

# Chemostratigraphy: a method to improve interwell correlation in barren sequences — a case study using onshore Duckmantian/Stephanian sequences (West Midlands, U.K.)

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Received 17 December 1997; accepted 14 July 1998

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## Abstract

Chemostratigraphy has been applied to onshore Duckmantian/Stephanian successions encountered in outcrop and penetrated by two boreholes from the West Midlands (U.K.). These successions represent the onshore equivalents of the 'Barren Red Measures' which are important hydrocarbon-bearing sequences in the Southern North Sea. Much is known about the onshore successions in terms of sedimentology, mineralogy and provenance and thus they provide the ideal test for the validity of chemostratigraphy as a stratigraphic tool. Reliable inorganic geochemical data have been acquired from geochemical analyses of core, sidewall core and cuttings samples, with 19 elements being determined. Stratigraphic variations in elemental concentrations are compared with known variations in the mineralogical data. The established lithostratigraphic units of the Duckmantian/Stephanian intervals can also be recognized from the geochemical data and by using these data can be subdivided further. This results in an independent chemostratigraphic correlation being established for the two boreholes, which has been assessed statistically by discriminant function analysis. From the geochemical and mineralogical data, distinct changes in provenance are identified within the Upper Carboniferous successions. The sediments of the Coal Measures were derived from a north westerly and westerly source (?Caledonian), whereas the Etruria Formation sediments came from the Wales Brabant Massif, the sediments having mixed Caledonian and Cadomian characteristics. Eventually these sediments were replaced by sediments from a southern Hercynian source (Halesowen and Salop Formations). © 1999 Elsevier Science B.V. All rights reserved.

*Keywords:* chemostratigraphy; correlation; provenance; Upper Carboniferous

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## 1. Introduction

Significant proportions of the world's hydrocarbon reservoirs occur in sequences that have very

poor stratigraphic control. These sequences are often barren and consequently, tenuous correlations sometimes are established based only on similar lithological and/or petrophysical properties. To refine the stratigraphy of such sections, palaeomagnetism, heavy mineral analyses and isotopic techniques are often utilized. Used together, they can aid in the construction of an integrated stratigraphic framework,

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but are not particularly beneficial when employed individually. These techniques usually work best when applied to cored sections or sections found in outcrop, but the type of lithology available and sample size can restrict their usefulness. Such constraints hamper the successful application of these methods to sequences penetrated by wells and boreholes, from which there is usually only very small amounts of core material available. Consequently, a need has arisen for a technique that can be applied to cuttings and core samples and which can provide an independent stratigraphic framework.

Chemostratigraphy, or ‘chemical stratigraphy’, involves the geochemical characterization and correlation of strata by using major and trace element geochemistry and is very useful when applied to sequences with poor biostratigraphic control. Bulk inorganic geochemical data can be used to correlate sequences on the basis of stratigraphic geochemical variations and this potential has been exploited for some time (Pettijohn, 1975). This obvious potential led to the development of downhole geochemical logging tools (Hertzog et al., 1987). However, the use of such tools is prohibitively expensive and the number of elements determined by them is limited. Furthermore, the resultant data obtained are often difficult to interpret without recourse to independent mineralogical data, if available. The data derived from the logging tool runs mostly relate to major elements (Hertzog et al., 1987; Primmer et al., 1990), which themselves are associated with quartz, feldspar and clay minerals. However, feldspar and clay minerals are susceptible to diagenetic alteration, which consequently weakens the confidence placed on any interwell correlations established from downhole geochemical logging tool data. More recently, focus has been directed towards variations in the less mobile elements Nb, Hf, Zr, Ta and certain rare earth elements (REEs) which cannot be analysed downhole. These elements have been used to invoke changes in sediment provenance (Bhatia and Crook, 1986; Taylor and McLennan, 1985; Floyd et al., 1991). With the advent of new, high precision, rapid throughput, mass acquisition instruments, it has only recently become possible to use a large array of elements, including major elements, trace elements and provenance-sensitive elements, as a basis for geochemical correlations. The techniques that have

made this possible are inductively-coupled plasma-atomic emission spectrometry (ICP–AES) and inductively-coupled plasma–mass spectrometry (ICP–MS).

