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Determining apparent exhumation from Chalk outcrop samples, Cleveland Basin/East Midlands Shelf

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Abstract – Porosity measurements of 22 Upper Cretaceous Chalk samples, and mean Chalk porosities derived from sonic logs in three wells, were used to quantify apparent exhumation (height above maximum burial-depth) in the onshore Cleveland Basin/East Midlands Shelf. Late Cretaceous/Tertiary exhumation of the East Midlands Shelf resulted in the removal of 1.2 km of section near the coast and more than 2 km of section inland, to the west. The southern margin of the Cleveland Basin was exhumed by 2 km, and exhumation increases northwards towards the recognized inversion axis running east–west along the basin's centre. The northwards increasing exhumation associated with the east–west trending inversion axis of the Cleveland Basin is superimposed upon the regional westward trend of increasing exhumation of eastern England. These two trends control the outcrop distribution of the Upper Cretaceous Chalk in the Cleveland Basin/East Midlands Shelf.

1. Introduction

It has been widely recognized that many of the Mesozoic sedimentary basins on- and offshore southern UK have been inverted and exhumed from their maximum burial-depth during Late Cretaceous–Tertiary times (e.g. references in Ziegler, 1987 and Cooper & Williams, 1989). Although it is relatively easy to recognize the occurrence of basin inversion from stratigraphic and structural evidence (Williams, Powell & Cooper, 1989), quantifying the amount of section removed as a result of inversion is more problematic. For example, there has been considerable debate on the amount of section eroded from the Cleveland Basin/East Midlands Shelf.

Marie (1975) estimated that the Cleveland Hills have been exhumed by a minimum of 1200–1800 m by comparing the maximum palaeo-depth derived from sonic velocities and the present depth of burial for the Triassic Bunter Shale. However, as noted by Hemingway & Riddler (1982), Marie's (1975) estimation of 1200–1800 m of exhumation, increasing westwards, is based only on offshore data. Kent (1980) stated that, based on evidence from sub-Upper Cretaceous Chalk thicknesses in areas adjacent to the Cleveland anticline, the end-Cretaceous/early Tertiary inversion of the Cleveland anticline may be estimated to have removed between 500–800 m of section, and possibly around 1000–1300 m of section if the former Chalk cover showed variations analogous to those of the Sole Pit Trough. Hemingway & Riddler (1982) agreed that Upper Jurassic and Cretaceous cover rocks of estimated thickness 1.0–1.25 km have been eroded from the axis of inversion running approximately east–west along the Cleveland Basin's centre, but noted that such a thickness alone is inadequate to satisfy the known palaeotemperatures of the Middle Jurassic along the axis. Based on the temperature of diagenesis determined from fluid inclusions in diagenetic sphalerite in the Middle Jurassic Dogger Formation, and Middle Jurassic coal vitrinite reflectance, Hemingway & Riddler (1982) concluded that 1.0–1.25 km of Tertiary sediment was also originally deposited in the region, then eroded, in addition to the 1.0–1.25 km of Upper Jurassic and Cretaceous rocks that were removed.

Using sonic velocities in shales within the Permian Upper Marls and the Coal Measures intersected by wells in the Cleveland Basin/East Midlands Shelf, Whittaker, Holliday & Penn (1985) interpreted a maximum of 2.5 km of post-Cretaceous exhumation of the inverted Cleveland Basin, and an east–west increase in exhumation from less than 200 m to more than 1600 m across the East Midlands Shelf. Hillis (1993) analysed sonic velocities from the Upper and Middle Chalk, the Kimmeridge Clay, the Lias, and Bunter Sandstone in the Cleethorpes-1 and Welton-1 wells of the East Midlands Shelf, inferring apparent exhumation of 1.4–1.6 km and 1.6–1.7 km respectively, where Whittaker, Holliday & Penn (1985) inferred only 0.3 km and 0.6 km of exhumation respectively.

Green's (1989) apatite fission track analyses (AFTA) suggested a maximum of around 3.5 km of exhumation in the inversion axis of the Cleveland Basin, decreasing to 2.7–3 km in the Triassic 'fringe' of the Cleveland Basin. In addition, Green (1989) interpreted 1.3–1.7 km of late Cretaceous/Tertiary exhumation in the onshore East Midlands Shelf at Cleethorpes, and suggested that this value is exceeded over much of the East Midlands Shelf. Bray, Green & Duddy (1992) combined vitrinite reflectance data from the East Midlands Shelf with AFTA results, and concluded there was a minimum of a little less than 1 km of exhumation over the area of Chalk outcrop near the coast, increasing westwards to more than 2 km towards the Pennines. The AFTA results of Green

(1989) and AFTA and vitrinite reflectance results of Bray, Green & Duddy (1992) yield higher exhumation estimates than the earlier compaction studies of Marie (1975) and Whittaker, Holliday & Penn (1985), but agree closely with the compaction-based exhumation estimates of Hillis (1993).

Based on the stratigraphic evidence of the thickest preserved post-Carboniferous sequences in surrounding areas, Holliday (1993) suggested a maximum of 1750 m of section had been removed from the Northern Pennines. Holliday (1993) argued that the use of a higher early Cenozoic mean surface temperature and a higher palaeogeothermal gradient in the exhumed section allows lower estimates of former cover to be made from Green's (1989) AFTA palaeotemperature determinations. Green's (1989) AFTA-based estimates of exhumation can thus be adjusted to give a closer correlation with estimates derived from stratigraphical data, or the mineralogical and shale compaction studies of Hemingway & Riddler (1982) and Whittaker, Holliday & Penn (1985) respectively. However, both Green (1989) and Hillis (1993) suggested that the discrepancy between their results and the earlier compaction studies of Marie (1975) and Whittaker, Holliday & Penn (1985) may be due to these studies using a reference compaction relationship from a region which is itself not at maximum burial-depth.

This paper constrains the magnitude of Late Cretaceous/Tertiary exhumation in the onshore Cleveland Basin/East Midlands Shelf using petrophysical properties of the Chalk as determined both from samples collected at the surface and petrophysical well logging of three onshore wells.

