Post-Carboniferous burial and exhumation histories of Carboniferous rocks of the Southern North Sea and adjacent Onshore UK

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SUMMARY

Previous AFTA studies in the UK Southern North Sea and adjacent onshore areas have generated considerable discussion, particularly concerning the timing and magnitude of additional burial and subsequent uplift and erosion. New AFTA and VR results confirm and extend the conclusions of these earlier studies. In the Southern Pennines, Carboniferous strata cooled from maximum palaeotemperatures around 100°C or more in Late Palaeozoic time, and from a peak palaeotemperature ~80°C in Early Palaeogene times. For reasonable palaeogeothermal gradients, this palaeotemperature suggests burial by 1-2 km of Late Palaeozoic and Mesozoic rocks prior to Cainozoic exhumation. New AFTA and VR data from offshore well 47/25-1 also show that rocks of Carboniferous to Upper Cretaceous age were buried more deeply prior to exhumation which began between 90 and 40 Ma. Data from neighbouring wells refine this timing to between 65 and 55 Ma. Combining the AFTA and VR data from the 47/25-1 well with sonic velocity-based constraints on palaeo-burial suggests that an additional 800 ± 200 metres of section were deposited in 30 million years or less, prior to the onset of exhumation in Palaeocene times. A distinct Neogene phase of exhumation is not resolved from these data, although regional evidence suggests a significant proportion of the total missing section may have been removed during Neogene times. "Palaeo-burial" of Carboniferous source rocks and their subsequent exhumation, recorded in AFTA, VR and sonic velocity data from the Southern North Sea, has played an important role in defining and shaping the occurrences of hydrocarbons across the region.

Reconstructing the post-depositional evolution of sedimentary sequences, in terms of both thermal histories and histories of burial and subsequent exhumation, is important for a variety of reasons including e.g. understanding the history of hydrocarbon generation and migration, diagenetic changes and their impact of reservoir properties, formation of mineral deposits and the structural and tectonic development of sedimentary basins. The role of palaeo-thermal indicators such as apatite fission track analysis (AFTA®) and vitrinite reflectance (VR) in providing such information has recently been reviewed by Green et al. (2002). The particular benefit of AFTA is that it not only constrains the magnitude of palaeo-thermal effects but also provides direct estimates of the timing of major cooling episodes.

The ability to obtain independent, objective constraints on the timing, as well as the magnitude, of exhumation episodes is particularly useful in reconstructing histories of sedimentary sequences containing major unconformities, where the incomplete nature of the section precludes reconstruction of the entire history based solely on preserved geological evidence. Cainozoic strata are missing across most of the UK Southern North Sea and adjacent onshore areas (Figure 1), and the age of sedimentary rocks at outcrop or sea bed increases from Late Cretaceous to Carboniferous in an east – west direction from the Sole Pit Axis to the Southern Pennines. In this area, therefore, AFTA can contribute significantly to reconstructing thermal histories in the preserved sedimentary section, particularly in providing control on events during intervals for which strata of the corresponding depositional age are not present.

A number of AFTA studies in the Southern North Sea and adjacent onshore area have been published, with somewhat controversial results. In the following, we first review these previous studies and the resulting discussion, and then present new data from the region, which confirm the conclusions drawn from those earlier studies and shed further light on the nature of underlying processes. The results have clear implications for the hydrocarbon prospectivity of the region, as well as other aspects listed above.

1. PREVIOUS AFTA STUDIES

Application of AFTA to samples from outcrops and hydrocarbon exploration wells on the East Midlands Shelf (EMS) and to samples from the UK Southern North Sea (SNS) wells has shown that the sedimentary section in this region has experienced major Cainozoic cooling (Green 1989, Bray et al. 1992, Green et al. 2001). Results in sedimentary rocks of Carboniferous to Triassic age from outcrops on the onshore EMS reveal cooling from palaeotemperatures between 70 and 90°C beginning some time between 65 and 55 Ma (Palaeocene). Results from sub-surface samples confirm this episode and also provide improved definition of the cooling history, revealing an additional subsequent cooling episode from lower peak palaeotemperatures which began some time between 25 and 5 Ma (Miocene). Vitrinite reflectance (VR) data from Carboniferous units in EMS wells are highly consistent with the Palaeocene palaeotemperatures defined by AFTA (Bray et al. 1992, Green et al. 2001), and it is clear that in these wells, Carboniferous units cooled from their maximum post-depositional palaeotemperatures in Palaeocene times, which effectively dates the termination of active hydrocarbon generation from Carboniferous source rocks in the region.

Attempts to understand the mechanisms responsible for the elevated Palaeocene palaeotemperatures and subsequent Cainozoic cooling, and also the exact timing at which cooling began, have been the subject of some discussion. Green (1989) reported that AFTA data in five EMS wells suggested that Palaeocene palaeogeothermal gradients were indistinguishable from present-day values, and that between 1 and 2 kilometres of section has been removed from the region by Cainozoic uplift and erosion. Bray et al. (1992) came to a similar conclusion, on the basis of a more rigorous statistical analysis of palaeotemperatures derived from AFTA and VR data from these wells. Bray et al. (1992) also reported that similar effects had been detected in wells from the offshore (SNS) portion of the EMS.

Although results of sonic velocity studies of wells in the region (Hillis 1991, 1993) supported the estimates of Cainozoic exhumation derived from AFTA and VR data, Holliday (1993) and Smith et al. (1994) considered these amounts to be unrealistically large, on the basis of regional geological trends. These concerns were echoed more recently by Holliday (1999). Specific comments included doubts about the validity of extrapolating linear palaeogeothermal gradients to estimate removed section, questions concerning the most appropriate values of palaeo-surface temperature, and, on the basis of criticisms by McCulloch (1994) which were shown to be erroneous by Green et al. (1995a), the precise timing at which cooling began.

Despite these concerns, subsequent work has supported the conclusions of these early AFTA studies. The general validity of the approach employed in the EMS wells has been confirmed by application to controlled situations in various parts of the world, where geological evidence provides independent constraints on both the amount of removed section and the timing of cooling. In such situations, estimates from AFTA are highly consistent with the independent geological constraints (e.g. Green et al. 1995b, Crowhurst et al. 2002), suggesting that the approach can be used with confidence in less well controlled settings.

More specifically, reassessment of AFTA data from the Rufford-1 well (Green et al. 2001), located on the onshore EMS, has confirmed both the Palaeocene timing for the onset of cooling and the requirement for around 1450 metres of post-Triassic cover removed during Cainozoic exhumation, much of which may have been removed during the Neogene. This most recent interpretation employs a palaeo-surface temperature of 20°C, as suggested by Holliday (1993), coupled with a Palaeocene palaeogeothermal gradient which is around 30% higher than the present-day value. Both these factors serve to reduce the amount of additional section required to explain the observed Palaeocene palaeotemperatures from those originally estimated by Green (1989) and Bray et al. (1992), although the amounts are still higher than suggested simply from regional geological tends which would suggest a maximum of around 800 to 900 metres (Green et al. 2001). Reasons for this discrepancy are the subject of ongoing investigations in the region.