A chemostratigraphic study that utilized more than 500 samples and a geochemical dataset comprised of 45 elements enabled Late Quaternary turbidites to be correlated successfully (Pearce and Jarvis, 1992a,b, 1995). The technique of chemostratigraphy subsequently has been employed for the petroleum industry in the correlation of offshore sequences from the ‘Barren Red Measures’ (Bolsovian/Westphalian D), the Triassic and the Tertiary. However, most of these studies are proprietary and few publications dealing with chemostratigraphy have been released. The only exceptions include Racey et al. (1995) and Preston et al. (1998), who both applied chemostratigraphy to Triassic sequences in the North Sea. Preston et al. (1998) demonstrate that the technique can be applied to sandstones and they stress the importance of differentiating between those elements associated with diagenetic activity and those more immobile elements which preserve the detrital signature of the rock. For example, during feldspar dissolution, the concentrations of Ca, Na, K, Pb, Rb, Sr and certain REEs can be modified considerably, thus these authors rely on the more immobile elements such as Al, Ti, Zr, Nb and Cr for the construction of reservoir-scale interwell correlations.

## 2. Sampling and analytical rationale

The grain-size of sedimentary rocks has a significant impact on sediment geochemistry and reflects the hydrodynamic sorting of the mineral components. As a result, the absolute elemental concentrations will decrease in coarser grain-size fractions due to dilution by quartz (Spears and Amin, 1981; Shail and Floyd, 1988). Thus it is not practical to use very coarse grained sandstones and conglomerates in chemostratigraphical studies, due to the difficulties encountered in obtaining homogeneous samples from these rock types. In contrast to sandstones, mudstones and claystones have uniform grain-sizes and therefore are likely to possess more homogeneous elemental distributions. Such distributions are

liable to remain relatively consistent over a wide area and therefore will provide a greater potential for correlation (Cullers, 1995). Furthermore, mudstone and claystone chips are better preserved than sandstones in cuttings, the latter often breaking down into monomineralic grains, thereby negating the collection of representative sandstone samples. As the mudstones and claystones are fine-grained and relatively homogeneous, a fairly representative composited sample can be obtained by picking between 100 to 200 chips from any one cuttings sample. Obviously, and this applies to other stratigraphic techniques as well, when using cuttings samples, the resolution that chemostratigraphy can achieve is controlled by the frequency that cuttings samples were collected during drilling. For instance, thin reservoir intervals (e.g., <30 m thick) cannot be studied in detail, as if the cuttings samples have 10 m spacings, then only three composited samples can be collected and analysed from such intervals. Therefore, for those sequences covered by cuttings alone, only major, long term geochemical changes can be identified, i.e., geochemical changes related to changes in provenance. However, these major changes in sediment geochemistry are more likely to persist over a wide area (field- to subregional scale). Furthermore, when considering long-term geochemical trends developed through thick sequences such as the 'Barren Red Measures', even the stratigraphic distributions of potentially mobile elements represent a means for crude correlations on the subregional scale. Evidence from towards the top of the 'Barren Red Measures' indicate a marked climatic change, which led to a drop in rainfall (Besly et al., 1993), the Lower Ketch unit sediments being deposited in humid conditions, whereas the Upper Ketch unit sediments were laid down in more arid environments. This climatic change is reflected by a change in clay mineralogy, with the Lower Ketch unit claystones being kaolinitic, whilst the claystones of the Upper Ketch unit are illitic, this unit also containing caliches (Cameron, 1993). These mineralogical changes are recognized quite clearly by variations in Al, K, Cs and Rb. Geochemical and mineralogical data acquired from core and cuttings samples are used together to recognize the Upper Ketch unit in several well sequences in the Southern Gas Basin. The validity of this correlation is com-

monly supported by the available biostratigraphic data.

Samples can be analysed by a number of instruments, although in most studies, data are acquired by either X-ray fluorescence (XRF), ICP–AES or ICP–MS. The analysis of samples by XRF (Preston et al., 1998) does, however, have significant analytical limitations when compared with ICP–AES and ICP–MS analyses. The XRF technique lacks the analytical sensitivity and detection limits that the ICP–MS technique has (Jarvis and Jarvis, 1995) and this prevents the accurate determination by XRF of provenance-sensitive elements such as Ta, Th, U, Hf, Rb, Cs and Sn. Although the method of sample preparation for ICP analysis is destructive, such analyses require only very small sample volumes, e.g., 0.25 g, and thus any sample loss is minimal. In contrast, XRF analyses typically need samples volumes of about 6–7 g for pressed pellets (Potts, 1987). As ICP analyses only need very small sample volumes, this makes the technique ideal to apply to the very small cuttings samples frequently archived by oil companies. Furthermore, all the major elements and a large number of trace elements can be analysed by ICP–AES and ICP–MS techniques by using a sample solution derived from a single preparation procedure. Conversely, when conducting XRF analyses, trace elements are best determined by using pressed pellets, whereas accurate major element determinations require a fusion disc preparation (Potts, 1987). In addition, not only does ICP analysis provide additional data for key elements, but it also generates K, U and Th data that can be compared directly with natural gamma ray spectrometry (NGT) data, which allows casing to be detected when cuttings samples have been analysed.

