & Kharitonova (1996) and Ware & Turner (2002) that porosity reduction with depth in a heterolithic sedimentary sequence is described by a single, average compaction coefficient (b in equations below). In order to determine the best-fit equation that describes the 'normal compaction' trend for Rockall and Porcupine shales (reference curve for exhumation analysis of Slyne Basin wells) the basic exponential function (see Chapter 2; Section

2.4.3) was logarithmically transformed to a linear expression and a least squares regression was then performed to find the value of *b* (exponential decay constant).

$$DT = DT_0 * \exp^{(-bx)} + C \quad \text{logarithmically transforms to}$$

$$\ln(DT-C)-\ln(DT_0) = -bx \quad \text{a linear equation}$$

where DT = sonic interval transit time in μsec/ft

DT_0 = sonic interval transit time at seabed (assumed = 180 μsec/ft)

b = exponential decay constant

x = True Vertical Depth in Feet sub-seabed

C = asymptote of exponential curve (in theory at x = infinity); in practice shift constant equivalent to mineral matrix transit time in μsec/ft (transit time at 'shale' zero porosity)

Key components of the curve fitting process are the 'fixing' of the DT_0 value (i.e. DT value at seabed) = 180 μsec/ft – the assumed transit time of claystone at the depositional surface (just below the transit time of seawater at 189-210 μsec/ft – Schlumberger 1985) and the derivation of the C value from the data. For the amalgamated Rockall and Porcupine 'shale' dataset separate columns of y [=$\ln((DT-C)/(DT_0))$; dependent variable] and x (TVD sub-seabed; independent variable) were generated in EXCEL and the regression function was used to output statistics (Table 3.2). The X Variable statistic is the exponential decay constant *b* which describes the best-fit curve.

The "add trend line" functionality in EXCEL was used to graphically display the best-fit regression line. In order to facilitate this display, all depths (TVD below seabed) were plotted as positive values, with depth along the X axis and DT-C along the Y axis. The result of this transposition is that, while DT asymptotically approaches some assumed 'shale' matrix value (e.g 60 μsec/ft) as depth (x) goes to infinity, the y intercept (DT-C intercept) is set at (180-60) 120 μsec/ft. This displayed curve is identical to the computed regression curve but transposed down the graph by 60 μsec/ft.

Best-fit curve optimization was achieved by running a number of 'C-Trials' (regressions with different values of C) and using the maximum coefficient of

determination, R-Square, to determine the best fit curve (Fig.3.19). The highest R-Square statistic for these ten regression trials, which occurred with a shift constant C (matrix transit time) of 56μsec/ft, indicates that 73% of the variance in sonic transit time values (μsec/ft) can be attributed to variation in depth below-seabed. [Typical rock matrix transit times range from 39μsec/ft for dolomites to 67μsec/ft for salt (Schlumberger 1989) with quoted shale matrix transit times ranging between 59-143 μsec/ft (Heasler & Kharitonova 1996). Magara (1976) suggested using 68μsec/ft for a shale matrix transit time, but shale matrix transit times as low as 59μsec/ft are reported in the East Irish Sea Basin study of Ware & Turner (2002). The lower matrix transit time (56 μsec/ft) derived in this study may reflect a higher residual sandstone or 'other lithology' component in the dataset or could be due to the more extensive shale compaction depth range available to this study.]

In this study, the equation which describes the selected 'normal compaction trend' reference curve is:

$$Y = \ln(DT-56)-\ln(124) = 0.000155258x \qquad \text{(Fig. 3.20)}$$

This reference curve was taken to represent the form of the unexhumed compaction curve for the Slyne Basin. Estimates of exhumation were achieved by comparing this curve with the filtered and edited Jurassic transit time data for each of the 8 Slyne Basin wells. The difference between the depth of the computed 'normal compaction reference trend' and the depth of each measured transit time point in an exhumed well (X_{Slyne}) yields a single estimate of net exhumation:

$$[(\ln(DT-56)_{Slyne\ Well} - \ln124)/(-0.000155258)] - X_{Slyne\ Well} = \textit{Net Exhumation Estimate}_{Slyne\ Well}$$

For each well, all the measured transit time points can be similarily evaluated to give a distribution of exhumation estimates which is characterized by the output from the descriptive statistics function (example output Table 3.3). *Net*

exhumation estimates and the key statistics are summarized for the 8 wells in Table 3.4. The mean value yields the *mean net exhumation* value for each well. The standard deviation captures the variability in the exhumation estimates for each well and the 95 % confidence interval indicates that there is 95% confidence that the population mean will occur within the specified range either side of the sample mean. A histogram has been generated for each well which illustrates the distribution of *net exhumation* estimates for that well (Figs 3.21-3.30).

The sensitivity of the methodology to the estimation of the best-fit normal compaction curve has been evaluated by comparing the results of the *mean net exhumation* estimate for well 27/13-1 under an alternative scenario. In this alternative case, the overpressured Upper Jurassic shales in 35/19-1 have been incorporated in the Rockall and Porcupine data to establish the reference curve (Fig. 3.31). Repeated C-trials resulted in a best-fit curve (R-Squared = 70%) for a C value of 57 μsec/ft (Fig. 3.32). When compared with the measured transit time data for 27/13-1, this reference curve resulted in a *mean net exhumation* estimate of 1488m (86m greater than the estimate derived by using the selected curve - Fig. 3.20).

Because post-exhumation re-burial has the effect of returning formerly exhumed rock towards their maximum burial depth, it is necessary to add to the *net exhumation* estimate the amount of burial that has occurred post-exhumation, in order to yield an estimate of *gross exhumation* (Table 3.4). The Early Bajocian Limestone is the main Jurassic seismic marker in the Slyne/Erris Basin (Dancer *et al.* 1999; Chapman *et al.* 1999) and estimates of its maximum burial depth at each well location is achieved by adding its present-day burial depth to the mean *net exhumation* estimate for that well (Table 3.4).

The results indicate that between 954-1814m of *net exhumation* has occurred in the Slyne Basin with *gross exhumation* estimates ranging from 1277m to 2154m for the 8 wells. The distribution of exhumation estimates in map view suggests that the highest estimates of *mean net exhumation* occur in the 3 southernmost wells (Fig. 3.33). Although the sonic transit time method *per se* does not provide information on the timing of exhumation in the Slyne Basin, evidence from seismic data suggests

that a major erosional event occurred in the North Slyne area during the early Cretaceous (see Chapter 2, Fig. 2.13). However, to the south, in wells 27/5-1 and 27/13-1, late Miocene rocks rest unconformably on Bathonian sediments (Dancer *et al.* 1999), so it is possible that major denudation in this area occurred post early Cretaceous and prior to late Miocene.

3.4 Conclusions

A sonic transit time scheme is presented for the estimation of magnitude of exhumation at 8 Slyne Basin wells. In contrast to published transit time schemes for other basins, this study utilizes actual measured transit time data (in adjacent basins) to establish an unexhumed compaction curve for the Slyne Basin. The results suggest that between 1.2 to 2.2 kms of post-Jurassic exhumation has occurred in the Slyne Basin, with a poorly constrained trend of increasing exhumation towards the south of the basin.

Chapter 4

Vitrinite reflectance – estimation of magnitude of exhumation in offshore (and onshore) basins.

4.1 Introduction.

Vitrinite reflectance (VR) is one method of evaluating the thermal alteration of sedimentary rocks (Héroux *et al.* 1979). It has been successfully demonstrated as a reliable indicator of organic maturation in sedimentary successions and is widely used in the oil industry to define potential areas of oil and gas generation in a basin (Peters & Casa 1994). In addition, lateral and vertical trends in vitrinite reflectance result from a range of basin-scale geological processes and can offer important constraints with respect to thermal evolution and exhumation history. VR data are of particular importance in exhumed basin settings, where a quantitative assessment of the peak palaeotemperatures achieved by potential source rocks, prior to uplift, is a critical factor in determining the hydrocarbon prospectivity. Furthermore, by establishing a peak palaeotemperature profile at a given well location, a palaeogeothermal gradient (at peak palaeotemperature exposure) can be determined and used to estimate the magnitude of exhumation at that location (see Chapter 2). A palaeogeothermal gradient may also provide some insight with respect to the mechanism of heating and cooling of the sedimentary rocks at that location (Bray *et al.* 1992; Duddy *et al.* 1994). In some cases, stratigraphic relationships can be used to constrain the timing of peak palaeotemperature exposure (Evans & Clayton 1998; Corcoran & Clayton 1999).

The first objective of this chapter is to present a summary overview of the compiled VR database for offshore and onshore Irish sedimentary basins (Figs. 4.1 and 4.2). This composite graphical approach (display of profiles from a number of wells together) to the analysis and interpretation of the VR data offers some insights into the thermal and exhumational history of Irish basins (Corcoran & Clayton, 2001). The second objective is to investigate the 'anomalous' VR trend in well 42/21-1, by generating some new VR analyses for this well location. The third objective is to provide estimates of the magnitude of exhumation from VR data for selected offshore

wells (due to the diffuse nature of many of the offshore, Mesozoic/Cenozoic, VR profiles, exhumation estimates from VR data are stated only for those wells where the estimate is rationalized with other geological evidence). [VR analysis for wells in the Corrib Field area of the Slyne Basin, are based on recently acquired (Statoil proprietary) VR datasets, and are not discussed in this chapter but are presented in Chapter 8 as part of an integrated exhumation study of the Corrib Field area (Corcoran & Mecklenburgh 2005)].

4.2 Vitrinite Reflectance – database overview

Vitrinite reflectance data (mean random reflectance - R_m%) have been compiled from 78 Irish offshore wells and 17 onshore boreholes (Fig. 4.1; Appendix 1). This database has facilitated the analysis of vitrinite reflectance versus depth behaviour by basin and by stratigraphic interval. The VR data have been compiled from a number of sources. For the onshore basins this paper draws upon the extensive VR datasets generated over the past decade by a number of research students at Trinity College Dublin: Baily (1992), Fitzgerald (1994), Goodhue (1996), Fernandes (1999) and associated publications including Goodhue & Clayton (1999) and Clayton & Baily (2000). For the offshore basins the available organic geochemical and maturation reports have been reviewed for 78 wells. These reports have been generated by various oil companies and contractors based on samples recovered from exploration wells drilled in these basins prior to 1996. In addition, this study incorporates the large VR dataset, pertaining to Carboniferous sections encountered in wells drilled in the Porcupine and Slyne/Erris/Donegal basins, produced by Robeson (1987) and Robeson *et al.* (1988).

For each well, sample depth and measured R_m% values have been compiled together with the stratigraphic age of the samples where available (Appendix 1). Sample type and number of vitrinite particles have also been recorded to assist with quality control of the database. All depths have been converted to metres true vertical depth below seabed (TVD Sub SB) or true vertical depth below ground level (TVD Sub GL) in the case of the onshore boreholes. In addition, peak palaeotemperature data has been computed from the measured R_m% for each sample, by utilising the three different

empirically-based schemes of Barker & Pawliewicz (1986), Barker & Goldstein (1990) and Barker (1988) plus the kinetic scheme of Burnham & Sweeney (1989). [Actual kinetic scheme palaeotemperature translation was executed via a nomogram supplied by Dr. P. Green, GEOTRACK, which assumes a heating rate of 1°C/Ma]

VR versus depth relationships are commonly presented in the literature as either 'linear' plots or 'semi-log' plots. Although, linear VR versus depth profiles are favoured by Stach *et al.* (1982), Suggate (1998) and others, the 'semi-log'methodology of Dow & O'Connor (1982) has been adopted here due to the large range of R_m% values (0.2-7.56 R_m%) contained within this VR database (Fig. 4.2). *Prima facie* inspection of this data suggests a weak correlation of R_m% with depth. However, by integrating the stratigraphic ages of the sample data some generic subsets of the database can be identified and characterised.

The stratigraphic information permits the differentiation of at least two VR populations in the data; VR recorded in Mesozoic/Cenozoic sections versus VR recorded in Palaeozoic (mainly Carboniferous) sections (Fig. 4.2). As might be expected, for a given present day burial depth, organic maturity levels of the Palaeozoic sections are generally higher than for the Mesozoic/Cenozoic sections. This is consistent with the observation that many of the Palaeozoic R_m% values pertain to the exhumed remnants of the onshore Carboniferous basins. In addition, these Carboniferous sections are characterised by more discrete, better-defined, VR profiles relative to Mesozoic/Cenozoic sections. This observation reflects the less complex vitrinite populations within the vitrinite-rich, paralic, sequences of coals and shales of Carboniferous age (Durand *et al.* 1986). In contrast, many of the Mesozoic/Cenozoic VR profiles exhibit a wide scatter (the exception being well 42/21-1, which shows little scatter – see below). Some of this scatter may be due to the presence of reworked vitrinite populations within the Mesozoic sedimentary column caused by the denudation of a Westphalian-Stephanian blanket which once covered the Irish landmass. A further contribution to this scatter may be provided by the presence of vitrinite-like 'bituminite' populations, within Mesozoic/Cenozoic marine sediments. These 'bituminite' populations have been identified as a major problem with respect to the determination of organic maturation trends within the Liassic sediments of the Paris Basin (Alpern & Cheymol 1978).

The Carboniferous subset of the data gives an indication of the range of individual maturity gradients within Carboniferous sections (Fig. 4.3). At present, the offshore sections are buried below a Mesozoic/Cenozoic cover of variable thickness. Maturity levels for this offshore subset of the data range widely from 0.44 R_m% to 6.1 R_m%. Discounting profile deviations associated with igneous intrusions, average maturity gradients, inferred from Robeson *et al.* (1988), range from 0.19 R_m% km^{-1} for Erris Basin well 19/5-1 up to 1.93 R_m% km^{-1} for wells in the north of the Porcupine Basin. In general, maturity gradients for these offshore sections are high with the exception of well 19/5-1 which manifests a maturity gradient more typical of Mesozoic sections. This 'anomalous' gradient at well 19/5-1 has important implications for the timing of Carboniferous source rock maturation in the Erris Basin. The gradient could represent overprinting by Mesozoic and Cenozoic burial following low heatflow in this area during the Late Carboniferous-Early Permian.

In contrast, the Mesozoic/Cenozoic subset of the VR database (Fig. 4.4) is characterised by lower levels of maturity (0.2-3.9 R_m%) and dominantly low magnitude, poorly defined maturity gradients (0.13-0.78 R_m% km^{-1}). By identifying the stratigraphic age and basin setting of the VR samples, *prima facie* evidence suggests that this subset of the data can be analysed in terms of the well documented late Mesozoic to Cenozoic exhumation history of northwest Europe (Roberts 1989; Brodie & White 1995; Menpes & Hillis 1995). Although the VR data manifest considerable scatter, it is possible to differentiate between those basins that are characterised by relatively continual subsidence, such as the Porcupine Basin, and those basins that have experienced exhumation during the Cenozoic, e,g. Slyne Basin, St. George's Channel and Celtic Sea basins (Fig. 4.4). Confirmation that a major phase of exhumation is post-Cretaceous in age is provided by the R_m% data that have been recorded in Cretaceous rocks in some of these offshore basins (Fig. 4.5). Displacement of the Cretaceous vitrinite maturity levels, away from the 'normal' depth trend towards higher maturity levels, suggests they have experienced post-Cretaceous exhumation. A familiar pattern is observed with higher R_m% values present at equivalent present day depth in basins, such as the Celtic Sea Basin, that have undergone exhumation during the Cenozoic (Fig. 4.5).

4.3 Pitfalls and sources of uncertainty with VR data

Many of the generic pitfalls and sources of uncertainty with respect to the interpretation of VR data have been itemized in Chapter 2, (Section 2.5.2). Chief among the sources of uncertainty with respect to this Irish offshore database may be the inherent difficulties in the comparison of VR determinations made by different workers in various laboratories (see Fig. 2.10 for Mesozoic section in well 50/3-1, offshore Ireland). Logistical factors which affect the quality of the offshore VR dataset include the problem of caving (cuttings samples) in well bores, consistent identification of vitrinite, differentiation of primary vitrinite and insufficient grains to make a reliable determination of the reflectance of the sample.

Nevertheless, in spite of these pitfalls, the generally consistent picture observed in these data suggests that the underlying thermal maturity 'signal' rises above the ambient 'noise' of the dataset, at least when the data are considered at a regional scale.

4.4 Translation of VR to Palaeotemperature

The thermal alteration of vitrinite proceeds via a series of irreversible chemical reactions. Consequently, VR is one of a number of organic thermal maturation indicators which provide a means of ascertaining the maximum temperature exposure of sedimentary rocks (Hood *et al.* 1975; Héroux *et al.* 1979). Nevertheless, conversion of VR values to absolute palaeotemperatures is still problematic. Much debate has centered on the relative influence of time and temperature on the increase of vitrinite reflectance. However, both recent kinetic models (Burnham & Sweeney 1989; Sweeney & Burnham 1990) and field studies, in areas where the duration of heating is well constrained (Barker 1988, 1991, 1993), indicate that VR is most sensitive to maximum temperature, under conditions of uniform heating rates. Barker (1991, 1993) demonstrated that in geologically young systems VR adjusts to changes in temperature over a geologically brief time period (10^3-10^5 years). However, Suggate (1982) suggested that 10^6-10^7 years was required to allow stabilization of vitrinite reflectance at peak temperature. Morrow

& Issler (1993) compared VR values, computed via a number of common forward modelling techniques, for known temperature histories under constant heating rates. They concluded that, within the range of organic maturity asssociated with oil and gas generation, the EASY%Ro algorithm of Sweeney & Burnham (1990) is the most appropriate method for the prediction of VR. However, they suggest that the algorithm slightly over estimates VR in strata of low to medium maturity (<0.9 R_m%).

A number of published empirically-based and kinetic schemes are available to translate VR data into peak palaeotemperature including Barker & Pawliewicz (1986), Barker (1988), Barker & Goldstein (1990), Burnham & Sweeney (1989) and Sweeney & Burnham (1990). The current study has utilised the well delineated global dataset (from ten non-inverted basins) of Rowley & White (1998), to derive some model data points allowing a comparison of the different VR to palaeotemperature translation schemes and the potential impact on the interpreted magnitude of palaeogeothermal gradients (Fig. 4.6). Assumption of a best-fit line, representing on average how VR behaves with depth in a basin characterised by continual subsidence, permits the examination of the peak palaeotemperature versus depth relationship derived from each translation scheme (Fig. 4.7). For example at VR values less than 0.9 R_m% the kinetic model (assumed heating rate 1°C/Ma) of Burnham & Sweeney (1989) will yield *higher* palaeotemperatures but *lower* palaeogeothermal gradients than the Barker (1988) empirical scheme. Between VR values of 0.9 to 1.3 R_m% the Burnham & Sweeney model will result in *lower* palaeotemperatures and *lower* palaeogeothermal gradients than the Barker (1998) scheme (Fig. 4.7). In general, over the narrow maturity range examined, these model curves indicate that the use of empirically-based translation schemes will result in the derivation of higher magnitude palaeogeothermal gradients than might be predicted by kinetic translation schemes. In addition, these model curves indicate that palaeotemperatures derived via the Barker (1988) translation scheme most closely approximate to the palaeotemperature output from the kinetic schemes of Burnham & Sweeney (1989). These results are consistent with the conclusions reached by Johnston *et al.* (1993) from their analysis of an extensive VR dataset from Alaska.

The impact on estimated palaeotemperatures and palaeogeothermal gradients of the Barker (1988) and Burnham & Sweeney (1989) schemes has also been

examined over a broader maturity range (Table 4.1; Fig. 4.8). VR data from well 35/15-1 in the Porcupine Basin has been used to compare these two palaeotemperature translation schemes. This well encountered Tertiary and Cretaceous sediments resting unconformably upon rocks of Early Carboniferous age. Recorded VR values range from 0.37 R_m% in the Tertiary section to 6.1 R_m% in the pre-Mesozoic section (Table 4.1). Although the interpretation of the palaeotemperature profile for this well is complicated by the local presence of igneous intrusions and/or caved material, a significant break in the palaeotemperature profile and change in the palaeogeothermal gradient, is observed at the Base Cretaceous unconformity (Fig. 4.8). The stratigraphic evidence from this well indicates that peak palaeotemperature exposure of the early Carboniferous section must have been achieved prior to the deposition of the Early Cretaceous, (Barremian) section, which directly overlies the Base Cretaceous unconformity. The very high palaeogeothermal gradients (97.4°C/Km computed via Baker (1988) empirical model) recorded in the early Carboniferous section suggests the influence of advective heating on these sediments and is consistent with the imprint of Late Carboniferous post-kinematic plutonism and hydrothermal activity which has been recorded elsewhere in the Variscan orogen (Schegg & Leu 1998).

A comparison of the estimated palaeogeothermal gradients for the Mesozoic/Cenozoic section indicates that the Barker (1988) scheme yields a *higher* palaeogeothermal gradient (37.3 °C/Km, with 95% confidence interval 19.5-55.1 °C/Km) than the Burnham & Sweeney model (30.4 °C/Km, with 95 % confidence interval 16.3-44.6 °C/Km). The reverse is true for the Palaeozoic section with the Barker (1988) scheme yielding a palaeogeothermal gradient of 97.4 °C/Km (95% confidence limits 76.7-118 °C/Km) which is significantly *lower* than the palaeogeothermal gradient (169.1 °C/Km, with 95 % confidence limits 99.5-238.7 °C/Km) estimated via the Burnham & Sweeney model. [Note that the kinetic model of Burnham & Sweeney (1989) is not calibrated above VR values greater than 4.7 R_m% and consequently, kinetically derived peak palaeotemperatures are not available for some of the deeper samples in the well (Table 4.1).] It is concluded that both the kinetic and empirical VR to palaeotemperature translation schemes indicate a significantly higher palaeogeothermal gradient in the Palaeozoic section of well 35/15-1, relative to the Mesozoic/Cenozoic.

Consequently, in the context of the VR database examined here, a considerable *difference* in palaeogeothermal gradients between Mesozoic/Cenozoic and Palaeozoic sections is evident, regardless of which of the two translation schemes is used (Corcoran & Clayton 2001). Both kinetic and empirical models rely upon some underlying assumptions. The advantage of the more theoretically rigorous, multiple-reaction, Arrhenius-based simulation methods of Burnham & Sweeney (1989) is somewhat undermined in this case by a limited knowledge of heating rates in Irish sedimentary basins throughout the approximately 400 Ma history represented by the samples in this VR database and by the absence of kinetic model calibration at VR values greater than 4.7 R_m%.

In this study, a nomogram (unpublished data provided by Dr. Paul Green of GEOTRACK) has been utilized to translate VR to palaeotemperature, between VR values of 0.29-4.0 R_m%. At higher values of VR the empirically-based equation of Barker (1988) has been employed to make the conversion to palaeotemperature (Appendix 1).

