

Organic maturation levels and thermal history of the Carboniferous rocks of the Dublin Basin

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Abstract

The Dublin Basin succession comprises sediments ranging in age from Mississippian (Courseyan) to Pennsylvanian (Langsettian). The Viséan part of the succession is dominated by turbiditic calcarenites interbedded with grey-black shales. Namurian and earliest Westphalian rocks preserved in the Kingscourt Outlier in the north of the basin are dominated by sandstones interbedded with siltstones and shales.

Vitrinite reflectance (VR) profiles were obtained from the Viséan succession using four exploration boreholes. Mean random vitrinite reflectance (% R_r) increases uniformly with depth. Maturation levels indicate that most of the Viséan succession is post-mature with regard to the 'oil window', falling within the dry-gas zone (2.0–3.0% R_r) or is overmature, even with regard to dry gas. The maturation levels measured for the Kingscourt Outlier indicate a position within the oil window for the Namurian succession.

The observed increase of maturity with the age of the stratigraphic succession is typical of maturation processes related to burial. The VR profiles also indicate that between 4.4 to 5.8 km of post-Viséan cover would be necessary to account for the current maturation levels. Maturation is considered to be pre-Variscan, i.e. before regional Variscan uplift and erosion, with maximum temperatures probably attained during Stephanian to Early Permian times. However, the timing of maturation is not well constrained and it is therefore possible that the maturation levels now observed could be due to reburial of the Carboniferous succession during Late Permian or later times.

Keywords: Dublin Basin, Ireland, maturation levels, thermal history.

Introduction

The Dublin Basin and the Kingscourt Outlier are located in East-Central Ireland. The bedrock geology in this region consists mainly of Mississippian (Lower Carboniferous) sedimentary rocks. Pennsylvanian (Upper Carboniferous) outcrop is restricted to the Kingscourt Outlier and to small outliers within the Mississippian (Fig. 1). Inland exposure is poor and the stratigraphy of this region is known mainly from cored mineral exploration boreholes in the northern part of the Dublin Basin.

Most of the Viséan rocks within the Dublin Basin are basal limestones and shales. These limestones were deposited as mass flows by turbidity currents and debris flows, in response to intense Viséan tecton-

ism (Nolan, 1986, 1989). The minimum thickness of Viséan sediments is 1000 m, with shales constituting approximately 50% of the overall thickness. The Namurian to Langsettian succession mainly comprises sandstones and shales deposited in fluvio-deltaic environments.

Haughey (1986) described VR (R_r) values ranging from 0.38–0.46% in the Upper Permian and 0.76–0.84% in the Pennsylvanian in the Kingscourt Outlier. Clayton et al. (1989) recorded R_r ranging from 0.6 to 4.0% in the Dublin Basin and the Kingscourt Outlier. Fitzgerald (1994) described VR ranging from 0.5 to 1.2% R_r in the Navan Mine area and suggested high heat flow possibly associated with mineralization. In the Athboy borehole, VR (R_r) ranges from 0.94 at

