Geothermic Variscan front defined from oil drilling in the Porcupine Trough, offshore West Ireland

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Cornford, C. 2006. Geothermic Variscan front defined from oil drilling in the Porcupine Trough, offshore West Ireland. *Geoscience in south-west England*, **11**, 222-228.

Oil exploration drilling in the Porcupine Trough west of Ireland, has targeted Mesozoic reservoirs and inadvertently provided samples of sub-Variscan Carboniferous sediments. Drilling from the Tertiary and Mesozoic into the Carboniferous (the Permo-Trias is essentially missing), has shown a substantial break in the typical burial profile as monitored by the vitrinite reflectance technique in 6 wells. When drilling across the Variscan unconformity, changes are seen both in terms of the absolute level of maturity and its rate of change with respect to depth (i.e. the maturity gradient). These changes are related to the amount of section lost during late-Variscan (Stephanian-early Permian) erosion and the elevated heat flow values required to calibrate 1-D basin models. The elevated palaeo-heat flow of 125-138 mW/m^2 calculated for the maximum Variscan burial event may be related to a gravity-defined basic igneous body at basal crust-upper mantle level. Uplift in the range <500 – 3,200 m maps with a WNW-ESE trend arguably related to Variscan thrusting based on analogues with the Sticklepath and parallel faults of SW England. The low levels of background maturity in Westphalian strata places the Porcupine Trough north of the thermal Variscan Front while weaker evidence from the orientation of uplift places the study area south of the structural Variscan Front.

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Introduction

The late Carboniferous collision between the Gondwanan and Eurussian tectonic plates produced the so-called 'Variscan suture' which is mapped at outcrop as the Variscan Front (Figure 1). Different geological disciplines define an orogenic front by a variety of characteristics (Table 1). This means that there may be a number of Variscan fronts, each based on observation of its own controlling parameter. In Northwest Europe, organic maturity is one of the thermal factors that defines the Variscan Front.

Reflectance-based maturity studies south of the Variscan Front are limited (Cornford *et al*., 1987), but north of the Variscan Front where the late Carboniferous depositional conditions favoured coals, coal rank maps form the best overview of maturity (Teichmuller, 1985), with detailed studies relating to oil and gas exploration e.g. in the southern North Sea gas basin (Cope, 1986). Anomalously elevated maturities have been described to the north of the Variscan Front in north Germany (Bramsche Massif, Niedersachsen), where coal rank has been influenced by deep igneous intrusions (Buntebarth and Teichmuller, 1979; Stadler and Teichmuller, 1971).

This paper reports some results from a petroleum geochemical study of source rocks, generation, migration and accumulation in the northern sub-basin of the Porcupine Basin between latitudes 51.5°N and 53.0°N (Collinson Jones Consulting Ltd. *et al*., 1996). The general geology has been extensively reviewed (Croker and Klemperer, 1989; Croker and Shannon, 1987), and the deep structure of the Porcupine Trough has recently been defined from virtual field data (Readman *et al*., 2005).

As in other NW European basins, the Carboniferous may have significant hydrocarbon source potential, particularly for gas (Cornford, 1998). Very little is known about the structures affecting the Carboniferous in the Porcupine Basin. The offshore position of the Variscan Front is critical from a source rock point of view as there is unlikely to have been any post-Variscan generation from the metamorphosed zone to the south of the front. Opinions seem to differ widely as to whether the front can be recognised in the Porcupine area.

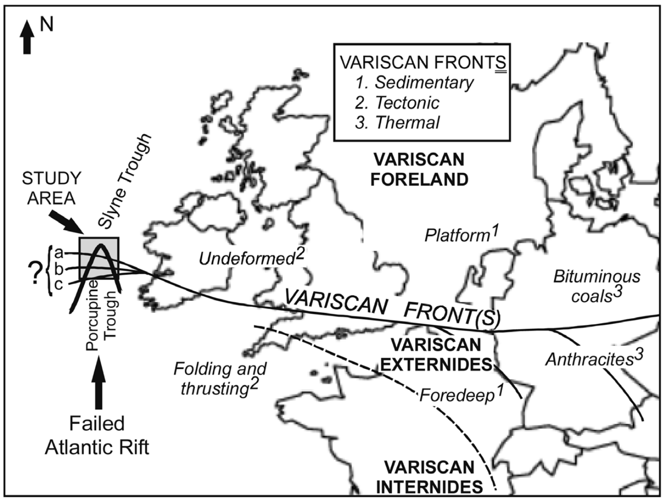

Figure 1. *Location of the Porcupine Trough study area in context of the Variscan Front of NW Europe.*

Control	Measurement	Comment
Thermal	Coal rank	Bituminous to the north, anthracites to the south
	Vitrinite reflectance	High reflectance to the south
	Illite crystallinity	High crystallinity to the south
Sedimentological	Platform v Basin	Carbonates and coals to the north and turbidites to the south
Structural	Deformation	Folded to the south and thrusting from the south versus stable shelf with undeformed and block faulted sediments to the north

Table 1. *Factors commonly used to define the Variscan Front in NW Europe.*

Max and Lefort (1984) suggest that the Variscan Front runs through the centre of the study area and is offset by a post-Variscan 130° dextral shear zone. The main evidence appears to be an E-W orientated magnetic feature on the Porcupine Bank at approximately latitude 52°40'. No evidence for this has been seen on seismic.