The identification of significant Neogene exhumation in the results from the Rufford-1 well (Green et al. 2001) is consistent with the suggestion by Japsen (1997) that much of the

Cainozoic exhumation in and around the UK Southern North Sea may have taken place during the Neogene, although the suggestion by Japsen (1997) that Palaeocene exhumation was restricted principally to onshore areas is shown to be incorrect by the results presented here.

Recent AFTA results from the Lake District of NW England (Green 2002) have also confirmed previous results from that region (which were also the subject of some discussion), and have finally provided a geologically plausible explanation of Palaeocene palaeotemperatures in that region as due to a combination of elevated basal heat flow and moderate amounts (generally between 700 and 1550 metres) of additional Late Palaeozoic to Mesozoic burial (with Cainozoic cooling due to subsequent exhumation and reduction in heat flow). In this context, the results from the EMS and SNS, discussed above, form part of a highly consistent regional picture.

With results from a variety of sources pointing to a consistent regional framework, the present study was undertaken in order to eliminate some of the remaining areas of uncertainty regarding the magnitude and mechanisms of Cainozoic palaeo-thermal effects across the region shown in Figure 1.

2. NEW DATA FROM THE SOUTHERN PENNINES

Despite the apparent consistency of a number of studies and growing acceptance of the concept of significant Cainozoic exhumation onshore, doubts about the validity of the interpretation of AFTA data have persisted (Holliday 1999), and some studies continue to discount the significance of Mesozoic burial in the region. This is particularly pronounced in the region of the Southern Pennines which, despite published evidence from AFTA of Early Tertiary palaeotemperatures up to 80 or 90°C at outcrop (Green 1989, Green et al. 2001), is commonly interpreted as a stable high during Mesozoic and Cainozoic times in palaeogeographic reconstructions (Cope et al. 1992, Fraser & Gawthorpe 1990, Fraser et al. 1990, Ziegler 1990). Studies related to mineralisation and hydrocarbon generation in this region have also downplayed the significance of Mesozoic or Cainozoic events, generally favouring palaeotemperatures around 60°C or less over the last 200 million years (e.g. Plant et al. 1988). Other workers have ignored any consideration of the likely magnitude of post-Carboniferous palaeo-thermal effects (e.g. Hollis 1998, Hollis & Walkden 2002), presumably based on the assumption that any such effects are insignificant.

To emphasize the importance of Early Tertiary effects in the Southern Pennines, new AFTA and VR results are presented (Tables 1, 2) from the Namurian Mam Tor Sandstone and Edale Shales, collected from the vicinity of Mam Tor, near Castleton on the northern flank of the Derbyshire Dome (Figure 1). The principles involved in application of AFTA and VR, and the extraction of thermal history solutions from these data, have been outlined elsewhere (e.g. Green et al. 2001, 2002, Crowhurst et al. 2002), and are not repeated here. AFTA data from two samples of Mam Tor Sandstone are illustrated in Figure 2, together with the resulting thermal history solutions. Note that AFTA does not constrain the entire thermal history of the host rock. Rather, the data are dominated by the major palaeo-thermal events that have affected the sample, and extraction of thermal history solutions from the data are designed with this in mind (Green et al. 2002).

In both samples, the AFTA data clearly require at least two major episodes of heating and cooling, as illustrated in Figure 2. In each sample, the earlier event is required to explain the fission track age data, with apatite grains over a range of Cl contents (up to 0.7 wt% Cl in sample RD41-47) giving ages which are consistently younger than the value expected if the sample has not been significantly heated since deposition (horizontal bars in the age vs Cl plots in Figure 2). Both the pooled fission track age of 211 ± 10 Ma in sample RD41-47 and the central age of 158 ± 14 Ma in sample RD41-46, are much younger than the depositional age of the host rock, again showing that the samples must have been much hotter at some time in the past. Evidence for the more recent event in each sample comes from the track length data. Comparison of the measured length distributions with those expected if the samples have remained at near-surface temperatures since deposition (Figure 2) shows that a large proportion of the tracks in each sample are shorter than expected on this basis, although a smaller proportion of tracks do have lengths closer to the expected range, suggesting that the samples have indeed spent some time at temperatures close to surface values.

Details of the thermal history solutions for each sample are listed in Table 2 and illustrated in Figure 2. Sample RD41-46 reached a maximum palaeotemperature between 100 and 110°C from which cooling began some time between 290 and 220 Ma, while sample RD41-47 reached a maximum palaeotemperature in excess of 110°C and began to cool between 240 and 180 Ma. Results from sample RD41-46 suggest a subsequent peak palaeotemperature of 80 to 90°C from which cooling began some time between 80 and 40 Ma, while for sample RD41-47 the data suggest a peak palaeotemperature of 75 to 85°C from which cooling began some time between 90 and 30 Ma.

As these two samples were taken from outcrops separated by a distance of only some tens of metres, they can be combined to suggest that cooling in the two events began in the intervals 240 to 220 Ma and 80 to 40 Ma, with respective peak palaeotemperatures of 100 to 105°C and 80 to 85°C. Mean VR values measured in four samples of Edale Shales immediately underlying the Mam Tor Sandstones are between 0.53 and 0.57%, equivalent to a maximum palaeotemperature of 88 to 94°C (Table 2). These values are lower than the corresponding estimates from AFTA, which is thought to be due to suppression of reflectance levels in these samples. Such effects are common in carbonaceous shales rich in hydrogen and/or sulphur (see discussion and references in Green et al. 2002), and have previously been identified in the Bowland Shales of Namurian age in the Irish Sea region by comparison of VR data with AFTA data in adjacent sandstones (Green et al. 1997).

The estimated timing for the onset of cooling from maximum palaeotemperatures in the Mam Tor Sandstones, at 240 to 220 Ma (Early to Mid-Triassic), is significantly later than the end-Carboniferous (~300 Ma) timing generally believed to apply to the Southern Pennines (e.g. Plant et al. 1988, Ewbank et al. 1995, Hollis 1998). This may simply reflect protracted cooling following Variscan tectonism. In this regard, it may be significant that AFTA data from the Apley Barn Borehole in the Oxfordshire Coalfield (Green et al. 2001) also showed cooling from palaeotemperatures in excess of 110°C some time between 270 and 245 Ma, distinctly later than Variscan (end-Carboniferous) events, which could be taken as evidence in support of protracted post-Variscan cooling. However, some aspects of regional geology suggest that the Carboniferous rocks of the Southern Pennines were close to the surface in Triassic times (P. Gutteridge, pers comm. 2002), which would suggest that the cooling seen in the AFTA data must be due to processes other than burial. An alternative explanation may be hydrothermal effects during Late Triassic – Jurassic times, for which a considerable body of evidence has been provided from K-Ar dating of clays associated with mineral deposits in the Southern Pennines and Northern England (Ineson & Mitchell 1972, Mitchell & Ineson 1988). In this case, palaeotemperatures associated with this event would have obliterated any Variscan effects in the AFTA data.