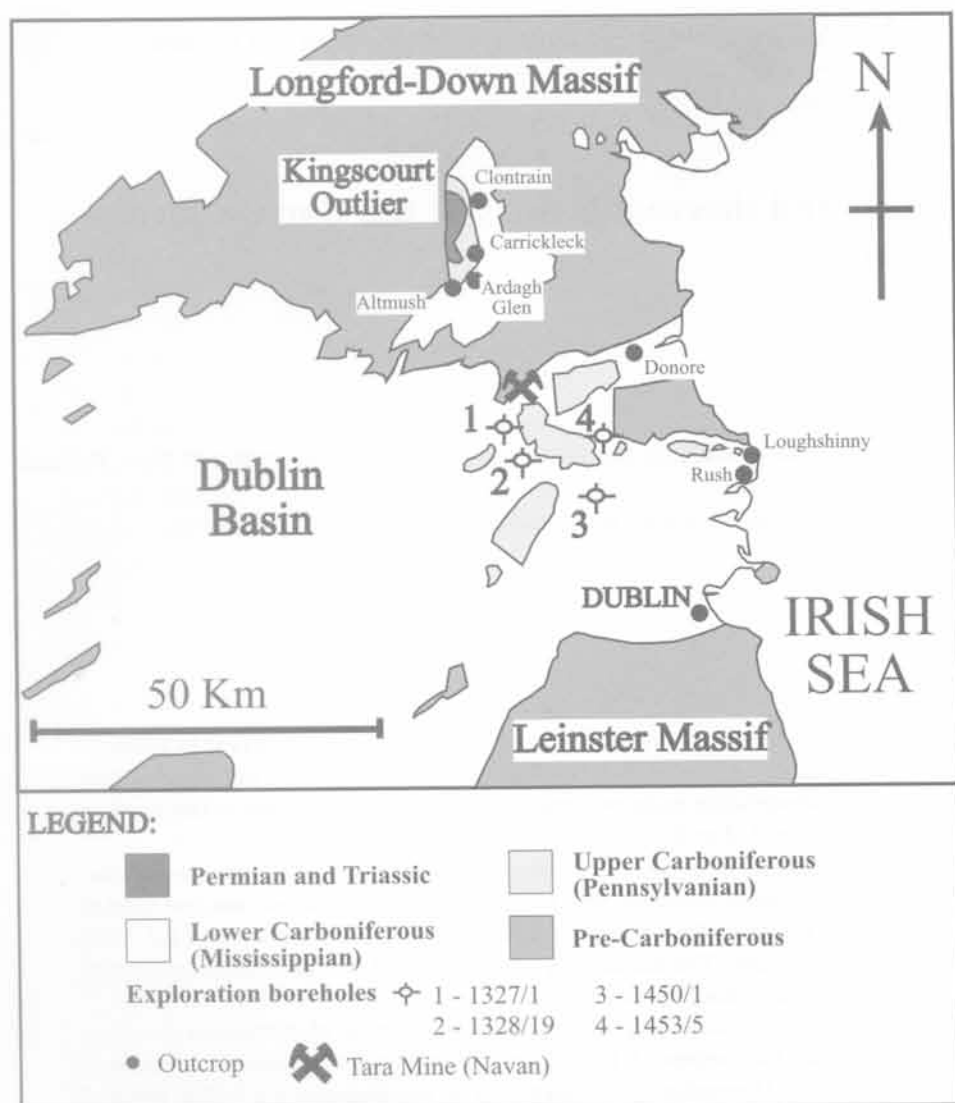


Fig. 1. Generalised geological map of Central Eastern Ireland showing the position of the boreholes and selected outcrops.

the top to 1.9% at the base, representing the regional gradient. The new organic maturation data presented here are used to interpret the thermal maturation history of the Dublin Basin.

Materials and methods

Four boreholes were investigated together with selected outcrop sections in the Kingscourt Outlier (Fig. 1). The dominant lithologies sampled were black non calcareous shales and grey calcareous shales. Mean random vitrinite reflectance (R_r) was determined employing standard techniques and when possible spore fluorescence and spore colour were also determined.

Borehole 1453/5 (Rathfeigh) (Fig. 2) penetrated 418 m of Carboniferous rocks resting unconformably on 12 m of Lower Palaeozoic slates and greywackes. In ascending order, the Carboniferous succession comprises a thin sequence (ca. 8 m) of platform limestones

followed by approximately 190 m of conglomerates and breccias made up of limestone clasts. The conglomerate and breccia beds pass upward into calciturbidite beds interbedded with shales. The first sandstone bed occurs at approximately 90 m depth, recording the first pulses of Namurian deltaic progradation. The core from borehole 1450/1 (Rackinstown) consists of a monotonous succession 797 m thick of calciturbiditic beds interbedded with calcareous shales and shales that range from late Chadian to Asbian in age. Borehole 1329/19 (Skreen) (Fig. 2) penetrated a 817 m thick sedimentary succession of Viséan (Holkerian to Brigantian) age. This succession consists of calciturbiditic beds interbedded with shales and calcareous shales. Beds of conglomerates and breccias of limestone clasts are also frequent through the whole sequence. Two sandstone horizons occur; the first is 7 m thick and was encountered at approximately 324 m depth; the second horizon occurs at 160 m depth and is 35 m thick. The top 120 m of

core from this borehole consists of black shales interbedded with black micritic limestones. Borehole 1327/1 (Ballinter Bridge) penetrated 797 m of redeposited carbonate sediments ranging from Holkerian to Asbian in age. The succession in this last borehole exhibits many similarities with borehole 1329/19, though conglomerates and breccias are scarcer and the overall mud content is lower.