This paper outlines the methodology of chemostratigraphy and demonstrates its potential as a correlation tool that can be applied to core samples and, more importantly, to cuttings samples. It considers the impact of sample type on sediment geochemistry and comments are made regarding the potential effects of drilling additive contamination of cuttings. The technique is tested on two onshore borehole sections which penetrate Upper Carboniferous successions, core and cuttings samples being available. These successions represent the onshore equivalents of the offshore hydrocarbon-bearing Westoe

Coal Formation and Schooner Formation (Cameron, 1993) found in the southern North Sea.

### 3. Study sequences

Sections of Duckmantian to Stephanian age have been analysed from eight locations in the coalfields of North and South Staffordshire and the Wyre Forest (Fig. 1), although this paper concentrates on chemostratigraphical studies undertaken on two borehole sections situated just south of the North Staffordshire coalfield, namely the Harts borehole (Grid ref.: 3941/3266) and the Allotment-1 borehole near Stafford (Grid ref.: 3946/3267). The stratigraphy of the Duckmantian–Stephanian sequences in the above coalfields, and their correlation with other coalfields in the West Midlands, have been hampered by poor biostratigraphic control and the usage of various local lithostratigraphic schemes. In this paper, the new Upper Carboniferous lithostratigraphic scheme developed by Besly and Cleal (1997) is utilized, which integrates and redefines the previous lithostratigraphic frameworks (Figs. 2–4). The study intervals from the two boreholes include the Coal Measures (Duckmantian), the Etruria Formation (Bolsovian), the Halesowen Formation (Westphalian D) and the Salop Formation (Westphalian D/Stephanian).

The Coal Measures is composed of grey argillaceous sediments of fluvial and deltaic origin that were deposited in poorly drained environments, with numerous interbedded coals and occasional sandstones and marine bands. In both boreholes, several correlative coals or marine bands are recognized (Figs. 2 and 4), the lowest correlative horizon being the Aegiranum marine band (Besly and Cleal, 1997).

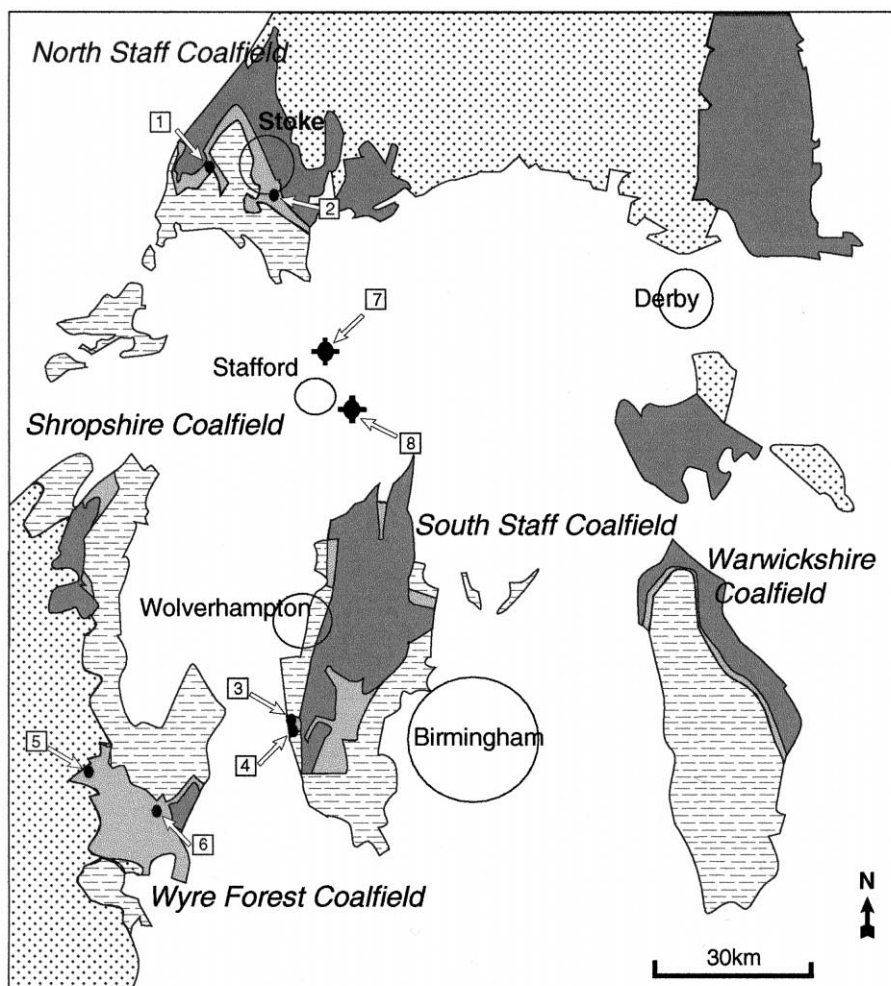
The overlying Etruria Formation comprises predominantly red-brown (mottled red/grey) silty claystones that were deposited in a well drained floodplain environment, along with some interbedded sandstones. The formation is overlain unconformably by the Halesowen Formation, the sediments of which were deposited in poorly drained floodplain areas. In contrast with the Etruria Formation, thick sandstones (20–30') are more frequent in the Halesowen Formation. Above the Halesowen Formation is the Salop Formation, which is com-