2. Post-Variscan geological history of the Cleveland Basin/East Midlands Shelf

The Cleveland Basin and East Midlands Shelf comprise the onshore flank of the Mesozoic Southern North Sea Basin (Fig. 1). Following the cessation of Variscan shortening, the region began subsiding in the Early Permian. Lower Permian aeolian and fluvial sands, lacustrine clays and halites were deposited into a Variscan postorogenic-

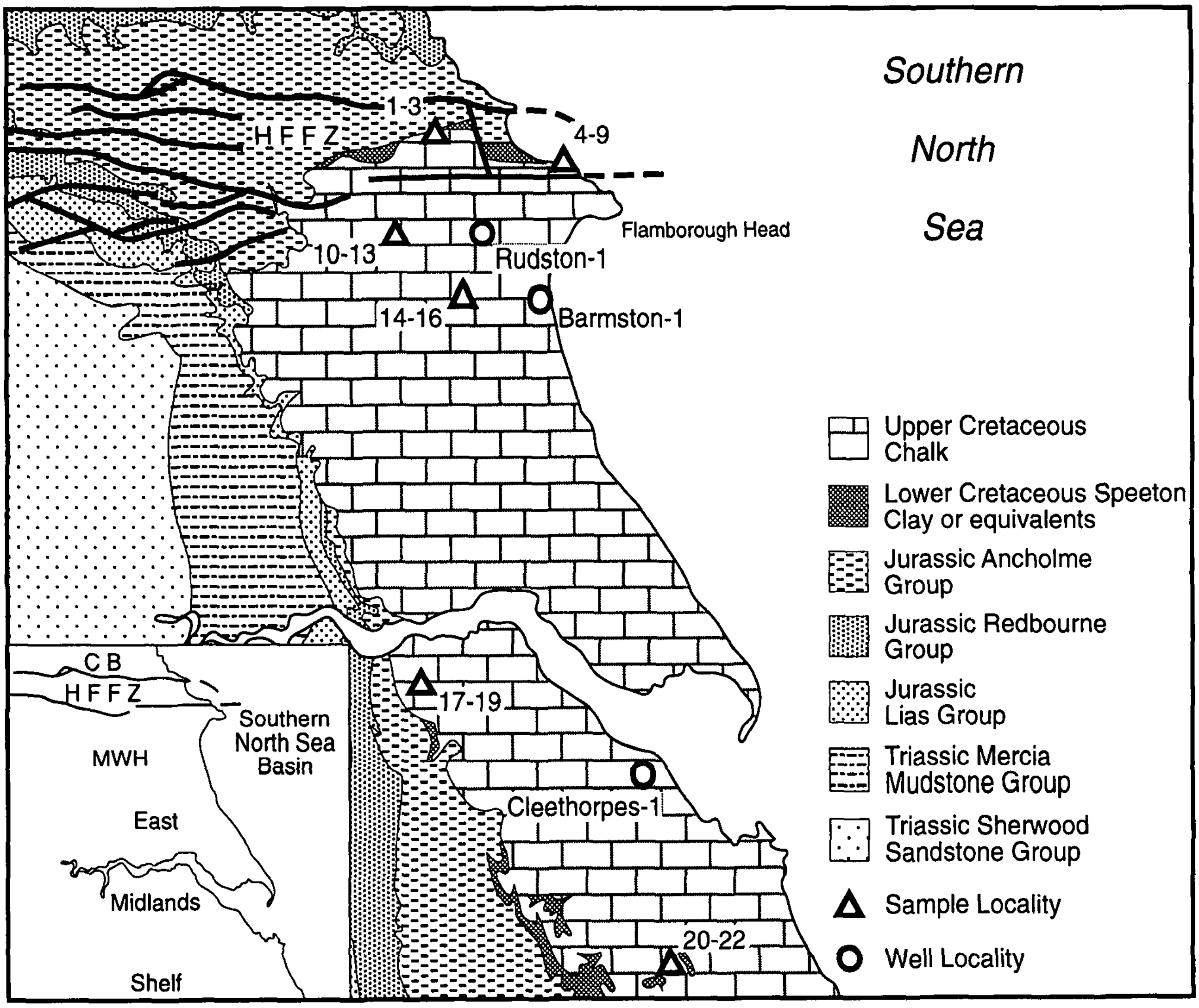

Figure 1. Simplified onshore geological map of the Cleveland Basin/East Midlands Shelf showing locations of outcrop samples (triangles) and wells (circles) (HFFZ = Howardian–Flamborough Fault Zone, CB = Cleveland Basin, MWH = Market Weighton High; Unit nomenclature after BGS 1:250 000 scale Spurn and Tyne Tees solid geology sheets).

collapse basin (Cameron *et al.* 1992) which extended eastwards as far as northern Germany (Ziegler, 1990). At this time, the northern East Midlands Shelf formed an intrabasinal high (Cameron *et al.* 1992). This basin configuration persisted through the Permian and most of the Triassic, with deposition of Upper Permian marine marls, sandstones, and evaporites giving way to the continental sandstones, evaporites, and mudstones of the Triassic Sherwood Sandstone and Mercia Mudstone Groups (Figs 1, 2).

The Cleveland Basin and East Midlands Shelf began to develop through differential subsidence at the end of the Triassic (Rhaetian), with the Howardian–Flamborough Fault Zone (HFFZ; Fig. 1) forming the southern margin of the basin (Rawson & Wright, 1992). The Market Weighton High in the northern East Midlands Shelf formed an area of slow subsidence and shallow water deposition for much of the Jurassic (Fig. 1), while the Cleveland Basin to the north was subsiding rapidly (Rawson & Wright, 1992). Subsidence in the Cleveland Basin slowed in the Upper Jurassic, with the basin becoming a stable shelf with attenuated shallow water deposits, whilst the southern East Midlands Shelf continued to subside (Kent, 1980).

The northern part of the East Midlands Shelf was uplifted and eroded prior to an Albian marine transgression (Kent, 1980), resulting in a hiatus that increases progressively towards the Market Weighton High, where Lower Cretaceous Speeton Clay equivalents overlie the Lower Jurassic Lias (Figs 1, 2). The shallow marine Upper Cretaceous Chalk which was subsequently deposited on the East Midlands Shelf shows little lateral variation in thickness or facies (Kent, 1980). The Cleveland Basin was inverted along a broadly east–west axis at the end of the Cretaceous/early Tertiary, resulting in the removal of the Upper Jurassic, Cretaceous, and Tertiary rocks of the basin (Hemingway & Riddler, 1982).