The oldest Namurian sedimentary rock unit that occurs in the Kingscourt Outlier is the Altmush Shale (Jackson, 1955). This formation is approximately 63 m thick and consists of black shales interbedded with basinal limestones that span the Viséan/Namurian boundary. The Pendleian part of the succession is well exposed in the Ardagh Glen. Here, the succession is ca. 63 m thick and consists of black shales that unconformably overlie upper Viséan platform limestones. The succession includes several doleritic sills between 1 to 4 m thick. In Carricleck Quarry, basal sandstones are overlain by approximately 12 m of mudrocks. The mudrocks yielded a spore assemblage that indicates a late Arnsbergian to early Chokierian age. The upper Kinderscoutian part of the succession is exposed in the Clontrain drainage channel, exhibiting features typical of deltaic sedimentation. Black shales at the base pass up into siltstones and then sandstones, generally terminating at the top with a seat earth horizon.

Maturation levels

VR profiles were obtained for the four Viséan borehole sections studied (Fig. 3). The full maturation data set can be provided on request. In borehole 1453/5, VR (R_r) increases downhole, ranging from 2.52% at the top to 2.87% near the bottom. VR increases linearly with depth with a good correlation coefficient ($r^2 = 0.81$). Spore colours showed consistent TAI values of 5 throughout the borehole, which is fully consistent with the VR. The VR levels indicate that the sedimentary succession penetrated by this borehole falls within the dry gas zone of hydrocarbon generation and is of anthracite rank. The lithological contrast between sandstones and limestones does not affect the maturity gradient. However, samples from the sandstone interval in the highest ca. 100 m of the core have R_r values slightly higher than predicted by the best-fit line.

VR in borehole 1450/1 increases from 2.44% R_r at the top to 3.31% R_r at the bottom of the section. Despite some fluctuations, VR values define a linear gradient with $r^2 = 0.69$. The boundary between the dry gas and the overmature zone is at approximately 500 m depth, coinciding approximately with the base of the Holkerian Stage. The TAI values determined

from the few samples that yielded spores were 5, which is consistent with the VR results. In relation to the coal rank, the section spans the boundary between semi-anthracite and anthracite.

In borehole 1328/19, VR ranges from 2.1% R_r at the top to 3.04% R_r at the bottom. A linear increase in reflectance with depth of burial is noted, defining a gradient with a correlation coefficient of $r^2 = 0.81$. Almost all the samples are located in the dry gas zone with the lowest few samples overmature, and are equivalent to semi-anthracite to anthracite in terms of coal rank. TAI values of 5 from all samples that yielded spores are again consistent with VR.

The lowest maturation levels for this part of the Dublin Basin were detected in borehole 1327/1. VR ranges from 1.28% R_r at the top, to 1.60% R_r at the base of the section and increases linearly with depth ($r^2 = 0.83$). In terms of hydrocarbon generation, this borehole proved to be the most interesting, with the boundary between the base of the 'oil window' and the wet gas zone intersected at approximately 300 m depth. Samples above 300 m show positive fluorescence with dark orange colours indicating a position close to fluorescence extinction. Below 300 m no spore fluorescence was observed. The cut-off of fluorescence in this section correlates approximately with VR of 1.36% R_r . TAI increases from 3+ at the top of the borehole to 4-/4 at the bottom. Values of 3+/4- were recorded for spores in samples spanning the horizon of fluorescence extinction. The VR corresponds to medium and low volatile bituminous coals in terms of coal rank.

The investigation in the Kingscourt Outlier encompassed only Late Brigantian to Namurian strata. The location of the different sections studied is given in the map in Fig. 1. Figure 4 shows the range of VR values determined. The maturation levels are clearly dependent on the age of the strata with a progressive decrease of VR in the younger strata. VR increases from a mean value of 0.88% R_r in the late Kinderscoutian strata to a mean value of 1.23% R_r in Early Pendleian rocks. Spore fluorescence colour shows the typical 'red-shift' that characterizes increasing maturation levels, down section from yellow to dark orange colours close to the fluorescence cut-off point. Spore colours (TAI) darken from 2+ in the Kinderscoutian to 3+ in the Pendleian.

