Post-Carboniferous burial and exhumation histories of Carboniferous rocks of the southern North Sea and adjacent onshore UK

From Earthwise

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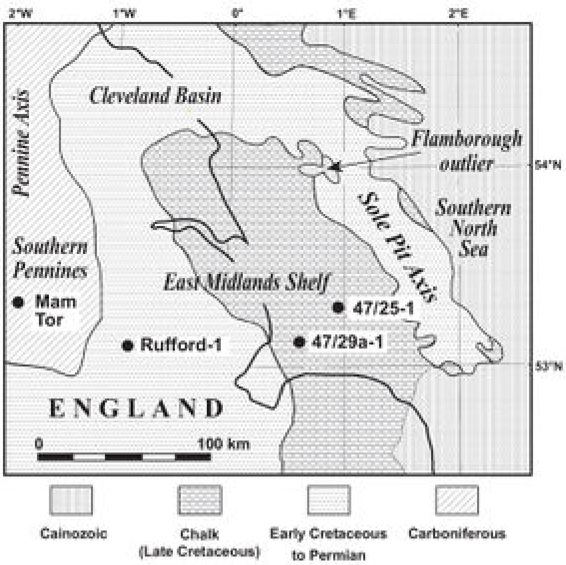

Figure 1 Location and simplified pre-Quaternary geological map.

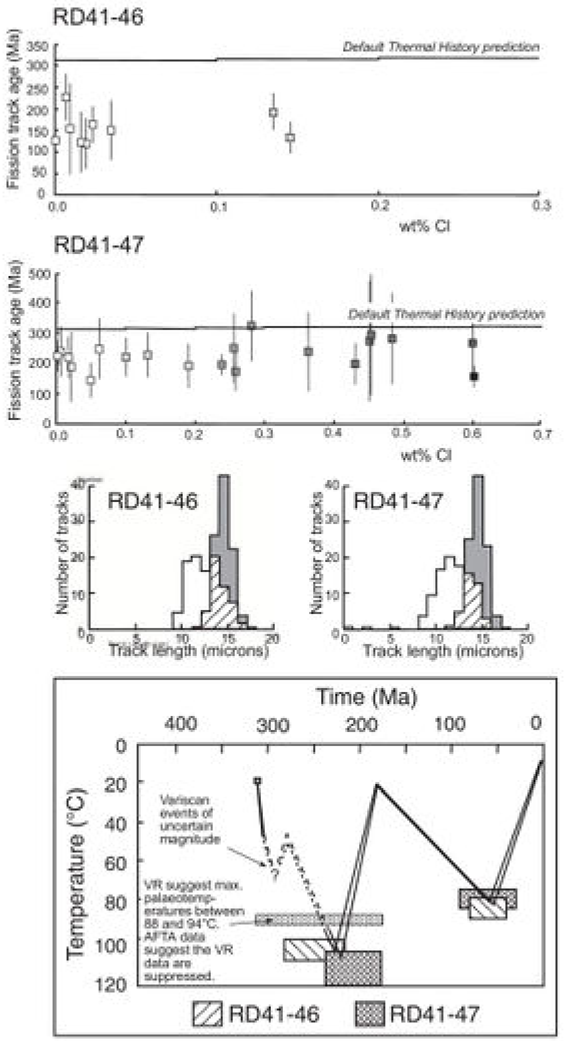

Figure 2 AFTA data, together with the resulting thermal history interpretation, from two samples of sandstone from outcrops in the vicinity of Mam Tor.

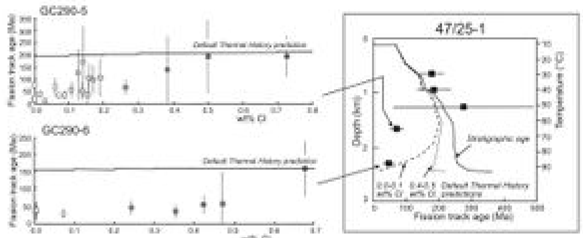

Figure 3 AFTA data from well 47/25-1.