4.5 VR analyses – well 42/21-1

Well 42/21-1, which was drilled in 1986, is situated along the northern flank of the St. George's Channel Basin. The well reached TD at 6650 feet (2027m) in Late Pliensbachian shales. Stratigraphically, the well encountered Quaternary sediments resting unconformably upon an Oxfordian sequence which in turn rested unconformably upon a relatively continuous Late Bathonian to Late Pliensbachian succession. The initial VR analyses of cuttings data from the well (documented in 1987 Exlog/Alpern report for Gulf Oil, now ChevronTexaco) resulted in an almost perfectly linear VR profile with a lack of scatter in the VR values about the trend with depth (Table 4.2; Fig. 4.9). This lack of scatter in the VR profile is anomalous in the context of the wide scatter observed in vitrinite populations in Mesozoic/Cenozoic sections in most of the offshore wells. As this VR data has been widely reported in VR and thermal history studies of the Irish Sea area (Allen *et al.* 1998; Corcoran & Clayton 1999; Welch & Turner 2000; Green *et al.* 2001) it was decided to reassess the VR data for this well by generating some new VR analyses.

4.5.1 Preparation and measurement of samples – well 42/21-1

Composite cuttings samples of approximately 25g (average estimate only) were taken from 'wet' sample bags over 37 depth intervals from 890-6650 Feet (Table 4.3) – courtesy of a visit to the PAD sample repository. No suitable sidewall core samples were available for analysis.

Kerogen concentrates were then prepared for microscopic examination using standard procedures for vitrinite reflectivity as follows:

1. Samples were washed and left to dry. Mortar and pestle was then used to crush the larger the chips followed by further washing, before loading into pre-cleaned and labelled plastic containers.
2. The samples were then treated with concentrated (40%) hydrochloric acid (HCL), diluted with water, and then left for 24 hours to dissolve all the carbonate content.
3. When the reaction with HCL was completed, the samples were neutralized by the addition of water followed by decanting.
4. To ingest the silicate fraction the samples were then treated with 40% hydrofluoric acid (HF), with the plastic containers placed in a water bath, in a fume cupboard, at a temperature of *c.* 60°C and stirred twice daily to stimulate reaction with HF. Standard decontamination procedures were effected to the plastic stir rod after each 'stirring' in order to preserve the integrity of individual samples.
5. After one week the HF was decanted off into a container and stored for safe disposal. To insure complete neutralization of the remaining residue distilled water was added to the sample, the residue was allowed to settle and was then decanted. This procedure was repeated at least five times.
6. The neutralized residue was then sieved through a 20μm mesh sieve.
7. This sieved organic residue was split into two uneven parts with the largest allocation, to be used for VR measurements, placed in a petri dish and allowed to dry overnight in an oven at a temperature of *c.* 60°C.
8. Polishing preparation techniques essentially followed those outlined by the British Standards Institution (1981).

9. *Epo-thin*, low viscosity epoxy resin was mixed with *Epo-thin* low viscosity epoxy hardner in a synthetic cup in the ratio of 100:35. This mixture was blended thoroughly with wooden stick, for approximately two minutes.
10. A small amount of this mixture was then added to a petri dish containing the sample residue, mixed and then poured into a plastic mould and left for twenty four hours.
11. After hardening the block was then squeezed from the plastic mould and labelled, with a diamond pen, on the upper (non organic) surface.
12. The next step was polishing of the blocks, which constituted a four step process. This involved coarse grinding of the blocks on water-wet silicon carbide paper of 320 and 1200 grade followed by polishing of the blocks with two progressively finer alumina (Al_2O_3) pastes in water. Between each polishing stage, the blocks were washed with water in an ultrasonic bath, to vibrate and clean grit from polished surface.
13. The polished blocks were dried and stored in a dessicator. Before measurement of R_m, the polishing was checked with the reflectance microscope and where unsatisfactory the process was repeated. In the case of a few samples, due to the paucity of vitrinite grains, polishing to deeper levels in the block was required. Individual blocks were mounted on glass slides using *'Blue Tac'*, levelled with a hand press before storing in the dessicator.

4.5.2 Reflectance microscope and R_m measurement – well 42/21-1

Vitrinite reflectance ($\%R_m$) determinations were made using a Leitz Ortholux 11 and MPV-1 compact microscope-photometer outfit under standard conditions (British Standard 6127: Part 5, 1981). The system consisted of a 12V/100W halogen lamp with a stabilized power supply, light controlling apertures, a removable polarizer and a graduated rotating stage. A strain-free x50 objective lens and viewing eyepieces of x10 magnification were used. Reflectance measurements were made in oil with a refractive index of 1.5193 at 20°C room temperature, in incident light with a wavelength of 546*nm*. Microscope and photometer power supplies were allowed to stabilize for one hour prior to a measurement session. All other lights within the microscope room were turned off during measurements to prevent extraneous light interference with the microscope system.

Measurement of $\%R_m$ was carried out immediately after calibration of the microscope with the reflectance standards (Spinel [McCrone No.307], Glass [Leitz No.998], Cubic Zirconia [McCrone No.319] with $R_{oil}\%$ standards of 0.42, 1.23 and 3.28 respectively). The system was recalibrated before the study of each new sample. Mean random vitrinite reflectance ($\%R_m$) was measured with the polarizer removed from the light path and the microscope stage clamped. Where possible, $\%R_m$ was measured on 100 vitrinite grains per block, but a number of blocks, particularily from the shallower samples, contained less than 50 grains. Histograms were generated for the distribution of $\%R_m$ values in each sample (Fig. 4.10a-e). The number of grains measured across each block was tabulated, and used to determine the arithmetic mean (true R_m for each sample) and standard deviation for individual samples (Table 4.3).

The primary objective of the microscope work was to measure the reflectance of fresh, *in situ*, vitrinite grains. This required differentiation of these grains from reworked and/or naturally oxidized vitrinite and other maceral groups with similar optical properties such as inertinite, bitumen or exinite group macerals. However, identification of vitrinite in kerogen residues is more difficult than in coals and whole-rock samples. The principal criteria used, in this study, for the identification of primary vitrinite were the morphology of the grains (isolated elongate stringers [indicating structureless, low relief morphology in transmitted light] were selected, as opposed to rounded grains which might indicate recycled vitrinite) and the colour (mid-light grey colours in reflected light compared with brighter grey to white colours of inertinite and the dark bluish grey colour of exinite). Once individual primary vitrinite grains were identified, the measuring spot was selected as centrally on the grain as possible (avoiding any blemishes or inclusions), the microscope stage was locked and the $\%R_m$ measurement was taken.

4.5.3 Comparison of original (Exlog/Alpern) vs new (this study) VR analyses

The VR profile which resulted from this new VR analyses is presented in Fig. 4.11 (also Table 4.3) with the Exlog/Alpern (1987) profile displayed for comparison. This new VR data manifests a more typical 'diffuse' profile with a trend of increasing VR with depth. This trend is semi-parallel to the 1987 data at a higher maturity level, but shows appreciably more scatter about the general trend than

observed with the earlier data. The main stratigraphic markers are displayed as are the casing points in the wellbore, to help differentiate caved from uncaved cuttings material. By 'benchmarking' against the cuttings samples, immediately beneath the casing points, an increasing trend of $\%R_m$ with depth is observed (at least for the section beneath the 13 3/8" casing point) which suggests that no significant caved material is present in this section. This rationale also holds for the earlier Exlog/Alpern dataset which contains little evidence for extensive caving.

In the new VR dataset, complex vitrinite populations are interpreted in the Late Bathonian-Late Jurassic sections, immediately beneath the Base Quaternary unconformity. A cluster of high $\%R_m$ vitrinite samples ($\%R_m$ 0.76-1.6) suggests that these determinations represent a reworked vitrinite population. Two of the samples in this cluster contained less than 20 vitrinite particles which undermines the accuracy of these determinations.

An independent assessment of the maturity of the succession in well 42/21-1 is provided by the pyrolysis T_{max} parameter (Fig. 4.12) – defined as the pyrolysis temperature at which the maximum amount of hydrocarbon compounds are generated from the thermal degradation of kerogen (Espitalié, 1986). T_{max} data for 25 sidewall cores (Exlog/Alpern 1987, Table 4.4) have been plotted *vs.* depth in Fig. 4.12. Although T_{max} is partly influenced by the type of organic matter in the sample, the heating rate and the morphology and weight of the samples, it can offer a guide to the degree of organic maturation of the sample. In this case a semi-vertical, low maturity, low T_{max} gradient (with a range of T_{max} values between 408-439°C) suggests that the Jurassic succession is immature to marginally mature in this well (Fig. 4.12). This is consistent with the earlier (Exlog/Alpern) VR profile ($\%R_m$ range 0.46-0.65) but represents a lower maturity level than that suggested by the new VR profile ($\%R_m$ range 0.45-1.13). However, Peters & Casa (1994) advise that T_{max} values are only valid when the pyrolysis production index (PI) is less than or equal to 0.1 in the T_{max} range of 390-435°C. Unfortunately, pyrolysis PI values for most of the sidewall core samples, from well 42/21-1, are higher than 0.1 suggesting contamination by drilling fluid or migrated oil and thus limiting confidence in the interpretation of the T_{max} values (Table 4.4).

Finally, the palaeotemperature profiles for both the 'old' and the 'new' VR datasets are displayed and compared with the apatite fission track results (see Chapter 5) for this well (Fig. 4.13). Based upon these palaeotemperature profiles the

computed palaeogeothermal gradients are 17.6°C/km and 23.2°C/km respectively, compared with present-day average geothermal gradient of 31.9°C, at this location. *Prima facie* inspection suggests that the 'old' VR data is more consistent with the AFTA results. However, the 'new' VR data may be consistent with the AFTA data if an earlier (late Jurassic-early Cretaceous?) heating event occurred (not recorded by AFTA as temperatures exceeded 110°C annealing threshold) followed by *c.* 3.5 kms of exhumation during the early Cretaceous. In this case AFTA data is indicating that a subsequent, lower magnitude (*c.* 2kms), exhumation event occurred during the Late Cretaceous-Early Tertiary.

4.6 Exhumation analysis

Exhumation analysis has been performed on the VR derived palaeotemperature profiles for all onshore and offshore wells in the VR database by generating a plot of peak palaeotemperature vs depth (TVD in metres, sub-seabed/ground level) for each well (Fig. 14a-l). A comparison of the VR derived palaeogeothermal gradients with present-day geothermal gradients is facilitated by displaying the following present-day geothermal gradients on each plot – wells from onshore basins, 26°C/km (Brock & Barton 1984); Porcupine Basin, 34°C/km (Corcoran & Clayton 2001); Kish Bank, Central Irish Sea and Celtic Sea basins, 32°C/km (Corry & Brown 1998). Displacement of the palaeotemperature profile from the present-day temperature profiles indicates a succession which has experienced higher temperatures in the past, either due to deeper burial or advective heating. A fundamental assumption of exhumation analysis is that the recorded peak palaeotemperatures result from a conductive heat flow regime and that the displaced palaeotemperature profile represents a stratigraphic succession that was exposed to higher temperatures through deeper burial and has subsequently been exhumed (for this and other assumptions – see Chapter 2).

EXCEL was used to determine a best-fit least-squares linear regression for each palaeotemperature profile, with depth as independent variable and temperature as the dependent variable. Where significant discontinuities existed in the palaeotemperature profiles (e.g between Carboniferous and Mesozoic successions), segmented linear regressions were performed. Average palaeogeothermal gradients

were derived from the slopes of these best-fit regression lines and the estimate of net exhumation was computed by assuming an average palaeo-surface temperature of 15°C for all well locations and exhumation events. [This assumed 'average value' of 15°C is based on published ranges (0-30°C) of mean annual surface temperatures for the relevant palaeolatitudes during the Cretaceous and Tertiary periods – Burchardt (1978); Barron & Washington (1984); Crowley & North (1996)]. The linear best-fit equation (in the form $y=mx+c$), R^2 (the success of the best-fit line in predicting palaeotemperature from depth) and the 'Net Exhumation' estimate are displayed for each well. For the onshore wells the estimate of the magnitude of net exhumation is coincident with the estimate of *gross* exhumation (see Chapter 2). However, in the offshore basins *gross* exhumation will exceed *net* exhumation as, in many cases, significant re-burial has occurred post the exhumation event (e.g. re-burial post early Cretaceous unconformity, in the Slyne Basin (–see Chapter 8). Gross exhumation estimates are not reported here (for Slyne Basin – see Chapter 8) for the offshore wells due to the limited access to detailed stratigraphic
information for these wells.

Wells with low, negative or vertically erratic palaeogeothermal gradients suggest that the relevant succession has been exposed to advective heating and therefore violates the fundamental assumption of conductive heat flow. Duddy *et al.* (1994) state that the occurrence of near vertical palaeotemperature-depth profiles is a characteristic of foreland basin settings typified by large-scale lateral fluid movement or hydrothermal circulation systems associated with igneous intrusions and volcanic piles. For each plot where net exhumation estimate is not possible (data limitations) or the palaeogeothermal gradient is unsuitable for exhumation analysis 'Net Exhumation = N/A' is displayed. For example the negative average palaeogeothermal gradients observed in onshore, Clare Basin, wells Doonbeg and IPP 2 render these palaeotemperature profiles unsuitable for exhumation analysis (Fig. 4.14b-c). Also, some of the recorded palaeotemperature profiles in the offshore wells are unsuitable for exhumation analysis. For example, VR derived palaeotemperatures in wells 43/13-1 (Porcupine Basin) and 47/30-1 (Celtic Sea Basin) are generally lower than the average present-day temperatures in these boreholes – indicating poor sample data possibly due to cavings in the well bore (Fig. 4.14f-g). In spite of the observation of discrete, well defined, palaeotemperature profiles in the onshore wells 1327/1, 1328/19, 1450/1 and

Lissycassy, the very high 'Net Exhumation' estimates [7253m, 5623m, 6837m and 6300m respectively] derived from these wells may be spurious, as these Carboniferous successions may have been subject to hydrothermal activity.

Onshore (North West, Dublin-Navan, Clare) Basins

The palaeotemperature profiles for the 17 onshore wells are generally discrete, well constrained by data points and show significant displacement from the average present-day geothermal gradient. Net exhumation estimates range from 3205-5552m in the North West Basin, 729-7253m in the Dublin-Navan Basin and 6300m (Lissycassy well only) in the Clare Basin with average palaeogeothermal gradient ranges of 23.4-43.7°C/km, 19.7-105.5°C/km, -9.1-46.8°C/km in these basins respectively (Table 4.5). The wide range in palaeogeothermal gradients (19.7-105.5°C/km) observed in close proximity in the Navan area of the Dublin-Navan Basin suggests that lateral fluid flow may have played a role in the heating of the Carboniferous successions in this area.

Evidence from the onshore VR data suggests that the Late Carboniferous-Early Permian thermal event is characterised by high palaeotemperatures and in general very high, though variable, palaeogeothermal gradients (estimated mean gradient ~60 °C/km – Corcoran & Clayton (2001)). These palaeogeothermal gradients are consistent with the elevated maturity gradients observed in other Variscan foreland settings (Robert 1989). Estimated palaeogeothermal gradients in excess of 80°C/km for the late Palaeozoic have been reported from northern Switzerland (Schegg and Leu 1998). These values are consistent with high heat flows induced by extensional collapse, post-kinematic plutonism and hydrothermal activity during the final phase of the Central European Variscan orogeny.

Intrusion of the Cornubian and Haig Fras granitic plutons to the south of Ireland (Gardiner & Sheridan 1981) established a mountain belt which acted as a recharge area for Carboniferous and Devonian aquifers and provided the hydraulic head to drive fluids northwards through the foreland basin. Vertical discharge of these heated fluids, along major fault systems in the foreland platform setting, offers a mechanism to account for the rapid lateral variation observed in Carboniferous palaeogeothermal gradients (Corcoran & Clayton 2001) and the general northwards decrease in Variscan maturity levels (consistent with a model of progressive heat dissipation from gravity-driven fluids discharging towards the north) (Clayton *et al.* 1989). Furthermore, it has

been suggested that hydrothermal flow in this foreland basin setting offers a mechanism for the emplacement of large hydrothermal sulphide ore bodies along fault systems active during Variscan deformation (Johnston 1999).

Offshore (Porcupine, Slyne/Erris/Donegal, Irish Sea and Celtic Sea) Basins

The palaeotemperature profiles for the offshore wells are generally more diffuse and highly variable (Fig. 4.14c-l). Net exhumation estimates vary widely both within basins and between basins. For example, estimates for the Erris Basin ranges from 397m (Late Palaeogene-Neogene episode - well 12/13-1a) to 3790m (Late Carboniferous-Early Permian episode - well 19/5-1) whereas in the Kish Bank Basin estimates range from 2006m to 5298m for a post-Namurian exhumation episode (Table 4.6). Within the Celtic Sea basins net exhumation estimates range between 34m (well 63/10-1) and 3289m (well 42/21-1). Although the early Cretaceous may represent a significant episode of exhumation in the Central Irish Sea and St. George's Channel basins (see above discussion re well 42/21-1 and Chapter 5) the seismic evidence and stratigraphic record from the North Celtic Sea Graben clearly indicates that basin inversion was initiated during the Palaeogene in this area (see Chapter 1).

The most significant aspect of the palaeotemperature profiles for wells in the Porcupine Basin is the dramatic discontinuity in profile that exists between the Mesozoic and Carboniferous successions in the north and east flank of the basin (e.g wells 26/28-1, 26/28-2, 34/15-1, 35/15-1). These data strongly support the view that the Carboniferous sections experienced significantly higher temperatures prior to uplift and erosion followed by re-burial during Mesozoic deposition (see Fig. 15, Corcoran & Clayton 2001). In contrast, there is no evidence, from VR data, of elevated heat flows during the Tertiary in Irish Atlantic Margin basins, except for local heat fluxes associated with Palaeogene igneous intrusions. In the Porcupine Basin, where substantial Cretaceous and Tertiary successions are preserved the VR derived palaeogeothermal gradients are generally sub-parallel to the present-day geothermal gradient (Fig. 4.14c-f).

In the Celtic Sea basins a wide range in palaeogeothermal gradients (0.6-72.8°C/km) and net exhumation estimates (34-3289m) is observed though some of the extreme palaeogeothermal gradients probably result from spurious or ill-defined palaeotemperature profiles (e.g. wells 49/10-1, 49/11-1, 49/13-1). The average net exhumation estimate for all Celtic Sea/Fastnet Basin wells is 1471m (Table 4.6).

Location with respect to the Tertiary inversion axis is likely to be the main control on the magnitude of exhumation at individual well locations (see Chapter 1).

4.7 Conclusions

VR data (R_m%) has been compiled from 78 Irish offshore wells and 17 onshore boreholes. This database has facilitated the analysis of VR versus depth behaviour by basin and by stratigraphic interval. A composite approach to the display and interpretation of VR and peak palaeotemperature profiles has been utilised to present an overview of this database and to gain insights into the thermal history of some of the Irish sedimentary basins. This regional VR dataset indicates that the morphology of the VR profiles vary considerably with location and stratigraphic succession. In general, VR profiles from Carboniferous sections are better delineated than those from Mesozoic and Cenozoic sections, reflecting the relatively less complex vitrinite populations within Carboniferous coals and shales.

Analysis of both model and real data points indicates that at low (R_m% <2.0) maturity levels, kinetic VR to palaeotemperature translation models suggest lower palaeogeothermal gradients than might be predicted from empirically-based VR to palaeotemperature translation schemes. Comparison of VR and palaeotemperature profiles reveals considerable inter- and intra-basin variation in thermal maturity and complex palaeogeothermal gradient patterns. In general, palaeogeothermal gradients are substantially higher in Carboniferous sections than Mesozoic/Cenozoic sections and provide evidence of elevated heat flows during the Late Carboniferous to Early Permian. A model of northwards focussed hydrodynamic flow of heated fluids, with vertical discharge along major fault systems in a foreland platform setting, offers a mechanism to account for two observations with respect to VR trends in Carboniferous rocks of the Irish sedimentary basins. Firstly, Variscan palaeotemperatures decrease up stratigraphy and to the north. Secondly, rapid lateral variation in Carboniferous palaeogeothermal gradients suggests that active fault systems and hydraulically induced fracture zones acted as vertical conduits for fluid flow, resulting in locally complex, vertical heat distribution patterns in Carboniferous sedimentary rocks.

There is no evidence, from VR data, of elevated heat flows during the Tertiary in Irish Atlantic Margin basins, except for local heat fluxes associated with Palaeogene igneous intrusions. In basins, with substantially preserved Tertiary

successions VR derived palaeogeothermal gradients are generally sub-parallel to the present-day geothermal gradient.

Exhumation analysis has been performed on the VR derived palaeotemperature profiles for all wells in the database. A summary map of the net exhumation estimates derived from VR data is presented in Fig. 4.15. The observed heterogeneous pattern, in terms of magnitude and timing, suggests that many of the onshore and offshore basins have experienced a multiphase exhumation history. The regional stratigraphic record combined with the VR database indicates that extensive regional uplift and erosion occurred across Ireland during Late Carboniferous to Late Permian times, during the early Cretaceous, and also during the Palaeogene and Neogene periods. This study documents a significant early Cretaceous exhumation episode in the Slyne Basin which is synchronous with uninterrupted, continuous, early Cretaceous deposition in the north of the Erris Basin (see Chapter 8). Likewise VR data combined with AFTA data suggests that up to 3 kms of early Cretaceous exhumation occurred in the Central Irish Sea Basin whereas the central Celtic Sea area was predominantly characterized by extensive 'Wealden' subsidence and deposition at this time.

The Late Carboniferous-Late Permian exhumation episode has important implications for the main Carboniferous-Triassic petroleum system in the Irish exhumed basins. Where Carboniferous source rocks are present, they will make a significant contribution to the hydrocarbon budget only in those basins where sufficient Mesozoic burial has occurred to expose the kerogen to higher palaeotemperatures than might have been achieved during the Late Carboniferous-Early Permian event.

Chapter 5

Apatite Fission Track Analysis.

5.1 Introduction.

Analysis of fission-tracks in volcanic glass and accessory minerals such as apatite, zircon and sphene, has been utilized worldwide in a range of geological settings to gain insights into the thermal, uplift and denudational histories of rocks and basins (Brown 1991; Crowley *et al.* 1985; Gleadow & Fitzgerald 1987; Hill & Gleadow 1989; Naeser 1993; Duddy *et al.* 1994; Andriessen 1995; Green *et al.* 1995; Gallagher & Brown 1997; Garver *et al.* 1999). In common with other radiogenic age determination techniques, such as Rb-Sr and K-Ar analysis of micas, fission-track (FT) analysis relies on isotopic systems in minerals to record a series of time and temperature points in a sample's history which can then be used to decipher the rates and styles of cooling and uplift (Hurford 1991).