Discussion

Very similar VR gradients are seen in the four boreholes, especially in the sections with VR within the range 2-3% R_r (Fig. 5), suggesting that they were produced by the same maturation event and with the

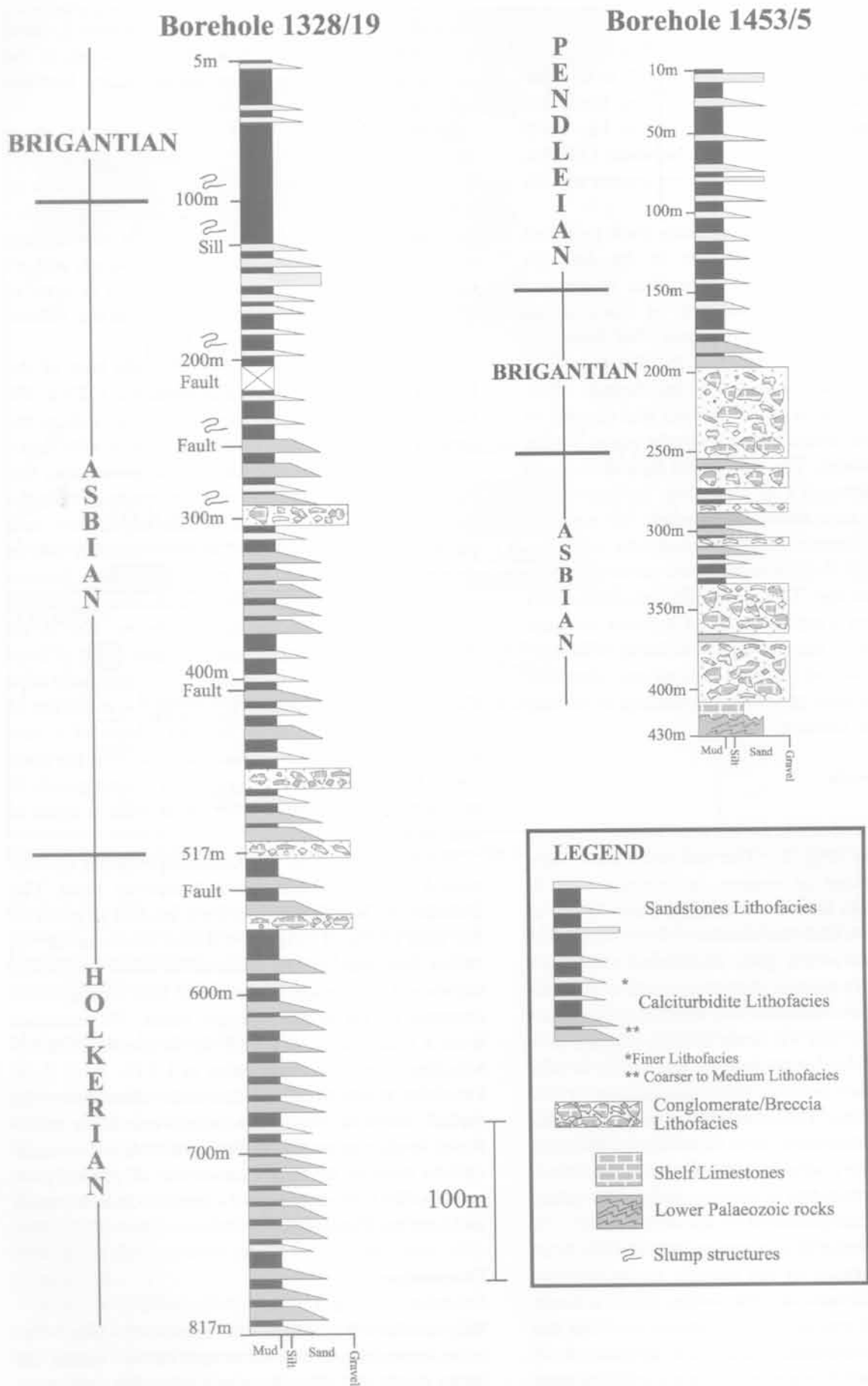


Fig. 2. General stratigraphy and lithofacies of the boreholes 1328/19 and 1453/5.