Evidence from AFTA for the more recent cooling event is more straightforward, with combined results from both samples consistent with cooling from 80 to 85°C some time between 80 and 40 Ma. This timing is consistent with the Palaeocene cooling event recognised from AFTA over a wider area of central and northern England (reviewed earlier), and the range of palaeotemperatures is similar in magnitude to values derived from AFTA data in other samples from the eastern flank of the Southern Pennines by Green (1989) and Green et al. (2001). For likely values of palaeogeothermal gradient (say 30 to 50°C/km), this palaeotemperature range suggests appreciable burial (1.2 to 2 km, assuming a Palaeocene palaeotemperature of 20°C) prior to Cainozoic exhumation, which is consistent with previously published results from wells and outcrop locations to the south.

As discussed earlier, previous studies have favoured an interpretation of the Southern Pennines as a long-term high since end-Carboniferous times, with the region receiving little or no sedimentary cover during the Late Palaeozoic and Mesozoic times. However, the results presented here suggest instead a history more similar to that recently advocated for the Lake District block (Green 2002), involving a former cover of up to 1 km or more of Late Palaeozoic and Mesozoic sediments, subsequently removed during Cainozoic exhumation. Such an interpretation is supported by sonic velocity data from wells onshore to the east of the

Southern Pennines (Whittaker et al. 1985) which clearly show a trend in estimates of “post-Cretaceous uplift” (more strictly “exhumation”) increasing from east to west and reaching values around 1.5 km immediately to the east of the Southern Pennines.

This trend of course also implies prior burial by corresponding thicknesses of cover rocks which, combined with the evidence from AFTA presented here, suggests the former presence of a continuous cover of Late Palaeozoic and Mesozoic sediments over the entire region. This implies, in turn, that all of the present-day upland regions of Northern England were probably completely submerged by the Chalk, in sharp contrast to conventional depictions of the Late Cretaceous palaeogeography of the region (Cope et al. 1992, Fraser & Gawthorpe 1990, Fraser et al. 1990, Ziegler 1990).

3. NEW RESULTS FROM SOUTHERN NORTH SEA WELL 47/25-1

Recently, a detailed investigation of sonic velocity data from wells in the Southern North Sea by Japsen (2000), in which results from both Late Cretaceous (Chalk) and Triassic units gave very consistent estimates of missing post-Chalk section across the EMS, has provided an excellent framework for reassessment of the AFTA data from the offshore region. AFTA and VR data from one offshore well (47/29a-1) were discussed by Bray et al. (1992). However, further investigation of the AFTA data from the 47/29a-1 well suggests that the deeper samples from that well are badly affected by contamination from an unknown source, and for this reason, we focus here on results from well 47/25-1 from a location nearby (Figure 1). While no VR data are available from the Carboniferous section intersected in this well, results from adjacent wells show that VR data provide estimates of maximum palaeotemperature which are highly consistent with those derived from AFTA, and therefore the results from AFTA in well 47/25-1 can be used with confidence to reconstruct the thermal history of Carboniferous source rocks in the region.

AFTA data from the 47/25-1 well are summarized in Table 1, and fission track ages measured in five samples are plotted against depth (below KB) in Figure 3. Also shown in this Figure are the trends of fission track age against depth for selected apatite Cl contents, predicted from the "Default Thermal History". This is the thermal history scenario derived from the preserved sedimentary section and the present-day thermal gradient, and is therefore based on the assumption that units throughout the section are currently at their maximum temperature since deposition. This forms the starting point for thermal history interpretation of AFTA and VR data, as explained in greater detail by e.g. Duddy & Erout (2001) and Green et al. (2002). Fission track ages from the two deepest samples are clearly less than the values predicted from the Default Thermal History, even for the most sensitive compositions (zero Cl), showing that the sampled units have been hotter in the past. Fission track ages in the shallower samples are older than the values predicted from the respective Default Thermal Histories, showing that these samples contain tracks formed prior to deposition, and have not been heated to palaeotemperatures sufficiently high to produce severe age reduction. But investigation of the track length data in these samples (not illustrated here) also shows that they must have been hotter than the present-day temperatures at some time after deposition.

The relationship between fission track ages of individual apatite grains and chlorine content are also shown in Figure 3 for the two deepest samples. In these plots, the horizontal black lines show the trends predicted from the Default Thermal History scenario. In sample GC290-5, apatites containing between 0.0 and 0.3 wt% Cl give ages which are significantly less than the predicted values, while apatites with higher Cl contents give older ages, closer to the expected values. This reflects the greater sensitivity of the lower Cl grains, which are more easily reset than the higher Cl grains. In sample GC290-6, all single grain ages are less than predicted, while the single grain containing almost 0.7 wt% Cl has undergone less age reduction than the lower Cl grains. These observations again emphasize that these samples have been hotter at some time in the past.

The single grain age data in the lower Cl grains in these two samples are highly consistent at around 50 Ma (allowing for scatter due to appropriate analytical uncertainties). Trends of single grain age vs Cl content such as these, with consistent ages over the range of lowest Cl contents, clearly show that the fission track ages of the lower Cl grains in each sample have been totally reset and therefore the measured fission track ages reflect the time at which the samples began to cool to palaeotemperatures sufficiently low that tracks could be retained. (Note that the measured ages are not equal to the time of cooling because of the effects of annealing of tracks formed during the period following the onset of cooling, and the age data must be considered in tandem with the track length data in order to define the actual time at which cooling began.)

Thermal history solutions derived from the AFTA data in samples from the well are summarized in Table 2, which also summarizes estimates of maximum palaeotemperature derived from VR data from the Jurassic section in this well. If we assume that results from this well represent the effects of a synchronous cooling episode, estimates of the onset of cooling from AFTA in the five samples suggest that cooling from maximum palaeotemperatures began some time between 90 and 40 Ma. The detail of the track length data in these samples also suggests a possible later cooling episode from a lower palaeothermal peak. This most likely represents the Neogene cooling identified from AFTA onshore (Green et al., 2001) and also suggested by Japsen (1997). However the detail of the Cainozoic cooling history is beyond the scope of this contribution and is not pursued here.

Cooling beginning between 90 and 40 Ma is consistent with the Palaeocene cooling identified in AFTA data from onshore wells and outcrop data (reviewed earlier), and the simplest interpretation of these data is that results from the 47/25-1 well also represent the effects of a regional cooling episode which began in the interval 65 to 55 Ma. While it is true that, at the limits of the data, cooling in the 47/25-1 well any time may have begun any time between 90 and 40 Ma, synthesis of results from other offshore wells in the vicinity of this well (to be published in detail elsewhere) also provide a tighter timing constraint to the interval 65 to 55 Ma for the onset of cooling. Therefore it seems beyond reasonable doubt that the preserved sedimentary units in the offshore EMS, as well as the onshore, has undergone major cooling through Cainozoic times, beginning at around 60 Ma.