In addition to these generic uses many specific applications have evolved from the study of fission-tracks in recent decades, including, the study of ore mineralization related to hydrothermal events and/or igneous intrusions (Arne 1992), the timing of illite/smectite transformations in K-bentonites (Roden *et al.* 1993) and the absolute dating of tephra beds (Naeser & Naeser 1984). Fission track dating of detrital minerals (particularily detrital zircons) has also been used in the discrimination of sediment source areas (Hurford & Carter 1991). However, it is the fission-track analysis of detrital apatites that has proved to be particularly useful in petroliferous sedimentary basin studies, as it can provide both time and temperature insights over a temperature range that coincides with at least part of the hydrocarbon generation window (Gleadow *et al.* 1983; Storzer & Selo 1984).

Compared to other radiogenic age determinations, FT apparent ages are systematically younger, except for rocks that cooled rapidly such as volcanics and shallow-depth intrusives (Andriessen 1995). This results from the hirearchy of annealing/closure temperatures of these mineral-isotopic systems. For example, complete annealing of fission tracks in apatites occur in the ~110-120°C range (Green *et al.* 2002), whereas the proposed closure temperature for fission track retention in zircon is 240°C ±50°C Hurford (1985) and sphene is 250°C ±50°C (Gleadow & Brooks 1979). This compares with the closure temperatures for the retention of radiogenic argon and

strontium in micas in the range of 300-500°C ±50°C (Hurford 1991). Laboratory measurement of fission-track density and fission-track length distributions in apatites, combined with a detailed knowledge of the kinetics of the fission-track annealing process for apatite and formal statistical procedures has facilitated the development of forward modeling programs which can simulate apatite fission-track age and track length distributions consistent with input time-temperature pathways (Green *et al.* 1989). Most of the fission-track analyses carried out to date, both onshore and offshore Ireland, pertains to fission tracks in detrital, plutonic and volcanic apatite grains.

5.2 AFTA - regional overview onshore and offshore Ireland

Consideration of the regional VR dataset for onshore and offshore basins (Chapter 4, Fig 4.1) indicates that for a given present-day burial depth, organic maturity levels of the Palaeozoic sections (mostly from the exhumed remnants of the onshore Carboniferous basins) are generally higher than for Mesozoic-Cenozoic sections in the offshore basins. This observation confirms that significant cover must have existed onshore to achieve these VR maturity levels, but has subsequently been removed as a result of uplift and erosion. This picture is confirmed by the evidence from the onshore apatite fission track (AFT) data compiled in Allen *et al.* (2002), summarised in Table 5.1. Mean Track Length (MTL) versus Apatite Fission Track Age for this dataset [over 180 Apatite Fission Track Analyses carried out on a wide range of lithologies (igneous, metamorphic and sedimentary) from widely distributed exposures across Ireland] is plotted in Fig. 5.1. Although detailed thermal history modelling of individual samples is required to understand the relevance of fission track ages and track length distributions, a number of observations can be made from this plot – with *prima facie* evidence for at least one Mesozoic/Cenozoic unroofing/cooling event.

Except for the four samples highlighted in red and yellow, all apatite samples in this dataset have been recovered from rocks deposited or emplaced prior to Middle Carboniferous time – indicated in blue on this diagram. It is clear that the fission track ages of the majority of samples are significantly less than their respective stratigraphic ages, regardless of the original depositional or emplacement age of the host rock. The paucity of grains with fission track ages older than 230 Ma indicates that widespread post-Variscan annealing of fission tracks has occurred. A cluster of fission

track ages between 110-230 Ma, with mean track lengths between 11.5-13.5 μm – suggests that many samples are characterised by reduced mean track lengths (resulting from a component of short tracks inherited from the source age, and a component of long tracks, formed after cooling from elevated temperatures) reflecting slow and continuous cooling through the partial annealing zone of apatite (Andriessen 1995). The absence of the distinctive boomerang/banana-shaped pattern of Gallagher & Brown (1997) suggests that this set of samples is likely to have experienced more than a single cooling episode. AFT analysis of one Triassic Sandstone sample has yielded a fission track age (369 ± 32 Ma) which is significantly older than the stratigraphic age of the sample, indicating an inherited fission track age from the detrital apatite contained in this sample. The youngest fission-track ages (28 Ma & 36 Ma with MTL c. 14 μm) are derived from two Mourne Granite (Palaeocene Granite) samples (which ion microprobe U-Pb dating indicates emplacement at ~56 Ma) and suggests rapid exhumation and cooling from temperatures in excess of 110°C (annealing threshold of fission tracks in Apatite) during the Oligocene.

Allen *et al.* (2002) used thermal history modelling of 139 of the onshore surface AFT samples, from this database, to construct maps to examine the spatial variability of exhumation and subsidence across the island for a number of time slices from Triassic to Late Miocene. Although the interpreted patterns of onshore denudation are complex, they concluded that cumulative denudation in this time interval (250-10 Ma) was relatively low (<2km) in the Irish Midlands and the extreme NE of the island but was highest along the western seaboard and in the eastern region between Dublin and County Down where up to 4kms of cumulative denudation is interpreted.

A limited amount of AFT data and/or AFTA (*trademark of GEOTRACK) has been published for wells offshore Ireland (42/12-1 - Duncan *et al.* 1998; 42/16-1, 42/21-1 - Green *et al.* 2001; 26/26-1, 26/28-1, 13/3-1 – McCulloch 1993) and is complimented by published data from wells and outcrops in the East Irish Sea Basin (110/7b-6, 112/25-1), Cheshire Basin (Heywood-1, Knutsford-1) and peripheral areas (Lewis *et al.* 1992) (Table 5.2; Fig. 5.2). Some additional apatite fission track age and mean track length data has been derived from unpublished Geotrack reports from released wells and boreholes offshore Ireland (12/13-1a, 18/20-1, 19/5-1, 27/5-1, 27/13-1, 33/17-2a; 16/28-sb01, 83/20-sb01; 83/24-sb02) (Table 5.3; Fig. 5.3). Allen *et al.* (2002) concluded that there was no definitive signature of an Irish Sea

Dome extending significantly across Ireland in Early Tertiary time. However, when mean track length and fission track age data for the Irish Sea (offshore wells) and peripheral areas is over-plotted on the onshore data (Fig. 5.2) a significant clustering of fission track ages is observed between 50-70 Ma, with samples containing long track lengths (>14μm) most likely to represent the onset of a cooling episode. In contrast, this 'Early Tertiary' clustering is not well represented in the sample dataset from the offshore wells on the Atlantic Margin (Fig. 5.3) where the majority of the samples manifests a more diffuse fission track age range (110-280 Ma). This plot suggests that these samples are likely to have experienced multiple cooling episodes.

5.3 Central Irish Sea – AFTA wells 42/21-1 and 42/16-1

Six composite cuttings samples (minimum estimated weight ~1kg) were retrieved (from the national offshore sample repository) from well 42/21-1 and two composite cuttings samples from well 42/16-1 (Fig. 5.4; Table 5.4), courtesy of the Petroleum Affairs Division, Dublin. These sample data were then sent to Dr. Paul Green, Geotrack International Pty Ltd., Australia who kindly undertook apatite fission track analysis of these data and provided detailed documentation of sample preparation, analytical details and interpretation in a standard Geotrack report (Geotrack Report #729, 1999), with the interpretation results summarised in Green *et al.* (2001).

5.3.1 AFTA wells 42/21-1 and 42/16-1 – analytical results

Analytical results for the 8 samples are summarised in Table 5.5 with age and track length data for each sample from the two wells also included in Table 5.3. Analytical procedures were similar to those outlined in detail in Green (1986) with interpretation procedures broadly following those outlined in Green *et al.* (2002). Neutron irradiations were carried out in a well-thermalised flux (X-7 facility) in the HIFAR research reactor in Australia. The apatite mounts were analysed by the external detector method (EDM) (Gleadow 1981) and apatite fission track ages were calculated using the zeta calibration method of Hurford & Green (1983). Age errors were computed either using the conventional method of Green (1981) for samples with chi-squared [$P(\chi^2)$] statistic values greater than 5% or the central age approach of Galbraith

and Laslett (1993) for samples with $P(\chi^2)$ values less than 5%. Confined track lengths were measured only on prismatic surfaces following the recommendations of Laslett *et al.* (1982). Chlorine (Cl) contents were measured in all apatite grains analysed using a fully automated Jeol JXA-5A electron microprobe, with AFTA data then grouped into compositional intervals of 0.1 weight % width. The thermal history solutions extracted from the AFTA data have incorporated a 'multi-compositional' kinetic model that makes full quantitative allowance for the effect of Cl content on the annealing rates of fission tracks in apatite (Laslett *et al.* 1987). VR data for these wells (available at time of AFTA study) were translated to maximum palaeotemperatures, using the kinetic model developed by Burnham & Sweeney (1989) and Sweeney & Burnham (1990), and used to constrain the higher temperature (>120°C) components of the thermal history interpretations which are not resolvable from AFTA alone.

5.3.2 AFTA wells 42/21-1 and 42/16-1 – interpretation

Timing constraints, (on the onset of cooling episodes from maximum palaeotemperatures), derived from AFTA of individual samples in these two wells is summarised in Table 5.6. Graphical representation of these data is presented in Fig. 5.5 where the thermal history solutions are compared with the AFTA interpretation for well 42/12-1, originally described in Duncan *et al.* (1998). Typical AFTA data will normally allow the resolution of up to two discrete palaeo-thermal episodes in a single sample. The AFTA data from each sample in this study have been interpreted in terms of two episodes of heating and cooling , using assumed heating and cooling rates of $1°C\ Ma^{-1}$ and $10°C\ Ma^{-1}$, respectively, during each episode (with the maximum palaeotemperature reached during the earlier episode). Using statistical procedures, iterations of peak palaeotemperatures and the timing of the onset of cooling for the two episodes are modelled to establish the 'thermal history' solution most compatible with the measured data (for modelling procedure see Chapter 2, Fig. 2.5). However in rare instances, such as in the shallower sample from well 42/16-1, information on three discrete episodes may be obtained from AFTA data in a single sample (Table 5.6; Fig. 5.5). In this case the sample was totally annealed in an early episode, cooled and was then reheated such that severe partial annealing was produced, cooled once more and then underwent moderate annealing relatively late in its history, such that the effects of all three events

can be identified. Alternatively, integration of VR and AFTA data may allow three episodes to be resolved in cases where the VR data reveals an earlier thermal event which is not resolved by the AFTA data alone.

The vertical bars plotted for each well in Fig. 5.5 highlight the range of timing of cooling episodes that is consistent with all samples from each well. Consequently, the AFTA results from all three wells can be explained in terms of three palaeo-thermal episodes, with cooling beginning in the Early Cretaceous (between 120 and 115 Ma), Late Cretaceous-Early Tertiary (between 70-55 Ma) and Late Tertiary (between 25-0 Ma) times. Palaeotemperature constraints derived from AFTA and VR, for all samples, are plotted against depth for four Irish Sea wells (including 42/21-1 and 42/16-1) in Fig 5.6 and are compared with present-day temperature profiles (derived from corrected BHT data) for each well. Results from the four wells suggest that palaeogeothermal gradients were close to present-day values since at least Early Cretaceous time and that the heating in each episode was due largely to deeper burial and not higher heat flow (Green *et al.* 2001).

Palaeotemperature constraints are coded for discrete palaeothermal episodes and profiles parallel to the present-day temperature profiles are drawn through the palaeotemperatures characterizing individual episodes for each well. Alternatively, for data that reveals multiple episodes of heating and cooling, separate palaeotemperature profiles can be constructed for each episode (Fig. 5.7) and these data can then be used to define the range of palaeogeothermal gradient and removed section (magnitude of exhumation) that are consistent (within 95% confidence limits) with the palaeotemperature constraints for each episode in each well and the assumed palaeo-surface temperature (Fig. 5.8). This analysis suggests that exhumation did not occur, during the Early Cretaceous, at the 42/21-1 well location but that *c.* 3kms of section were removed at 42/16-1 well location during this episode (120-110 Ma). During the Late Cretaceous-Early Tertiary episode (70-55 Ma) *c.* 2 kms of exhumation occurred at both locations, whereas during the Late Tertiary event *c.* 1 km of section was removed from both locations.

On the basis of the integration of AFTA and VR data for wells in the Central Irish Sea Basin (42/12-1, 42/16-1 and 42/17-1) this thermal history synthesis concluded that the Carboniferous sections in these three wells reached their maximum palaeotemperatures during Early Cretaceous time. No significant palaeo-thermal effects have been interpreted as associated with the Late Carboniferous-Early Triassic

unconformity in these wells and the stratigraphic evidence of the preservation of Stephanian sections in wells 42/12-1 and 42/16-1 offers support to the proposition of limited exhumation and denudation at this time. However, palaeotemperatures derived from singular Jurassic (42/17-1) and Triassic (42/16-1) VR data points are lower than would be expected if maximum palaeotemperatures throughout the Triassic and older sections are attributed to an Early Cretaceous episode and are inconsistent with the current interpretation (Fig. 5.6). [Both data points have been discounted as possible unreliable VR data and have been omitted from the current synthesis.] Given the regional occurrence of major heating and cooling associated with Variscan (Later Carboniferous-Early Permian) events onshore Ireland and peripheral to the Irish Sea area, it seems likely that some palaeo-thermal effects undoubtedly affected the Carboniferous and older section in the Central Irish Sea Basin (Fig. 5.9).

5.4 Conclusions

Interpretation of AFTA and/or VR data for four hydrocarbon exploration wells located in the Central Irish Sea area reveal three major episodes of heating and cooling, each of regional extent. Palaeozoic-Mesozoic sediments in wells 42/12-1, 42/16-1 and 42/17-1 (Central Irish Sea Basin) began to cool from their maximum post-depositional palaeotemperatures in the Early Cretaceous, between 120 and 115 Ma. Cooling from subsequent palaeotemperature peaks began in the Late Cretaceous-Early Tertiary (between 70 and 55 Ma) and Late Tertiary (25-0 Ma). Results from well 42/21-1 (St. George's Channel Basin) are dominated by the two more recent episodes, and show no evidence of the Early Cretaceous episode. This is thought to reflect the different structural setting of this well.

Palaeotemperature profiles suggest that heating in each episode was due largely to deeper burial, with subsequent cooling due mainly to uplift and erosion. A maximum of around 3 km of additional section (of Late Triassic to Early Cretaceous age) is required to explain the observed Early Cretaceous palaeotemperatures. Appropriate values for the Late Cretaceous-Early Tertiary and Late Tertiary episodes of exhumation are ~2 km and ~1 km, respectively, suggesting that the overall magnitude of exhumation in each episode decreases over time.

These three cooling episodes correlate closely with similar episodes recognised from AFTA studies in surrounding regions, from onshore Ireland, Scotland, South Wales and Northern, Eastern, Central and SW England, and each appears to be of truly regional extent (Lewis *et al.* 1992; Murdoch *et al.* 1995; Green *et al.* 1997; Green *et al.* 1999; Green *et al.* 2002; Floodpage *et al.* 2001; Holford *et al.* 2005). Although it seems likely that a modest? cooling episode may also have affected the Central Irish area during the Late Carboniferous –Early Permian time.

Chapter 6

Implications for hydrocarbon systems and prospectivity

6.1 Introduction.

Petroleum systems in exhumed basin settings manifest some common characteristics which are the result of physical and chemical changes induced by uplift, erosion and removal of overburden (Corcoran & Mecklenbergh 2005). In these basins, the explorationist must place particular emphasis on the timing of thermal 'switch-off' of source rock units, the compactional and diagenetic constraints imposed by the maximum burial depth of reservoirs (prior to uplift) and the physical and mechanical characteristics of cap-rocks during and post-exhumation. In addition, attention must be focussed on the structural evolution of traps and the hydrocarbon emplacement history. Realization early in the exploration programme, that a basin has been exhumed, gives rise to a different approach to hydrocarbon exploration and can help to constrain resource and risk prediction (Doré *et al.* 2002).

Empirical observation suggests that the application of conventional resource assessment and risk evaluation methodologies to exhumed basins may result in the overestimation of the undiscovered resource potential for these basins. In the past this approach has resulted in unfulfilled expectations and an inappropriate comparison of the exploration potential of exhumed basins with those basins characterised by continual subsidence. Nyland *et al.* (1992) and Doré & Jensen (1996) were among the first to highlight the impact of exhumation on petroleum systems. MacGregor (1995) noted that exhumed petroliferous basins were characterised by concentrated field size distributions (most of basin reserves in one large field) as opposed to the more typical dispersed distributions (<25% basin reserves in largest fields) of 'continually subsiding' basins. He also indicated that the mechanism of exhumation may be important, in terms of petroleum resource preservation, suggesting that regional uplifts of compressional origin may be more destructive of a basin's petroleum system than uplifts of isostatic or thermal origin. A systematic and comprehensive review of the implications of exhumation for prospect assessment and risking has been provided by Doré *et al.* (2002) and is summarised below. A detailed review of the implications of exhumation for one

element of a petroleum system (top-seal) has been outlined in Corcoran & Doré (2002*a*) and Corcoran & Doré (2002*b*) and is summarised in Chapter 7.

6.2 Prospect resource estimation in exhumed basins.

For any petroliferous basin, the computation of the potential hydrocarbon recoverable reserves contained in a prospect (potential hydrocarbon trap) is usually achieved via a standard equation of the form:

$$\mathbf{RR = GRV*N/G*\phi*S_{hc}*FVF*RF} \quad \text{where}$$

RR = recoverable hydrocarbon reserves, expressed as a volume
GRV = gross rock volume; volume of reservoir rock contained within the trap
N/G = net-to-gross ratio; fraction of the reservoir capable of containing moveable hydrocarbons
ϕ = interconnected porosity in the reservoir, expressed as a fraction
$\mathbf{S_{hc}}$ = hydrocarbon saturation; fraction of pore volume occupied by hydrocarbons
FVF = formation volume factor; a multiplier which accounts for the expansion of gas or the contraction of oil (owing to the exsolution of dissolved gas) as the hydrocarbons are brought to surface pressure and temperature conditions during production
RF = recovery factor; the proportion of the hydrocarbons in the prospect that can be recovered to surface given an assumed production method

For any given prospect these reserve assessment parameters are estimated based upon the predicted depth of the prospect and local and regional data and analogues. The critical factor with respect to prospect assessment in an exhumed basin setting is the recognition that present-day burial depth is not the maximum burial depth of the prospect and that depth vs ϕ relationships established for 'continually subsiding' basins cannot be used as predictors in an exhumed basin (see Chapter 2 Fig. 2.9). The effects of exhumation on each of these volumetric parameters have been discussed in detail by Doré *et al.* (2002) and are summarised here below and in Fig. 6.1 (Fig. 3 of Doré *et al.* 2002).

In general the gross rock volume parameter (GRV) is independent of exhumation. However, the trap fill factor may be less than one due to post-exhumation leakage of hydrocarbons, post-exhumation reburial contraction of gas or syn- and post-exhumation amplification of the structural trap. The net-to-gross ratio (N/G), porosity (ϕ) and hydrocarbon saturation (S_{hc}) parameters are interlinked and in the case of an exhumed prospect are generally degraded relative to a prospect at an equivalent burial depth in a 'continually subsiding' basin. Formation volume factor (FVF) is a function of pressure-temperature-volume relationships at a given, present-day, depth and as such is independent of exhumation. In general, the recovery factor (RF) parameter can be enhanced by exhumation (where fractures are induced) or degraded due to the relatively lower porosity and permeability of the exhumed reservoir.

6.3 Prospect risk analysis in exhumed basins

The general challenge of prospect risk analysis is to assist the translation of a resource and reserve assessment of geological models (prospects) into economic values (Rose 1987). Explorationists address prospect uncertainty at two levels – uncertainty in the evaluation of the possible range of reserves associated with a particular prospect (geological model) and uncertainty with respect to the existence of the prospect (chance that the geological model, as described, is present, or the chance of discovering hydrocarbons). 'Range of reserves' uncertainty is traditionally addressed by assuming a distribution of values for each prospect assessment parameter (Gross rock volume, Net/Gross, Porosity, Hydrocarbon Saturation, Formation Volume Factor, Recovery Factor) and by applying stochastic simulation procedures to generate ranges of reserve estimates from these individual parameters. This procedure is independent of basin setting, provided that the appropriate midpoint value and distribution is established for each prospect parameter. In contrast, estimation of the chance of success or chance of discovery of hydrocarbons in an exhumed prospect challenges the explorationist to understand the *history* of the petroleum system in addition to describing the petroleum system *per se*.

Pre-drill uncertainty with respect to the chance of discovering hydrocarbons is usually quantified via a generalized equation (Fig. 6.2; see Fig.2 of Doré *et al.* (2002)) of the form:

$$P_{hc} = P_r * P_s * P_t \text{ where}$$

P_{hc} = probability of finding some specified quantity of hydrocarbons

P_r = probability of reservoir presence with quality sufficient to allow production of hydrocarbons

P_s = probability of source rock presence with sufficient maturity to have generated hydrocarbons and charged the prospect

P_t = probability of presence of viable, sealed, hydrocarbon trap

And the probability of an oil or gas accumulation is given by:

$$P_{hc} = P_o + P_g \text{ where}$$

Po = probability of discovering oil accumulation

Pg = probability of discovering gas accumulation

Although there is a complex interplay between the timing and magnitude of an exhumation event and the evolutionary status of a petroleum system, some generalizations can be made with respect to the effects of exhumation on the probabilities (chance of adequacy) of the individual prospect elements (Fig. 6.2). In general, the probability of reservoir presence is unlikely to be affected by exhumation, though the reservoir quality can be reduced (in the case of extreme burial prior to exhumation) or enhanced (in the case of fracturing induced by local and regional vertical displacements). The probability of source rock presence is severely reduced where exhumation has resulted in the erosion of the source rock intervals (e.g see below Peel Basin) or where the residual hydrocarbon budget, post thermal 'switching-off' of source rock maturation, is insufficient to fill the available hydrocarbon traps. The probability of the presence of a sealed trap can be increased (e.g. by tilting of structural 'noses') or decreased (e.g hydraulic fracturing of claystone seals) by an exhumation event. Empirical observation, from basins along the northeast Atlantic Margin, suggests that there is an increased probability of discovering gas accumulations in the exhumed basin setting (Doré & Jensen 1996; Doré *et al.* 2002).