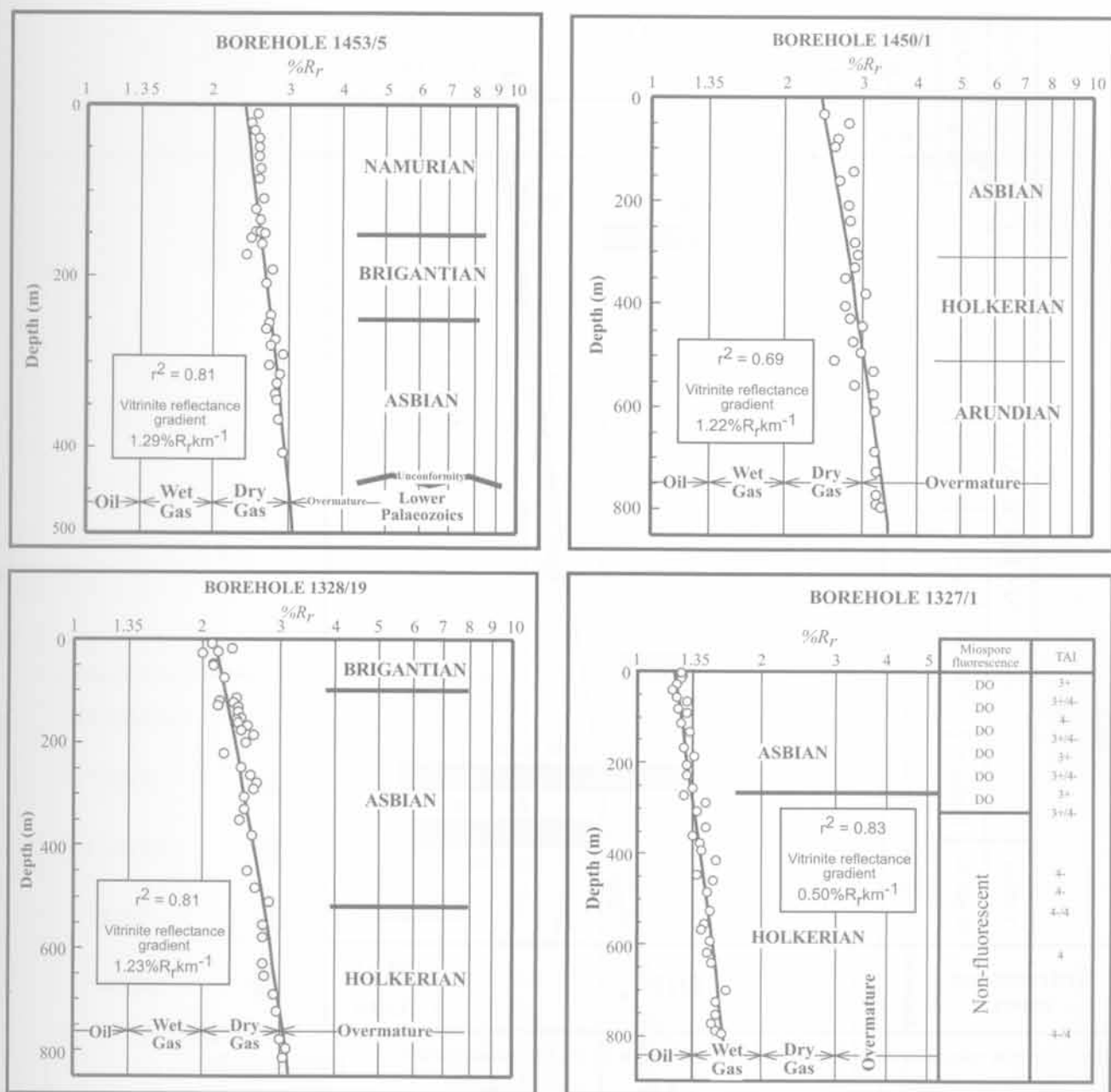


Fig. 3. Vitrinite reflectance profiles of the boreholes.

same regional geothermal gradient. Linear reflectance gradients often characterize sedimentary basins where maturation was achieved by continuous subsidence (Dow, 1977) with maturation levels primarily dependent on depth of burial.

The VR profiles were also used to estimate the amount of the eroded section. Using the method described by Dow (1977), which extrapolates the well-constrained gradients to 'zero coalification' (ca. 0.2% R_r), the amount of eroded section necessary to account for the maturation levels observed was estimated to be 4.4 to 5.8 km. Since this cover was late Viséan or younger and the thickness of the Namurian–Langsetian section is locally only 720 m, sedimentation probably continued through the Westphalian and

possibly the Stephanian. The considerable thickness of post Langsetian strata implied is consistent with the thicknesses of successions in Lancashire and the British Midlands, with a total composite thickness of Pennsylvanian rocks more than 3 km (Ramsbottom et al., 1978).