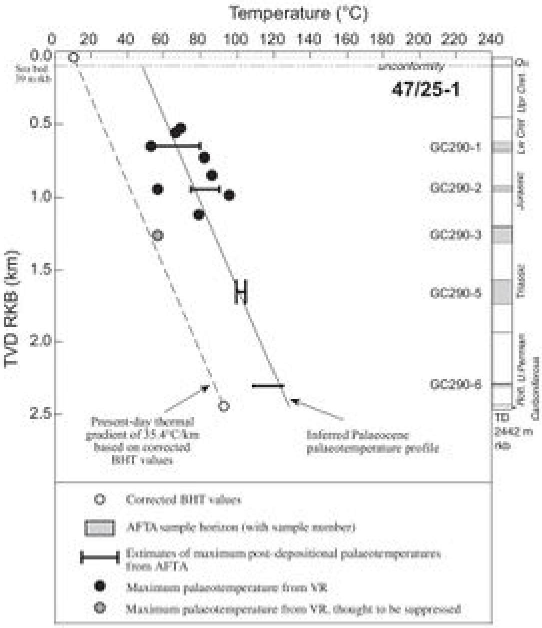

Figure 4 Palaeotemperatures determined from AFTA and VR data in well 47/25-1 .

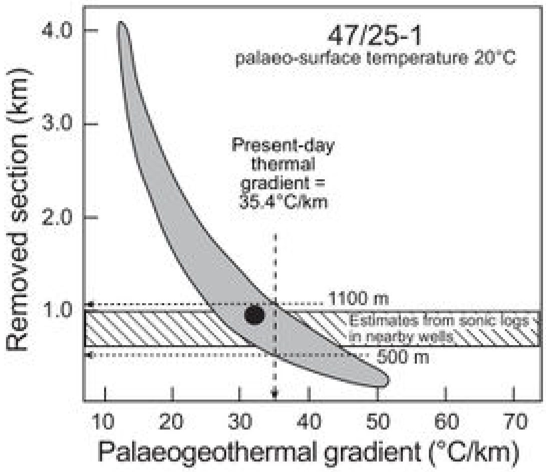

Figure 5 Fitting a linear palaeotemperature profile to the constraints derived from AFTA and VR data in SNS well 47/25-1 (Figure 4) .

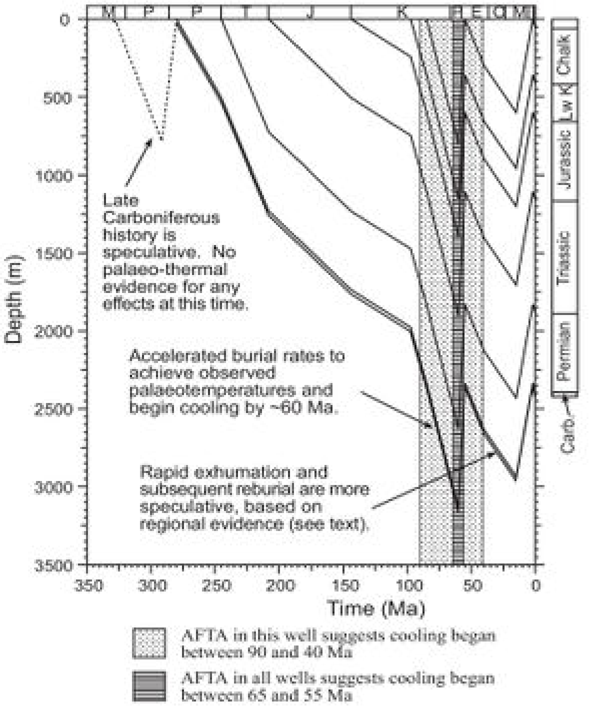

Figure 6 Schematic illustration of the reconstructed burial and exhumation history for well 47/25-1, derived from AFTA and VR data.

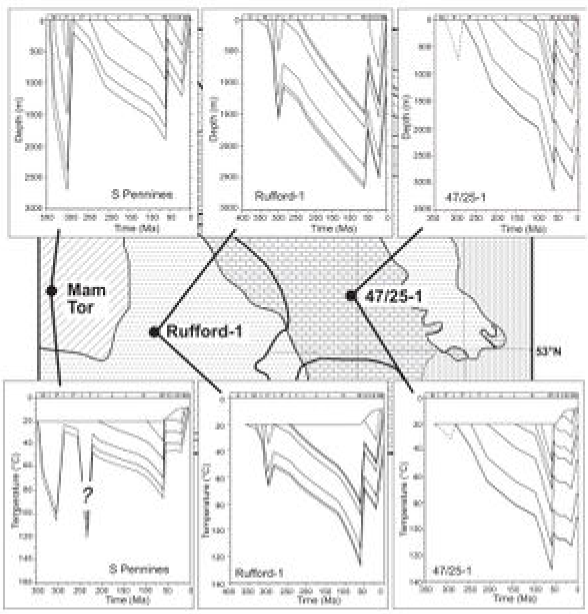

Figure 7 Schematic illustrations of reconstructed burial and exhumation histories and thermal histories for well 47/25-1, onshore well Rufford-1, and Edale Shales from outcrop in the southern Pennines.