6.4 Petroleum systems and prospectivity in exhumed basins, offshore Ireland.

Ireland is virtually encircled by sedimentary basins which can be categorized into two groups (Fig 6.3) The first group, which consists of the basins of Northern Ireland, the Irish Sea and Celtic Sea areas, and the inboard basins (Slyne, Erris and Donegal) of the Atlantic margin region, typically manifest a NW-SE elongate morphology and are located in relatively shallow waters (<1000m). In addition, these inboard basins all appear to have experienced a multiphase exhumation history. The second group, which is composed of the outboard basins of the Atlantic margin region (Goban Spur, Porcupine, Rockall and Hatton basins), lies in deeper water and are characterised by a more extensive surface area, relatively continual post-rift subsidence history, and typically contain a predominantly Cretaceous and Tertiary succession. Three decades of petroleum exploration in these basins have yielded very modest results (Fig 6.4). Over one hundred and fifty wildcat and appraisal wells have now been drilled (plus, in the UK sector, 2 wells in the Peel Basin and 1 in the North Channel Basin), resulting in only 4 commercial discoveries (3 producing gas fields in the North Celtic Sea Basin - Kinsale Head, Ballycotton and Seven Heads Fields plus the Corrib Field, in the Slyne Basin, which is currently sanctioned for development) and a number of oil and gas discoveries which have disappointed upon appraisal. A failure to recognize the implications of the exhumation history for petroleum systems in the inboard basins may have contributed to the low exploration success rates encountered in some of these basins offshore Ireland.

There is a growing body of tectonic, thermal, compactional and stratigraphic evidence which suggests that one or more phases of exhumation have influenced the evolution of the inboard basins (Brodie & White 1995; Corcoran & Clayton 2001; Green *et al.* 2001; Holford *et al.* 2005). At least four, potentially regional, exhumation episodes are now interpreted to have occurred - a Late Carboniferous to Early Permian event, an Early Cretaceous event, and Early Tertiary and Late Tertiary episodes (see Chapter 1). In spite of the well documented impact that the uplift and removal of overburden has on petroleum systems within basins (Nyland *et al.* 1992; Doré & Jensen 1996), few published studies have been dedicated to this aspect of the evolution of these Irish offshore basins. Murdoch *et al.* (1995) were among the first to employ a multi-disciplinary approach to assess the magnitude and timing of Tertiary uplift events and their impact on the maturity of the Jurassic source rocks in the

North Celtic Sea Graben. Scotchman & Thomas (1995) identified a number of consequences, for the Jurassic petroleum system in the Slyne Basin, of 1-2 km of late Mesozoic to early Cenozoic exhumation in this area. Duncan *et al.* (1998) addressed the impact of a multiphase inversion history on the Carboniferous to Triassic petroleum system in the Central Irish Sea area and highlighted evidence for an Early Cretaceous exhumation event in this area in addition to describing uplift phases at the end of the Carboniferous and during the Tertiary. Corcoran & Clayton (2001) outlined the evidence for a Late Carboniferous-Early Permian exhumation event in Irish offshore basins and the implications for timing of maturation of Carboniferous source rocks in some of these basins.

A brief 'clockwise' resume is offered here of the impact of exhumation events on the petroleum systems and hydrocarbon prospectivity of these exhumed inboard basins. In the context of this review, a petroleum system is defined as "a natural system that encompasses a pod of active source rock and all the related oil and gas and which includes all the geological elements and processes that are essential if a hydrocarbon accumulation is to exist" (Magoon & Dow 1994). A basin by basin synopsis of the main petroleum systems and the exploration drilling record to date is presented in Table 6.1.

Lough Indaal Basin & Rathlin Basin

Although there are favourable indications for the presence of a Carboniferous sourced petroleum system in the Lough Indaal and Rathlin basins, no offshore hydrocarbon exploration drilling has occurred to date in either basin (Fitzsimons & Parnell 1995). Consequently, the resource potential of these basins is unknown and the presence of a petroleum system remains unproven. Carboniferous source rocks exposed in North Antrim (Ballycastle Coalfield) and in West Scotland (Machrihanish Coalfield), on the margins of the Rathlin Basin, indicate mixed potential for oil and gas generation (Parnell 1991). However, it is unclear if these source rocks are preserved towards the center of the basin due to Variscan inversion. In the onshore, Magilligan-1 borehole, Triassic (Sherwood Sandstone Group) sediments rest unconformably upon a Namurian to Visean section. Middleton *et al.* (2001) presented AFTA and VR data which suggests that these Visean and Namurian sediments achieved peak palaeotemperature exposure prior to Triassic time, most likely during the Late Carboniferous, prior to Variscan exhumation. Their AFTA data is also consistent with

subsequent episodes of exhumation and cooling during the early Cretaceous and early Tertiary. There is some evidence for the preservation of both reservoir rocks (Lower Triassic Sherwood Sandstone Group) and gypsiferous seal rocks (Upper Triassic Mercia Mudstone Group), locally, within the Rathlin and Lough Indaal basins (Fitzsimons & Parnell 1995). However, much of the post-rift succession is absent due to Mesozoic and/or Cenozoic exhumation (for Lough Indaal Basin – see Fig. 4d Brodie & White 1995).

North Channel Basin

The main exploration risks in the North Channel Basin have been identified as the presence of Carboniferous source rocks and the timing of hydrocarbon generation relative to trap formation (Maddox *et al.* 1997). Only one well (UK111/15-1) has been drilled to date in the offshore North Channel Basin, but in common with the onshore basin margin wells (Larne-1, Larne-2, Newmill-1, Ballytober-1, Anaghmore-1, Ballynamullan-1) was abandoned as a dry hole (Shelton 1997). The postulated presence of Brigantian to Westphalian coals and mudstones, although immature to oil-mature in outcrop along the onshore margins of the basin, suggests that oil and gas generation could have occurred in the offshore North Channel area beneath a thick Permo-Triassic succession (Parnell 1997). Minor oil shows were reported in the onshore Anaghmore-1 well (Naylor & Shannon 1999). However, AFTA and VR thermal history modelling of Green *et al.* (2000) indicates that the main phase of hydrocarbon generation pre-dated trap formation, occurring during the Late Carboniferous, pre-Variscan exhumation and deformation. Subsequent phases of hydrocarbon generation may have occurred after the development of hydrocarbon structural traps during the Permian to Jurassic extensional episodes or as a result of early Tertiary heating (Maddox *et al.* 1997). Analysis of sonic velocity data from Triassic (MMG and Sherwood) sections in the onshore boreholes has yielded a range of post-Triassic exhumation estimates of 655-2267m (Shelton 1997). Although the AFTA data for the onshore well Larne-2 (Green *et al.* 1999) is dominated by early Tertiary heating, caused by hydrothermal fluid circulation beneath a basalt cover, it does suggest that approximately 450m of Tertiary uplift and erosion may have occurred at this location. Reservoir quality sandstones of Triassic (Sherwood Sandstone Group) and Permian age have been encountered in the onshore wells and there is

seismic evidence to suggest that the halites and shales of the Mercia Mudstone Group provides an adequate regional top-seal to the Sherwood sandstone reservoir, over much of the North Channel Basin.

Peel Basin

The limited resource potential of the Peel Basin is primarily the result of the phase of exhumation and basin inversion which occurred during the Late Carboniferous-Early Permian (Newman 1999; Floodpage *et al.* 2001). Strong erosional truncation is manifest beneath the Variscan (Saalian) unconformity on seismic lines through the Peel Basin (see Fig. 7c Floodpage *et al.* 2001). This exhumation event (Variscan compressional inversion) has resulted in the almost complete removal of the Westphalian to Namurian section which contains the source rocks for the oil and gas encountered in the adjacent East Irish Sea Basin. Geochemical analysis of the preserved Dinantian section in wells UK111/25-1A and UK111/29-1 indicates average total organic carbon (TOC) content of 0.04 wt.% and negligible hydrocarbon source potential. Both reservoir rocks (Lower Triassic Sherwood Sandstone Group) and seal rocks (Upper Triassic Mercia Mudstone Group) are preserved within the Peel Basin. However, no indications of hydrocarbons were encountered in either of the two wells drilled to date in the basin. These drilling results combined with integrated basin analysis suggest that a working petroleum system has not been preserved in this basin.

Kish Bank Basin

A Carboniferous sourced petroleum system is present in the Kish Bank Basin. Drilling results have proven the presence of the Triassic reservoir (SSG) and seal (MMG) couplet. The principal source rocks, which have not been penetrated by drilling, are interpreted from seismic and regional data to be Upper Dinantian to Lower Namurian organic-rich basinal shales which are the main source of the oil and gas in the EISB (Armstrong *et al.* 1997; Haig *et al.* 1997; Yaliz 1997). Five metres of residual oil shows were recorded at the top of the Sherwood Sandstone in well 33/17-1, as was oil staining and fluorescence in the Westphalian section of well 33/22-1 (Dunford *et al.* 2001). In addition, gas indications from high-resolution shallow seismic data and geochemical analysis of seabed cores have been interpreted as evidence of active hydrocarbon seepage in the Kish Bank Basin (Croker 1995; Dunford *et al.* 2001). However, Corcoran & Clayton (1999) have interpreted this evidence of shallow gas as

primarily the result of bacterial activity in Namurian-Westphalian coal beds stimulated by geologically-recent meteoric flushing and low aquifer temperatures. Four exploration wells have been drilled to date in the Kish Bank Basin, with three of these wells testing valid hydrocarbon traps (Naylor *et al.* 1993; Dunford *et al.* 2001). This suggests that understanding Mesozoic-Cenozoic exhumation history, the timing of hydrocarbon migration and the timing of trap formation are the key factors to be addressed in order to delimit the residual resource potential in the Kish Bank Basin.

Central Irish Sea Basin

The major factor controlling hydrocarbon prospectivity in the Central Irish Sea Basin is the limited presence of effective source rocks in the Carboniferous section (Floodpage *et al.* 2001) and/or the timing of peak maturity of the Carboniferous source rocks, - possibly as early as Late Carboniferous-Early Permian (Corcoran & Clayton 1999). AFTA data suggests that peak maturation could have occurred during Jurassic time, followed by *c.* 2000m of exhumation during the Early Cretaceous (Duncan *et al.* 1998; Green *et al.* 2001). Rocks of Namurian to early Westphalian age have not been encountered by drilling to date in the CISB. As a result, some palaeogeographic reconstructions suggest that the CISB area remained high during the Dinantian to early Westphalian period (Cope *et al.* 1992) and that the onlapping Westphalian C-D section is organically lean and dominated by refractory, inertinitic, kerogen with limited potential for gas generation (Floodpage *et al.* 2001). Minor gas shows were recorded in Carboniferous to Triassic sandstones in well 42/16-1. Five wells have been drilled to date in the Irish sector of the CISB and all have been plugged and abandoned as dry holes.

St. George's Channel-Cardigan Bay Basin

A Jurassic sourced petroleum system is present in the St. George's Channel-Cardigan Bay Basin with potentially producible gas reserves in the Dragon discovery close to the UK/Ireland median line and oil shows in a further three wells (DTI 2002). Light oil (42° API) and condensate was also recovered from an Upper Jurassic sandstone reservoir in the Dragon discovery well, 103/1-1 (Scotchman 2001). Drilling results in this basin suggest that additional reservoir targets are present in the Lower Triassic (Sherwood Sandstone) and Middle Jurassic shallow-marine sandstones

and limestones. Organic rich claystones of Late Sinemurian-Pliensbachian and Toarcian age are the main source rock intervals within the basin though the quality of these source rocks deteriorates towards the Mochras Borehole in the northeast (Barr *et al.* 1981).

A potential, Carboniferous sourced, petroleum system is also present in the St. George's Channel Basin, to the north of the Variscan Front. Gas-prone Westphalian coal measures have been preserved in the South Wales coalfield and may have been preserved along strike to the northwest (Maddox *et al.* 1995). However, with respect to Mesozoic and younger hydrocarbon traps, the timing of maturity is problematic as peak gas generation may have occurred during the late Carboniferous, prior to Variscan deformation and exhumation.

North Celtic Sea – Fastnet Basin

In excess of 70 exploration and appraisal wells have been drilled in the North Celtic Sea-Fastnet Basin. Two Jurassic petroleum systems are proven in the basin, with recovered oil and gas correlated to thermally mature Liassic and Portlandian source rocks (Caston 1995; Murdoch *et al.* 1995; Taber *et al.* 1995). However, exploration to date has yielded two producing gas fields (Kinsale Head and Ballycotton), a third gas field (Seven Heads) which is currently being developed, and a further six sub-commercial oil and gas discoveries (e.g. Helvick, Ardmore). The primary reservoir in the producing gas fields is the shallow marine Albian Greensand with secondary production occurring from the fluvial sandstone reservoirs of the Wealden. Within the basin, oil has also been recovered from these Cretaceous reservoirs as well as from Bathonian shelf limestones and Oxfordian fluvial sandstones in the North Celtic Sea Graben (Millson 1987; Doré *et al.* 2002). In addition, good oil shows have been described in Sinemurian, shallow marine, sandstones in the Fastnet Basin (Robinson *et al.* 1981). Mesozoic subcrop patterns indicate that regional end Carboniferous-Permian exhumation has removed the potential for a Carboniferous sourced petroleum system within the North Celtic Sea-Fastnet area. The Jurassic petroleum systems within the Fastnet Basin have been extensively modified by a major late Jurassic to early Cretaceous erosional event (only two of the nine wells drilled in the Fastnet Basin encountered preserved Middle to Upper Jurassic sediments) with a significant depositional hiatus also developed during Maastrichtian to Middle Eocene time (Robinson *et al.* 1981). In the North Celtic Sea Basin two major Cenozoic

denudational events have resulted in the seafloor subcrop of Cretaceous Chalk in the center of the basin and the complete removal of Cretaceous sediments in the northeast of the basin (Murdoch et al. 1995). Peak maturity of the Liassic and Portlandian source rocks, which occurred in the center of the basin during the late Cretaceous, was succeeded by regional exhumation during the Palaeogene. Local and regional inversion followed during the Oligo-Miocene which has resulted in Jurassic petroleum systems with a characteristic 'exhumed' signature – concentrated reserve distribution, basin centered gas accumulations (Kinsale Head and Seven Heads), residual oil columns and peripheral hanging wall oil accumulations (Helvick, 50/6-1) (Doré et al. 2002).

South Celtic Sea, Bristol Channel & Cockburn Basin

The presence of a petroleum system remains unproven in the South Celtic Sea, Bristol Channel and Cockburn basins. No wells have been drilled in the Cockburn Basin. Although potential reservoirs of Cretaceous (Wealden) and Triassic (Sherwood Sandstone) age have been encountered in the South Celtic Sea-Bristol Channel Basin, no hydrocarbons were found in the seven wells (3 wells in Irish sector) drilled to date (Tappin *et al.* 1994). In general, these wells indicate that the Jurassic organic rich shales, which are the main source for the hydrocarbon accumulations in the North Celtic Sea basin, are sparsely developed, of poor quality and are thermally immature in the South Celtic Sea Basin. Organically rich claystones were encountered in the Toarcian interval of 49/29-1 (Murphy *et al.* 1995) and, elsewhere in the basin, in the early Cenomanian interval (Kamerling 1979) but have not reached thermal maturity. Mesozoic subcrop patterns to the south of the Variscan Front indicate that Late Carboniferous rocks have been removed from this area by erosion during Variscan deformation (Musgrove *et al.* 1995). In the Celtic Sea-Bristol Channel area most of the wells that have reached TD in pre Mesozoic rocks have encountered Triassic sediments resting unconformably upon early Carboniferous (Culm Facies) or Devonian sections (Gardiner & Sheridan 1981). Furthermore, regional examination, of palaeogeothermal gradients in Carboniferous successions, suggests that any potential Carboniferous source rocks in the South Celtic Sea area would have reached thermal maturity prior to late Carboniferous exhumation (Corcoran & Clayton 2001). Consequently the timing of Carboniferous source rock maturity is not propitious for the charging of any potential Mesozoic traps in this basin.

Slyne-Erris Basins

Two petroleum systems have been documented by the drilling to date in the Slyne-Erris basins. The primary petroleum system consists of the Lower Triassic Sherwood Sandstone reservoir in structural traps, sealed by Upper Triassic evaporites and mudstones, and charged from Namurian-Westphalian claystones and coals. Sporadic exploration in the Slyne-Erris area over the last 25 years has resulted in the drilling of 6 exploration wells, which have yielded a single gas discovery (Corrib Field 18/20-1). With estimated reserves of approximately 1 TCF (Doré *et al.* 2002). An Early Jurassic petroleum system has also been documented in the Slyne Basin, with residual oil columns in Middle Jurassic deltaic sandstone reservoirs sourced from Sinemurian and Toarcian source rocks (Scotchman & Thomas 1995). The limiting factor to the Jurassic petroleum system appears to be the retention capacity of the Middle Jurassic intra-formational claystone seals during post-Jurassic exhumation (Corcoran & Doré 2002a). Middle Jurassic traps tested to date are characterized by residual, biodegraded, and water-washed oil shows which is a characteristic signature of meteoric flushing induced by basin exhumation (Macgregor 1995a). It is not known if any Middle Jurassic oil accumulations have survived the Cretaceous and Tertiary phases of exhumation in the Slyne-Erris Basins. In the Slyne Basin a major gap in the stratigraphic record exists between the Bathonian and Miocene. However, regional stratigraphic and seismic evidence, from the Corrib field area and the Erris Basin, suggests that the major phase of exhumation occurred during the Early Cretaceous in response to footwall uplift triggered by rifting in the Rockall Basin.

Donegal Basin

A potential Carboniferous sourced petroleum system is also present in the Donegal Basin. The single well (13/3-1) drilled to date encountered Miocene rocks resting unconformably on a Westphalian B-D section and reached TD in a large (interpreted from size of the thermal aureole) gabbroic intrusion, which has yielded a Permian age from a single grain AFTA sample (Robeson *et al.* 1988; Chapman *et al.* 1999). Numerous gas shows plus one oil show were recorded in the well and 38m of coal was penetrated in the Westphalian B-C section. In the south of the Donegal Basin, Dobson & Whittington (1992) have interpreted, from seismic data and shallow boreholes, the presence of in excess of 2500m of Permo-Triassic to Middle Jurassic

basin fill. Consequently, it seems likely that the Triassic Sherwood Sandstone (reservoir) and MMG (seal) pairing is preserved beneath the Miocene unconformity, in this area of the basin. A secondary, Jurassic, petroleum system may also be present in the south of the Donegal basin. However, the potential of this system may have been negatively impacted by Cretaceous to late Tertiary exhumation events.

6.5 Summary and conclusions

Although a number of potential petroleum systems are present in the Irish offshore basins, two petroleum systems dominate within the exhumed inboard basins and are, to date, the source of the only commercially extractable hydrocarbon reserves, offshore Ireland. A Carboniferous (Namurian-Westphalian) sourced petroleum system, with Triassic reservoir (SSG) and seal (MMG) elements, is prevalent in the inboard basins along the northwestern, northern and eastern seaboards, and a Jurassic (Liassic) sourced petroleum system, with Jurassic and Cretaceous reservoirs and seals, predominates in basins along the southern and western seaboards (Table 6.1, Fig. 6.5). The source rocks for these petroleum systems can be differentiated on a modified van Krevelen diagram (Fig. 6.6). The Carboniferous (Namurian-Westphalian) source rock family is dominated by terrestrially derived, Type III, organic matter (with rare exinite rich coals and oil shales present) and is characterized by low hydrogen indices. In contrast, the Jurassic (Liassic) source rock family is relatively rich in marine kerogens, with mixed Type II and Type III organic matter, and is characterized by higher hydrogen indices. Compositional and isotopic comparison of the gas from the Kinsale Head Field (Cretaceous, Greensand reservoir) with the gas from the Corrib Field (Triassic, Sherwood Sandstone reservoir) confirms the hydrocarbon imprint of these two source rock systems, in the main proven hydrocarbon reserves of the inboard basins (Fig. 6.7).

The hydrocarbon prospectivity of the Lough Indaal, Rathlin, and Cockburn basins is poorly understood due to the absence of exploration drilling in these basins. A combination of hydrocarbon prospectivity and/or the 'wells to area ratio' suggests that limited hydrocarbon resource potential remains in the Peel, Kish Bank, Central Irish Sea, and Fastnet basins. Although some residual exploration potential may

be present in all these basins, future exploration effort in the inboard basins is likely to be focused on those basins with proven petroleum systems, such as the North Celtic Sea and Slyne basins and adjacent analogous (Erris and Donegal) basins.

Chapter 7

Implications for top-seal assessment in exhumed basin settings – some insights from Atlantic Margin and borderland basins.

7.1 Introduction

On a geologic time-scale the evolution of oil and gas accumulations is a dynamic process which is a function of the rates of ingress and egress of petroleum from the hydrocarbon trap. Top-seals are rocks which prevent the vertical migration of hydrocarbons out of traps. Therefore, an effective regional cap-rock constitutes an essential element of all petroleum systems.

During the evolution of a petroliferous basin any lithology can serve as a top-seal for a hydrocarbon accumulation provided that its capillary entry pressure exceeds the upwards buoyancy pressure exerted by the hydrocarbon column in the underlying accumulation. In practice, however, the vast majority of effective seal rocks are evaporites, fine-grained clastics and organic-rich mudrocks (Downey, 1994). Worldwide empirical observation of the 25 largest oil and gas accumulations indicates that they all depend on shale or evaporite seals (Fig. 7.1) (Grunau, 1987).

The basic physical principles governing the effectiveness of petroleum caprocks are well established (Hubbert, 1953; Berg, 1975; Schowalter, 1979 and Watts, 1987). Lithology, uniformity of stratigraphy and thickness are factors which influence seal capacity (Downey, 1984). However the fundamental rock properties which control seal performance are the capilliary entry pressure of the seal (dominantly controlled by pore throat diameter) and the ductility of the seal rock which is a function of pressure, temperature and lithology. Although top-seal integrity is recognised as a major exploration risk factor in exhumed basins few systematic studies of top-seal performance in these settings have been published to date (Gabrielsen & Kløvjan, 1997; Seedhouse & Racey, 1997; Spain & Conrad, 1997; Cowan *et al.*, 1999).

In all petroliferous basins the adequacy of the hydrocarbon charge together with the timing and rate of fill, spill and vertical or lateral leakage are key determinants of the present-day in-place oil and gas volumes preserved in hydrocarbon traps. However, in exhumed basins, the interplay between top-seal performance and hydrocarbon fill, spill and leakage is more critical as the 'switching off' of hydrocarbon generation during regional uplift may result in a lower probability of trap replenishment post-exhumation (Doré & Jensen 1996). Physical processes which may impact caprocks during exhumation include erosion, tectonic deformation, shear failure, hydrofracturing due to disequilibrium pore pressure conditions and a changing hydrodynamic regime. Furthermore, there is an increased risk of net hydrocarbon losses due to diffusion where gas accumulations are dependent upon porous and permeable shale seals.

The aim of this chapter is to offer some insights with respect to the physical properties and processes which impact top-seal performance in exhumed basin settings. Empirical evidence from exhumed basins of the Atlantic Margin and borderland basins is then discussed in the context of these observations.

7.2 Top-seal leakage mechanisms – a summary

There are four generic mechanisms by which top-seals leak - tectonic breaching, capillary leakage, hydraulic leakage, molecular transport (diffusion). Figure 7.2 is a summary of the physical principles governing these mechanisms, which have been articulated by numerous authors (Schowalter 1979; Gretener 1981; Kroos *et al.* 1992; Davis & Reynolds 1996 and others). These four generic leakage mechanisms are here reviewed in the context of exhumed basin settings of the Atlantic margin.