3. Methodology for quantifying apparent exhumation

Since depth-controlled compaction is largely irreversible, units that are now at shallower depths of burial than their maximum burial-depth will be overcompacted with respect to their present burial-depth (see, e.g. Magara, 1976; Lang, 1978; Bulat & Stoker, 1987; Hillis, 1991; Issler, 1992; Hillis, Thomson & Underhill, 1994). It is assumed that all units follow a normal compaction (that is, porosity) trend with burial, and that compaction is not reversed by subsequent exhumation. With these assumptions, the displacement of exhumed sedimentary rocks above their maximum burial-depth (termed apparent exhumation) is given by the displacement, along the depth axis, of the observed compaction trend from the

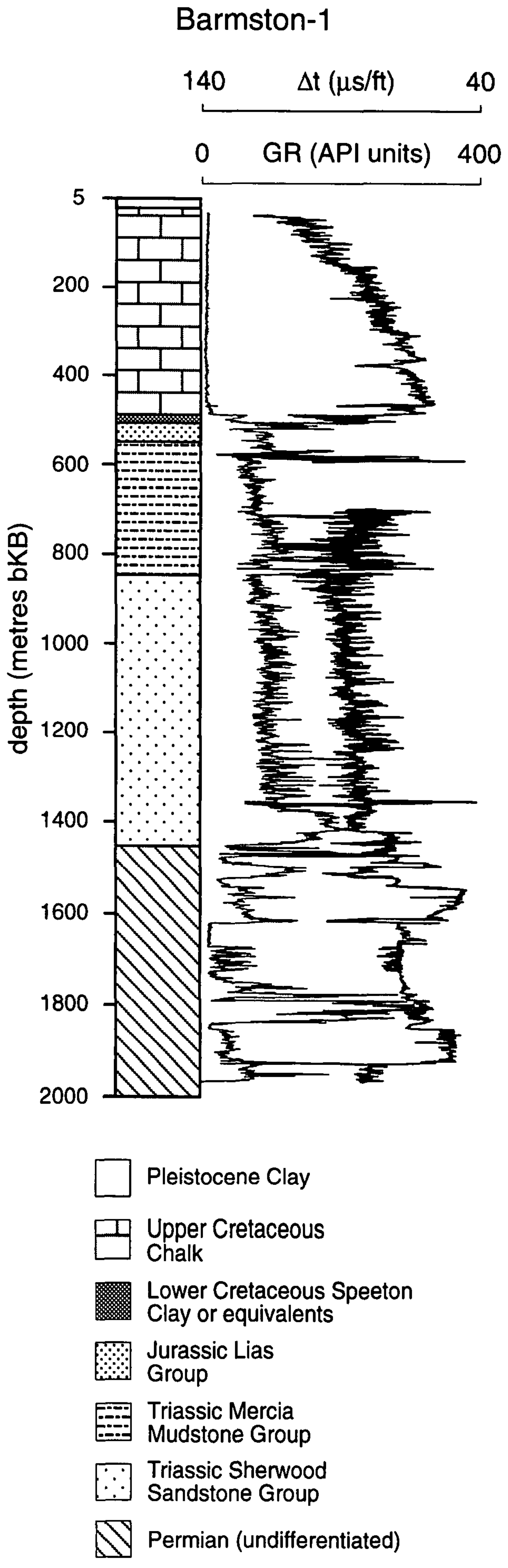

Figure 2. Sonic transit time (Δt) and gamma ray (GR) log for Barmston-1, illustrating log characteristics for the Cleveland Basin/East Midlands Shelf.

normal, undisturbed trend (Fig. 3). Although porosity directly describes compaction state, sonic velocity is widely used as an indicator of compaction because it is strongly dependent on porosity (see, e.g. Wyllie, Gregory & Gardner, 1956; Raiga-Clemenceau, Martin & Nicoletis, 1988) and routinely logged in wells.

The term exhumation (as opposed to erosion or uplift) is used here in the sense of England & Molnar (1990) to describe displacement of rocks with respect to the surface. As stated above, compaction-based studies quantify displacement above maximum burial-depth, a measurement with respect to the surface, and not uplift of rocks or surface uplift, which are measured with respect to an equipotential surface of gravity such as the geoid (England & Molnar, 1990).

The velocities of shales have generally been analysed in the compaction-based quantification of exhumation (e.g. Jankowsky, 1962; Marie, 1975; Magara, 1976; Lang, 1978; Wells, 1990; Issler, 1992; Skagen, 1992; Japsen, 1993). Shales have generally been preferred to other lithologies because of the, usually implicit, assumption that shales show the most predictable and directly burial-depth controlled compaction (that is, velocity/depth) trends. However, lithologies other than shales have been demonstrated to give reliable results. Bulat & Stoker (1987) quantified exhumation in the southern North Sea using every stratigraphic unit above and including the Carboniferous, with the exception of the Upper Permian Zechstein evaporites. Hillis (1991) showed that compaction in the Chalk of the South-Western Approaches was strongly burial-depth controlled, and used velocities in the Chalk to quantify exhumation. Velocities in the Chalk and the Kimmeridge Clay of the Inner Moray Firth yield statistically similar exhumation magnitudes (Hillis, Thomson & Underhill, 1994), as do velocities in the Chalk, the Bunter Shale and the Bunter Sandstone of the Southern North Sea (Hillis, 1995).

Apparent exhumation (E_A) is the vertical displacement of the porosity/depth trend (for a particular unit) from that of the normal compaction relation (Fig. 3). The normal compaction relation is the porosity/depth trend (for that unit) where undisturbed by exhumation. Apparent exhumation can be estimated graphically from plots of mean porosity against depth. However, in practice it is determined numerically using the equation:

$$E_A = \frac{1}{m}(\phi_U - \phi_O) - d_U \qquad (1)$$

where m is the reference porosity/depth gradient, ϕ_U and ϕ_O are the mean porosities of the well or sample under