Present day maturity values of the pre-Mesozoic of the northern Porcupine Trough range from oil-mature to post gas-mature bordering in some cases on greenschist metamorphic grade. The mudstones in the TD core of well 35/15-1 are described as slightly cleaved by Robeson *et al.* (1988). These somewhat conflicting observations seem to place the area to the south of the Variscan Front. In contrast, where not overprinted during Mesozoic-Tertiary burial, the maturity gradients in all the pre-Mesozoic sections are high. This explains why maturity values in the Namurian and Lower Carboniferous are very high (2 - 6 %Ro), while Westphalian maturity values are substantially lower (typically 0.5 - 1.5 %Ro). These low values suggest that the Carboniferous at least in the northern part of the basin lies to the north of the Variscan metamorphic zone. The elevated maturities reported here are largely a function of high Variscan heat flow values coupled locally with variable amounts of uplift. This is arguably a parochial thermal/tectonic anomaly in generally low maturity terrain lying to the north of the thermal Variscan Front.

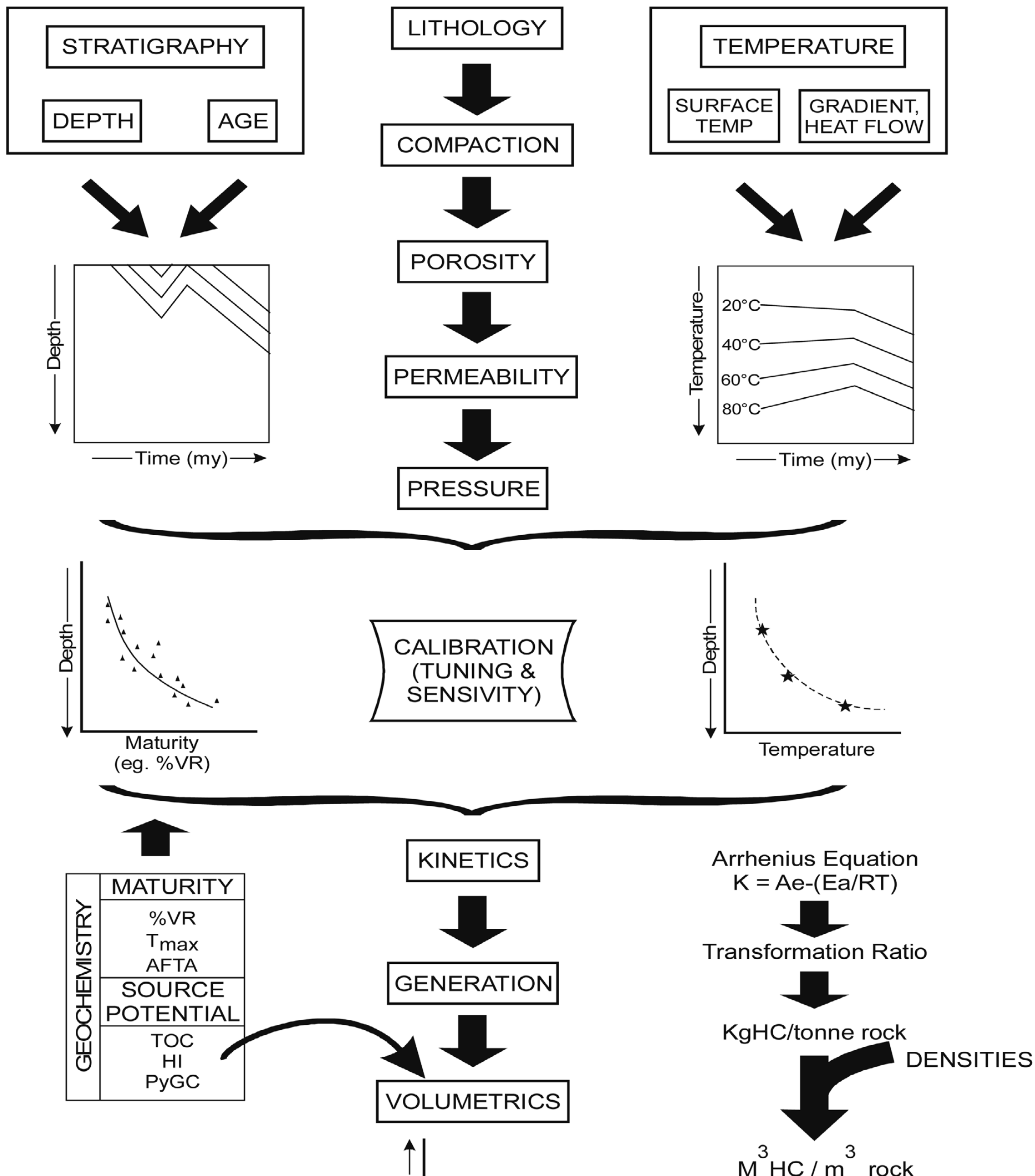

Figure 2. *Building burial history models from stratigraphic and thermal information to track the thermal history of each stratum (upper), calibration against measured temperatures and maturity data (middle), and the kinetic prediction of the amounts of oil and gas generated through time (lower).*