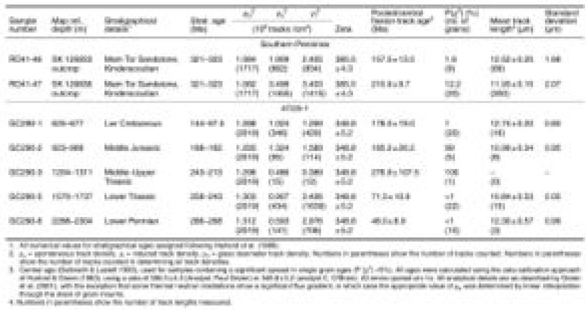

Table 1 Sample details and apatite fission-track age data.

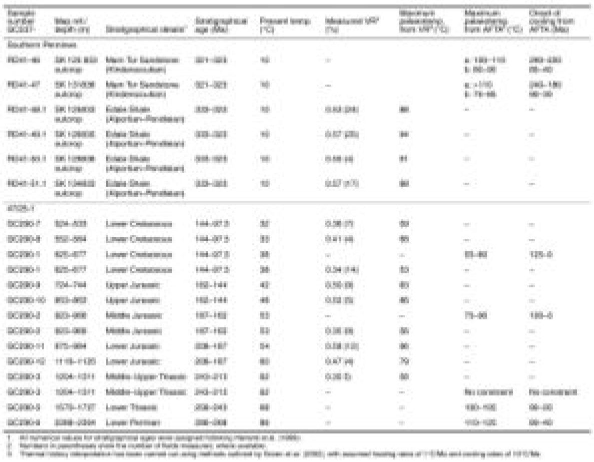

Table 2 Thermal-history interpretation summary of AFTA and VR data.

By Paul F. Green

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Contents

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 about 100°C or more in Late Palaeozoic times, and from a peak palaeotemperature of ~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 that began between 90 and 40 Ma. Data from neighbouring wells refine this timing to 65–55 Ma. Combining the AFTA and VR data from the 47/25-1 well with sonic velocity-based constraints on palaeoburial suggests that an additional 800±200 m 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. “Palaeoburial” of Carboniferous source rocks and their subsequent exhumation, recorded in AFTA, VR and sonic velocity data from the southern North Sea, have played an important role in defining and shaping the occurrences of hydrocarbons across the region.

Introduction

Reconstruction of the postdepositional evolution of sedimentary sequences, in terms of thermal histories and of histories of burial and subsequent exhumation, is important for a variety of reasons, including, for example, 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 palaeothermal 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 palaeothermal 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 the reconstruction of 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.

Several 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 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 of 70–90°C beginning some time between 65 and 55Ma (Palaeocene). Results from subsurface 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 Ma and 5 Ma (Miocene). Vitrinite reflectance 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 postdepositional 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 AFTA data from five EMS wells. He suggested that Palaeocene palaeogeothermal gradients were indistinguishable from present-day values, and that 1–2 km of section have been removed 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 palaeosurface temperature, and, on the basis of criticisms by McCulloch (1994) that 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 about 1450 m of post-Triassic cover removed during Cainozoic exhumation, much of which may have been removed during the Neogene. This most recent interpretation employs a palaeosurface temperature of 20°C, as suggested by Holliday (1993), coupled with a Palaeocene palaeogeothermal gradient about 30 per cent 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 about 800–900 m (Green et al. 2001). Reasons for this discrepancy are the subject of continuing 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 northwest 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 being attributable to a combination of elevated basal heat flow and moderate amounts (generally 700–1550 m) of additional Late Palaeozoic to Mesozoic burial (with Cainozoic cooling caused by subsequent exhumation and reduction in heatflow). 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 palaeothermal effects across the region shown in Figure 1.