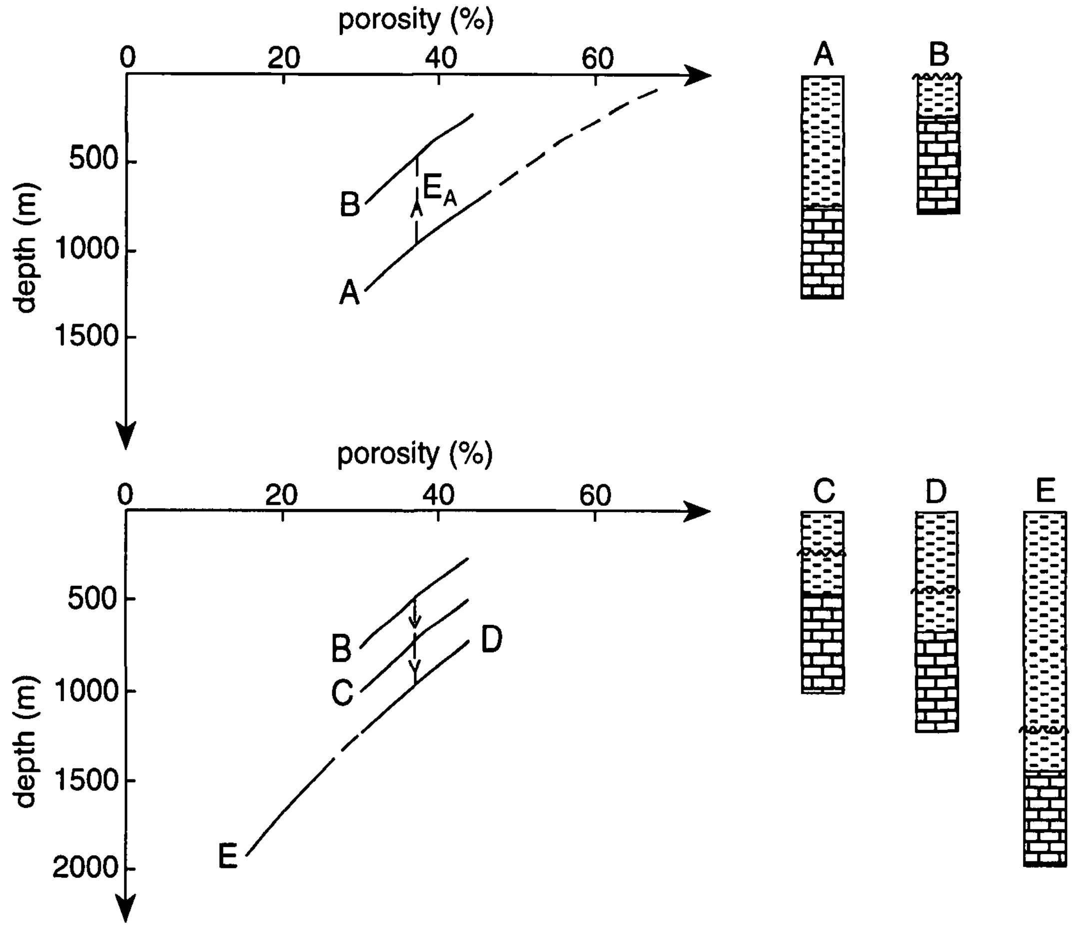

Figure 3. Porosity evolution for a chalk unit (brick pattern) during burial (A), subsequent exhumation (B), and post-exhumational burial (C, D and E). The apparent exhumation (E_A) is the amount of exhumation not reversed by subsequent burial (that is, height above maximum burial-depth).

consideration and the surface porosity respectively, and d_U is the depth of the formation mid-point below sea-bed of the well under consideration, or the depth below the land surface of the sample under consideration. Although the porosity/depth relationship is exponential, over the depth range being considered, a linear relationship between porosity and burial-depth yields equivalent results (see, e.g. Hillis, 1991).

The quantity determined from porosity data is referred to as apparent exhumation because it is exhumation not reversed by subsequent burial. It is not necessarily the same as the amount of exhumation that occurred at the time the rocks were being denuded. If renewed burial follows exhumation, the magnitude of apparent exhumation determined from porosity data is reduced by the amount of that subsequent burial (Fig. 3, well C). Once the unit again reaches its maximum burial-depth (Fig. 3, well D), it is normally compacted, and no evidence of previous exhumation can be detected by this method.

In an area subject to exhumation, the wells with the highest porosity (lowest velocity) for their given burial-depth should be taken to be normally compacted, provided their relatively high porosity is not due to phenomena that may inhibit normal compaction (such as overpressure or hydrocarbon-filled porosity). For a linear decrease of porosity with depth, any two wells that can be linked by a straight line that has no points falling to its right, less compacted side, define normal compaction. These are termed the reference wells.

As previously indicated, the Cleveland Basin/East Midlands Shelf comprises the onshore flank of the Southern North Sea Basin, hence previous offshore compaction studies in the Southern North Sea Basin may be used to define a suitable normal compaction relation. Hillis' (1995) normal compaction relation for the Upper and Middle Chalk, constrained by the normally compacted, or reference, wells 38/25-1 and 44/29-1A, has been used in this study.

The crux of apparent exhumation determination from compaction (porosity) data lies in the selection of the normal compaction relation, and hence in the selection of two reference wells as defined above. The success (or otherwise) of the compaction methodology depends upon the accuracy of the normal compaction relation. A normal compaction relation defined by two wells at maximum burial-depth cannot exactly represent the undisturbed, pre-exhumational burial depth/porosity relationship in all wells. The normal compaction relation in different wells would exhibit some scatter around the defined normal compaction relation. The amount of this scatter is unclear because exhumation cannot be separated from other, broadly sedimentological/ diagenetic influences on the porosity/depth relationship. If there was an unlimited amount of porosity data from wells drilled in structurally low areas of maximum burial-depth, a scatter may be observed around the proposed normal compaction relation, and hence a more accurate estimate of the normal compaction relation could be made. The proposed normal compaction relation may even itself be shown to be overcompacted.

In studies involving a large number of wells such as that of Hillis (1995) in the southern North Sea, the occurrence of a number of wells on or near the normal compaction curve increases the confidence that the normal compaction curve defined by the above methodology is the best possible approximation of the true normal compaction relation. In addition, studies such as Hillis (1995) which derive statistically similar apparent exhumation estimates from different formations and different lithologies, also increase the confidence in the normal compaction relation of each formation.

Skagen (1992) suggested that shale compaction-based estimates of exhumation have a potential accuracy of ± 200 m. Menpes & Hillis (1995) examined the spread of the sonic logs of the reference wells around the normal compaction relation for the Upper Cretaceous Chalk in the Celtic Sea/South-Western Approaches, and suggested that an empirical estimate of the error in the apparent exhumation relation was ± 250 m. A potential error in the normal compaction relation of ± 250 m is also suggested for this study.

3.a. Calculation of mean porosities from well data

Three Cleveland Basin/East Midlands Shelf wells intersecting geophysically logged Chalk units, Barmston-1, Cleethorpes-1 and Rudston-1, were analysed in this study (Fig. 1). The top and base of the Upper Cretaceous Chalk were picked from vertically-compressed (1 : 4000 depth-scale) plots of the sonic and gamma ray logs (e.g. Fig. 2). In each case the top of the Chalk was picked at the first reliable sonic log data, as geophysical logging commen-ced within the Chalk. The base of the Chalk is marked by a distinctive (downwards) increase in both the gamma ray and sonic logs (Fig. 2), and the base was picked at the top of this increase. The mean sonic interval transit time (Δt, the reciprocal of velocity) of the Chalk was determined from digital log data for the Chalk interval thus defined.