Thermal geohistory models

Part of the study required the building and calibration of 1-D thermal geohistory models (Figure 2). These models, run with commercial software (Platte River's BasinMod® 1-D package), track the burial history of all modelled strata, and with a knowledge of the present and palaeo-geothermal gradient, their thermal history. Knowing that oil is normally generated in the 110-155°C window (Cornford, 1998), this approach allows the prediction of both the depth of oil and gas generation at the modelled location, and the timing of entry of each stratum into the oil window. The objective of the project was to study oil and gas generation in the Mesozoic and Tertiary sections of the Porcupine Basin. However, a number of wells penetrated and sampled the pre-Mesozoic section. As is common offshore NW Europe, the wells are referred in terms of the 'Quadrant/Block–number' format.

An example of a thermal geo-history plot for a Porcupine well is shown in Figure 3. As with most wells, 26/28-1 was drilled on the crest of a large rotated fault block developed during the (failed) Jurassic rifting event prior to successful Atlantic opening to the west. The rapid late Jurassic uplift and subaerial erosion is based on the amount of truncation seen in the geo-seismic section through the well location, and not from any maturity break. In contrast the Variscan uplift is constrained by vitrinite reflectance calibration (see Figure 4).

Pre Mesozoic of the Porcupine Trough

Broadly the N-S Porcupine Trough and its northerly extension the Slyne Trough record a failed Mesozoic rift deriving from earlier attempts to form the North Atlantic. The Palaeozoic rocks form the rift shoulders, due to foot-wall uplift synchronous with Mesozoic basin subsidence. The failed rift appears to have dissected an east-west trending Carboniferous basin which arguably extends into the onshore Clare Basin and Shannon Trough (Croker, 1995). Thus, pre-Mesozoic rocks are mainly known from the margins of the Porcupine Trough where they have been penetrated by at least 11 wells (26/21-1, 26/26-1, 26/27-1b, 26/28-1, 26/28-2, 26/30-1, 34/5-1, 34/15-1, 34/19-1, 35/15-1 and 36/16-1). The two wells which sampled a sub-Carboniferous section recorded Carboniferous sedimentation on Caledonian (26/30-1) or older (26/26-1) basement. Unfortunately, not all these wells have been analysed to generate the maturity data required for thermal geohistory analysis.