7.2.1 Tectonic breaching

Where deformation of a cap-rock occurs post-emplacement of hydrocarbons there is an increased risk of tectonic breaching and cap-rock leakage. Top-seal failure via tectonic breaching is the most readily recognised form of seal failure at the scale of seismically defined hydrocarbon traps. In addition, tectonic

breaching may be facilitated by sub-seismic resolution faulting where the top-seal consists of mudrock layers interbedded with permeable siltstones and sandstones.

The style and magnitude of tectonic deformation in any sedimentary basin is influenced by a number of factors, including plate tectonic setting, pre-existing structural grain and the presence or absence of detachment layers. During basin inversion, compressional, transpressional or reactivated extensional deformation may result in leakage through cross-fault juxtaposition of reservoirs from different stratigraphic levels (Fig. 7.2a(i)) or through the development of a connected network of juxtaposed leaky beds within the cap-rock interval (Fig. 7.2a (ii)). In addition, radial extension fractures will develop above the neutral surface of inversion folds and may result in leakage into the overlying sediments (Fig. 7.2a (iii)). Hall *et al.* (1997) have shown from case studies in the deep Central Graben of the North Sea that reservoir objectives lying above or close to the neutral surface of an inversion fold have a higher probability of being breached than reservoirs lying below.

Tectonic breaching is an important leakage mechanism in the exhumed basin settings of the Atlantic margin where syn-exhumation extensional fault reactivations are probable in addition to the overprint of compressional deformation resulting from the far-field signature of Alpine orogenesis and ridge push phenomena (Murdoch *et al.* 1995; Doré *et al.* 1999).

7.2.2 Capillary leakage

The driving force for petroleum movement in the sub-surface is buoyancy influenced by overpressure and hydrodynamics. The force opposing the movement of petroleum is the capillary resistance of porous rocks (Fig. 7.2b). Standard equations have been developed to describe these opposing forces P_{buoy} and P_{cap} at the interface of a hydrocarbon reservoir and cap-rock (Hubbert 1953; Berg 1975; Schowalter 1979; Watts 1987; Clayton & Hay 1994).

Theoretically, for capillary leakage to occur the upwards buoyancy pressure of a hydrocarbon column plus any excess overpressure or hydraulic head must exceed the

P_{cap} of the top-seal. Clayton & Hay (1994) have modelled the capillary seal capacity of a mudstone seal in a continually subsiding basin, based on appropriate figures for interfacial tension, contact angle, largest interconnected pore throat radii and subsurface density difference of gas and water (Fig. 7.3). The computed seal capacity curve for methane indicates that the modelled mudstone would retain a gas column of 500-1000 m depending upon depth.

In an exhumed basin the predicted capillary retention capacity of an average mudstone is likely to be higher at any present day depth as the higher compaction state of the exhumed mudstone will result in smaller interconnected pore throats. With respect to the exhumed basins of the Atlantic margin the magnitude of all known gas columns, discovered to date, is less than 500 m, considerably less than the capillary seal retention capacity modelled for an average mudstone (Fig. 7.3).

7.2.3 Hydraulic leakage

Where the capillary entry pressures to a cap-rock (evaporite or super tight shale) are so high that capillary failure is implausible, hydraulic leakage may occur through brittle top-seals due to the generation of new tension fractures (hydrofractures), shear fractures or the dilation of pre-existing fault planes (Fig. 7.2c). Hydraulic fracturing can occur, independent of tectonic breaching and results from changes in effective stress conditions in the cap-rock. These changes may be induced by the development of disequilibrium pore pressure conditions or by changes in the tectonic load (Fig. 7.4). For example, a reduction in the minimum compressive stress (σ_3) induced by *extension* during regional uplift, may *per se* result in the formation of dilatant shear fractures of certain orientation within the cap-rock (Fig. 7.4a). Shear fractures will also be formed when the prevailing stress field results in conditions of high differential stress in the cap-rock (large σ_1-σ_3). Under this scenario the gradual elevation of pore fluid pressures prior to exhumation, or the removal of overburden without the re-equlibration of elevated pore fluid pressures, will result in Coulomb failure along planes in the rock which make appropriate angles with σ_1 (Fig. 7.4b). Pre-existing fractures, joints or faults (in fact any planes of reduced cohesion) have important implications for the mechanical behaviour of cap-rocks during exhumation.

When fractures are present their physical characteristics and their orientation must be known in order to evaluate their structural significance (Gretener, 1981).

Hydrofractures occur under conditions of low differential stress when pore fluid pressure at the cap-rock-reservoir interface reduces the minimum effective horizontal stress below zero to the tensile strength of the rock (Fig. 7.2c). In extensional basins, where the minimum compressive stress (σ_3) is significantly less than the maximum compressive stress (σ_1), these hydrofractures are invariably vertical to semi-vertical in orientation and form perpendicular to the minimum horizontal stress (σ_3). For hydrofractures to develop in preference to shear fractures the conditions $P_f = \sigma_3 + T$ and $\sigma_1 - \sigma_3 < 4T$ must be satisfied (P_f is the pore fluid pressure, σ_1 is the maximum compressive stress, σ_3 is the minimum compressive stress and T is the tensile strength of the cap-rock) (Hubbert & Rubey 1959; Secor 1965; Sibson 1995). These conditions can occur in highly overpressured systems undergoing continual subsidence or during exhumation when rapid denudation, without re-equilibration of overpressures, results in tensile failure. In either case, when this state prevails, pervasive tension fractures may develop in the cap-rock which will result in a catastrophic loss of any pre-existing hydrocarbon fill.

Hubbert & Rubey (1959) demonstrated that when the pore fluid pressure in a sedimentary basin approaches the lithostatic pressure the fluid pressure is released by rock failure. Palciauskas & Domenico (1980) supported these observations by showing theoretically that microfractures can develop in overpressured sedimentary beds while undergoing burial. Capuano (1993) provided direct petrographic evidence of the occurence of microfractures *in situ* at depths of 3-5 kms, in geopressured Oligocene shales of the Gulf Coast Basin. Furthermore, the computed fracture permeabilities (order of 10^{-13} m^2) in these shales combined with paragenetic relationships indicate that fluid flow occurred preferentially through these microfractures rather than through the matrix of these shales. The development of these hydrofractures during burial is facilitated by a mechanism of episodic tensile failure in a low differential stress environment (Secor 1965). Under these conditions, the raising of the pore fluid pressure

will result in the cracking of the rock in tension and the release of the fluid pressure, followed again by a rising of fluid pressure and a repetition of this cycle (Fig. 7.4b).

In contrast with this pressure cyclicity which is manifest in a continually subsiding basin, depressurization of a reservoir during exhumation could potentially occur as a 'singular' catastrophic event. This may arise because some of the processes which produce overpressure (Osborne & Swarbrick 1997), such as disequilibrium compaction, dehydration reactions and kerogen transformation will have been arrested once exhumation begins. Once catastrophic failure via fracturing has occurred during exhumation, the cap-rock unit can only regain 'seal status' when the high permeability open fractures are healed or annealed. Fracture closure, during or post-exhumation, can occur through a range of mechanisms, including cementation and increased horizontal compressive stress. Cementation in the fracture may be caused by the cooling of upwards flowing fluids with the resulting redistribution of silica and other mineral phases or, in the absence of fluid flow, by the chemical diffusion of solids into the fracture driven by local thermodynamic potentials (Pedersen & Bjørlykke 1994).

7.2.4 Molecular Transport (Diffusion)

Diffusion is a continual and ubiquitous process in sedimentary basins and its role in hydrocarbon migration has been analysed by several workers (Fig. 7.2d) (Montel *et al.* 1993; Krooss *et al.* 1992; Schlomer & Krooss 1997). The diffusive transport mechanism primarily pertains to the dismigration of natural gas accumulations in certain circumstances and has little relevance for oil dismigration due to the increased size of oil molecules relative to shale pore throat dimensions. Although the modelling studies of Kettel (1997) indicate that methane diffusion constants for rock salt are non-zero over geological time-scales, diffusion losses from gas accumulations capped by thick evaporitic seals are considered minimal. Empirical observation of long lived gas accumulations in Upper Proterozoic reservoirs sealed beneath Lower Cambrian salt in the extensively exhumed Lena-Tunguska province of the former Soviet Union supports this conclusion (Kontorovitch *et al.* 1990)

In contrast, Leythaeuser *et al.* (1982) have demonstrated that gas may diffuse through water saturated cap-rocks over geological time-scales. This diffusion model suggests that the evolution and preservation of natural gas accumulations is dependent upon the ratio of gas supply to the trap and gas losses through the cap rock. For example, a case study of the Harlingen gas field, offshore Netherlands, indicated that half the 68 bcf contained in the Lower Cretaceous reservoir would be lost by diffusion through the shales and marls of the Hauterivian caprock (390 m thick) in 4.5 million years (Leythaeuser *et al.* 1982). Subsequent re-evaluation of these estimates by Krooss *et al.* (1992), suggests that the rate of diffusive hydrocarbon losses through the cap-rock at Harlingen are an order of magnitude lower (approximately 70 million years to dissipate half the in place gas via diffusion through the cap-rock).

In a petroliferous basin that is characterised by continual subsidence, hydrocarbon escape by diffusion and other processes can be wholly or partly offset by an active generation and migration system. However, in an exhumed basin setting, where the hydrocarbon generation and migration system is 'switched off' during regional uplift, diffusive losses through water saturated shaley cap-rocks will increase with time since uplift and may be significant.

7.3 Cap-rocks – some physical properties

The examination of cap-rocks to hydrocarbon accumulations is primarily concerned with the properties of the weakest point of the reservoir-top-seal interface. As highlighted by Downey (1994) measured properties of a random core sample may not be relevant to the physical properties of the cap-rock at the leak point. Furthermore, geohistory is an important control on the sealing properties of top-seals (Knipe *et al.* 2000) and the location of the potential leak point throughout the evolution of the hydrocarbon trap. Some of the petrophysical and mechanical properties which most influence top-seal performance are summarised below.

7.3.1 Lithology, porosity and permeability

Evaporites and mudrocks are commonly found as effective top-seals to hydrocarbon accumulations because they typically possess very low porosity and permeability, high capillary entry pressures are relatively ductile and are often laterally continuous at the basin scale. However, other lithologies, such as siltstones and sandstones, have been identified as having capillary retention capacity and can form the top-seal to a hydrocarbon column (Spain & Conrad, 1997).

In most sedimentary basins, mudstone porosities range from 5-80%, depending upon compaction state (Sclater & Christie 1980). Mudstone permeabilities vary by ten orders of magnitude (10^{-4} to 10^{-15} mD) and by three orders of magnitude at a single porosity, primarily due to grain size variations (Dewhurst *et al.* 1999). However, the largest interconnected pore throat diameter is the critical factor with respect to the capillary entry pressure of the mudstone. In tight mudrocks (permeabilitiy 10^{-9} D range) the risk of capillary failure and Darcy flow through the matrix is low, as the capillary entry pressure commonly exceeds the buoyancy force of any potential hydrocarbon column (Fig. 7.3). In this case, the top-seal retention capacity of the mudrock is a function of the ductility of the mudstone and the potential for the formation of dilatant fractures under tectonic deformation or changing pore fluid pressure conditions.

Halite forms an excellent top-seal as a result of two characteristics - it has a practically infinite capillary entry pressure and it flows plastically under deformation. When it forms a continuous layer over the potential hydrocarbon trap and is immediately juxtaposed above the hydrocarbon-bearing reservoir, the seal risk for that trap is considerably reduced, even where the trap has experienced post-emplacement tectonic deformation and exhumation.

At both the hydrocarbon trap and basin scale, cap-rock units can manifest vertical and lateral heterogeneities. Internal lithostratigraphy of the unit can vary, with mud rocks often interbedded with large amounts of leaky strata such as siltstones or sandstones. These lithologies will be more prone to leakage than the mudrocks and can result in multimodal pore throat diameter distributions within the cap-rock interval and

the development of 'waste zones', if the siltstones are located immediately above the reservoir unit. In a study of hydrocarbon seals in the exhumed East Irish Sea Basin, Seedhouse & Racey (1997) utilised mercury injection porosimetry to identify pore throat distributions in the Mercia Mudstone Group (MMG) seal and to describe some of the heterogeneities observed in this cap-rock interval. These authors identified the presence of halite immediately above the reservoir as a key factor in the retention of hydrocarbon columns in the exhumed Triassic Sherwood Sandstone Group reservoir. In addition, their study found that Sherwood Sandstone accumulations with significant hydrocarbon columns, but which are directly capped by mudrocks, invariably manifested hydrocarbon shows within the cap-rock interval up to the level of the first halite bed encountered above the reservoir. This suggested that the buoyancy forces exerted by the individual hydrocarbon columns were sufficient to overcome the capilliary entry pressure of the heterogeneous MMG at these locations, but not the capillary resistance of the halite units.

7.3.2 Strength, ductility and brittleness

The mechanical response of rocks to an applied stress varies under different conditions so a valid comparison of the strength and ductility of rocks can only be made if the conditions of deformation are also known. Ductility is a rock property which pertains to the amount of strain that a material can withstand prior to brittle failure if it undergoes brittle failure at all. Ductile rocks respond to an applied stress by an initial, though limited, elastic deformation, followed by sustained plastic deformation before failure. Brittle rocks respond to an applied stress by first shortening elastically and then failing by the formation of discrete fractures and faults. A rock is considered ductile when it can accommodate strains of 8-10% without fracturing and brittle when strain is less than 3% before fracturing (Fig. 5). Rock ductility is a function of lithology, confining pressure, pore fluid pressure, temperature, differential stress and strain rate (Davis & Reynolds 1996).

Because the matrix permeability of buried and compacted mudrocks is extremely low, it is the fracture permeability that primarily controls seal capacity of these rocks. More relevant definitions are offered by Ingram & Urai (1999) who describe a ductile mudrock as one that can deform without dilatancy and the creation of

fracture permeability, and a brittle mudrock as one that dilates and develops fracture permeability.

Experimental studies have shown that, for most lithologies, both rock strength and ductility increase with rising confining pressure (Handin *et al.* 1963; Gretener 1981). In the context of this discussion confining pressure refers to the lithostatic pressure exerted by the overlying rock column which is simply related to the thickness and mean density of the overlying material (Park 1983). This suggests that sedimentary rocks, including mudstones, increase in ductility during burial because confining pressure increases with depth. However, this inference results from treating the compaction of mudrocks as only a mechanical process and ignores the effects of chemical compaction in the deeper part of sedimentary basins (>2-3 km, 70-100°C) (Bjørlykke 1999).

Bulk density (ρ_b) is one measured parameter which can be used to indicate the compaction state of mudrocks. However, mudrock density is also a function of matrix mineralogy, porosity, applied load, temperature and pore fluid pressure. Experimental results (using a population of Neogene mudstones from Japan) in Hoshino *et al.* (1972) have indicated that, for a constant confining pressure, ductility decreases as density increases, thereby supporting the view that compaction and diagenetic changes alter the picture of ductility at increased burial depths in the sedimentary column (Fig. 7.5). Shales with densities less than ~2.2 g/cc exhibit ductile behaviour; shales with densities ~2.2-2.5 g/cc are transitional and probably exhibit a wide range of mechanical behaviour; shales with densities in excess of 2.5 g/cc manifest brittle behaviour by fracturing at strains of less than 3%. If mudrock density can be used as a proxy for ductility then the onset of shale embrittlement can be estimated when the density/depth or porosity/depth behaviour of the claystone is known (Fig. 7.6). This collection of Neogene mudrocks presented in Magara (1968) indicates the potential role of overpressure in defining the shale embrittlement threshold for any given basin. Geothermal gradient and palaeotemperature history also exert a critical control on diagenesis and hence the rheological evolution of mudrocks.

With respect to cap-rock integrity during basin inversion the key factors are the timing and magnitude of the deformation and the mechanical behaviour (brittle vs ductile) of the cap-rock at the time of deformation. Brittle shales are more likely to rupture and leak than ductile shales and evaporites which may exhibit plastic flow under the applied deformation. However, even evaporitic rocks which serve as extremely efficient ductile seals, when overburden burial exceeds 1000 m, can manifest brittle behaviour at shallow depths (Downey, 1994). Bolton *et al.* (1998) have shown experimentally that although elevated pore-fluid pressures reduce effective stress and enhance shear deformation, it is the consolidation state at the onset of shear that is the crucial factor with respect to the deformation style and resulting permeability. Timing of overpressure is particularly relevant in this regard as it can change the consolidation state of a mudstone caprock with respect to effective stress. Ingram & Urai (1999) have indicated that claystone cap-rocks that have undergone substantial uplift are prone to the formation of dilatant fractures as they are likely to be over-consolidated and have anomalous strength. However, in the context of exhumed basins, the mechanical behaviour of a mudstone cap-rock will be dependent upon whether or not embrittlement has been achieved prior to exhumation.

7.4 **Physical processes which occur during exhumation**

A number of physical processes may impact cap-rocks during exhumation, including erosion, tectonic deformation, shear failure, hydrofracturing due to disequilibrium pore pressure conditions and a changing hydrodynamic regime. Each of these processes must be examined in the context of the evolutionary changes that may be occurring in the cap-rock, in the petroleum system and at the basin scale. For example both the shear strength and tensile strength of mudrocks increase through burial and compaction (Fig. 7.7), hydrocarbons may migrate into the trap thereby locally increasing overpressure in the trap, and hydraulic head may be developed due to the uplift of the basin margins.

Fluids in the subsurface may manifest static behaviour (hydrostatic condition) or dynamic behaviour (hydrodynamic condition). Hubbert (1953) demonstrated that under hydrodynamic conditions accumulations of oil or gas will

invariably exhibit inclined oil- or gas-water interfaces and in such cases the computation of hydrocarbon columns, based on the assumption of hydrostatic conditions, will be spurious. Water flow in sedimentary basins is driven by geographic variations in water potential which can change considerably in nature and distribution during the evolution of a basin (Wells, 1988). The early compaction history of an extensional basin, characterised by continual subsidence, will result in up-dip water flow to the basin margins. The driving force of this system is the relatively high water potential in the basin centre generated by water released through the processes of mechanical compaction and clay mineral transformation. This water-potential system changes if significant topographic relief forms adjacent to the basin, due to isostatic effects or some other mechanism. The earlier hydraulic system of the basin is then reversed. Elevated water tables along the basin margin creates a hydraulic head which drives water flow inward towards the basin centre, provided upward discharge is possible there.

A significant consequence of basin inversion is a change in hydrodynamic conditions within the basin. The pattern of exhumation convolved with the pre-existing basin morphology may result in the cropping out of key aquifers, a redistribution of recharge and discharge areas and a change in the direction of gravity driven fluid flow within the basin. The existence of regional, topographically-driven groundwater flow-systems has been documented for several exhumed sedimentary basins (Wells 1988; Deming *et al.,* 1992; Deming, 1994b; Bredehoeft *et al.,* 1994; Cramer *et al.,* 1999).

Hydrodynamic effects on seal capacity may, for all practical purposes, be ignored except in those basins which manifest clear evidence of hydraulic gradients. In these basins hydrodynamic flow may modify seal retention capacity by either increasing or decreasing the driving pressure against the seal (Allen & Allen, 1990). When the hydrodynamic force has an upward vector, it adds to the buoyancy force thus reducing the hydrocarbon column heights the seal can support. In the case of a downward vector it reduces the buoyancy force on the seal and permits the retention of an increased hydrocarbon column.

7.5 Empirical observations and discussion– exhumed Atlantic Margin and borderland basins.

Many Atlantic margin and borderland basins are characterised by exhumation during the Cenozoic (Fig. 7.8) Although prior exhumation events may have occurred during the evolution of these basins, in terms of top-seal assessment, Cenozoic exhumation is most critical as it generally occurs in these basins after the initial migration of hydrocarbons into traps.

Shale and evaporite caprocks form the main regional seals to hydrocarbon accumulations in exhumed basins of the Atlantic Margin and borderlands (Fig.7.9). Shale cap-rocks of Jurassic-Cretaceous age are prevalent in the Celtic Sea, Inner Moray Firth, West of Shetlands and Barents Sea basins and mixed evaporite and shale seals of Triassic age are encountered in three basins (Slyne Trough, East Irish Sea and Southern North Sea). The prodigious Zechstein evaporite seal is caprock to an estimated EUR of >150 TCF in the southern Permian Basin, including the giant Groningen accumulation (97 TCF) and approximately 35 TCF contained in 35 accumulations in the UK sector of the Southern North Sea Basin (Glennie 1997) (Fig. 7.9).

There are a number of hydrocarbon trapping and top-seal configurations observed in these exhumed basins. In the Celtic Sea Basin, a maximum gas column of 91 m in the Kinsale Head Gas Field is retained by 46 m of Gault claystone in a compressional anticlinal flexure (Fig. 7.10). This basin centered accumulation experienced approximately 900 m of exhumation during the early Cenozoic and has been overprinted by a compressional deformation which is poorly constrained but probably post-Palaeocene in age (Murdoch *et al.* 1995). Local evidence suggests that the maximum burial depth of the Gault claystone was in the range of 1700-1800 m which may not have been sufficient to achieve shale embrittlement prior to the applied deformation associated with exhumation and compressional inversion. Under this scenario, it is postulated that fracture development was inhibited as the Gault claystone responded by plastic flow to Cenozoic deformation. This hypothesis is consistent with the experimental results of Bolton *et al.* (1998) which suggests that underconsolidated clayey sediments, undergoing shear, deform by bulk volume loss which reduces

permeability, and result in weakly developed deformation fabrics which have little impact on the hydrological properties of the claystone.

All four generic leakage mechanisms (tectonic breaching, capillary leakage, hydraulic leakage and diffusion) operate in both continually subsiding basins and exhumed basin settings. However, the critical aspect of trap leakage in exhumed basin settings is a lower probability of trap replenishment due to the 'switching off' of hydrocarbon generation during regional uplift. In such cases, top-seal failure (induced by tectonic breaching or hydraulic leakage) *during exhumation* may result in the catastrophic loss of a pre-existing hydrocarbon fill whereas *post-exhumation* these traps can only be replenished from a curtailed hydrocarbon budget, which consists primarily of re-migrating oil and gas. This is consistent with the observation that a number of hydrocarbon accumulations in exhumed basin settings along the Atlantic margin are characterised by underfilled traps (Fig. 7.11). Empirical observation also indicates that, hydrocarbon accumulations in exhumed basins are characterised by hydrostatically pressured or modestly overpressured reservoirs, whereas, significantly overpressured reservoirs are common in basins which have experienced relatively continual subsidence (Fig. 7.12). This suggests a close causal relationship between regional uplift, hydrocarbon re-migration and dissipation of overpressures.