2. New data from the southern Pennines

Despite the apparent consistency of several studies and the 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 80–90°C at outcrop (Green 1989, Green et al. 2001), is commonly interpreted as a stable high during Mesozoic and Cainozoic times in palaeogeographic reconstructions (Fraser & Gawthorpe 1990, Fraser et al. 1990, Ziegler 1990, Cope et al. 1992). Studies related to mineralization 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 past 200 million years (e.g. Plant et al. 1988). Other workers have ignored any consideration of the likely magnitude of post-Carboniferous palaeothermal 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 (Table 1), (Table 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 palaeothermal 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 (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 per cent Cl in sample RD41-47) giving ages consistently younger than the value expected if the sample has not been significantly heated since deposition (horizontal bars in the age versus 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 of 100–110°C, from which cooling began some time between 290 Ma and 220 Ma, whereas sample RD41-47 reached a maximum palaeotemperature in excess of 110°C and began to cool between 240 Ma 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, and 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 240–220 Ma and 80–40 Ma, with respective peak palaeotemperatures of 100–105°C and 80–85°C. Mean VR values measured in four samples of Edale Shales immediately underlying the Mam Tor Sandstones are between 0.53 and 0.57 per cent, equivalent to a maximum palaeotemperature of 88–94°C (Table 2). These values are lower than the corresponding estimates from AFTA, which is thought to result from the suppression of reflectance levels in these samples. Such effects are common in carbonaceous shales rich in hydrogen or sulphur (see discussion and references in Green et al. 2002), and have been previously 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 240–220 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 Ma 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, personal communication 2002), which would suggest that the cooling seen in the AFTA data must be attributable to processes other than burial. An alternative explanation may be hydrothermal effects during Late Triassic to 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°C to 85°C some time between 80 Ma and 40 Ma. This timing is consistent with the Palaeocene cooling event recognized 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 30–50°Ckm–1), this palaeotemperature range suggests appreciable burial (1.2–2 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, some 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 that clearly show a trend in estimates of "post-Cretaceous uplift" (more strictly exhumation) increasing from east to west and reaching values about 1.5 km immediately to the east of the southern Pennines (Whittaker et al. 1985).

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 (Fraser & Gawthorpe 1990, Fraser et al. 1990, Ziegler 1990, Cope et al. 1992).

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). Although 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 that 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, therefore, it is 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, for example, 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 high enough to produce severe age reduction; however, 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 weight per cent Cl give ages significantly less than the predicted values, whereas apatites with higher-Cl contents give older ages, closer to the expected values. This reflects the greater sensitivity of the grains with lower-Cl contents, which are more easily reset than those with higher-Cl contents. In sample GC290-6, all single grain ages are less than predicted, and the single grain containing almost 0.7 weight per cent 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 about 50 Ma (allowing for scatter attributable to appropriate analytical uncertainties). Trends of single-grain age versus 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 low enough for tracks to 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 Ma 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 Ma 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 that began in the interval 65–55 Ma. Although it is true that, at the limits of the data, cooling in the 47/25-1 well may have begun at any time between 90 Ma and 40 Ma, synthesis of unpublished results from other offshore wells in the vicinity of this well also provide a tighter timing constraint to the interval 65–55 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, have undergone major cooling through Cainozoic times, beginning at about 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, subparallel to the present-day temperature profile (also shown in Figure 4) but offset to higher values by a difference of about 40°C.

These features of the palaeotemperature profile suggest that heating was predominantly caused by 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 the range of values of palaeogeothermal gradient and missing section that are consistent with these data. Assuming a palaeogeothermal gradient similar to the present-day value of 34.5°Ckm–1, and a palaeosurface temperature of 20°C as advocated by Holliday (1999), results from this well require 500–1100 m 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 600–1000 m derived from sonic velocity data from both Late Cretaceous and Triassic strata in this and neighbouring wells by Japsen (2000). Thus, evidence from AFTA, VR and sonic velocity data are consistent with a scenario involving 800±200 m 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 Cameron et al. 1992; fig. 82) 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 history 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°Ckm–1), but the comparison with results based on analysis of sonic velocity data presented by Japsen (2000) suggest that a situation 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 history 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 having undergone significant exhumation (Green et al. 2002), suggesting that this may be important in terms 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 blocks 42/29 and 47/4b, which they termed the Flamborough Outlier (Figure 1). They suggested that these strata are a remnant 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: 172) 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 emphasize again that the results of reassessing the regional AFTA dataset, some of which are reported here, confirm 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 have been expected if the sedimentary section is more complete in that region. Instead, values of Japsen's (2000) "burial anomaly" remain at about 0.8–1.0 km across the region of the outlier, suggesting that, even 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 Ma (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 recognized 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) that they suggested represented the dominant erosional episode across the region.

The foregoing discussion shows that many 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 and 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 many 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 hydrocarbon accumulations, as shown by residual oil columns, for example (Fraser et al. 1990), accounting at least in part for the relatively small size of the accumulations in this region. Farther 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 structures formed earlier, were available for charging.

The phenomena of palaeoburial of Carboniferous source rocks and their subsequent exhumation, recorded 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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