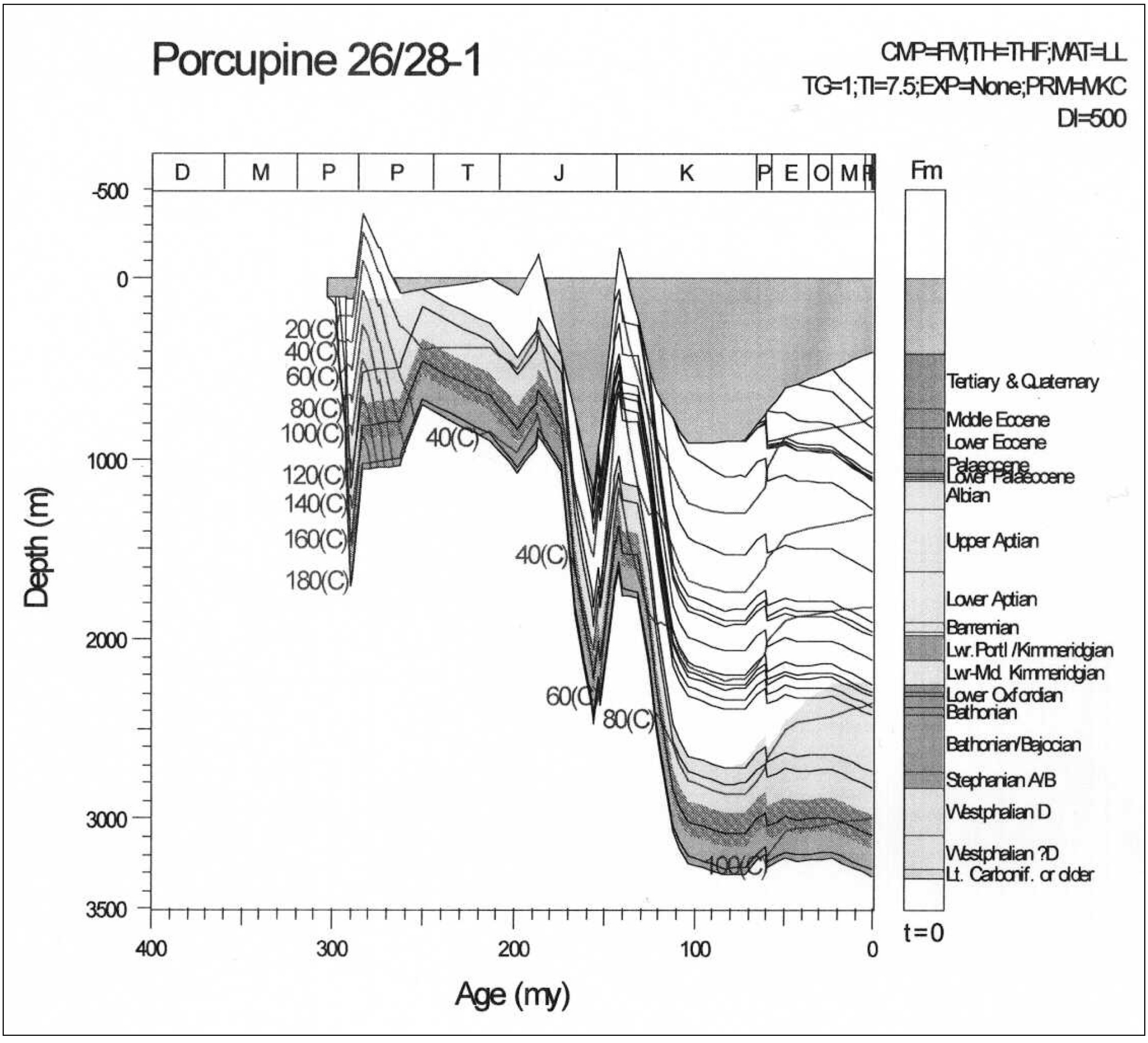

Figure 3. *Thermal geo-history for Porcupine well 26/28-1 drilled on the crest of a Jurassic rotated fault block - see Figure 4 for location.*

The most detailed account of the Carboniferous of the Porcupine area, based solely on well data, is given by Robeson *et al.* (1988) who propose that a very thick sedimentary sequence ranging from Dinantian to Stephanian-Autunian in age was deposited. Sediments dated as Stephanian to Autunian are known from the uppermost parts of the pre-Mesozoic in 26/28-1, 26/28-2 and 34/5-1, with possible sections of this age in 26/21-1, 34/19-1 and 34/15-1. Lithologies are typically grey to red claystones, siltstones and sandstones with thin limestones and occasional traces of anhydrite.

Westphalian Coal Measures form the most commonly encountered interval with penetrations in the Connemara Field wells (Block 26/28) and substantial sections reported in wells 34/5-1, 36/16-1 and 26/27-1b. Generally these consist of interbedded sandstones, shales and minor coals. The Namurian has only been seen in two wells; 26/26-1, where it is very thin, and 36/16-1. In the latter flank well the Namurian occurs in a dominantly argillaceous basinal facies. In both wells the Namurian is unconformably overlain by Westphalian, the maturity trends described in this report lending some support to this break. Dinantian (Lower Carboniferous) strata are seen in well 26/26-1, where they comprise limestones with thin shales, and sandstones near the base. In well 35/15-1, dubious Lower Carboniferous (or Devonian?) sandstones and siltstones with interbedded thin limestones and claystones are reported.

The six wells which contain Carboniferous sections together with maturity and temperature data for calibration are shown in Figure 4, where each well is posted with the amount of Variscan uplift (metres) and the heat flow operating during maximum Variscan burial.

TEMPERATURE DATA

Present day down-hole temperatures from 15 wells are shown in Figure 5, and show a typical present day geothermal gradient of ~35°C/km, but with extremes from 26 to 43°C/km. The present day heat flow values (inset) are derived from the combined effects of the thermal conductivity values of all modelled strata:

Heat flow (mW/m²) = Geothermal Gradient (°C/km) x Thermal Conductivity (W/m°C)

The thermal conductivity of each sedimentary unit is a function of both mineralogy which varies laterally with lithofacies, and porosity (i.e. compaction) which varies progressively with burial depth.

The apparent present day heat flow values show considerable variation with (generally) low values in the main trough, and high values on the shoulders of the rift. This is surprising as heat flow is, in principal, uniform this long after a crustal stretching event (i.e. the mid-late Jurassic failed rifting event). In addition, a simple crustal thinning model for rifting would predict higher and not lower heat flow in the trough axis. With Tertiary depo-centres defining the trough axis the observed heat flow distribution is attributed to lateral heat transport by continued de-watering of the thick clastic succession carrying convective hydrothermal heat to the basin margin.