The four well-constrained VR profiles obtained also revealed high maturation gradients within the Mississippian rocks of the Dublin Basin. The gradients established range from 0.5 to 1.29% $R_r km^{-1}$ and are similar to gradients obtained for the Navan mine area (0.55 to 1.15% $R_r km^{-1}$) by Fitzgerald (1995). This supports the interpretation of high geothermal gradients as the principal cause for the maturation levels now observed in the north part of the Dublin Basin.

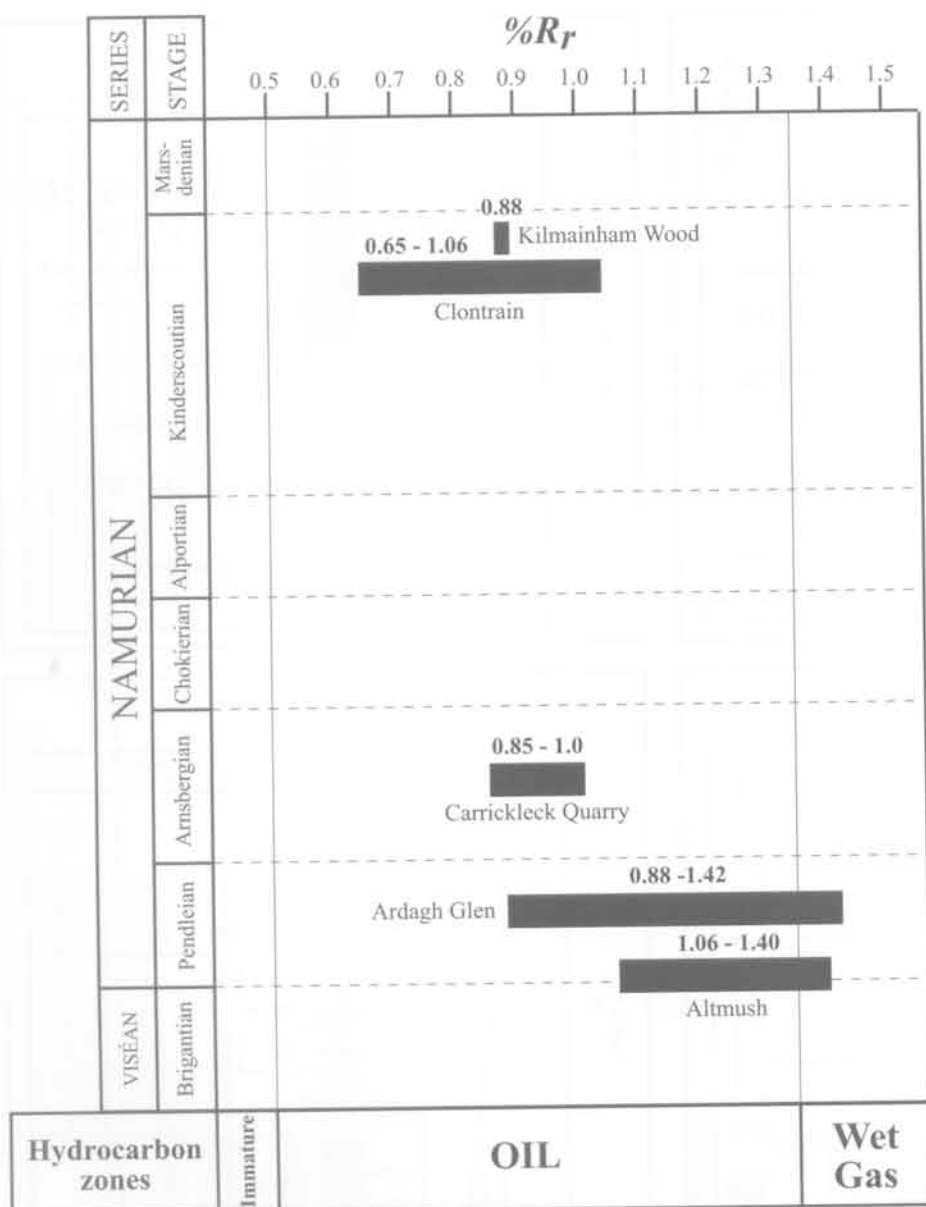


Fig. 4. Vitrinite reflectance range of values *vs.* age of the strata for the Kingscourt Outlier.