To enable comparison with sample porosities, it was necessary to convert interval transit time, as measured by the sonic log, to porosity. The mean interval transit times for the three Cleveland Basin/East Midlands Shelf wells, and the wells defining Hillis' (1995) normal compaction relation, were converted to porosity using the equation of Raiga-Clemenceau, Martin & Nicoletis (1988):

$$\Delta t_{\log} = \frac{\Delta t_{ma}}{(1-\phi)^x} \qquad (2)$$

where $\Delta t_{\log}$ is the sonic log interval transit time, Δt_{ma} is the matrix transit time, and the exponent x is specific to matrix lithology. In this case, for calcite, the appropriate matrix transit time is 47.6 µs/ft, and x is 1.76 (Raiga-Clemenceau, Martin & Nicoletis, 1988). The mid-point depths, mean interval transit times, and mean porosities of the Chalk intervals are given in Table 1.

Table 1. Mid-point depths (metres below sea-bed/land surface), mean interval transit times (μs/ft), and mean porosities (%) for the wells analysed in this study

Well	Mid-point depth (metres)	Mean interval transit time (μs/ft)	Mean porosity (%)
38/25-1	1630	83.7	27.4
44/29-1A	1860	70.6	20.0
Barmston-1	260	78.4	24.7
Cleethorpes-1	180	81.6	26.0
Rudston-1	220	70.6	20.1

Mean porosities were calculated from mean interval transit times using equation 2.

3.b. Determination of porosity of Chalk samples

A sequence exposed at the land surface that is suitable for estimating exhumation from porosity measurements should consist of one lithotype present over a large stratigraphic thickness, so that any porosity trends observed are independent of changes in lithology (Wells, 1990). In this respect, the Upper Cretaceous Chalk of the Cleveland Basin/East Midlands Shelf is an ideal lithology, as it consists of a thick, regionally extensive pure white limestone, composed of calcareous algal plates (coccoliths) deposited as copepod faecal pellets (Rawson & Wright, 1992). Provided care is taken to avoid the flint and marl bands within the Chalk, the sampler can be reasonably assured of sampling a consistent lithotype.

With the exception of the coastal cliff sections such as at Flamborough, much of the Chalk outcrop is limited to ten-metre-scale exposures in the numerous small quarries throughout the Cleveland Basin/East Midlands Shelf area. This limited vertical outcrop at inland exposures, combined with the generally flat-lying nature of the Chalk beds, limited sampling to restricted stratigraphic sections at individual locations. A minimum of three samples were taken from regularly-spaced intervals at the sampling sites shown in Figure 1 in order to determine Chalk porosity for the locality. The 100-m-high section of Chalk exposed in the Bempton Cliffs on the north side of Flamborough Head (samples 4–9 on Fig. 1) was sampled at a 15 m interval, to give an indication of the variation in porosity in the Chalk on a larger scale.

Care was taken at all times to ensure samples were fresh and well-consolidated, to avoid the possibility of weathered rock giving erroneous results. Where possible, samples were cut into two pieces to enable two density/porosity calculations for each sample, as a test of the variation inherent in the methodology described below.

A number of sample sites were also chosen for their proximity to onshore wells, to enable a comparison between exhumation estimates from samples and adjacent wells. However, it was found that wherever wells have been drilled where the Chalk crops out, geophysical logging did not commence until the base of the Chalk, hence no direct comparisons could be made.

Porosities of the 22 samples were determined using a modified version of the water imbibition method described by Emerson (1990). Each sample was soaked in deionized water for 72 hours to ensure saturation of the effective (interconnected) porosity of the rock. A Sartorius 2007 MP electronic balance was used to determine the mass of the water saturated sample when submerged in deionized water (m_{sub}), and to determine the mass of the water saturated sample (m_{sat}). The bulk volume V_B of the sample was calculated using Archimedes' buoyancy principle (equation 3), where ρ_w is the density of deionized water (0.99821 g/cm^3).

$$V_B = \frac{m_{sat} - m_{sub}}{\rho_w} \qquad (3)$$

Each sample was then heated to 150°C for 24 hours to expel all water from the pore spaces of the rock, and the dry mass (m_{dry}) was determined. The dry bulk density ρ_B of the sample was calculated using equation 4.

$$\rho_B = \frac{m_{dry}}{V_B} \qquad (4)$$

Chalk porosity cannot be reliably determined from the volume of imbibed water because the water imbibition method assumes that occluded voids are negligible (Emerson, 1990). The low permeability of the Chalk prevents fluid access to much of the primary porosity of the rock, thus the apparent porosity calculated from the volume of imbibed water is significantly less than the true total porosity of the rock. Similarly, estimates of the grain density of the samples could not be calculated using this method. However, if the Chalk grain density (ρ_g) can be assumed to be 2.71 g/cm^3 (that of calcite), the porosity (ϕ) can be calculated using the relation:

$$\phi = \frac{\rho_g - \rho_B}{\rho_g} \qquad (5)$$

It should be noted that the low permeability of the Chalk does not affect measurement of bulk volume using Archimedes' principle, and assuming oven drying removes all water from primary porosity, the calculated dry density may be used to calculate porosity as above without causing erroneous results.

The modified water imbibition experimental procedure was repeated for each of the 22 samples to ensure that the bulk volumes calculated using equation 3 were consistent. The results are given in Table 2. The measurement of the saturated mass proved to be the most likely source of error, as water began evaporating from the sample as soon as it was exposed to the atmosphere. However, the rate of