The above discussion places limits on the present day heat flow, but there is evidence that the palaeo-heat flow, particularly that operating during the maximum burial event prior to Variscan uplift, was higher. Palaeo-heat flow can not be directly measured, but can be modelled via its effect on organic maturity parameters such as the reflectance of vitrinite, illite crystallinity and apatite fission track length length (Kosakowski *et al.*, 1999; McCulloch, 1993). The change in thermal gradient is mirrored in the maturity gradient as illustrated for the north-western well 26/28-1 in Figure 6. Fitting these higher pre-Variscan gradients to heat flow require values in the 125-138 mW/m² range (Figure 6). This compares with a background palaeo-heat flow value of 60 mW/m² used for similar modelling in the Frankenwald, Germany (Kosakowski *et al.*, 1999).

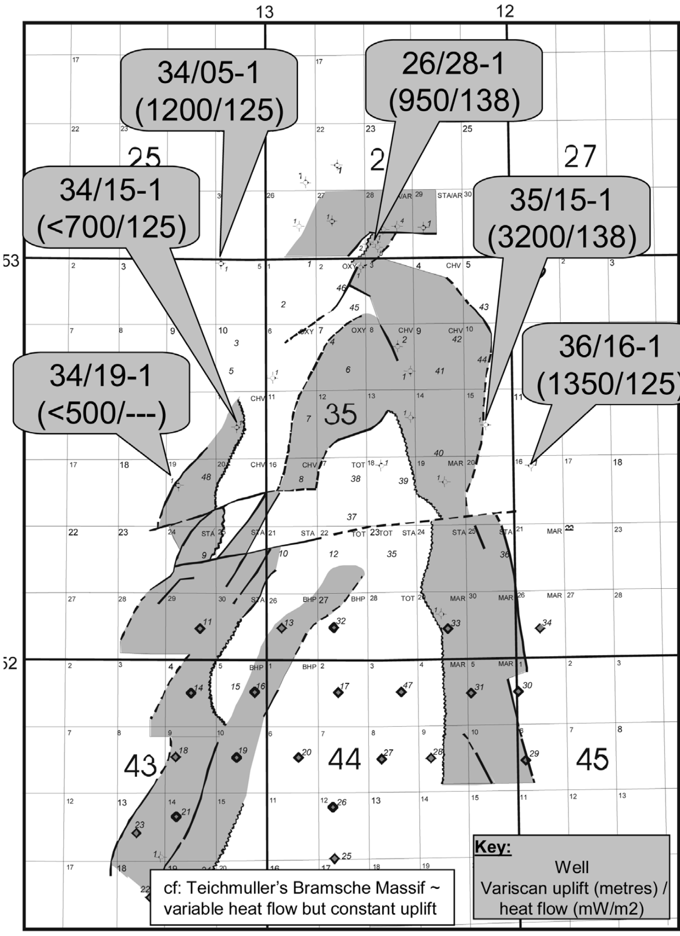

Figure 4. Location of north Porcupine wells with measured maturity data across the Variscan unconformity showing uplift (metres) and heat flow (mW/m²) required to fit the Variscan maturity break and maturity gradient within the Carboniferous.

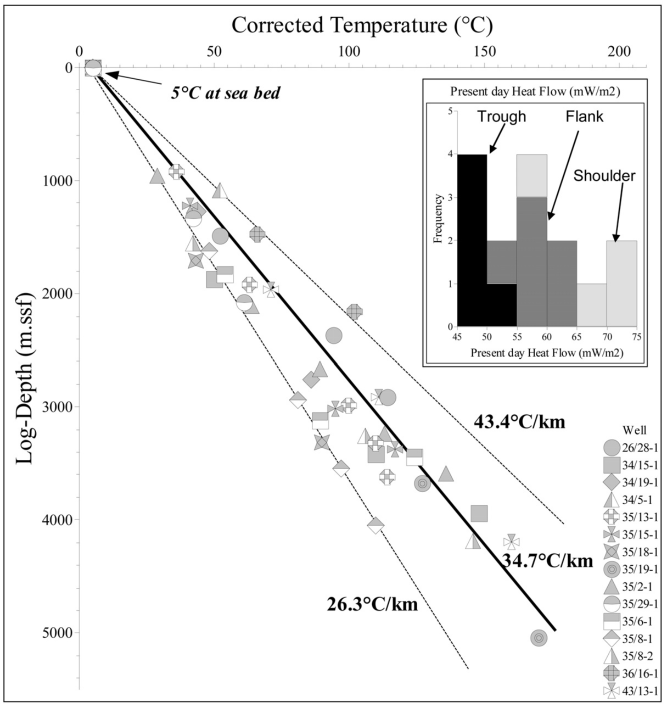

Figure 5. Plot of down-hole corrected temperatures (°C) versus depth (metres sub-sea floor) showing minimum, mean and maximum geothermal gradients, and (inset) histogram of the calculated present day heat flow values (mW/m²).