Estimates of maximum palaeotemperature derived from AFTA and VR data in the 47/25-1 well are plotted against depth (from KB) in Figure 4. The values derived from VR show some scatter, but overall are consistent with the palaeotemperatures indicated by the AFTA data. One value appears to be much lower than the majority, which we interpret as representing suppression of the reflectance level in this sample, similar to the Edale Shales from outcrop, discussed earlier. Omitting this lower VR value, the combined palaeotemperature constraints from AFTA and VR define a linear palaeotemperature profile, sub-parallel to the present-day temperature profile (also shown in Figure 4) but offset to higher values by a difference of around 40°C.

These features of the palaeotemperature profile suggests that heating was predominantly due to deeper burial. Figure 5 shows the results of quantitative analysis of the palaeotemperature constraints derived from AFTA and VR data (Bray et al., 1992) to define of the range of values of palaeogeothermal gradient and missing section which are consistent with these data. Assuming a palaeogeothermal gradient similar to the present-day value of 34.5°C/km, and a palaeo-surface temperature of 20°C as advocated by Holliday (1999), results from this well require between 500 and 1100 metres of removed section (from the upper and lower limits of the shaded region in Figure 5).

As also illustrated in Figure 5, this amount of missing section is highly consistent with estimates in the region of 600 to 1000 metres derived from Sonic velocity data from both Late Cretaceous and Triassic strata in this and neighbouring wells from Japsen (2000). Thus, evidence from AFTA, VR and sonic velocity data are consistent with a scenario involving an additional 800 ± 200 metres of additional section. This section must have been deposited subsequent to deposition of the youngest preserved Chalk in the 47/25-1 well (of Coniacian age, based on Figure 82 of Cameron et al. 1992) and prior to the onset of cooling, which synthesis of AFTA from all wells suggests must have been prior to 55 Ma. Thus, all data point to a scenario involving a considerable thickness of sediment being deposited within an interval of not much more than 30 Ma and subsequently eroded, possibly in two stages based on tentative evidence from AFTA in the 47/25-1 well (above) and more conclusive evidence from AFTA data onshore (Green et al. 2001).

Note that palaeogeothermal gradients slightly higher than the present-day value would be allowed by the palaeotemperature constraints from this well (up to ~52°C/km), but the comparison with results based on analysis of sonic velocity data presented by Japsen (2000) suggest that a scenario involving a palaeogeothermal gradient similar to the present-day value is more likely for this well.

The final reconstructed history of burial and subsequent exhumation for the 47/25-1 well (Figure 6) shows a marked acceleration in the rate of burial during the Late Cretaceous, prior to the onset of exhumation in the Early Tertiary. This is a common feature of such reconstructions based on AFTA and VR data in the region, and is a central factor in previous criticisms of such studies (reviewed in an earlier section). Nevertheless, not only the AFTA and VR data but also sonic velocity data (from both Late Cretaceous and Triassic units, incorporating results from neighbouring wells) consistently support the scenario shown in Figure 6, and we see no reason to doubt the validity of this reconstruction. The acceleration in the rate of burial prior to the onset of exhumation was also emphasized in the context of results from the onshore EMS by Green et al. (2001). This accelerated burial appears to be a common feature in areas which have undergone significant exhumation (Green et al. 2002), suggesting that this may be significant in terms of the nature of the underlying mechanism(s).

4. THE RELEVANCE OF THE FLAMBOROUGH OUTLIER

Stewart & Bailey (1996) reported a previously unrecognized package of sedimentary rocks of Late Palaeocene to Mid-Eocene age straddling SNS blocks 42/29 and 47/4b, which they termed the “Flamborough outlier”. They suggested that these strata represent part of the previously more extensive sedimentary cover responsible for the regional burial effects identified from sonic velocity studies and studies based on AFTA, VR etc. This, in turn, suggests that the cooling episode identified from earlier AFTA-based studies must have begun after deposition of these sediments, suggesting that cooling must have begun later than Middle Eocene times (~40 Ma). Stewart & Bailey (1996) commented that the previous AFTA-based studies had been interpreted as requiring deposition of missing section during Campanian to Danian times "based on the assumption that no significant thickness of sediment accumulated on the East Midlands Shelf following the onset of uplift (Bray et al., 1992)". This statement is not accurate. The interpretation that the now eroded sedimentary units were of Campanian to Danian age was based solely on the timing constraints derived from AFTA, showing that cooling must have begun by ~60 Ma, which requires that the additional burial required to produce the observed heating must have been deposited prior to this time. We emphasise again that the results of reassessing the regional AFTA dataset, some of which is reported here, confirms the Palaeocene timing for the onset of cooling.

The results presented here show quite clearly that the main erosional episode on the East Midlands Shelf must have occurred after deposition of the youngest preserved Chalk and prior to deposition of the Palaeogene strata recognized by Stewart & Bailey (1996). Evidence in support of this conclusion is seen in the estimates of missing section derived by Japsen (2000) from sonic velocities, which show no evidence of any reduction in the amount of missing section in the vicinity of the outlier of Palaeogene strata, as might be expected if the sedimentary section is more complete in that region. Instead, values of Japsen's (2000) "burial anomaly" remain around 0.8 to 1 km across the region of the outlier, suggesting that even in the region where the Palaeogene strata are preserved, an additional ~1 km or so of strata have been deposited and eroded.

In fact, these observations lead to the conclusion that, at least in the vicinity of the outlier, erosional removal of the additional strata must have been complete prior to deposition of the Palaeogene strata preserved in the outlier. With the age of the oldest Palaeogene units in the outlier being of Late Palaeocene (Early Thanetian) age, the timing constraints from AFTA for the onset of cooling suggest that exhumation must have been extremely rapid, with the entire package of additional strata removed in as little as perhaps 5 Myr (taking the oldest limit on cooling from AFTA of 65 Ma and an age of ~60 Ma for Early Thanetian from Harland, 1989).

Erosion of sedimentary rocks of similar (Palaeogene) age to those in the outlier from adjacent regions of the Shelf was probably achieved during the more recent (Miocene) episode of exhumation recognised in regional AFTA data, particularly onshore (see earlier discussion). This episode most likely correlates with the phase of Late Miocene inversion recognized in the SNS by Stewart & Bailey (1996) which they suggested represented the dominant erosional episode across the region.

The foregoing discussion shows that numerous lines of evidence point to the conclusion that the offshore as well as the onshore EMS has undergone two major episodes of burial and subsequent exhumation during the Latest Cretaceous and Cainozoic. This is consistent with the conclusion reached by Japsen (1997), although the relative contributions of the two episodes may not vary exactly as he suggested. This aspect of the AFTA data from the Southern North Sea will be discussed in detail, together with the regional dataset, elsewhere.

5. IMPLICATIONS FOR HYDROCARBON PROSPECTIVITY

Figure 7 shows a summary of thermal histories and burial/exhumation histories for Carboniferous rocks in the 47/25-1 well and the Southern Pennines, based on the results presented here, and in the Rufford-1 well (based on Green et al. 2001). This Figure emphasizes the increasing degree of Cainozoic exhumation from east to west across the region, as well as the dominance of earlier events (Variscan and possibly Triassic hydrothermal effects) in the west.