Exhumation may also have positive implications for the capillary and hydraulic retention capacity of mudrock seals. Increased mechanical compaction due to burial, results in reduced interconnected pore throat sizes and increasing shear strength and tensile strength for a claystone rock. For example, when a claystone is exhumed it retains the tensile strength of its maximum burial depth and consequently, a higher pore fluid pressure will be required to induce hydrofracturing than for a claystone in a continually subsiding basin at the same depth. Leak-off tests (LOTs) and Formation Integrity tests (FITs) from a sub-set of the Atlantic Margin basins support these observations (Fig. 7.13). These data indicate that, for any given burial depth, the minimum horizontal stress or fracture pressure (defined by the lower envelope of LOT pressures) is higher in exhumed basins than in those basins characterised by continual subsidence. Critically, there are a number of FITs performed on exhumed claystones of Carboniferous, Triassic and Jurassic age which indicate that these seal rocks have very high tensile strengths, appropriate to their maximum burial depth, prior to exhumation. This suggests that *post-exhumation* top-seal integrity is relatively high in many of the

Atlantic Margin and borderland basins under low differential stresses. However, the anomalously high shear strength of exhumed mudstones may result in the development of dilatant shear fractures (under low confining pressures) if shale embrittlement has been achieved prior to exhumation. The absence of seismic chimneys across major gas accumulations in many of these basins (e.g. Celtic Sea, EISB, SNS) suggests that dynamic leakage through the top-seal is not occurring present day and that pore fluid pressures are below the top-seal capillary and hydraulic leakage thresholds for these accumulations.

7.6 Conclusions

A number of effective regional cap-rocks are recognised in the petroleum systems of exhumed Atlantic margin basins. However, the observation of underfilled traps, close to hydrostatically pressured reservoirs and breached traps with residual oil and gas shows, suggests that top-seal behaviour exercises a critical control on hydrocarbon distribution and re-distribution in exhumed basin settings. The following are the principal conclusions of this review:

1. Lithofacies is a major control on top-seal efficiency in exhumed basins settings. The juxtaposition of a halite directly above the hydrocarbon bearing reservoir offers the most favourable condition for the retention of hydrocarbons in exhumed traps. However, the empirical evidence from the Atlantic margin suggests that mudrocks can form efficient top-seals in exhumed basins under certain conditions.
2. The behaviour of any cap-rock lithology during exhumation is dependent upon the physical and mechanical characteristics of the cap-rock at the time of exhumation and the timing and conditions of the associated deformation relative to the timing of hydrocarbon emplacement.
3. Mudrocks may form effective cap-rocks in exhumed basins when the deformation associated with exhumation occurs prior to embrittlement and the cap-rock exhibits ductile behaviour. Where exhumation occurs post embrittlement the shale cap-rock will facilitate hydrocarbon leakage through the development of extensive fracture networks.

4. *Syn-exhumation* top-seal efficiency (fluid retention capacity) is a major exploration risk in exhumed basin settings, though *post-exhumation* top-seal integrity in these basins may be relatively high. This suggests that a major exploration risk factor in exhumed basin settings pertains to the limited hydrocarbon budget available post-regional uplift and the efficiency of the re-migration process.

Chapter 8

Exhumation of the Corrib Gas Field, Slyne Basin, offshore Ireland – an integrated approach to the assessment of exhumation

8.1 Introduction

Exhumation, the removal of overburden resulting from the vertical displacement of rocks from maximum burial depth, is a global process that occurs at a range of scales and in a variety of tectonic settings (Ring *et al.* 1999; Corcoran & Doré 2005). Exhumation events can have a profound effect on the evolution of sedimentary basins, the evolution of hydrocarbon systems contained in petroliferous basins, the distribution of hydrocarbons within these basins and exploration success rates (MacGregor 1995b; Doré & Jensen 1996). Consequently, the quantification of the magnitude and timing of exhumation events has direct economic importance, as it is an important first step in determining the impact of exhumation on the distribution of petroleum resources in exhumed basin settings. A systematic review of the implications of exhumation for the assessment and risking of prospects has been provided by Doré *et al.* (2002).

From the perspective of hydrocarbon exploration quantification of *net exhumation* – the difference between present-day burial depth of a reference unit (source, reservoir or seal) and its maximum burial depth prior to exhumation - is of critical importance. This arises because, regardless of the number of unconformities contained in a stratigraphic succession, maximum burial depth (when coincident with maximum compaction and temperature exposure) is a key first-order control on the maturation, compaction and diagenetic state of source, reservoir and seal rocks and consequently, has important implications for the hydrocarbon prospectivity of a basin. *Gross exhumation* (or total exhumation) is a measure of the magnitude of erosion, which must have occurred at a particular unconformity prior to post-exhumation re-burial.

Numerous techniques are available to assess the magnitude and timing of exhumation of sedimentary successions in offshore basins, where measurement of vertical rock displacements is generally made with respect to four frames of reference – tectonic (e.g. subsidence curves), thermal (e.g. vitrinite reflectance, apatite fission track

analysis), compactional (e.g. core porosity, sonic velocity) or stratigraphic (e.g. section correlation, seismic section subcrop analysis) (see Chapter 2 – summary Fig. 8. 1) (Corcoran & Doré, 2005). The aim of this chapter is to present the results of an integrated study which has utilised palaeo-thermal indicators, sonic transit time data, seismic interpretation and regional stratigraphic evidence to assess the magnitude and timing of exhumation of the Corrib Gas Field.

8.2 **Corrib Field**

The Corrib Field is located approximately 70 kms west of Ireland, in 350m of water (Fig. 8.2). It was discovered in 1996 with the drilling of the 18/20-1 exploration well, which was plugged and abandoned as a gas discovery. Subsequently, 5 appraisal wells have been drilled, tested (with maximum flow rates up to 64 mmscf/d) and suspended for re-entry as producers. In early 2001, the field was sanctioned for development via sub-sea tieback to shore, with the remaining impediment to development being planning permission for an onshore processing plant.

Geologically, the field is located at the northern end of the Slyne Basin (Fig. 8.2), where the near-seabed geology includes a thin (<300m), heterogeneous, Early Tertiary (K-Ar dates of 54-43 Ma) lava field overlying an 80-300m thick, exceptionally hard, Late Cretaceous chalk layer. Together these high-velocity layers present a significant impediment to the seismic imaging of the pre-chalk stratigraphy and structure of the area – a challenge that has been primarily addressed through the application of low frequency 3D acquisition techniques and pre-stack migration processes (Dancer & Pillar 2001; Silva & Corcoran 2002).

The petroleum system of the Corrib Field consists of a Triassic fluvial sandstone reservoir (Sherwood Sandstone Group) charged by gas generated in thermogenically mature Namurian-Westphalian coals and claystones and sealed by late Triassic evaporites (Mercia Mudstone Group, MMG). The trap is comprised of a modestly faulted NE-SW trending anticlinal structure, which retains a gas column of *c.* 310m (Fig. 8.3a). The most likely seismic interpretation suggests that the structure is underfilled, with a free water level (FWL) at -3600m and an anticlinal spill point to the south, at *c.* –3850m TVDSS. Although controls on the FWL are poorly understood, there is a potential 'fault intersection' leak-point coincident with the FWL in the southwest of the field, where the Sherwood Sandstone reservoir is possibly juxtaposed

against sandstones that stratigraphically overlie the MMG halites and mudstones. This underfilled characteristic of the trap is common to a number of Triassic gas fields in exhumed basin settings of NW Europe, although the causal effect of the underfilling may vary among these fields (Corcoran & Doré 2002).

An outline model for the structural evolution of the Corrib Field has been presented by Dancer *et al.* (2005). The present-day morphology and evolution of the trap has been influenced by a number of elements (Fig. 8.4): an underlying Carboniferous horst block; 'double-decker' halokinesis, above and below the Sherwood Sandstone reservoir, which is effectively sandwiched between two mobile halite layers; a crestal 'collapse' graben which detaches on the upper, MMG, halite layer; and the angular discordance of the Jurassic section to the overlying, truncated, Cretaceous and Tertiary succession.

Although all of the wells drilled on the field have reached TD in the Triassic reservoir, the presence of a Zechstein halite dome beneath the Sherwood reservoir is postulated based upon seismic evidence and the presence of 200m of Zechstein halite in well 27/5-1 (Fig. 8.2). All 6 wells on the field have encountered a basal halite layer, within the MMG, immediately above the Sherwood reservoir. The original depositional thickness of this halite unit is interpreted to have been in the region of 50-100 metres, yet in excess of 770 metres of halite was encountered in well 18/20-2z (Fig. 8.3b). Dramatic variation in the isopach of this unit indicates that a narrow, elongate, NE-SW trending diapir is developed along the crest of the Sherwood anticline and is coincident with the footwall face of the listric detachment structure in the Jurassic carapace (Figs 8.3b & 8.4). Examination of 3D seismic time slices (Fig. 8.5) supports the interpretation of the MMG halite layer as a décollement between the structure in the Jurassic carapace and the pre MMG section.

Structural modelling indicates that the Jurassic evolution is complex, with an initial (early-middle Jurassic) westerly dipping listric fault supplanted by the present-day, easterly dipping, fault during the middle-late Jurassic (Fig. 8.6). This flip in polarity may have been caused by MMG salt movement or vice versa may have initially triggered halokinesis in the MMG halite layer. Subsequently, during the Late Jurassic, extensional roll-over anticlines were developed in the hanging wall of the main listric fault and the basin-bounding fault to the east of the field (Fig. 8.4). Cessation of Jurassic rifting was followed by a major phase of exhumation, during the Early Cretaceous, which has resulted in the pronounced post-rift unconformity observed on seismic at the

base of the Cretaceous succession (Fig. 8.4). The severely truncated post-rift stratigraphic record indicates that the Cretaceous and Tertiary subsidence of the area was punctuated by a number of uplift and erosion episodes.

In the Slyne Basin, the general depositional model for the Sherwood Sandstone indicates that it was deposited during the early-mid Triassic as a high energy, low sinuousity, fluvial system on a wide braid plain. In the area of the Corrib Field, the reservoir is dominated by channel facies that offers good lateral and vertical connectivity, although in detail, control on reservoir quality is exercised by the primary depositional fabric (grain size), the quantity of clay and the distribution of dolomite, silicate and anhydrite cements (Schmid *et al.* 2004). Conventional core analysis indicates that the reservoir is a good quality gas reservoir with measured core porosities ranging up to 18% [average 8.5%] and core permeabilities up to 736 mD [average 15.2mD] (Fig. 8.7). However, it is the observation that the average porosity of this reservoir is anomalously low, for its present-day burial depth, that has important implications for the remaining Triassic gas prospects in the Slyne Basin and prompted an assessment of the magnitude and timing of exhumation at Corrib.

A comparison of the measured Triassic core porosities for wells (Corrib wells, 27/5-1 and 26/22-1 – for location see Fig. 8.2) from the Slyne area with the mechanical compaction curve of Sclater & Christie (1980) for shaley sandstones, and the behaviour of some Tertiary shaley sandstone reservoirs with burial in the North Sea Basin, offers *prima facie* evidence that pervasive exhumation has occurred in this region. In spite of the significant differences, in terms of mineralogy, texture and diagenetic cements, between these Triassic and Tertiary reservoirs and the difficulty in reducing porosity to "average" values due to intra-reservoir variations in sorting and chemical compaction, the "average" porosity for these wells yields a first-order estimate of the magnitude of exhumation at each location. For example, the average core porosity, for the Sherwood reservoir at Corrib, is displaced from the theoretical curve of Sclater & Christie (1980) by *c.* 1600m, suggesting that the Sherwood reservoir could have been displaced above maximum burial depth by up to this amount (Fig. 8.7).

8.3 Exhumation estimates from palaeo-thermal analysis

Vitrinite reflectance (VR) data is available from a number of contractor studies for three of the Corrib wells (18/20-1, 18/20-2/2z, 18/25-1). This VR data is of variable quality and is primarily derived from acid-digested concentrates of cuttings samples (together with a limited number of picked coals, mounted as polished whole rock mounts, from 18/20-2 and 18/25-1) recovered from the Jurassic successions penetrated at these 3 locations. VR analyses of acid-digested concentrates of 38 sidewall core (SWC) samples were available for well 18/20-1. Analyses of these SWCs were performed by a different laboratory to that which performed the majority of the cuttings analyses for 18/20-1.

Only 3 VR determinations were recorded in Cretaceous sediments (i.e. above the major unconformity identified on seismic) with none recorded in the Tertiary. The VR data has been interpreted and high-graded based upon the petrographic comments of the VR analysts, the histogram distributions of R_m% (mean random vitrinite reflectance) and the number of R_m% determinations per sample. The kinetic model of Burnham & Sweeney (1989) has been employed to translate VR into palaeotemperature. For each well these VR derived palaeotemperatures were plotted versus true vertical depth (TVD) sub-seabed, in conjunction with mean homogenization temperatures (T_h) for diagenetic fluid inclusions recorded in the Triassic Sherwood sandstone reservoir, where available (Figs 8.8, 8.9 & 8.10). Maximum palaeotemperatures determined from apatite fission track analysis (AFTA) were available for well 18/20-1 only. A best-fit, least-squares, linear regression line (segmented in the case of 18/20-1) was established for each section, with depth as the independent variable and temperature as the dependent variable. The slope of this line was assumed to represent the average palaeogeothermal gradient (at maximum palaeotemperature) during the Late Jurassic-Early Cretaceous and by extrapolation to the assumed palaeo-surface temperature at that time (15°C) yields an estimate of *net exhumation* for the Jurassic section. *Gross exhumation* was determined by adding the amount of post-exhumation re-burial, post the Base Cretaceous unconformity, to the *net exhumation* amount for each well location. Summary statistics and exhumation estimates derived from these palaeo-thermal data are outlined in Table 8.1. For the 3 wells the average *net* exhumation is 1023m and average *gross* exhumation is 1429m.

The timing of exhumation is difficult to determine from the VR data *per se*, due to the paucity of VR determinations, in all 3 wells, for the Cretaceous and Tertiary sections. However, palaeotemperatures derived from two VR datapoints in the Cretaceous succession of well 18/25-1 suggest a sharp discontinuity in the palaeotemperature profile coincident with the Base Cretaceous unconformity (Fig. 8.10). This observation, in conjunction with biostratigraphic dating, indicates that the main exhumation event occurred post-Portlandian and pre-Late Albian (*circa* 146-100Ma).

The VR data and available AFTA data (confidential data report), for well 18/20-1, has proved difficult to interpret, possibly due to the effects of hydrothermal fluid flow, the presence of an igneous sill, identified on seismic, close to this location and the deviation of the lower part of the wellbore towards the MMG halite diapir (for location see Fig. 8.3b). The divergence between the palaeotemperatures obtained from the SWC derived VR populations and those derived from the cuttings data, above 2400m (TVD Sub-seabed), is troubling. Possible explanations for the presence of this low reflecting vitrinite? population in the SWCs, include VR suppression caused by the presence of hydrogen-rich vitrinites or, more likely, the mis-identification of the vitrinite maceral in these SWCs. The deepest AFTA samples, from the Triassic section, are characterized by annealed fission tracks resulting from present-day temperatures above 110°C. This is consistent with palaeotemperatures derived from fluid inclusion homogenization temperatures (T_h) and the VR data at this depth, but yields no information with respect to the timing of exhumation events. AFTA samples from the Middle Jurassic section, when integrated with the high-graded VR data, produce a "diffuse" palaeotemperature profile. Higher palaeotemperatures derived from AFTA may be interpreted as due to hydrothermal heating within permeable sand-prone units, whereas lower palaeotemperatures have been derived from VR grains contained in the inter-fingered, low permeability, mudrocks. The AFTA data for these four Middle Jurassic samples suggest heating to peak palaeotemperatures in the range of 60-95°C, with subsequent cooling commencing between 100-20 Ma. This interpretation is not inconsistent with the most likely timing of hydrothermal activity in the Corrib area, which probably occurred during the emplacement of the local igneous intrusion and the extensive Early Tertiary volcanics and lava field, which has yielded K-Ar dates of 55.5-40 Ma.

8.4 Exhumation estimates from compaction analysis

Sonic transit time data from five of the six Corrib wells have been used to assess the compaction state of the Jurassic shaley sections in these wells and derive estimates for the magnitude of exhumation. The generic methodology involves the comparison of a sonic transit time *vs* depth curve for the individual well locations with a reference curve which represents the 'normally buried' unexhumed succession in the basin. However, it is not possible to directly define a baseline 'normal compaction' curve from wells in the Slyne basin, as the limited preservation of post-rift sediments indicates that this area has been affected by regional exhumation. As a result, and in contrast to published transit time schemes for other exhumed basins (Heasler & Kharitonova 1996; Ware & Turner 2002), this study utilizes actual measured transit time data from adjacent basins (Rockall and Porcupine basins) to establish a 'normal shale compaction' reference curve for the assessment of exhumation in the Corrib area. This reference curve has been established by selecting 5 deep wells [approx. 9,000-18,000 ft (2750-5500m) below seabed], with extensive shale sections, from the Rockall and Porcupine basins (Fig. 8.11). Although some of these well locations may have experienced a phase of transient uplift during the Early Cretaceous and again in the Early Eocene (Jones *et al.* 2001), the Mesozoic and Cenozoic sections, in all 5 wells, are at their maximum burial depth present-day. The selection of these wells is rationalized by the opportunity they offer to examine the compaction behaviour of Jurassic, Cretaceous and Tertiary shales over a large depth range, which incorporates the maximum burial depth of the Jurassic successions in the Slyne Basin.

All depths were adjusted to sub-seabed depths – the compactional frame of reference. All wells were edited for logging artefacts and filtered to remove the transit time data for 'non-shale' lithologic sections such as chalk, volcanics, halite, carbonates and major sandstone intervals. Extensive overpressured shale sections have not been identified in the Corrib wells. Regional evidence suggests that the Jurassic section in the Slyne Basin is hydrostatically pressured although some mild overpressure may be present in the organically rich Sinemurian to Toarcian shale sections. However, some overpressured shaley sections were identified in the Porcupine wells, most notably the Late Jurassic shales in well 35/19-1. These overpressured shales were removed prior to amalgamation of the 5 wells to establish the 'normal compaction reference curve' (Fig. 8.12a, b).

This study follows the fundamental assumption of Heasler & Kharitonova (1996) and Ware & Turner (2002) that porosity reduction with depth in a heterolithic sedimentary sequence is described by a single, average compaction coefficient (*b* in equations below). In order to determine the best-fit equation that describes the 'normal compaction' trend for Rockall and Porcupine shales (reference curve for exhumation analysis of Corrib wells) the basic exponential function was logarithmically transformed to a linear expression and a least squares regression was then performed to find the value of *b* (exponential decay constant).

$$DT = DT_0 * \exp^{(-bx)} + C \quad \text{logarithmically transforms to}$$

$$\ln(DT-C)-\ln(DT_0) = -bx \quad \text{a linear equation}$$

where DT = sonic interval transit time in μsec/ft

DT_0 = sonic interval transit time at seabed (assumed = 180 μsec/ft)

b = exponential decay constant

x = True Vertical Depth in Feet sub-seabed

C = asymptote of exponential curve (in theory at x = infinity); in practice, a shift constant equivalent to mineral matrix transit time in μsec/ft (transit time at 'shale' zero porosity)

Best-fit curve optimization was achieved by running a number of 'C-Trials' (regressions with different values of C) and using the maximum coefficient of determination, R-Square, to determine the best-fit curve (Fig. 8.12b).

In this study, the equation which describes the selected 'normal compaction trend' reference curve is:

$$Y = \ln(DT-56)-\ln(124) = 0.000155258x \quad \text{(Fig. 8.12b)}$$

This reference curve was taken to represent the form of the non-exhumed compaction curve for the Slyne Basin. Estimates of exhumation were achieved by comparing this curve with the filtered and edited Jurassic transit time data for each of the Corrib wells.

The difference between the depth of the computed 'normal compaction reference trend' and the depth of each measured transit time point in an exhumed well (X_{Corrib}) yields a single estimate of net exhumation:

$$[(\ln(DT\text{-}56)_{Corrib\ Well} - \ln 124)/(-0.000155258)] - X_{Corrib\ Well} = \textit{Net Exhumation Estimate}_{Corrib\ Well}$$

For each well, all the measured transit time points can be similarily evaluated to give a distribution of exhumation estimates which is characterized by standard descriptive statistics (Fig. 8.12c, d; Table 8.2). The mean value yields the *mean net exhumation* value for each well. The standard deviation captures the variability in the exhumation estimates for each well and the 95 % confidence interval indicates that there is 95% confidence that the population mean will occur within the specified range either side of the sample mean. A histogram has been generated for each well, which illustrates the distribution of *net exhumation* estimates for that well (Fig. 8.13).

Because post-exhumation re-burial has the effect of returning formerly exhumed rock towards their maximum burial depth, it is necessary to add to the *net exhumation* estimate the amount of burial that has occurred post-exhumation (in the case of Corrib, post early Cretaceous), in order to yield an estimate of *gross exhumation* (Table 8.2). The Early Bajocian Limestone is the main Jurassic seismic marker in the Slyne/Erris Basin (Dancer *et al.* 1999; Chapman *et al.* 1999) and estimates of its maximum burial depth at each well location is achieved by adding its present-day burial depth to the mean *net exhumation* estimate for that well (Table 8.2). Average 'mean *net exhumation*' for the 5 wells derived from compaction analysis is 1044m (compared with an average of 1023m from palaeo-thermal analysis and the 1600m derived from average core porosity of the Sherwood Sandstone), which supports the interpretation that the Sherwood Sandstone reservoir in the Corrib Field has been displaced, on average, at least 1 km above its maximum burial depth.

In the case of the Corrib wells, little information is yielded, with respect to the timing of exhumation events, from compaction analysis. The post-Jurassic stratigraphy of the Corrib Field is dominated by volcanics, chalk and sandstone,

lithologies that are unsuitable for comparison with the compaction analysis of the Jurassic shale sections. Extensive sonic transit time data, in the shallow Cretaceous and Tertiary sections, is available for one Corrib well only (18/20-2). The limited occurrence of shales and siltstones within the Late Albian-Cenomanian (Cromer Knoll Group) section of this well manifest transit times in the range of 130-125μsec/ft whereas, beneath the early Cretaceous unconformity (in the uppermost 300m of the Kimmeridgian-Portlandian section), these same lithologies have transit times in the range of 130-100μsec/ft. This evidence offers tentative support to the notion of a compaction discontinuity at the early Cretaceous unconformity, which is consistent with the interpretation of a major exhumation event between 146-100 Ma.