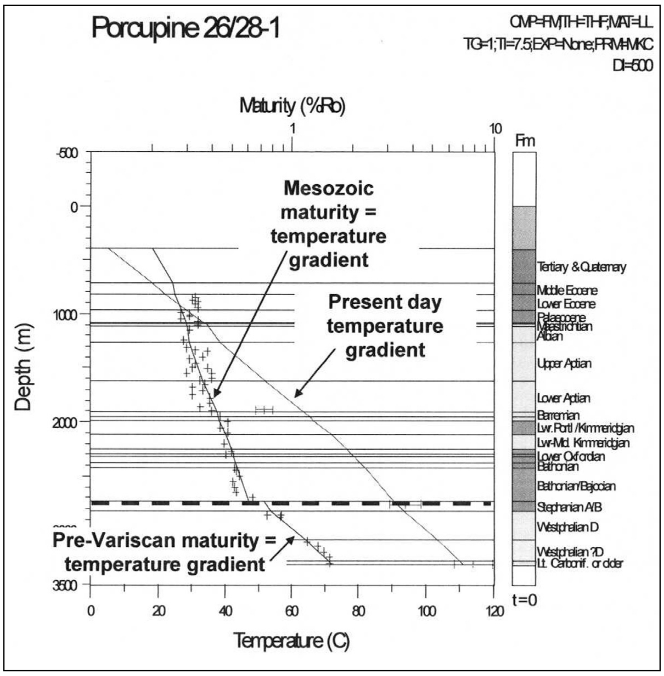

Figure 6. Thermal and maturity calibration of Porcupine well 26/28-1 showing the change in vitrinite reflectance gradient across the Variscan unconformity (dashed line).

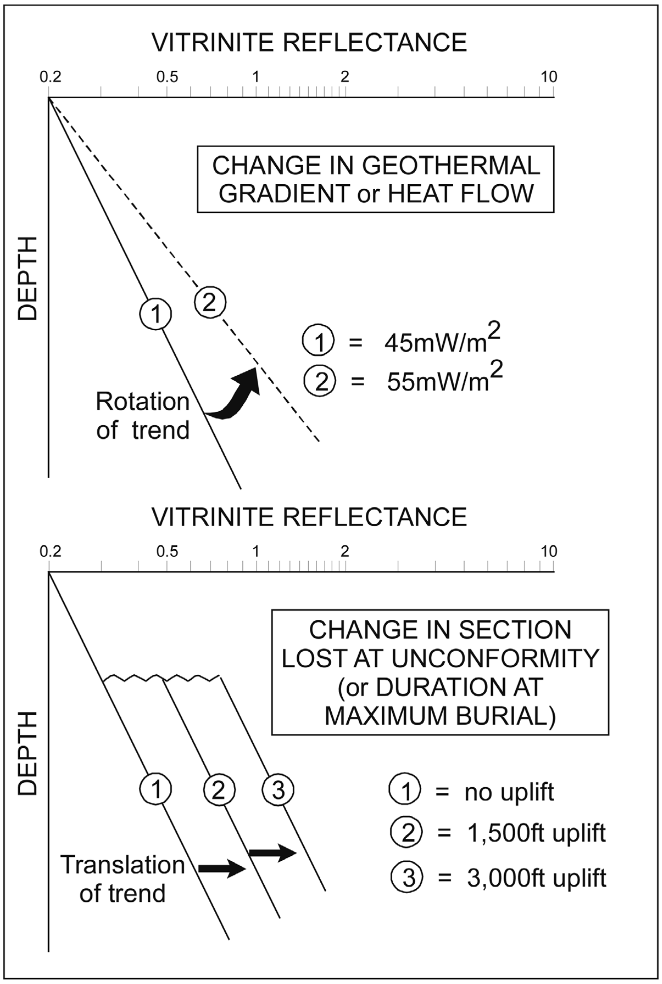

Figure 7. Discriminating between the rotation of maturity trends with change in heat flow and hence geothermal gradient (upper) and the translation of maturity trends at unconformity surfaces resulting from uplift and erosion (lower).

Maturity depth trends

Maturity-depth trends reflect the geothermal gradient (and hence broadly heat flow, see equation above) operating during the maximum burial event. The other major effect on the maturity values encountered below an unconformity is uplift and erosion. Figure 7 illustrates how maturity-depth plots differentiate between the change (rotation) in maturity gradient due to change in geothermics (upper) and the shift (translation) of the maturity gradient resulting from uplift and erosion (lower).

The typical maturity-depth gradient determined in the Carboniferous section of Porcupine wells is unusually high when compared with typical Carboniferous maturity gradients (Cope, 1986; Cornford *et al.*, 1987). This is reflected by the high modelled palaeo-heat flow values as shown for the six wells in Figure 4.