This contrast in thermal history styles is consistent with the variation in hydrocarbon occurrence across the region. In the west, the lack of success of exploration wells such as Edale-1 (Gluyas & Bowman 1997), despite the presence of excellent oil-prone source rocks, can be understood in terms of hydrocarbon generation taking place during Carboniferous burial prior to formation of structures during Variscan (end-Carboniferous tectonism (Fraser & Gawthorpe 1990, Fraser et al. 1990). On the onshore East Midlands Shelf, the presence of numerous small oilfields attests to the later timing of the main phase of hydrocarbon generation in this region, during Mesozoic burial, well after the formation of structures. Tilting as a result of Cainozoic exhumation may have resulted in loss of a significant proportion of the reservoired hydrocarbon accumulations, as shown by residual oil columns etc (Fraser et al. 1990), accounting at least in part for the relatively small size of the accumulations in this region. Further offshore, around and east of the Sole Pit Axis, major gas reserves were generated during Cainozoic burial in the more basinal areas to the east, and structures formed during Cainozoic inversion, as well as earlier-formed structures, were available for charging.

The phenomena of “palaeo-burial” of Carboniferous source rocks and their subsequent exhumation, recorded only in the AFTA, VR and sonic velocity data in the Southern North Sea, have clearly played an important role (coupled with the subsequent exhumation history) in defining and shaping the occurrences of hydrocarbons across the region.

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FIGURE CAPTIONS

Figure 1: Location map showing basic pre-Quaternary geology together with wells and localities discussed in this paper.

Figure 2: AFTA data, together with resulting thermal history interpretation, from two samples of Mam Tor sandstone from outcrops in the vicinity of Mam Tor. Upper plots show fission track ages of individual apatite grains within each sample, plotted against wt% Cl. The horizontal black lines show the trend of fission track age vs Cl predicted from the respective "Default Thermal History" (i.e. the history predicted if all units through the preserved sedimentary section are now at their maximum temperatures since deposition). Track length distributions in each sample are also shown. Stippled shading defines the distribution of track lengths predicted from the Default Thermal History, while the white shading denotes the measured length distribution. The area of overlap is shown with diagonal hatching. Lower plot shows a schematic illustration of the thermal history interpretation of the AFTA data. It should be emphasised that AFTA only defines the dominant palaeo-thermal episodes, and cannot resolve the fine detail of the thermal history.

Figure 3: AFTA data from SNS well 47/25-1. On the right, fission track ages measured in five samples are plotted against depth, together with the variation of stratigraphic age with depth and the trend of fission track age vs depth predicted from the "Default Thermal History", for apatites from two compositional groups. On the left, fission track ages in individual grains of apatite are plotted against wt% Cl for the two deepest samples. The horizontal black lines in these plots again show the trend of fission track age vs Cl predicted from the respective Default Thermal History. The consistency of the younger fission track ages in the lowest Cl apatites in these samples shows that these apatites were totally annealed prior to cooling, and therefore these ages reflect the time at which cooling began.

Figure 4: Palaeotemperatures defined from AFTA and VR data in well 47/25-1 define a linear depth profile (solid line), sub-parallel to the present-day temperature profile (dashed line) derived from corrected BHT values in this well, and offset to higher temperatures by ~30 to 40°C. This suggests that heating was due primarily to deeper burial, with little or no difference in heat flow compared to the present day.

Figure 5: Fitting a linear palaeotemperature profile to the constraints derived from AFTA and VR data in SNS well 47/25-1 (Figure 4) and extrapolation to an assumed palaeo-surface temperature of 20°C allows estimation of the range of palaeogeothermal gradients and removed section that are consistent with the data within 95% confidence limits, as shown by the shaded zone. The methods employed in constructing this Figure, and the assumptions embodied in the analysis, have been described e.g. by Bray et al. (1992), Crowhurst et al. (2002) and Green et al. (2002). Also shown is the range of values of removed section defined by sonic velocity data from Triassic and Upper Cretaceous units in this and adjacent wells, from Japsen (2000). For a palaeogeothermal gradient close to the present-day value of 35.4°C/km, allowed values of removed section derived from the AFTA and VR data are highly consistent with those derived from the sonic velocity data, and data from three independent systems give consistent indications of between 600 and 1000 metres of missing post-Chalk section.

Figure 6: Schematic illustration of the reconstructed burial and exhumation history for SNS well 47/25-1, derived from AFTA and VR data. This history is based on compacted sedimentary rock thicknesses, for simplicity, and highlights only the major features, viz: No detectable Variscan effects; Maximum burial depths in the Palaeocene, with between 600 and 1000 metres of additional Late Cretaceous section removed during Cainozoic exhumation; Rapid exhumation in the Early Cainozoic followed by further deposition of Palaeogene units and a Late Miocene episode of exhumation (based on arguments discussed in the text related to the "Flamborough Outlier"). Note that the most recent episode is not revealed by

AFTA data in this well, and should be regarded as speculative. Delineation of this aspect of the history forms a focus of ongoing work in the region.

Figure 7: Schematic illustrations of reconstructed burial and exhumation histories and thermal histories for SNS well 47/25-1, onshore well Rufford-1 and Edale Shales from outcrop in the Southern Pennines, based on results presented here and in Green et al. (2001). The exact form of particularly the Mesozoic history for the Southern Pennines is highly speculative, and only the points of peak palaeotemperature/burial in the Early Tertiary are well constrained, but the data discussed here suggest that the broad nature of the history is probably reliable. The earlier palaeo-thermal event revealed by AFTA in this area is shown as a discrete Triassic hydrothermal event (see text), although this remains speculative. Palaeo-surface temperatures have been held constant at 20°C prior to Late Cretaceous times in the thermal reconstructions, as the data are not sensitive to this part of the history. AFTA data from the Rufford-1 well provide strong evidence for two distinct episodes of cooling during the Cainozoic (Green et al. 2001), although this part of the history for the other two situations remains somewhat speculative at present.