The regional stratigraphy and maturation levels observed in the Kingscourt Outlier provide additional data on the timing of maturation. Here, a basin inversion episode is recorded by the unconformity between the Pennsylvanian and the Upper Permian (Jackson, 1955, 1965). Maturation levels in the Pennsylvanian range from 1.40% R_r to 0.88% R_r , whereas those in the Late Permian are considerably lower at 0.38 to 0.46% R_r (Clayton et al., 1989). This evidence supports the hypothesis that maturation of the Carboniferous rocks was not due to Mesozoic but was a consequence of deposition of a significant thickness of Pennsylvanian strata in the northern part of the Dublin Basin. This thick Carboniferous succession was subsequently uplifted and largely eroded either following Variscan tectonism or a later tectonic episode.

Palaeogeothermal gradients were also calculated from the four boreholes studied using Barker and Goldstein's (1990) model based on correlation of VR with homogenisation temperatures of calcite fluid inclusions. These gradients range from 42°C km⁻¹ to 59°C km⁻¹ which are much higher than the present day geothermal gradient of ca. 20°C km⁻¹ in the Navan area determined by Brock & Barton (1984). Assuming a value of 52°C km⁻¹ as the average palaeogeothermal gradient for the Kingscourt Outlier, a post-Kinderscoutian eroded cover of 2.2–2.6 km was estimated. This value is regarded as the minimum value for the Variscan uplift in this region.

Igneous activity is often responsible for high geothermal gradients through long periods of time. Major igneous activity of Variscan age is not known in the area studied. However, important Permo-Carboniferous