With respect to the continuity of maturity depth trends across the Variscan unconformity surface, the wells of the northern Porcupine Trough can be defined into three categories, (Figure 8, A, B & C). There is no evidence for thermal control at post Variscan unconformities (D). The first type of maturity profile (Figure 8A) shows both a change in gradient and translation (uplift) at the Variscan unconformity. This situation can occur with little Mesozoic-Tertiary burial or, where the Variscan erosion has bitten deeply into the Carboniferous section and exposed high maturity strata. In contrast, with less Variscan erosion and/or more Mesozoic-Tertiary burial, the elevated Variscan maturity values and gradients will be overprinted (Figure 8B). In some cases, the overprinting is complete (Figure 8C). It is noted that in no cases do wells show any maturity discontinuity at the break-up unconformity between the Middle Jurassic and overlying Jurassic or Cretaceous layers (Figure 8D).

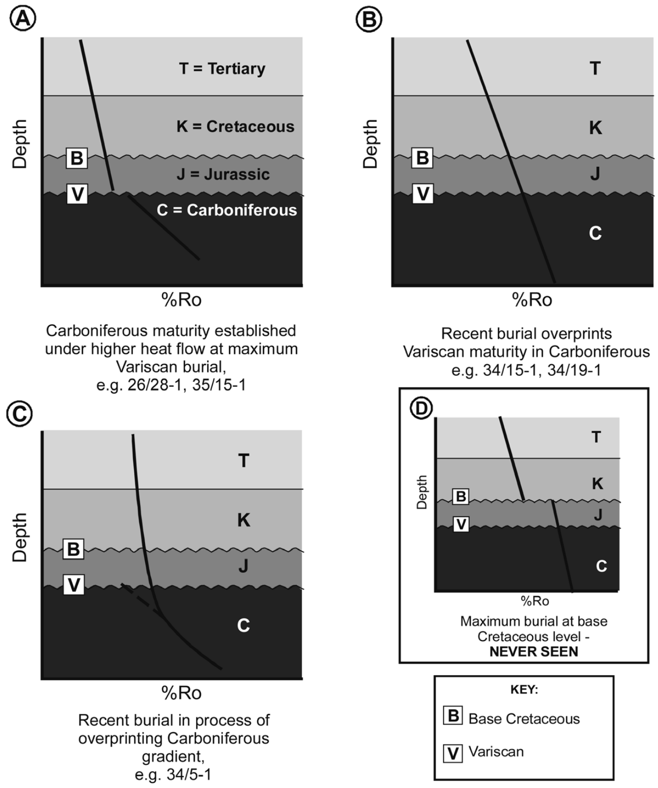

*Figure 8. Classification of wells into (**A**) wells with both change in gradient and uplift at the Variscan unconformity, (**B**) wells showing Mesozoic and Tertiary burial in the process of overprinting Variscan maturity and (**C**) wells showing total overprinting by Mesozoic and Tertiary burial. Maturity breaks across unconformities within the Mesozoic and Tertiary (**D**) are never seen.*