Table 2. Measured sample masses and calculated sample bulk volumes

Sample	First measurement			Repeat measurement			Dry	Average	% error
number	m_{sub}	m_{sat}	v_b	m_{sub}	m_{sat}	v_b	Mass	v_b	in v_b
1	22.29	37.98	15.72	22.20	37.85	15.68	35.21	15.70	0.30
2	18.73	31.76	13.05	18.71	31.77	13.09	29.67	13.07	0.27
3A	40.07	67.53	27.51	39.98	67.45	27.52	63.93	27.52	0.04
3B	44.21	74.37	30.22				70.17	30.22	
4	22.06	37.08	15.05	22.04	37.08	15.06	34.92	15.06	0.09
5	15.38	25.32	9.95	15.36	25.31	9.96	24.44	9.96	0.07
6	16.43	27.56	11.15	16.40	27.56	11.18	25.97	11.16	0.26
7A	17.88	30.29	12.43	17.81	30.26	12.47	28.35	12.45	0.27
7B	35.23	59.11	23.92				55.97	23.92	
8A	17.26	29.60	12.36	17.23	29.59	12.38	27.34	12.37	0.21
8B	15.03	26.06	11.05				23.78	11.05	
9	12.73	21.12	8.40	12.69	21.17	8.50	20.22	8.45	1.12
10A	28.85	49.75	20.95	28.76	49.67	20.95	45.69	20.95	0.00
10B	41.66	71.69	30.09				66.09	30.09	
11A	17.52	30.74	13.25	17.40	30.62	13.25	27.74	13.25	0.02
11B	24.63	43.62	19.02				39.66	19.02	
12	13.34	23.29	9.97	13.26	23.20	9.96	21.13	9.96	0.05
13	20.16	34.87	14.74	20.14	34.85	14.74	31.93	14.74	0.01
14A	11.99	22.08	10.11	11.96	21.96	10.01	18.98	10.06	0.94
14B	25.39	46.38	21.03	25.39	46.32	20.97	40.28	21.00	0.30
15A	21.56	37.68	16.16	21.42	37.49	16.10	34.27	16.13	0.36
15B	34.10	59.92	25.86	34.14	59.94	25.85	55.15	25.86	0.06
16A	30.12	52.66	22.58	30.05	52.53	22.52	47.85	22.55	0.28
16B	34.18	59.55	25.42	34.20	59.52	25.37	54.45	25.40	0.22
17A	25.49	44.70	19.24	25.43	44.65	19.26	40.49	19.25	0.09
17B	24.07	42.08	18.04				38.34	18.04	
18	28.63	49.49	20.90	28.53	49.43	20.93	45.60	20.92	0.17
19A	28.20	48.61	20.45	28.15	48.60	20.48	44.69	20.47	0.16
19B	30.42	52.64	22.26				48.46	22.26	
20A	34.87	58.92	24.09	34.85	58.88	24.08	55.57	24.08	0.05
20B	51.40	87.06	35.73				82.11	35.73	
21	67.62	114.25	46.72	67.52	114.06	46.62	107.57	46.67	0.21
22A	33.07	57.90	24.88	32.99	57.74	24.79	52.27	24.84	0.35
22B	39.83	69.63	29.85				63.15	29.85	

m_{sub} = mass of water saturated sample suspended in water (in grams); m_{sat} = mass of water saturated sample (in grams); v_b = bulk volume (cm^3) calculated by equation 3. Where more than one piece of a sample was weighed, a second iteration was not performed.

Table 3. Bulk densities and porosities calculated from equations 4 and 5

	Bulk density (g/cm^3)		Porosity (%)		
Sample	A	B	A	B	Difference
1	2.24		17.24		
2	2.27		16.22		
3	2.32	2.32	14.26	14.31	0.05
4	2.32		14.43		
5	2.46		9.41		
6	2.33		14.15		
7	2.28	2.34	15.96	13.65	2.31
8	2.21	2.15	18.44	20.57	2.14
9	2.39		11.70		
10	2.18	2.20	19.51	18.94	0.57
11	2.09	2.08	22.74	23.08	0.34
12	2.12		21.75		
13	2.17		20.04		
14	1.89	1.92	30.41	29.21	1.19
15	2.12	2.13	21.59	21.29	0.30
16	2.12	2.14	21.69	20.89	0.80
17	2.10	2.13	22.38	21.58	0.80
18	2.18		19.55		
19	2.18	2.18	19.41	19.68	0.26
20	2.31	2.30	14.85	15.19	0.34
21	2.30		14.95		
22	2.10	2.12	22.34	21.94	0.40

A and B are portions of an individual sample. The difference between the A and B calculated porosities where applicable is given.

water loss was sufficiently slow that a relatively accurate measurement of saturated mass could be made, as shown by the maximum percentage difference in calculated bulk volume of 1.1 % (Table 2). Much of the difference between the sample masses between the first and second iteration can be attributed to loss of sample during handling, especially as a result of repeated saturation and desiccation, as the measurements for the second iteration are consistently lower. However, this sample loss has no effect on the calculated bulk density.

As previously mentioned, where possible samples were halved to give an indication of the variation in bulk density and hence porosity within a sample. As can be seen in Table 3, there is a maximum difference of 2.3 % between porosity measurements from two halves of the same original sample. This variation has an insignificant influence on estimates of apparent exhumation.

The porosities and grain densities of three of the samples were also measured using a commercial mercury injection technique (Emerson, 1990). The porosities calculated using the modified water imbibition method are at most 2 % different to those calculated using the mercury injection technique, as shown in Table 4. The modified water

Table 4. Comparison between porosities determined using the modified water imbibition and mercury injection techniques

Sample number	Porosity (%) determined by water imbibition	Porosity (%) determined by mercury injection	Percentage error	Grain density (g/cm^3)
14B	29.2	28.7	1.74	2.70
15B	21.3	21.1	0.95	2.71
16B	20.9	20.8	0.48	2.71

The grain densities of the three samples were measured using the mercury injection technique.

imbibition method is thus considered a sufficiently accurate procedure for determining Chalk sample porosities.

4. Apparent exhumation in the Cleveland Basin/East Midlands Shelf

The calculated porosity of each of the samples, and the mean porosity for the Chalk in each of the wells, was plotted against the mid-point depth (Fig. 4). With the exception of the samples from Flamborough Head (samples 4–9), all of the samples were at the surface, hence in these cases the depth d_U in equation 1 is zero. Table 5 gives the apparent exhumation values for each of the samples calculated using equation 1, as well as the average and standard deviation for each sample locality. The consistency of results from Flamborough Head (samples 4–9), where 100 m of section was sampled at the same location, suggests that even stratigraphically-limited Chalk outcrop samples may be used to reliably determine apparent exhumation based on overcompaction.

Figure 5a shows the contoured map of the mean apparent exhumation estimate for each sample and well locality. Apparent exhumation estimates from the Upper and Middle Chalk of 13 offshore wells analysed by Hillis (1995) are also incorporated in the contour map of Figure 5a. Figure 5a shows an increase in apparent exhumation from east to west across the onshore East Midlands Shelf. In addition, the inversion of the Cleveland Basin is evident in the change from an east–west gradient to

Table 5. Apparent exhumation values calculated from equation (1) for each sample/well, with mean and deviation for each sample locality

Sample no./ well	E_A (metres)	Average E_A	Standard deviation
1	1950	2000	40
2	1980		
3A	2040		
3B	2040		
4	1940	1970	100
5	2110		
6	1980		
7A	1940		
7B	2010		
8A	1870		
8B	1810		
9	2090		
10A	1880	1830	50
10B	1890		
11A	1780		
11B	1770		
12	1810		
13	1860		
14A	1540	1730	140
14B	1580		
15A	1810		
15B	1820		
16A	1810		
16B	1830		
17A	1790	1840	40
17B	1810		
18	1870		
19A	1880		
19B	1870		
20A	2020	1930	120
20B	2010		
21	2020		
22A	1790		
22B	1800		
Barmston-1	1460		
Cleethorpes-1	1490		
Rudston-1	1640		

$m = -3.24 \times 10^{-4}$ and $\phi_0 = 0.802$ in equation (1).