8.5 Exhumation estimates – constraints from stratigraphic analysis

Seismic interpretation, together with local and regional stratigraphic evidence offers important constraints with respect to the magnitude and timing of exhumation in the Corrib area. For example, the stratigraphic relationships of the Cretaceous and Tertiary successions, which outcrop onshore in Northern Ireland have long been studied and offer particular insights with respect to the timing of post-Jurassic exhumation in the Slyne Basin (Fig. 8.14). The geological maps and cross-sections of George (1967), Wilson & Manning (1978) and Lyle (1993) clearly identify at least three major unconformities in the onshore Mesozoic and Cenozoic successions – a *c.* 90 Ma gap in the rock record between the Lower Jurassic and Upper Cretaceous rocks (Early Cretaceous Unconformity), a *c.* 5 Ma gap between Early Maastrichtian chalk and Paleocene basalts (Early Tertiary Unconformity) and a *c.* 20 Ma gap between the youngest Palaeogene basalts and Oligocene clays (Middle Tertiary Unconformity). In addition, the absence of Mio-Pliocene deposits in this northeastern part of Ireland (Shelton 1997) indicates that a significant hiatus and/or erosion (Late Tertiary Unconformity) occurred during the Neogene period.

8.5.1 Early Cretaceous Unconformity

Within the Corrib Field area a major unconformity is recognized at the base of the Cretaceous succession, with interbedded claystones and glauconitic

sandstones of Albian age resting unconformably upon Middle to Late Jurassic sediments (Fig. 8.15). The youngest rocks dated beneath this unconformity yield a Portlandian age but Bathonian sediments subcrop the unconformity in one well. The absence of a minimum of 504m of Upper Jurassic sediments from the 18/20-1 footwall block suggests that local differential exhumation has occurred within the field area as a result of syn-exhumation extensional faulting during the late Jurassic-early Cretaceous. Examination of the high-resolution 2D seismic data (Fig. 8.4) indicates a well developed sub-unconformity truncation pattern, beneath the gently dipping Cretaceous successions, to the east and west of the crestal graben area. In addition, the undrilled sequences beneath this Cretaceous unconformity, to the east of the crestal graben, manifest conformable stratigraphic relationships (constant isopach, parallel planar geometries, absence of onlap) with the Kimmeridgian-Portlandian section encountered in Well 18/20-2. Depth conversion using well velocities indicates that this section is approximately 830m thick, which represents an additional section of Late Portlandian(?) sediments, which have been removed from the crestal area during the Early Cretaceous exhumation episode.

Pre-Albian Cretaceous sediments have not been encountered by drilling in the field area and also are absent from the Slyne Basin to the south of Corrib (Fig. 8.16). However to the north, in the Erris Basin, a relatively continuous, conformable, Late Ryazanian-Aptian succession (650m thick) is preserved in well 12/13-1a. This suggests that up to an additional 650m of section could have been deposited in the Corrib area prior to erosion at a pre-Albian unconformity. Although seismic evidence indicates that several minor unconformities affect the Early Cretaceous sediments in the Erris Basin, the most dramatic sub-unconformity truncation is associated with a mid-late Aptian event (Chapman *et al.* 1999). Hence, the end member stratigraphic constraints on the timing of Early Cretaceous exhumation suggest either exhumation commencing during Late Portlandian-Valanginian time with continued elevation of the Corrib structure until Albian transgression or relatively continual subsidence and deposition during the Late Portlandian to early Aptian, with rapid exhumation during the mid-late Aptian, succeeded by Albian transgression.

Above this Early Cretaceous unconformity, the preserved Albian succession is approximately 50-100m thick within the field area (Fig. 8.16). Limited thickening, observed in the hanging wall of the main listric fault (Fig. 8.4), suggests

minor extensional reactivation at this time. Late Albian shales are overlain by Middle-Late Cenomanian (18/20-2) and Middle-Late Turonian (18/25-2) chalks, suggesting that only a minor hiatus is present in the Middle-Late Cretaceous succession of the Corrib Field.

8.5.2 Early Tertiary Unconformity

In the Corrib area, a major depositional hiatus is observed at the base of the Tertiary interval, which contains a heterogeneous succession of lavas, volcanics and interbedded weathered layers resting unconformably upon chalk of Maastrichtian age (Fig. 8.16). Onshore, a spectacular unconformity is observed where Paleocene basalts of the Antrim Lava Group infill a palaeokarst surface created in the underlying Santonian to Maastrichtian chalks (Ulster White Limestone) (Simms 1998). Across the Corrib area the preserved chalk sequence varies in isopach from 292.5m (18/20-2) to 77.8m (18/20-1). Although the precise age of the chalk is not known in all of the Corrib wells (returns to seabed while drilling this section), the preservation of Early Maastrichtian chalk in both 18/20-1 and 18/20-2 suggests limited regional exhumation of the field area at this time. However, local reactivation of the main listric detachment fault resulted in increased erosion of chalk from the 18/20-1 footwall block (Fig. 8.16).

In contrast, an almost complete Cenomanian to Danian chalk succession is preserved in Erris Basin well 12/13-1a. The upper 67m of this section consists of Maastrichtian to Danian chalk which is consistent with the extent of latest Cretaceous chalk deposition in the Porcupine Basin (121m continuous succession of Maastrichtian-Danian chalk encountered in well 34/15-1), one of the main depocentres at this time. Onshore, the thickest preserved section of Ulster White Limestone (chalk) is the 146 metres (base not reached) encountered in the Aughrimderg borehole in the Lough Neagh-Larne Basin (Fletcher 1977) (Fig. 8.17). The combined local and regional evidence suggests that the maximum thickness of chalk eroded from the Corrib Field area is of the order of 50-150m, which forms an upper boundary on the magnitude of exhumation at this Early Tertiary unconformity.

8.5.3 Middle Tertiary Unconformity

In the Corrib area, the volcanic section which immediately overlies the Early Tertiary unconformity is 50–120m thick and has yielded a K/Ar date of 40-43 Ma from well 18/20-1 [lavas in nearby BH-1 have yielded a K/Ar date of 54.3 +/_1.2 Ma] (Fig. 8.16). Original depositional thickness of these volcanics is unknown. Although the nearest postulated Early Tertiary igneous centre, St. Brendan's igneous centre, occurs to the south of the Slyne Basin (approximately 100km south of Corrib), the preservation of the 'younger' lavas in well 18/20-1 suggests that the extent of volcanic deposition in the Corrib area was limited to a few hundred metres with the volcanics onlapping the prevailing chalk topography. Onshore, the maximum original thickness of the lava flows is also unknown due to post Paleocene erosion. However, up to 780 metres of the Antrim Lava Group succession was penetrated in the Langford Lodge borehole (McCaffrey & McCann 1992) (Fig. 8.16), although this area was more proximal to the central igneous complexes of western Scotland and Northern Ireland.

The extent of post-volcanics Late Eocene to Oligocene sedimentation in the Slyne Basin is unclear; however, in the Erris Basin a minimum of 156m of Eocene siltstone, claystones and marls were penetrated by well 12/13-1a. Onshore, in the southwest of the Lough Neagh-Larne Basin stratigraphic relationships clearly indicate an episode of exhumation, probably related to inversion of a Mesozoic extensional fault (Roberts 1989), which has locally removed a minimum of 780m of basalt prior to deposition of Oligocene sediments. Limited compressional reactivation may have occurred in the Corrib Field area at this time, but the evidence of a relatively flat-lying volcanic section (Fig. 8.4) with a Late Eocene K-Ar age, suggests a maximum constraint on pre-Oligocene (Middle Tertiary Unconformity) exhumation of 200-300m.

8.5.4 Late Tertiary Unconformity

The youngest sediments in the Corrib Field area consist of a Late Miocene-Recent succession (23-46m thick), which rests unconformably upon the Late Eocene volcanics (Fig. 8.4). Consequently, the Middle Tertiary and Late Tertiary unconformity surfaces are merged in the Corrib area and there is no direct evidence to suggest that significant thicknesses of Oligocene-Middle Miocene sediments were deposited in this area. However, onshore in the Lough Neagh Basin, a lignite rich, siliclastic, lacustrine succession of at least 350m was deposited during the Late Oligocene (Shelton 1997).

This succession (which subcrops the Quaternary) is locally folded and has been interpreted as evidence of Miocene compressional inversion (George 1967; Roberts 1989). Minor post-Middle Miocene? compressional reactivation has also been interpreted on a number of faults in the Slyne Basin area (Dancer *et al.* 1999) although there is no direct evidence for this phase of inversion at Corrib.

In contrast, Mio-Pliocene deposits are unknown in the northeast of Ireland (Shelton 1997), which suggests that a significant hiatus or erosional unconformity was developed in this area during the 20 Ma Neogene period. This landscape has been modified subsequently by glacial erosion during the Quaternary ice ages which itself has driven further erosion through isostatic rebound post removal of the ice load. Confirmation of ongoing isostatic readjustment of shorelines (in response to removal of the ice load) is provided by the preservation of sea caves 5-10 metres above present-day seal level (Lyle 1993). The combined onshore and offshore stratigraphic evidence suggests that Miocene (Late Tertiary Unconformity) exhumation at Corrib was unlikely to have exceeded 300-400m.

In summary, the integration of local seismic interpretation and regional stratigraphic analysis offers a number of important constraints with respect to the timing and magnitude of exhumation events at the Corrib Field. The most likely interpretation suggests that a kilometer scale (minimum 830m *gross exhumation* at well 18/20-2) exhumation episode occurred during the Early Cretaceous, with at least three subsequent, relatively minor, pulses of exhumation triggered during the Early Cenomanian-Middle Turonian, Late Maastrichtian-Late Paleocene and Late Eocene-Middle Miocene periods (Fig. 8.18).

8.6 Exhumation drivers – Corrib Field area and Slyne Basin

Although local differential exhumation (during both the Early Cretaceous and Early Tertiary episodes) is clearly documented within the Corrib Field area, the truncated post-rift rock record throughout the Slyne Basin suggests that longer wavelength processes are the primary drivers of the post-Jurassic exhumation events. The absence of clear evidence for compressional inversion indicates that the observation of heterogeneous exhumation at Corrib is best accounted for by the superposition of regional (wavelengths of 10-100 kms) exhumation and local, short-wavelength, extensional fault movements. This model has previously been proposed by Argent *et al.*

(2002) as the kinematic option most consistent with the observed heterogeneous, Cenozoic, exhumation in the western Moray Firth.

In the Slyne Basin area a number of factors could have contributed to long-wavelength, epeirogenic, exhumation. Jones *et al.* (2001) concluded, from tectonic subsidence analysis of wells in the north of the Porcupine Basin, that transient, epeirogenic, uplift events affected the area during the Early Cretaceous (200-700m) and Early Eocene (300-600m), possibly due to mantle hot-spot activity. However, the present day elevation of the syn-rift sediments at Corrib and adjacent areas suggests that the uplift of the Slyne Basin was not transient. Another factor is the response of the Slyne Basin to the major phase of rifting in the Rockall Basin, which occurred during the Early-Mid Cretaceous (Knott *et al.* 1993; Musgrove & Mitchner 1996). Large scale (>2 kms) rift shoulder uplift has been documented along the margin (west of Corrib) of the north Slyne and Erris basins (Chapman *et al.* 1999) which is consistent with the magnitude of the lithospheric extension estimated for the Rockall Basin (England & Hobbs 1997). This uplift could have induced significant exhumation of the Jurassic section during the Early Cretaceous.

This evidence points to long-wavelength processes, such as mantle hot-spot activity and shoulder uplift linked to the rifting and thermal subsidence of the Rockall Basin, as the primary drivers of exhumation in the Corrib area during the Early Cretaceous. Subsequent exhumation events were likely to have been driven by hot-spot activity and minor pulses of compressional inversion.

8.7 Conclusions

Compactional, thermal and stratigraphic frames of reference have been used to assess the magnitude and timing of exhumation in the Corrib Field area of the Slyne Basin. The following are the principal conclusions of this study:

1. The principal exhumation episode occurred during the Early Cretaceous, following maximum burial during the Late Portlandian. Initiation of exhumation most likely occurred during the Ryazanian-Valanginian with continued elevation and erosion of the Corrib structure until Albian transgression.
2. Average *gross* exhumation estimates for the Base Cretaceous unconformity vary from 1429m (palaeothermal data, 3 wells) to 1482m (compactional data, 5

wells). Seismic interpretation and stratigraphic evidence suggest a minimum constraint on the magnitude of exhumation at the 18/20-1 and 18/20-2 locations is 1330m and 830m respectively.

3. A number of post-Aptian re-burial and exhumation events also occurred in the Corrib area but are unlikely to have exceeded the earlier maximum burial of source, reservoir and seal rocks achieved during the Late Jurassic. Local and regional stratigraphic evidence suggest potential for relatively minor episodic exhumation during the Early Cenomanian- Middle Turonian, Late Maastrichtian-Late Palaeocene, Late Eocene –Early Oligocene, Early-Middle Miocene. However, the later two episodes are not stratigraphically resolved at Corrib due to the merging of the Middle and Late Tertiary unconformity surfaces.
4. Large uncertainty is associated with exhumation estimates derived from individual techniques. However, in this study, the mean estimates from the individual techniques converge with the conclusions derived from seismic interpretation and stratigraphic analysis and support the view that kilometre scale (800-1700m) erosion of the Jurassic overburden has occurred in the Corrib area.

Chapter 9

Conclusions, synthesis and implications for petroleum geology

9.1 Summary of conclusions

A variety of individual techniques is available to assess the exhumation of sedimentary successions, but generic categorisation indicates that 'point' measurements of rock displacement, in the offshore arena, are made with respect to four frames of reference – tectonic, thermal, compactional or stratigraphic. These techniques have been critically reviewed in the context of some of the exhumed offshore sedimentary basins peripheral to the Irish landmass. This review confirms that large uncertainty is associated with estimates from individual techniques but that the integration of seismic interpretation and regional stratigraphic data provides valuable constraints on estimates from the more indirect tectonic, thermal and compactional methods.

Evidence from VR, AFTA and compaction data combined with seimic and stratigraphic interpretation indicates that Irish offshore basins have experienced a complex, multi-phase Late Palaeozoic-Cenozoic exhumation history. Regional exhumation episodes occurred during the Late Carboniferous-Early Permian, early Cretaceous, early Palaeogene followed by a number of late Palaeogene-Neogene events. Exhumation analysis of a regional VR dataset indicates that average net exhumation (by basin) ranges from 0.8 kms to 3.7 kms for the sampled offshore basins as compared with an average net exhumation range of 3.6-4.5 kms for two onshore basins. Sonic compaction analysis for 8 wells in the Slyne Basin yields a mean net exhumation of 1.2 kms, with a range of 0.95-1.8 kms occurring within the basin. This result is consistent with the mean net exhumation estimate (1.02 kms) derived from VR data from 3 wells in the Slyne Basin. Critically, this study documents a significant early Cretaceous exhumation episode in the Slyne Basin which is synchronous with uninterrupted, continuous, early Cretaceous deposition in the north of the Erris Basin (see Chapter 8). Likewise VR data combined with AFTA data suggests that up to 3 kms of early Cretaceous exhumation occurred in the Central Irish Sea Basin whereas the central Celtic Sea area was predominantly characterized by extensive 'Wealden' subsidence and deposition at this time.

With respect to the Corrib Field area of the Slyne Basin, the principal exhumation episode occurred during the Early Cretaceous, following maximum burial during the Late Portlandian. Initiation of exhumation most likely occurred during the Ryazanian-Valanginian with continued elevation and erosion of the Corrib structure until Albian transgression. Average *gross* exhumation estimates for the Base Cretaceous unconformity vary from 1429m (palaeothermal data, 3 wells) to 1482m (compactional data, 5 wells). Seismic interpretation and stratigraphic evidence suggest a minimum constraint on the magnitude of exhumation at the 18/20-1 and 18/20-2 locations is 1330m and 830m respectively. A number of post-Aptian re-burial and exhumation events also occurred in the Corrib area but are unlikely to have exceeded the earlier maximum burial of source, reservoir and seal rocks achieved during the Late Jurassic. Local and regional stratigraphic evidence suggest potential, in the Slyne Basin, for relatively minor episodic exhumation during the Late Cenomanian-Early Campanian, Late Maastrichtian-Late Palaeocene, Late Eocene –Early Oligocene, Early-Middle Miocene. However, there is no evidence, from VR data, of elevated heat flows during the Tertiary in Irish Atlantic Margin basins, except for local heat fluxes associated with Palaeogene igneous intrusions.

9.2 Synthesis

The Irish landmass and inboard basins and much of the northwest European Atlantic Margin have been subject to widespread exhumation, although the timing, magnitude and causes of this uplift are a source of considerable debate. Evidence from the 'Irish' area indicates that spatially complex patterns of exhumation are likely to be encountered at both the intra-basin and inter-basin scales – reflecting such controls as basin orientation, prevailing stress regime, structural inheritance, differential erosion rates and the superimposition of the erosional signatures of a number of separate tectonic episodes. With respect to the Irish inboard basins the remnant stratigraphic record for these basins, combined with AFTA and VR data, indicates that at least four phases of regional exhumation occurred in this area – during late Carboniferous-early Permian, early Cretaceous, early Palaeogene and late Palaeogene-Neogene, with some 'local' exhumation during Triassic-early Jurassic time, recorded by AFTA data from the southeast of the island (Fig. 9.1).

Late Carboniferous-early Permian

A pervasive regional unconformity exists at the base of the Permian-Mesozoic successions throughout the Irish onshore and offshore area (see Fig. 9.1 and Chapter 1). Published AFT and VR studies – from onshore and offshore Ireland (Clayton *et al.* 1989; Corcoran & Clayton 2001), from onshore southeast Ireland (Keeley *et al.* 1993), from onshore Ireland and northwest Wales (Green *et al.* 2000; Green *et al.* 2001), from the East Irish Sea Basin (see interpretation of Well 110/20-1 in Holford *et al.* 2005a; Green *et al.* 1997) and from unpublished AFTA studies in the Erris and Donegal basins - support the interpretation of a major regional cooling and exhumation episode between 300-250 Ma.

Although this exhumation episode appears to have been regional in extent there is some evidence to suggest that it has been influenced by broadly co-eval epeirogenic uplift and tectonic inversion. Significant late Carboniferous-Permian igneous activity throughout northwest Europe ['Irish' area Stephanian-early Permian volcanism, summarised in Corcoran & Clayton (1999)], suggests thermally driven uplift occurred during this time (Coward 1990). These observations are consistent with the extensive calc-alkaline to subalkaline volcanism of the Permo-Carboniferous Pangaean province, reviewed by Doblas *et al.* (1998) and interpreted as evidence of a mantle plume impinging upon the base of the lithosphere at this time.

In contrast, the Variscan Orogeny, which reached its climax during the Late Carboniferous-Early Permian, produced pulses of strike-slip deformation and a north-west-directed regional compression (Warr 2000). This force field resulted in the development of an extensive fold-and-thrust belt in southern Britain and Ireland and widespread basin inversion at least as far north as the Peel and Solway-Northumberland basins (Floodpage *et al.* 2001; Fraser & Gawthorpe 1990; Chadwick *et al.* 1993) and possibly as far north as the East Shetland Platform (Coward 1993). Detailed studies of Variscan inversion tectonics indicate that inherited basement grain is an important control on the style and orientation of these Variscan structures (Coward 1993; Corfield *et al.* 1996). For example, the NE-SW trending Carboniferous basins (orthogonal to direction of maximum shortening) were strongly inverted, with complete expulsion of the post-rift (post early Carboniferous rift) fill occurring in the case of the Bowland and Dublin basins (a minimum shortening of 10-15%; exhumation of 3-4 kms – Corfield *et al.* 1996; Fraser & Gawthorpe 1990). In general, the N-S and NW-SE trending basins were less strongly inverted resulting in the retention of their late

Carboniferous, post-rift, fill. This model suggests that the presence of an appropriate N-S 'Carboniferous' structural orientation could account for the local preservation of Stephanian-Autunian sediments in the northwest of the Porcupine Basin (Robeson *et al.* 1998) and Stephanian sediments in the Central Irish Sea Basin (Green *et al.* 2001) and consequently the heterogeneous exhumation pattern developed through these Irish basins during the late Carboniferous-early Permian time.

Triassic-Early Jurassic

Stratigraphic, VR and AFT data all suggest that the inboard basins were dominated by subsidence during the Triassic-early Jurassic, though limited, spatially heterogeneous, exhumation probably occurred in the onshore area at this time (Green *et al.* 1997; Green *et al.* 2001; Allen *et al.* 2002). Interpretations of AFTA data from onshore NW Wales indicate a period of Triassic-early Jurassic (230-185 Ma) footwall uplift and cooling ocurred in this region as a flexural-isostatic response to co-eval hanging wall subsidence (in the Cardigan Bay Basin) along the basin-bounding Mochras-Tonfanau-Bala fault system (Holford *et al.* 1995a). A significant cooling event, commencing around 200 Ma, is also identified by Keeley *et al.* (1993) in an AFT dataset from onshore southeast Ireland. This suggests that a period of footwall readjustment may also have occurred along the northern margin of the North Celtic Sea Graben at this time. Repeated local influxes, of shallow marine/deltaic sands, along this northeast margin during the late Sinemurian-Pliensbachian represent the sedimentological response to these extensional readjustments, prior to the resumption of the ambient marine carbonate and mud deposition during the Liassic (Petrie *et al.* 1989; Kessler & Sachs 1995). Furthermore, the presence of Bajocian-Bathonian lacustrine clays within karstified Tournasian limestones at Cloyne, Co. Cork, (Higgs & Beese 1986) indicates that an active karst system may have have been developed, at least close to the southern coastline, as early as Bajocian times. Keeley *et al.* (1993) estimated that the cooling of this area, from the maximum palaeotemperatures during the Triassic, required the unroofing of 2-3 kms of sediment during the early Jurassic.

Denudational modelling of the onshore AFT data by Allen *et al.* (2002) indicates that the Triassic-Early Jurassic period is generally characterised by limited (<1 km during the Triassic) amounts of denudation. Their estimated average denudation rate (<20m Ma^{-1}) for the onshore area during the Early Jurassic is difficult to reconcile with palaeogeographical models of widespread subsidence under an extensive

Early Jurassic sea (Fleet *et al.* 1987) - perhaps suggesting that a more widespread basin and block morphology prevailed, onshore Ireland, during Triassic to early Jurassic time. In any case it seems likely that the primary driver for exhumation at this time was foot-wall readjustment in response to local fault extension, thus highlighting the potential contribution of non-epeirogenic processes to Mesozoic and Cenozoic exhumation in this area.

Early Cretaceous

Kilometre-scale early Cretaceous exhumation has been documented in a number of the 'Irish' inboard basins – East Irish Sea Basin (Green *et al.* 1997; Holford *et al.* 2005a); Central Irish Sea Basin (Green *et al.* 2001); South Celtic Sea-Bristol Channel Basin-Wessex Basin (McMahon & Turner 1998); Cardigan Bay Basin (Holford *et al.* 2005b); Slyne Basin (Corcoran & Mecklenburgh 2005); Erris Basin (Chapman *et al.* 1999); Peel Basin (Floodpage *et al.* 2001). Relatively minor local exhumation occurred at this time in the North Celtic Sea Basin which was dominated by limited extensional reactivation, subsidence and the influx of Wealden sediments (Rowell 1995). Stratigraphic analysis by McMahon & Turner (1998) has highlighted the presence of two distinct early Cretaceous unconformities in the Celtic Sea, Western Approaches and Wessex basins – an older Berriasian unconformity (*c.* 146-141 Ma) representing kilometers of missing section in the Western Approaches and the South Celtic Sea basins and a younger Aptian unconformity (*c.* 125-112 Ma) apparently associated with lower magnitudes of erosion.