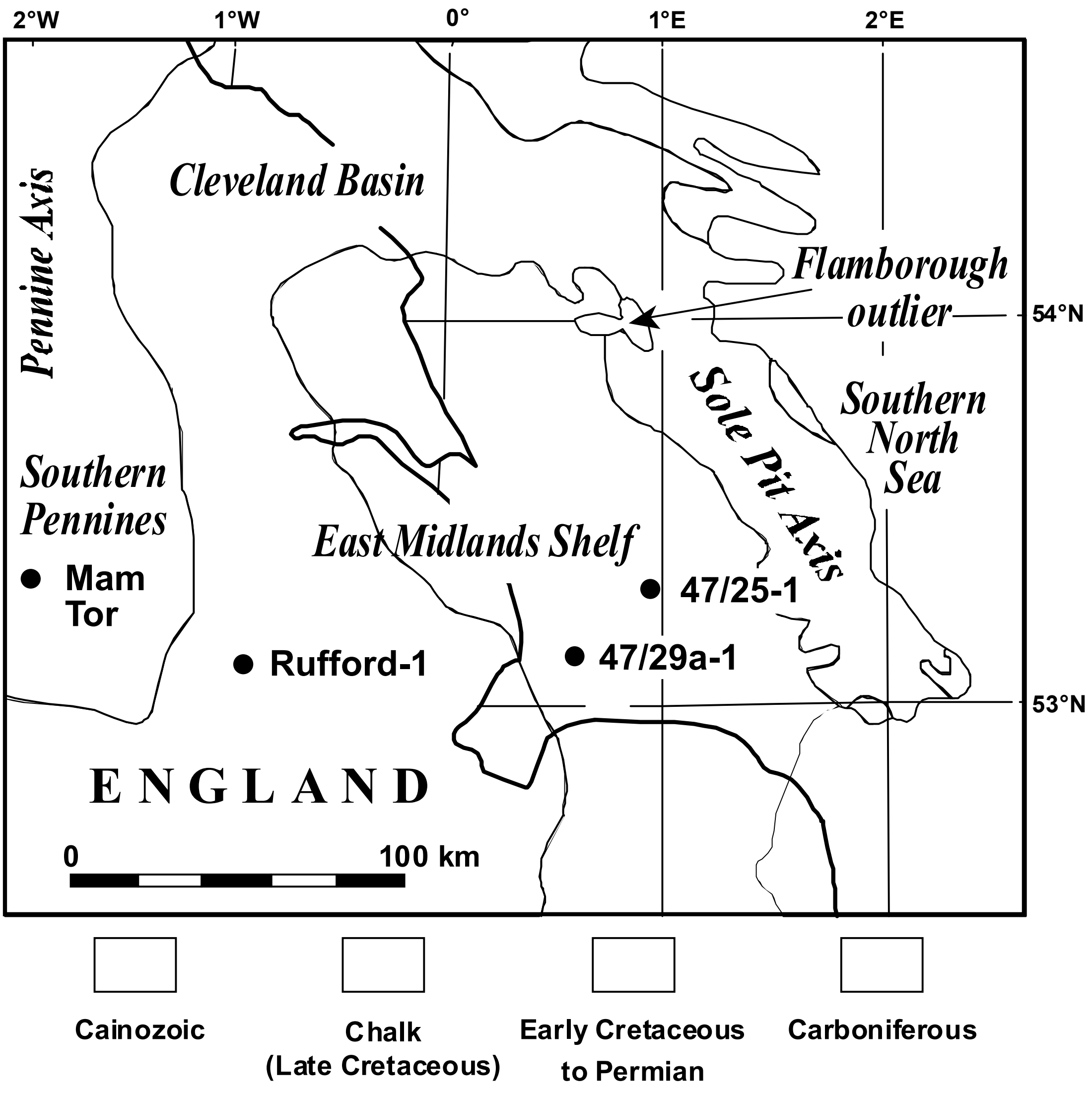

2°W
1°W
0°
1°E
2°E
54°N
53°N
Pennine Axis
Cleveland Basin
Flamborough outlier
Sole Pit Axis
Southern North Sea
Southern Pennines
East Midlands Shelf
Mam Tor
47/25-1
Rufford-1
47/29a-1
ENGLAND
0
100 km
Cainozoic
Chalk (Late Cretaceous)
Early Cretaceous to Permian
Carboniferous

Figure 1

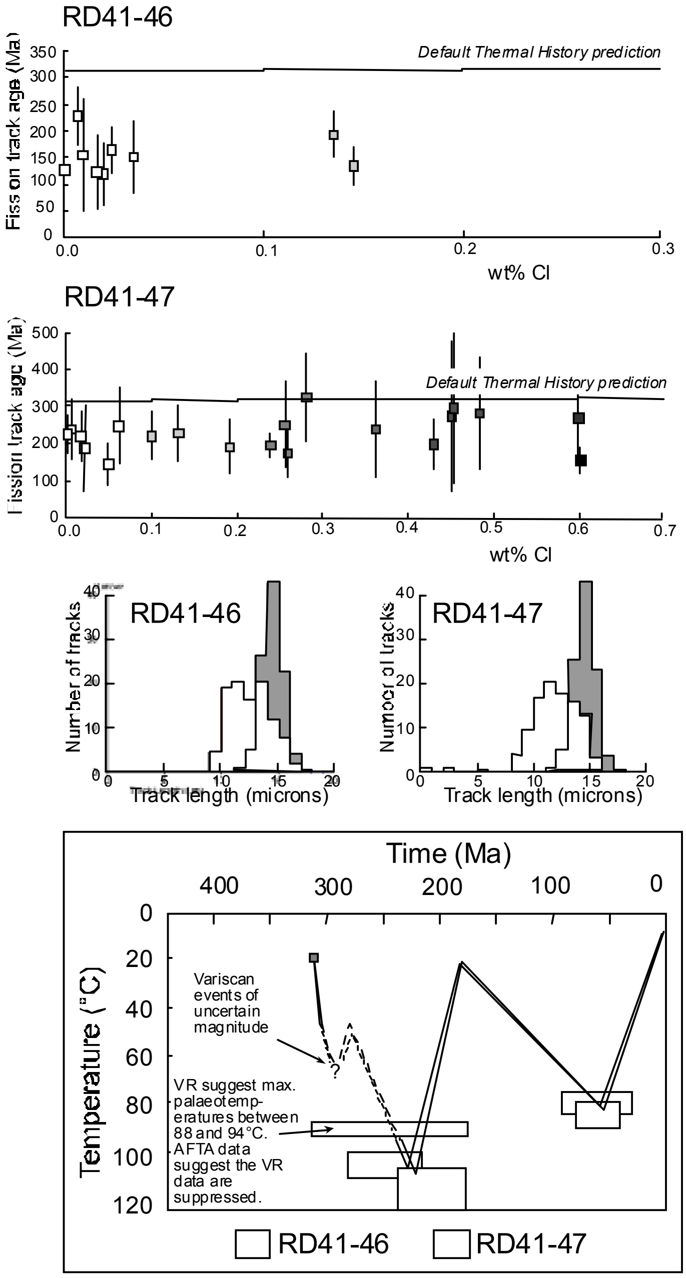

RD41-46
Fission track age (Ma)
Default Thermal History prediction
wt% Cl
RD41-47
Fission track age (Ma)
Default Thermal History prediction
wt% Cl
RD41-46
Number of tracks
Track length (microns)
RD41-47
Number of tracks
Track length (microns)
Time (Ma)
400
300
200
100
0
Temperature (°C)
0
20
40
60
80
100
120
Variscan events of uncertain magnitude
?
VR suggest max. palaeotemperatures between 88 and 94°C. AFTA data suggest the VR data are suppressed.
RD41-46
RD41-47