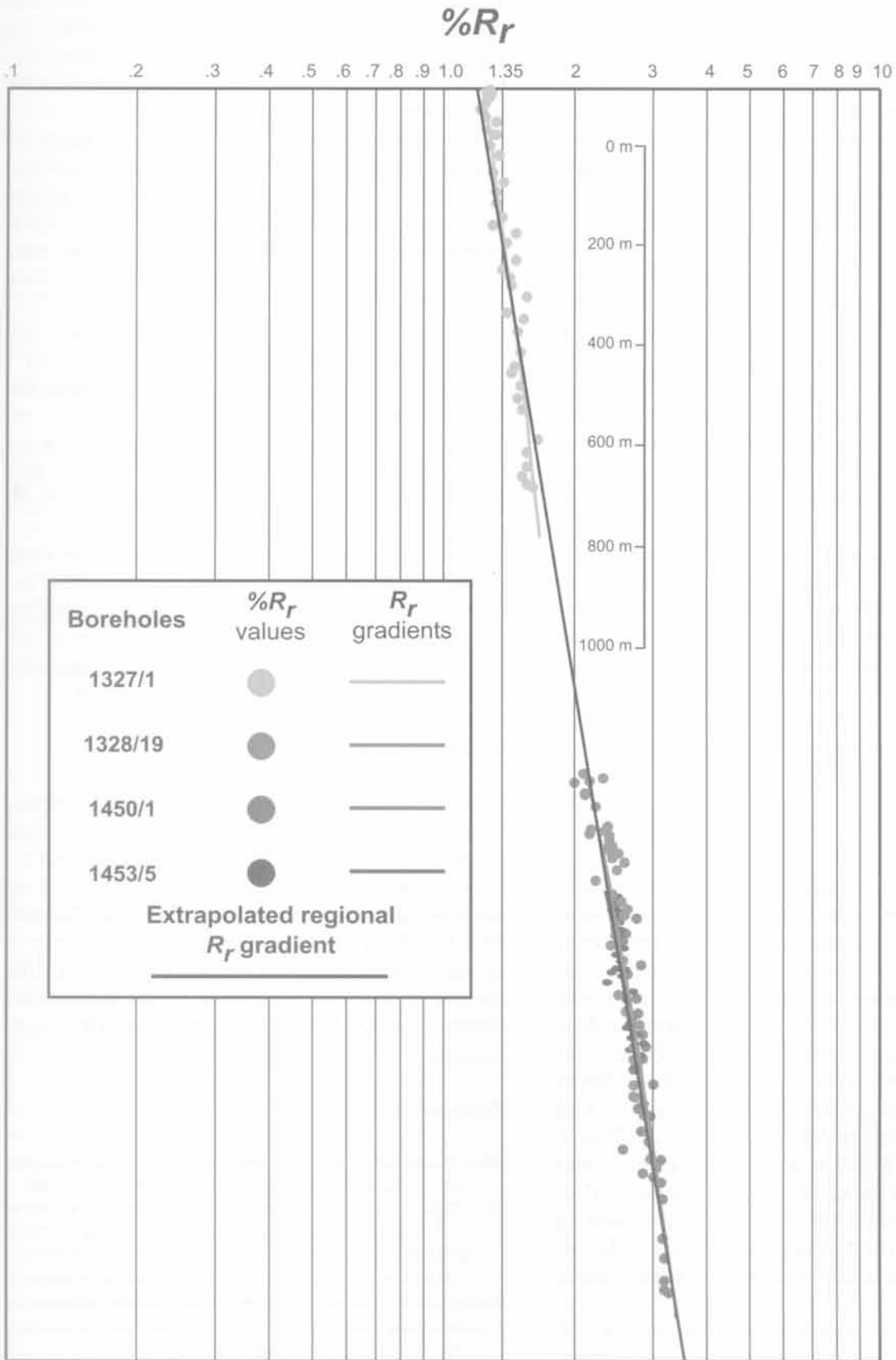


Fig. 5. Extrapolated regional vitrinite reflectance gradient for the north Dublin Basin.

throughout Northwest Europe has been suggested (Doblas et al., 1998) that might have been significant in the Central Irish Sea Basin (Corcoran & Clayton, 1999). Small to medium scale Tertiary sills and dikes in the Dublin Basin have produced only very localised effects upon organic maturation.

The palaeogeothermal gradients calculated are comparable to gradients characteristic of active sedimentary basins, especially basins that were formed by extensional processes (Robert, 1988; Allen & Allen, 1990). The stratigraphic record supports this, with several events indicating tectonic instability possibly related to extensional tectonics (Nolan, 1986, 1989). The timing of maturation and elevated palaeogeothermal gradients found for the Dublin Basin are also consistent with the hypothesis of a Late Carboniferous to Early Permian mantle plume beneath the Supercontinent Pangaea proposed by Doblas et al. (1998).

Deposition probably continued without break from the latest Carboniferous (Stephanian) into the Lower Permian in both the western and eastern offshore Irish Basins (Robeson et al., 1988; Corcoran & Clayton, 1999). Therefore, it is suggested that thick Late Carboniferous to Early Permian successions also probably accumulated in the Dublin Basin and Kingscourt Outlier. Maturation levels observed in the Dublin Basin were probably due to a combination of burial under a thick sedimentary cover (Carboniferous to Early Permian) combined with elevated Stephanian–Early Permian geothermal gradients.

Conclusions

Mean random VR (% R_r) measured from the boreholes increases gradually with depth, defining linear vitrinite reflectance profiles with good to fair regression lines. VR values from three of the boreholes studied are very consistent and increase with depth from approximately 2.0% to 3.3%. In the fourth borehole (1327/1), maturation levels are substantially lower, increasing with depth from 1.28% to 1.6% R_r . Spore colour (TAI) increases from 3⁺ to 4, consistent with the VR data. Outcrop VR values from the Dublin Basin range from 1.48% to 4.0% R_r and increase with increasing age of the strata. In the Kingscourt Outlier, R_r ranges from 0.65% to 1.42%, again showing strong correlation with the age of the strata. TAI values and fluorescence are consistent with the vitrinite reflectance data.

The maturation levels estimated for the Dublin Basin sections (both boreholes and outcrops) indicate that in most areas the rock units are overmature with regard to the oil window, and either lie within the dry-gas zone (2.0–3.0% R_r) or are overmature in re-

lation to all hydrocarbons (>3% R_r). However, the succession in borehole 1327/1 is a notable exception with the floor of the oil window intersected at around 200 m depth. Maturation data from the Kingscourt Outlier indicate a position within the oil-window for all the samples investigated.

The linear increase of maturation with the age of the stratigraphic succession observed both in boreholes and outcrop samples is typical of maturation related to burial. VR profiles from the boreholes indicate that between 4.4 and 5.8 km of post-Viséan cover was necessary to account for the current observed maturation levels.

Palaeogeothermal gradients for the boreholes, calculated from the VR results range from 42°C km⁻¹ to 59°C km⁻¹ and are considerably higher than the present day regional geothermal gradient of ca. 20°C km⁻¹. The estimated eroded covers obtained by the different methods are both consistent with the thickness of the relevant Pennsylvanian succession preserved in northwest England.

The maturation levels of the Carboniferous rocks in the area investigated were probably attained before Variscan uplift and erosion, possibly during Stephanian to Early Permian times. However, the possibility that maturation was caused by post Early Permian reburial cannot be totally discounted.

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