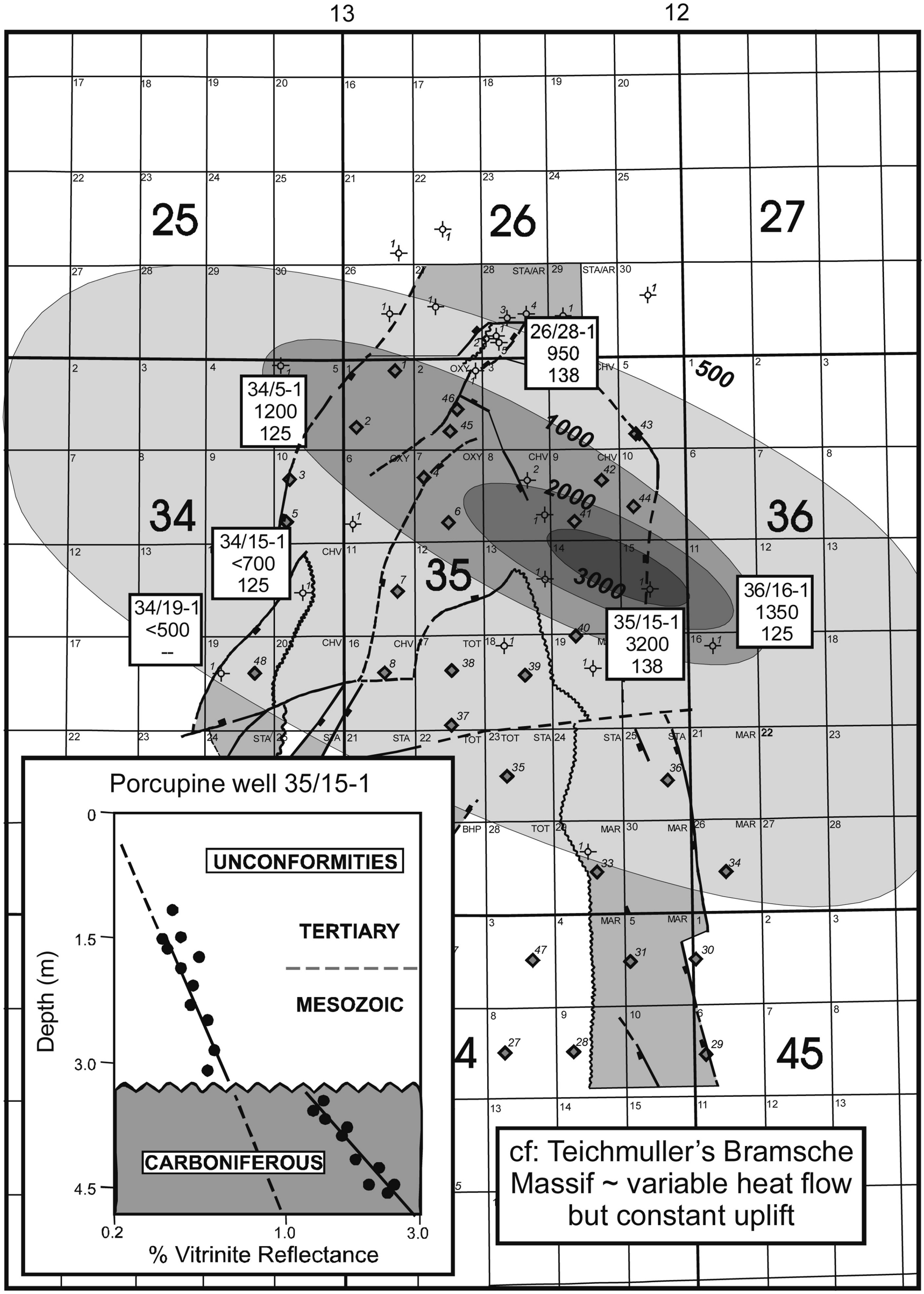

Figure 9. *Cartoon illustrating the distribution of uplift at the Variscan unconformity for wells of the northern Porcupine Trough.*

Mapping pre-Mesozoic maturity gradients

Mapping out the pre-uplift heat flow (i.e. the heat flux at maximum Variscan burial), and the uplift required to calibrate the maturity gradients observed in the Carboniferous sections shows the former to be essentially constant (125-138 mW/m^2), and the latter to suggest concentric contours (Figure 9). Given only six modelled wells, the contouring can only be considered as one possible explanation of the observed uplift values. The contours suggest an uplifted elongate dome with an east-southeast – west-southwest axis sub-paralleling the anticipated Variscan strike, and sinestral fracture zones arguably reactivating the Variscan structural trend (Masson and Miles, 1986; Readman *et al*., 2005).

Based on gravity modelling, Readman *et al.* (2005) have suggested that the northern sector of the Porcupine Trough is underlain by a dense sepentinised peridotite body at the lower-crust or upper mantle level, and that this body was exhumed during Mesozoic extension. This implies the igneous body pre-existed Mesozoic rifting. If the body was present during the maximum Variscan burial event, then it would explain the observed elevated heat flow.

Discussion and conclusions

Calibrating maturity profiles across the Variscan unconformity in six wells in the northern Porcupine Trough demands both an unusually high heat flow at maximum Variscan burial and variable Variscan uplift across the area. Previous studies of maturity anomalies associated with the Variscan Front have been described for Niedersachsen north of the Variscan Front (Buntebarth and Teichmuller, 1979) and Frankenwald within the fore-deep basin (Kosakowski *et al*., 1999), both areas being in Germany. In both cases the anomalies form closed maturity contours as possible with the limited Porcupine data; both the German interpretations attribute the maturity-depth anomalies to locally elevated heat flow associated with intrusions rather than differential uplift and erosion. In the Porcupine data both effects are seen. In contrast, the maturity of the country rocks into which the granites of Southwest England are intruded show minimal elevated heat flows (very thin organic thermal aureole), with intrusion into a previously matured rock mass (Cornford *et al*., 1987).

Recent gravity data have been used to argue for a dense igneous body at lower-crust to upper mantle level in the northern Porcupine Trough from latitude ~51.6 to ~52.4°N (Readman *et al*., 2005). Though Readman and co-authors assume that this igneous body was associated with Cretaceous (Santonian) opening of the Porcupine Trough, the observed maturity anomalies reported here suggest that this body was emplaced during the latest Variscan prior to uplift and erosion. Indeed it has been suggested that Atlantic rifting may have initiated in the late Variscan (Rotliegendes) and that a proto-Porcupine Trough contained oceanic-transitional crust of this age (Haszeldine, 1984).

As to the uplift observed, the orientation of this feature relates to the NW-SE wrench fault zones observed to cut the Porcupine Trough, with one arguably truncating the dense igneous body (Readman *et al*., 2005). In the case of the long-lived NW-SE faults cutting SW England (e.g. Sticklepath Fault), Pembroke and southern Ireland (Ruffell and Carey, 2001), these may be Mesozoic reactivations of Variscan thrusts. This tentative evidence places the Porcupine Trough south of the structural Variscan Front.

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