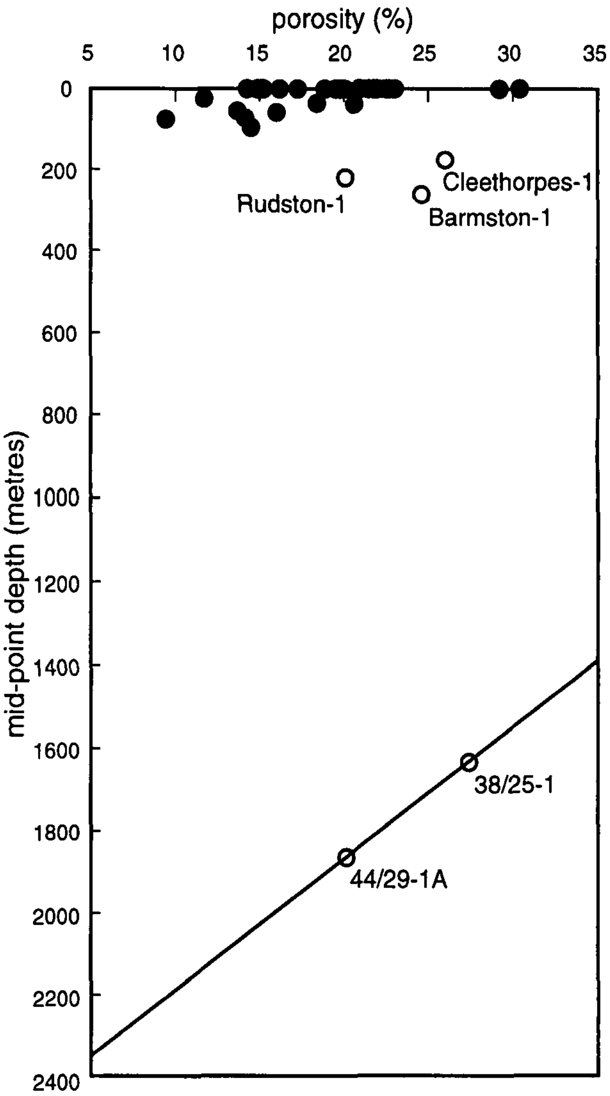

Figure 4. Porosity versus mid-point depth plot for the Upper Cretaceous Chalk, where depth is in metres below surface for onshore wells, and metres below sea-bed for offshore wells. Open circles are wells, and closed circles are samples. Equation for normal compaction trend is $\phi = 0.802 - (3.24 \times 10^{-4})d$.

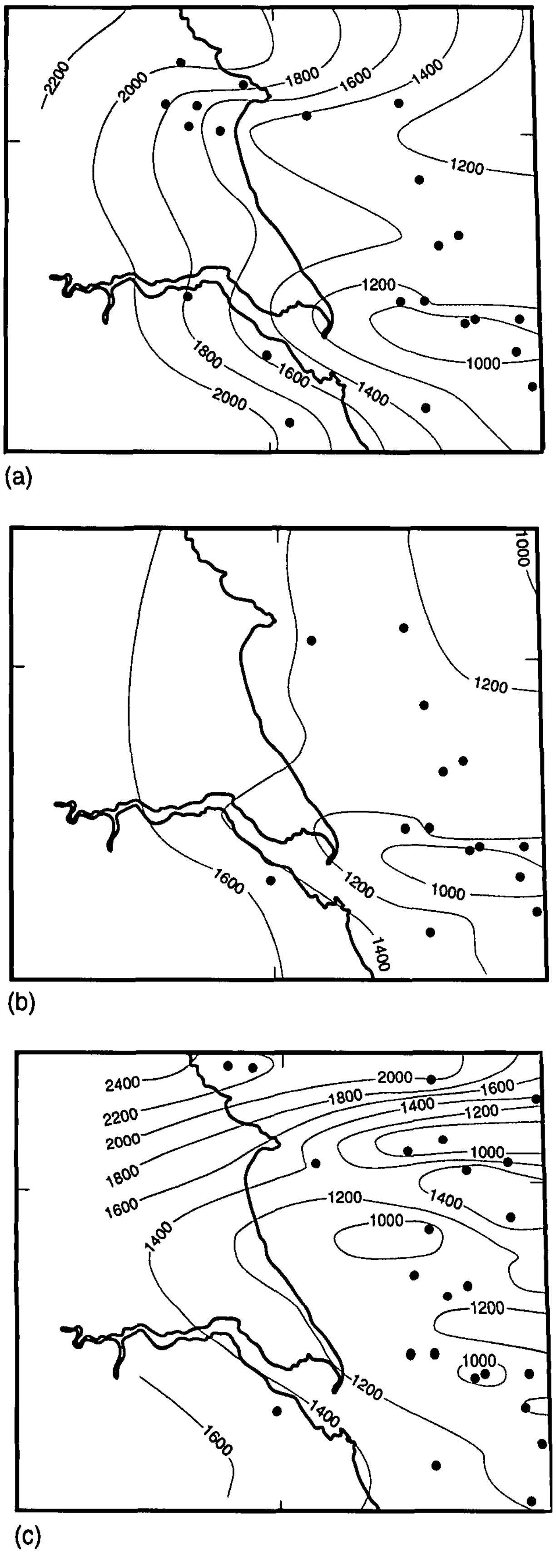

Figure 5. Apparent exhumation maps for (a) the Upper Cretaceous Chalk, (b) the Upper and Middle Chalk of Hillis (1995), and (c) the mean of estimates from the Upper and Middle Chalk, Bunter Sandstone, and Bunter Shale analysed in Hillis (1995).

a northwards increase in apparent exhumation, with the maximum apparent exhumation occurring in the Cleveland Basin. The change in orientation of the apparent exhumation contours from north–south in the East Midlands Shelf to east–west at Flamborough Head is coincident with the Howardian–Flamborough Fault Zone (Fig. 1), which forms the southern margin of the Cleveland Basin. The apparent exhumation trends of Figure 5a clearly mirror the onshore geology shown in Figure 1, with greater apparent exhumation associated with the Cleveland inversion axis superimposed on a regional westward increase in apparent exhumation. The 2 km apparent exhumation contour closely coincides with the outcrop pattern of the base of the Upper Cretaceous Chalk.