Figure 2

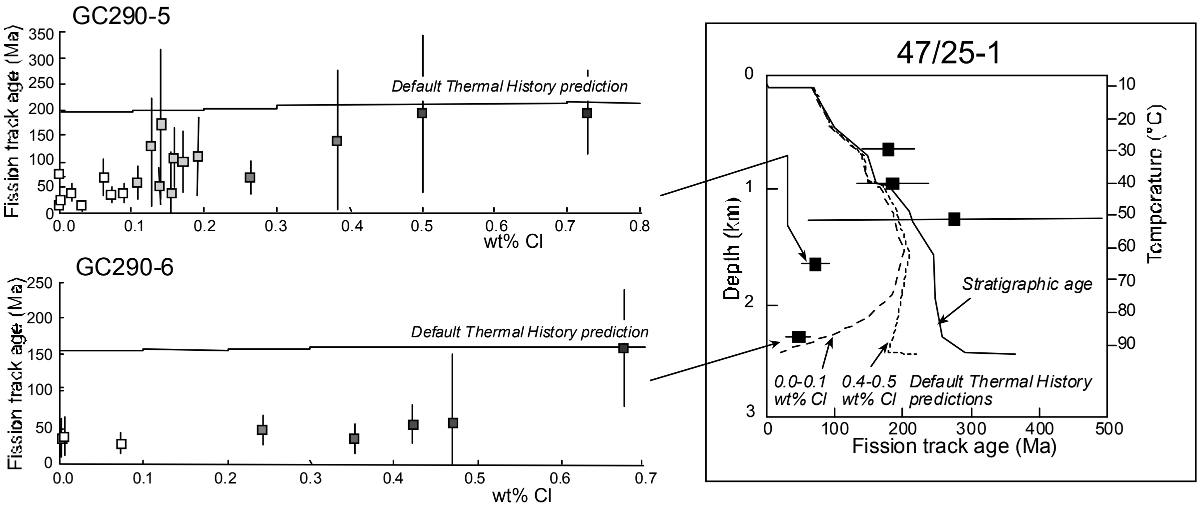

GC290-5
Fission track age (Ma)
0
50
100
150
200
250
300
350
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
wt% Cl
Default Thermal History prediction
GC290-6
Fission track age (Ma)
0
50
100
150
200
250
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
wt% Cl
Default Thermal History prediction
47/25-1
Depth (km)
0
1
2
3
Temperature (°C)
10
20
30
40
50
60
70
80
90
Stratigraphic age
0.0-0.1 wt% Cl
0.4-0.5 wt% Cl
Default Thermal History predictions
0
100
200
300
400
500
Fission track age (Ma)

Figure 3

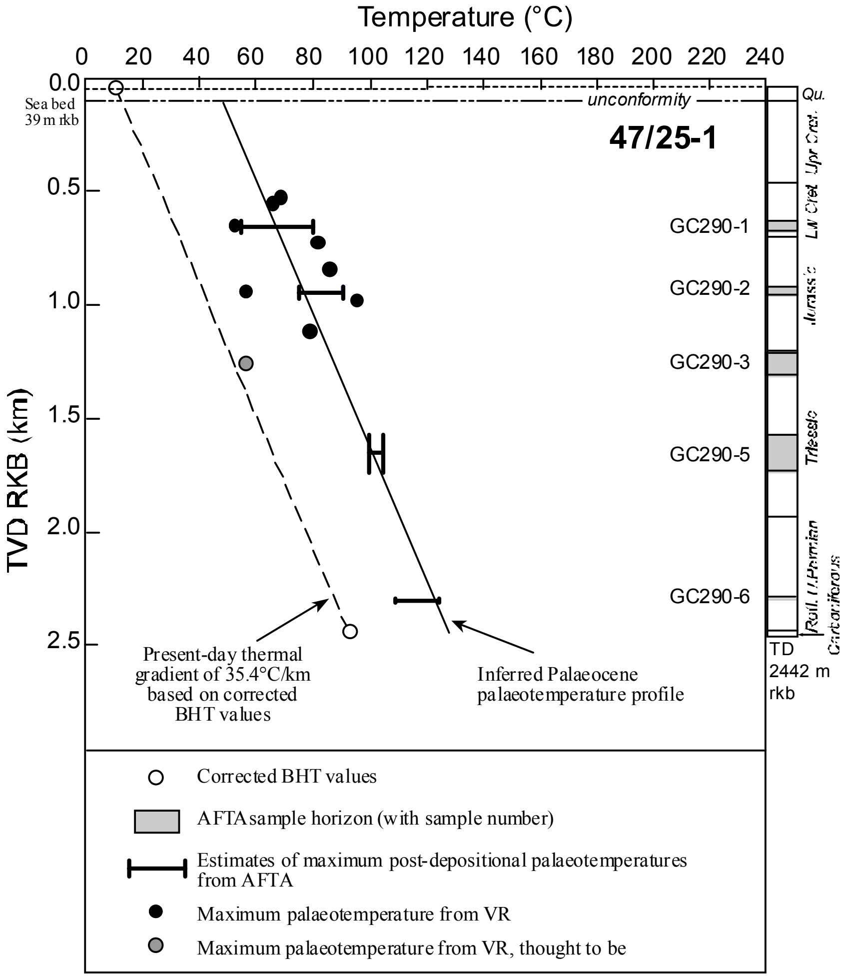

Temperature (°C)
0
20
40
60
80
100
120
140
160
180
200
220
240
TVD RKB (km)
0.0
0.5
1.0
1.5
2.0
2.5
Sea bed
39 m rkb
unconformity
47/25-1
GC290-1
GC290-2
GC290-3
GC290-5
GC290-6
Qu.
Upr Cret.
Lwr Cret.
Jurassic
Triassic
Rotl. U.Permian
Carboniferous
TD
2442 m
rkb
Present-day thermal gradient of 35.4°C/km based on corrected BHT values
Inferred Palaeocene palaeotemperature profile
Corrected BHT values
AFTA sample horizon (with sample number)
Estimates of maximum post-depositional palaeotemperatures from AFTA
Maximum palaeotemperature from VR
Maximum palaeotemperature from VR, thought to be