AFTA and VR data confirm the early Cretaceous episode as the main phase of post-Palaeozoic exhumation to affect the Irish Sea basins – with up to 3 kms of section removed from this area during the early Cretaceous. AFTA timing constraints, in these Irish Sea basins, suggest that the onset of regional exhumation-related cooling occurred between 120-115 Ma (Holford *et al.* 2005a). These constraints are consistent with the timing of a major exhumation episode (145-112 Ma - deduced from the stratigraphic evidence at Corrib) in the Slyne Basin (Corcoran & Mecklenburgh 2005) and the early Cretaceous timing (deduced from seismic stratigraphy) of footwall uplift along the western margin of the Erris Basin (Chapman *et al.* 1999).

The early Cretaceous was a period of changing plate margin dynamics along the northwest European Atlantic Margin. Significant plate

margin events which occurred at this time include – accelerated rifting in the Rockall Basin during the Berriasian-Hauterivian (146-132 Ma) (Scrutton & Bentley 1998); coalescence of the northerly propagating 'Atlantic' rift with the southerly propagating 'Arctic' rift to form a single linked rift system during the Berriasian-Valanginian (146-135 Ma) (Roberts *et al.* 1999); rotation of the direction of extension (σ_3) from E-W to NW-SE during the Hauterivian (135-132 Ma) (Doré *et al.* 1999); initiation of seafloor spreading between Iberia and the Grand Banks (within the Bay of Biscay) during Aptian times (c. 118 Ma) (Johnston *et al.* 2001). In addition, intra plate volcanism (offset from the main area of North Atlantic volcanism) was a feature of the Hauterivian-Barremian period in the Goban Spur, Brittany Basin and Cornubian platform (Ziegler 1987) and occurred during Apto-Albian times in the Western Approaches Basin (Bennet *et al.* 1985). The presence of these 'non-rift related' volcanics in the area of the Cornubian platform prompted McMahon & Underhill (1995) to propose a thermal mechanism for the generation of Early Cretaceous uplift over this area (an area of 375,000 km^2 based on subcrop mapping).

Within the Slyne Basin, local differential exhumation (during the Early Cretaceous) is clearly documented within the Corrib Field area, though the truncated post-rift rock record throughout the Slyne Basin suggests that longer wavelength processes are the primary drivers of post-Jurassic exhumation (see Chapter 8). The absence of clear evidence for compressional inversion indicates that the observation of heterogeneous exhumation at Corrib, during the early Cretaceous, is best accounted for by the superposition of regional (wavelengths of 10-100 kms) exhumation and local, short-wavelength, extensional fault movements. This model has previously been proposed by Argent *et al.* (2002) as the kinematic option most consistent with the observed heterogeneous, Cenozoic, exhumation in the western Moray Firth.

In the Slyne Basin area a number of factors could have contributed to long-wavelength, epeirogenic, exhumation. Jones *et al.* (2001) concluded, from tectonic subsidence analysis of wells in the north of the Porcupine Basin, that transient, epeirogenic, uplift events affected the area during the early Cretaceous (200-700m) [and also during the Early Eocene (300-600m)], possibly due to mantle hot-spot activity. However, the present day elevation of the syn-rift (Jurassic) sediments at Corrib and the relatively flat-lying, truncated, post-rift (Cretaceous and Tertiary) sediments suggests that the Slyne Basin underwent permanent uplift during the early Cretaceous, most likely in response to magmatic underplating.

Shoulder uplift, linked to the rifting and thermal subsidence of the Rockall Basin, is also likely to have been a significant driver of local (sub-regional) exhumation in the northern Slyne and Erris basins during the early Cretaceous. A major phase of rifting occurred in the Rockall Basin during the Early-Mid Cretaceous (Knott *et al.* 1993; Musgrove & Mitchner 1996). Large scale (>2 kms) rift shoulder uplift has been documented along the western margin of the northern Slyne and Erris basins (Chapman *et al.* 1999) which is consistent with the magnitude of the lithospheric extension estimated for the Rockall Basin (England & Hobbs 1997). This uplift could have induced significant exhumation of the Jurassic section, in this area, during the early Cretaceous. However, the presence of a continuous Late Berriasian-Aptian succession in Well 12/13-1a in the north of the Erris Basin suggests that the shoulder uplift did not affect this area of the basin or that it predates the Late Berriasian.

In summary, the heterogeneous exhumation patterns developed in these inboard basins, during the early Cretaceous, are likely to be the product of far-field plate margin processes (linked to the onset of North Atlantic seafloor spreading) and near-field local extensional fault movements and sub-regional shoulder uplifts - thus highlighting the variety of mechanisms which have potentially contributed to Mesozoic and Cenozoic exhumation offshore Ireland.

Early Palaeogene

Thermal history modelling of AFT and VR data (Green *et al.* 1997; Green *et al.* 2001), inverse modelling of basin subsidence (Rowley & White 1998), compaction studies (Hillis 1995b; Ware & Turner 2002) and stratigraphic arguments (Holiday 1993; Murdoch *et al.* 1995; Cope 1997) have been used to identify and constrain an episode of Late Cretaceous-Early Palaeogene exhumation in basins peripheral to the Irish landmass. Mechanisms by which the Irish Sea area was exhumed during early Palaeogene times have been widely discussed in the literature with proposed mechanisms tending to nucleate around 'thermal uplift' models and 'compressional inversion' models at either end of the spectrum (e.g. Brodie & White 1995; Blundell 2002). Proponents of 'thermal uplift' models cite the following evidence in favour of a 'thermal trigger' (hotspot, plume, underplating) for the regional exhumation of the Irish Sea area during the Early Tertiary - the presence of a long wavelength free-air gravity anomaly beneath the Irish Sea (Tiley *et al.* 2004); Mesozoic outcrop patterns onshore England (Cope 1994); widespread intrusive and extrusive

Palaeogene volcanism across the entire continental shelf to the west of Britain and Ireland (Brodie & White 1995); pillow of high-velocity and high-density lower crust identified in the northern Irish Sea from wide-angle reflection seismic (Al-Kindi *et al.* 2003); the current elevation of the Irish landmass and these inboard extensional basins (Brodie & White 1995). Proponents of 'compressional inversion' models rely, primarily, on the well documented seismic and outcrop evidence for compressional and transpressional Palaeogene inversion structures in the southern Irish Sea and Celtic Sea basins and onshore southern Britain (Murdoch *et al.* 1995; Blundell 2002; Williams *et al.* 2005; Holford *et al.* 2005a). The absence of recognized Palaeogene inversion structures across the central and northern Irish Sea region is attributed to erosion of the evidence (reverse fault displacements) in the deeply exhumed basins such as the Peel, Solway and East Irish Sea Basin (Holford *et al.* 2005a).

Evidence for early Palaeogene shortening has been preserved in a number of the southern basins where local tectonic inversion and crustal shortening can be attributed to the far-field deformational response to lithospheric stresses generated by Alpine plate convergence (Blundell 2002). The uplift response to the NW-oriented compressional stress appears to have been strongly influenced by the rheological characteristics of the individual Mesozoic extensional basins. For example, the rheological characteristics of the St. George's Channel Basin favoured strain partitioning and this NW-directed compression resulted in a pattern of noncoaxial inversion, with co-eval transpression and transtension focused at restraining bends and stepovers on major basin margin faults (Williams *et al.* 2005). In contrast, a distinctly coaxial pattern of inversion is developed in the North Celtic Sea Graben (Murdoch *et al.* 1995) and in the Central Irish Sea Basin (Izatt *et al.* 2001) where maximum early Palaeogene exhumation appears to have been axially focussed along the centre of both basins (although it is difficult to deconvolve the effects of Late Palaeogene-Neogene exhumation in both these basins).

Recent reviews (Green *et al.* 2001; Holford *et al.* 2005b) suggest that the magnitude of early Palaeogene exhumation may have been overstated (at least in the Irish Sea basins) in previous studies. Furthermore, the preservation of Maastrichtian chalk successions in wells in the northern Slyne Basin (Corrib area), Erris Basin (Well 12/13-1a) basins and onshore Northern Ireland suggests that only limited (<200m ?) regional exhumation (Corcoran & Mecklenburgh 2005) occurred in these areas prior to the deposition (onshore) of the Lower Basalt Formation at 58 Ma

(Anderton 2000). Compressional inversion structures of early Palaeogene age have not been recognised to date in the Slyne and Erris basins – perhaps because of unfavourable structural orientation. This evidence suggests that intraplate shortening and tectonic inversion could have contributed significantly to regional exhumation during the early Palaeogene – particularily, in those basins which are oriented orthogonal to the direction of maximum shortening during the Laramide phase of the Alpine Orogeny. However, a component of regional uplift may have been associated with magmatic underplating in the northern Irish Sea area, and is likely to increase in importance towards the northern inboard basins.

Late Palaeogene-Neogene

There is significant stratigraphic evidence to suggest that a number of phases of both local and regional exhumation occurred in the 'Irish' area during Late Palaeogene-Neogene. For example, major Plio-Pleistocene prograding shelf margin wedges and basin floor fans (Donegal and Barra fans) in the Rockall Basin are interpreted as the sedimentary response to regional, Late Neogene, uplift and denudation of northwest Ireland and Scotland (Stoker 2002). In the onshore area, the sporadic occurrence of continental and lacustrine deposits of Oligocene to Pliocene age [marine Tertiary deposits are absent from the onshore rock record (Naylor 1992)] is consistent with the results of the AFT studies of Allen *et al.* (2002) which indicate a predominance of denudation over subsidence during this period.

However, separating the effects of these Late Palaeogene-Neogene exhumation episodes is difficult due to the patchy preservation of mid-late Cenozoic sediments onshore Ireland and in the inboard basins. In addition, the superimposition of the erosional signatures of a number of separate Late Palaeogene-Neogene tectonic episodes leaves an ambiguous picture. For example, in the Corrib area of the Slyne Basin the Middle Tertiary and Late Tertiary unconformity surfaces are merged and there is no direct evidence to suggest that Oligocene-Middle Miocene sediments were deposited in this area (Corcoran & Mecklenburgh 2005). Likewise, a major unconformity at the base of the Mio-Pliocene section, resulting from regional Neogene uplift of the northwest flank of Ireland and the adjacent continental shelf, has removed the evidence of earlier Cenozoic exhumation episodes (Stoker *et al.* 2001; Allen *et al.* 2002). However, onshore in the Lough Neagh Basin, a Late Oligocene lignite rich, siliclastic, lacustrine succession of at least 350m has been preserved

(Shelton 1997). This succession (which subcrops the Quaternary) is locally folded and has been interpreted as evidence of a Miocene compressional inversion episode which post-dates the pre-Oligocene deformation and inversion of the base Tertiary basalt surface (George 1967; Roberts 1989).

Thick successions of Eocene-Miocene sediments accumulated in parts of the Irish Sea and have been deformed by folding and extensive contractional reactivation of previously extensional faults (Williams *et al.* 2004). In the North Celtic Sea Graben regional early Palaeogene exhumation was succeeded by deposition during Eocene-Oligocene time. These sediments were also folded during the Oligo-Miocene in response to compressional inversion (characterised by basin doming and fault reversal) driven by late stage Alpine Orogeny (Murdoch *et al.* 1995). Local Mid to Late Tertiary transpressional structures have been reported from the Slyne Basin (Dancer *et al.* 1999) though the precise Cenozoic timing of these structures is poorly understood. Badley (2001) demonstrated that footwall uplift and hanging-wall subsidence (succeeded by further isostatic uplift following glacial erosion during the Pleistocene) accompanied Neogene extensional displacements along the Erriff Fault and exercised a fundamental control on recent exhumation history and the overall form of present-day topography, in the onshore area.

The underlying causes of Neogene exhumation along the Atlantic margins are poorly understood (Japsen & Chalmers 2000; Doré *et al.* 2002a). Late Paleogene-Neogene intra-plate compression, associated with Alpine lithospheric shortening and ridge push from North Atlantic sea floor spreading, has resulted in the generation of large scale, multiphase, Cenozoic inversion structures through the Hatton, Rockall, Faroe-Shetland, Møre and Vøring basins (Boldreel & Andersen 1993; Doré & Lundin 1996; Doré *et al.* 1999; Hitchen 2004; Johnson *et al.* 2005) and is likely to have influenced the formation of localized inversion structures in the Irish Sea, Celtic Sea, Lough Neagh-Larne and Slyne basins at this time (George 1967; Dancer *et al.* 1999; Williams *et al.* 2005; Holford *et al.* 2005a). Regional exhumation of onshore Norway, Scotland, Faeroe Islands, Svalbard and Barents Sea Basin during the Neogene may have been triggered by intraplate compressive stress (Cloetingh *et al.* 1990) but was magnified by changes to a wetter climate (during the Neogene) and ultimately glacial erosion and isostatic readjustment during the Pleistocene (Japsen & Chalmers 2000; Doré *et al.* 1999).

In summary, a complex and heterogeneous pattern of exhumation exists onshore Ireland and in the Irish inboard basins. This pattern reflects the superimposition of the erosional signatures of a number of exhumation episodes and the overprinting of the effects of epeirogenic uplift, tectonic inversion and short-wavelength extensional fault movements on a variety of reheological templates inherited from the pre-exhumation basin evolution. The timing of the main regional exhumation events is generally consistent with significant deformational episodes at the Atlantic and Alpine plate margins. This correlation suggests that plate margin processes are important drivers of exhumation in intra-plate regions.

9.3 Implications for petroleum geology

The timing and magnitude of exhumation events has important implications for the evolution of hydrocarbon systems contained in petroliferous basins, the distribution of hydrocarbon resources within these basins and exploration success rates. Exhumed petroliferous basins are characterized by concentrated field size distributions (most of basin reserves in one large field) as opposed to the more typical dispersed distributions (<25% basin reserves in largest fields) of 'continually subsiding' basins (MacGregor 1995). Discovered resource distributions in the exhumed 'Irish' inboard basins are consistent with this pattern (Morecambe Gas Fields – East Irish Sea Basin; Kinsale Head Gas Field – North Celtic Sea Graben; Corrib Field – Slyne Basin). Compared to a similar prospect in a 'continually subsiding' basin, resource levels in an exhumed prospect are generally lower and prospect risks are generally higher (probability of finding hydrocarbons generally lower). A systematic review of the implications of exhumation for the assessment and risking of prospects is provided by Doré *et al.* (2002b).

Although there is a complex interplay between the timing and magnitude of an exhumation event and the evolutionary status of a petroleum system, some generalizations can be made with respect to the effects of exhumation on the probabilities (chance of adequacy) of the individual prospect elements. In general, the probability of reservoir presence is unlikely to be affected by exhumation, though the reservoir quality can be reduced (in the case of extreme burial prior to exhumation) or

enhanced (in the case of fracturing of tight reservoirs induced by local and regional vertical displacements and a changing stress regime during exhumation). Generally, higher levels of reservoir diagenesis (with respect to present day burial depth) prevails in exhumed basins and this tends to negatively impact the assessment of net-to-gross ratio, porosity, permeability, water saturation and recovery factor for the exhumed reservoir.

The probability of source rock presence is severely reduced where exhumation has resulted in the erosion of the source rock intervals or where the residual hydrocarbon budget, post thermal 'switching-off' of source rock maturation, is insufficient to fill the available hydrocarbon traps. In cases where a limited hydrocarbon budget is available, post-regional uplift, the efficiency of the re-migration process becomes a key exploration risk factor. On the other hand source rocks presently at shallow (sub-mature) burial depths may have been mature prior to exhumation. In addition, the local re-deposition of the erosional products of exhumation may give rise to an isolated working hydrocarbon kitchen.

Empirical observation, from basins along the northeast Atlantic Margin, suggests that there is an increased probability of discovering gas accumulations in the exhumed basin setting. This arises due to the prevalence of such processes as gas exsolution from oil, gas expansion, methane exsolution from formation waters and methane desorption from coals primarily in response to pressure reductions during uplift. In contrast, basin exhumation may facilitate the introduction of a light oil budget resulting from retrograde condensate drop-out caused by pressure reduction during uplift.

The probability of the presence of a sealed trap can be increased (e.g. by tilting of structural 'noses') or decreased (e.g hydraulic and shear fracturing of claystone seals) by an exhumation event. Empirical observation (of trap fill ratios and initial reservoir pressures) indicates that hydrocarbon accumulations in exhumed basins of the Atlantic margin are commonly characterised by underfilled traps and hydrostatically pressured or modestly overpressured reservoirs.

The fluid retention capacity of any cap-rock lithology during exhumation is dependent upon the physical and mechanical characteristics of the cap-rock at the time of exhumation and the timing and conditions of the associated deformation relative to the timing of hydrocarbon emplacement. The permeability and deformational characteristics of halite renders it an excellent cap-rock with a high retention capacity,

even under conditions of exhumation. However, mudrocks may also form effective cap-rocks in exhumed basins when the deformation associated with exhumation occurs prior to embrittlement and the shale cap-rock exhibits ductile behaviour. Shale and evaporite caprocks form the main regional seals to hydrocarbon accumulations in exhumed basins of the Atlantic Margin and borderlands. Syn-exhumation top-seal efficiency (fluid retention capacity) is a major exploration risk in these basins, though post-exhumation top-seal integrity in these basins may be relatively high under certain conditions. Observation of claystone seals in exhumed Atlantic Margin basins suggests that hydraulic retention capacity (not capillary retention capacity) is more commonly the limiting factor with respect to the sealing of hydrocarbon columns in these basins.

The Late Carboniferous-Late Permian exhumation episode has important implications for the main Carboniferous-Triassic petroleum system in the Irish exhumed basins. Where Carboniferous source rocks are present, they will make a significant contribution to the hydrocarbon budget only in those basins where sufficient Mesozoic burial has occurred to expose the kerogen to higher palaeotemperatures than might have been achieved during the Late Carboniferous-Early Permian event. Jurassic petroleum systems have been preserved only in the Celtic Sea-Cardigan Bay and Atlantic Margin exhumed basins. Unravelling the impact of multiple Mesozoic and Cenozoic exhumation episodes is a critical step in understanding the areal and temporal extent of the Jurassic source kitchens in these basins.

MacGregor (1995) indicated that the mechanism of exhumation may be an important determinant of petroleum resource preservation, suggesting that regional uplifts of compressional origin may be more destructive of a basin's petroleum system than uplifts of isostatic or thermal. Given the superimposition of epeirogenic uplift and tectonic inversion in many of the exhumed Irish inboard basins, a detailed analysis of exhumation history in these basins is likely to yield a more refined assessment of exploration risks for these areas.

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Exhumation in Irish sedimentary basins and implications for hydrocarbon exploration, offshore Ireland.

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Abstract

Exhumation, the removal of overburden resulting from the vertical displacement of rocks from maximum burial depth, occurs at both regional and local scales in offshore sedimentary basins and has important implications for the prospectivity of petroliferous basins. In these basins, issues to be addressed by the petroleum geologist include, the timing of thermal 'switch-off' of source rock units, the compactional and diagenetic constraints imposed by the maximum burial depth of reservoirs (prior to uplift), the physical and mechanical characteristics of cap-rocks during and post-exhumation, the structural evolution of traps and the hydrocarbon emplacement history. Central to addressing these issues is the geoscientist's ability to identify exhumation events, estimate their magnitude and deduce their timing.

In this study exhumation techniques are critically reviewed in the context of some of the exhumed offshore sedimentary basins peripheral to the Irish landmass. Vitrinite reflectance, apatite fission track analysis and sonic compaction data for specific wells have been combined with seismic and stratigraphic evidence to estimate the magnitude and timing of exhumation at a number of offshore locations. This analysis reveals a heterogeneous pattern (spatially and temporally) of exhumation which manifests both inter- and intra-basin variation. Exhumation analysis of a regional VR dataset indicates that average net exhumation (by basin) ranges from 0.8 kms to 3.7 kms for the sampled offshore basins as compared with an average net exhumation range of 3.6-4.5 kms for two onshore basins. Sonic compaction analysis for 8 wells in the Slyne Basin yields a mean net exhumation of 1.2 kms, with a range of 0.95-1.8 kms occurring within the basin.

The magnitude and timing of exhumation events have implications for the source, reservoir, seal and trapping elements of a petroleum system. Therefore exhumation must be considered when assigining risk factors used to estimate the probability of discovery for a prospect. Compared to a similar prospect in a 'continually subsiding basin', resource levels in in an exhumed prospect are generally lower.

Empirical observation indicates that hydrocarbon accumulations in exhumed basins of the Atlantic margin are commonly characterised by underfilled traps and hydrostatically pressured or modestly overpressured reservoirs. These observations are reviewed here in the context of the generic mechanisms by which top-seals leak, the properties of cap-rocks and the physical processes which occur during exhumation. *Syn-exhumation* top-seal efficiency (fluid retention capacity) is a major exploration risk in these exhumed basins, though *post-exhumation* top-seal integrity may be relatively high under certain conditions. Consequently, a further exploration risk factor in exhumed basin settings pertains to the limited hydrocarbon budget available post-regional uplift and the efficiency of the re-migration process.

The Carboniferous-Triassic petroleum system contains most of the undiscovered resources in the exhumed basins to the east, north and west of the island. The Corrib Gas Field, in the Slyne Basin, presents in microcosm some of the key challenges with respect to understanding the evolution of this petroleum system. Here, the post-Triassic overburden manifests a complex evolution with indications of flipped polarity, extensional, faulting on a crestal detachment structure during the Jurassic, succeeded by alternate episodes of burial and exhumation from the Early Cretaceous onwards. Compactional and thermal data supported by stratigraphic analysis and seismic interpretation indicate that kilometre scale (800-1700m) exhumation and erosion of the Jurassic overburden has occurred in the Corrib area during the early Cretaceous. A number of post-Aptian re-burial and exhumation events also occurred but are unlikely to have exceeded the earlier maximum burial of source, reservoir and seal rocks achieved during the Late Jurassic. Regional synthesis of the VR, AFT and stratigraphic data from the Irish inboard basins indicates that at least four phases of regional exhumation occurred in this area – during late Carboniferous-early Permian, early Cretaceous, early Palaeogene and late Palaeogene-Neogene, with some 'local' exhumation during Triassic-early Jurassic time, recorded by AFTA data from the southeast of the island.

This study confirms the importance of integrating constraints from seismic interpretation and regional stratigraphic data with estimates from the more indirect tectonic, thermal and compactional methods.