Hillis' (1995) study of exhumation in the southern North Sea, based on velocities in the Upper Cretaceous Chalk, was poorly constrained near-shore and onshore because of a lack of wells (Fig. 5b). However, Hillis' (1995) map of the mean of apparent exhumation estimates from velocities in the Upper and Middle Chalk, the Bunter Sandstone and Bunter Shale (Fig. 5c) is better constrained (by more wells) than that based on velocities from the Chalk alone. The inclusion of the onshore estimates from this study results in a better constrained map of apparent exhumation based on compaction of the Upper Cretaceous Chalk (Fig. 5a) than that of Hillis (1995). This improved map shows close agreement with Hillis' (1995) mean apparent exhumation map based on velocities in the Upper and Middle Chalk, Bunter Sandstone, and Bunter Shale (Fig. 5c).

As the Upper Cretaceous Chalk has been eroded from most of the Cleveland Basin, this study can only provide an apparent exhumation estimate for the very southern margin of the basin. This estimate of 2 km exceeds the minimum exhumation estimate by Marie (1975) of 1200–1800 m for the Cleveland Basin. Whittaker, Holliday & Penn (1985) also suggest lower values of exhumation for the Cleveland Basin/East Midlands Shelf than presented herein. The discrepancy between these compaction-based studies and the results of this study may be due to these earlier studies using a normal compaction relation from a region that is itself not at maximum burial-depth, as suggested by Green (1989) and Hillis (1993).

There has been much debate (e.g. Holliday, 1993; Green, Duddy, & Bray, 1995; and the discussions/replies of McCulloch, 1994/Holliday, 1994; Smith, Gatliff, & Smith, 1994/Hillis, 1994) addressing aspects of both AFTA and compaction-based techniques which may lead to these methods over-estimating exhumation. As this debate has been published in detail elsewhere, this paper only addresses those issues directly related to the Cleveland Basin/East Midlands Shelf.

Holliday (1993) suggested that it was necessary to use higher early Cenozoic mean surface temperatures and palaeogeothermal gradients to lower Green's (1989) AFTA-based estimates of exhumation for the East

Midlands Shelf, whilst assuming heat flow remained constant. Chadwick, Kirby & Baily (1994) used this approach in the Lake District Block, and estimated post-Cretaceous exhumation of the central Lake District was typically less than 1750 m, compared with estimates of around 3 km by Lewis *et al.* (1992). However, Bray, Green & Duddy (1992) argued that a heat flow-based approach to thermal history reconstruction is subject to considerable uncertainty. These authors used a combined AFTA and vitrinite reflectance methodology to estimate the palaeogeothermal gradients for a number of East Midland Shelf and Cleveland Basin wells, with the estimated palaeogeothermal gradients resulting in lower apparent exhumation estimates than those of Green (1989), as suggested by Holliday (1993).

However, Bray, Green & Duddy (1992) suggested that to explain the observed cooling in the Cleveland Basin/East Midlands Shelf, approximately 1 km of exhumation is still required in the Cleethorpes-1 well, increasing westwards to more than 2 km towards the Pennines, with up to 2.6 km of Tertiary exhumation necessary in the southern Cleveland Basin. These results are comparable with the compaction-based estimates in this study, which are not subject to the same uncertainties due to thermal history reconstruction. The results herein thus provide independent support for the kilometre-scale exhumation of the Cleveland Basin/East Midlands Shelf suggested by the AFTA and vitrinite reflectance-based methods of Bray, Green & Duddy (1992).

Scotchman (1994) used organic biomarkers (triterpanes, steranes and triaromatic steranes) to accurately determine maturity levels and hence burial history for the Kimmeridge Clay from the onshore UK. The resulting hopane and sterane maturity values suggested that the Kimmeridge Clay had been exhumed by between 1.26 km and 1.53 km on the southern margin of the Cleveland Basin near the coast, increasing to between 2.0 km and 2.1 km inland, and between 1.05 km and 1.26 km of exhumation had occurred on the East Midlands Shelf. The results of Scotchman (1994) provide further support for the magnitude of apparent exhumation suggested for the Cleveland Basin/East Midlands Shelf by this study and by Bray, Green & Duddy (1992).

Several authors (e.g. Holliday, 1993; Smith, Gatliff & Smith, 1994) have suggested that there are difficulties reconciling the amount of apparent exhumation suggested by AFTA and compaction methods for the Cleveland Basin/East Midlands Shelf with the Mesozoic and Cenozoic stratigraphy preserved in the sedimentary basins around northern England. However, if Tertiary exhumation was regional as the above estimates based on petrophysical properties suggest, then the technique of reconstructing maximum probable sediment thickness from preserved thicknesses (see, e.g. Kent, 1980; Holliday, 1993) is flawed. Indeed, a previously unrecorded outlier of Tertiary sediments on the northeast corner of the East Midlands Shelf, about 50 km from the Humberside coast, has recently been documented by Stewart & Bailey (1996). Stewart & Bailey (1996) suggested that the erosive truncation of sediments within the outlier shows that they are remnants of a more extensive Palaeogene cover on the East Midlands Shelf. This outlier provides some indication of the sedimentary sequences that compaction-based estimates of apparent exhumation suggest were eroded from the East Midlands Shelf. Kent (1980) and Holliday (1993) made no allowance for such eroded Tertiary sedimentary rocks in their stratigraphic reconstruction of the maximum burial-depth of northern England.

5. Conclusions

(1) The modified water imbibition method for determining density and porosity described in this paper yields similar results to the more expensive mercury injection laboratory method, provided an assumption for the grain density can be made. For a consistent lithotype such as the Upper Cretaceous Chalk of eastern England, such an assumption is valid, provided care is taken to avoid flint bands within the Chalk when sampling.

(2) The consistency of results from Flamborough Head (samples 4–9), where 100 m of section was sampled at the same location, suggests that even stratigraphically-limited Chalk outcrop samples may be used to reliably determine porosity and thus apparent exhumation.

(3) Sample and geophysical log-based Chalk porosities suggest that Late Cretaceous/Tertiary exhumation in the East Midlands Shelf increased from 1.2 km near the coast to more than 2 km inland to the west. The southern margin of the Cleveland Basin was exhumed by 2 km, with exhumation increasing towards the structural inversion axis in the basin centre. This pattern of apparent exhumation controls the regional outcrop distribution of the Upper Cretaceous Chalk in the Cleveland Basin/East Midlands Shelf.

(4) The apparent exhumation estimates for the Cleveland Basin/East Midlands Shelf presented herein, whilst being greater than earlier compaction-based estimates such as those of Marie (1975) and Whittaker, Holliday & Penn (1985), show very good agreement with the recent AFTA-based exhumation estimates of Bray, Green & Duddy (1992), and the organic biomarker-based estimates of Scotchman (1994).

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