Figure 4

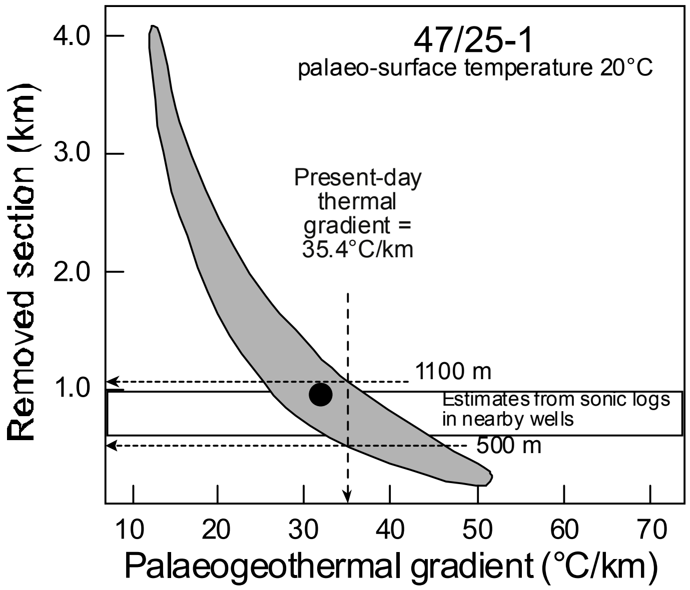
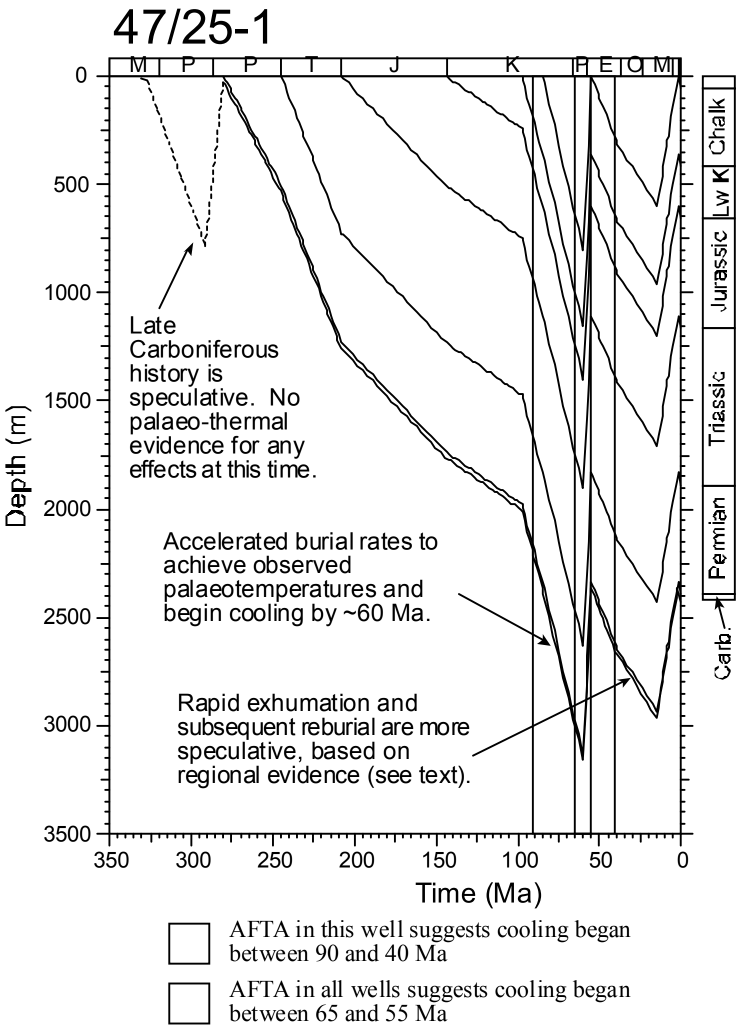

47/25-1
palaeo-surface temperature 20°C
Present-day thermal gradient = 35.4°C/km
1100 m
Estimates from sonic logs in nearby wells
500 m
Removed section (km)
4.0
3.0
2.0
1.0
10
20
30
40
50
60
70
Palaeogeothermal gradient (°C/km)

Figure 5



Late Carboniferous history is speculative. No palaeo-thermal evidence for any effects at this time.

Accelerated burial rates to achieve observed palaeotemperatures and begin cooling by ~60 Ma.

Rapid exhumation and subsequent reburial are more speculative, based on regional evidence (see text).

☐ AFTA in this well suggests cooling began between 90 and 40 Ma

☐ AFTA in all wells suggests cooling began between 65 and 55 Ma

Figure 6

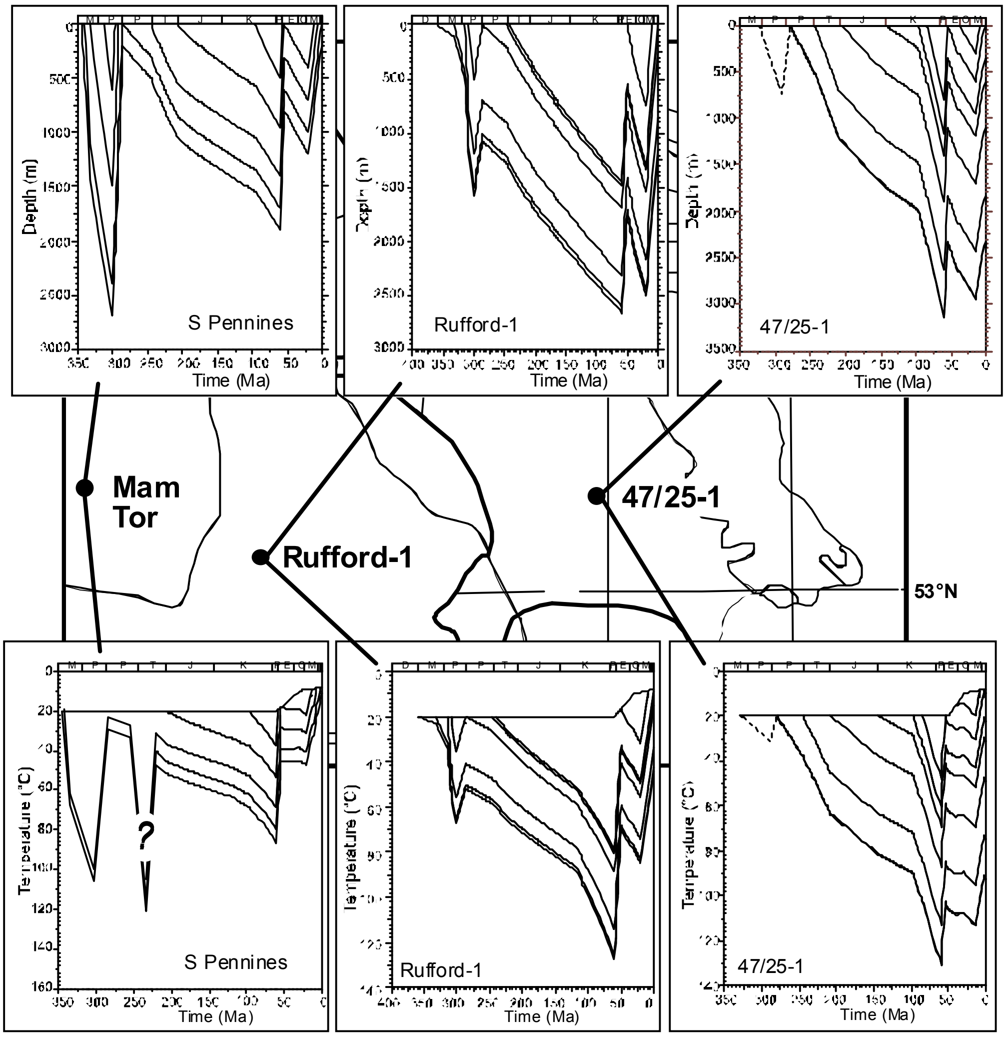

S Pennines
Rufford-1
47/25-1
Depth (m)
Temperature (°C)
Time (Ma)
Mam Tor
Rufford-1
47/25-1
53°N
?

Figure 7