posed of interbedded fluvial sandstones and floodplain mudstones. However, the occurrence of occasional limestone horizons and the predominant red-brown colour of the sediments suggests that the depositional environment was well drained and that the climate at the time possibly had become more arid (Glover and Powell, 1996).

In the Allotment-1 borehole, the Carboniferous interval is overlain unconformably by Triassic sediments (Figs. 2 and 4). In the Harts borehole, sample collection terminated in the Salop Formation.

### 4. Geological summary

The analysed sequences recently have been the focus of mineralogical and provenance studies (Hallsworth, 1992 and Lott, 1992, in Glover and Powell, 1996; Besly and Cleal, 1997; Glover and Powell, 1996). It was thought that the Coal Measures and Etruria Formation sediments were derived from a northern Caledonian source. Recently, however, the source for the majority of the Coal Measures has been shown to be from the north west and west, the source area(s) itself being many hundreds of kilometres distant (Rippon, 1996). Glover et al. (1996) note that in Duckmantian/Bolsovian times, the central parts of the Pennine Basin were being fed by systems derived from the west and south of the basin. The Etruria Formation is now believed to have been derived from the Wales Brabant massif, this area becoming more important as a sediment source during Bolsovian times as tectonism related to the Hercynian orogeny intensified (op. cit.). Following a period of localized uplift, folding and erosion, Halesowen Formation sediments were deposited unconformably upon these older successions, these sediments probably having come from a southern provenance area (Hercynian). Similarities have been noted between the Halesowen Formation sediments and the Pennant Sandstone of South Wales (Besly, 1988; Waters et al., 1994; Glover and Powell, 1996) and thus they may have had a common source lying to the south (Kelling, 1974). Chromian spinel in the Halesowen Formation may have been derived from a source similar to the Lizard Complex, although the only likely source to the south for chloritoid is the Île de Groix in Brittany (Glover and Powell, 1996).















Stratigraphy	Localities
 Pre Westphalian	 Stoke quarry 1
 Westphalian A-C Productive Coal Measures	 Stoke quarry 2
 Westphalian A-C Etruria Formation	 Dudley quarry 1
 Westphalian D-Autunian Halesowen, Salop and Clent Fms.	 Dudley quarry 2
	 Shropshire quarry 1
	 Shropshire quarry 2
	 Allotment 1 borehole
	 Harts borehole

Fig. 1. Location map illustrating the outcrop distribution of Pre-Duckmantian and Duckmantian–Autunian rocks in the West Midlands. The map illustrates the location of the principal coalfields in the area, the location of the Harts and Allotment-1 boreholes and certain quarries from which samples have been collected and analysed (not discussed in this paper). Unshaded area = post-Carboniferous.

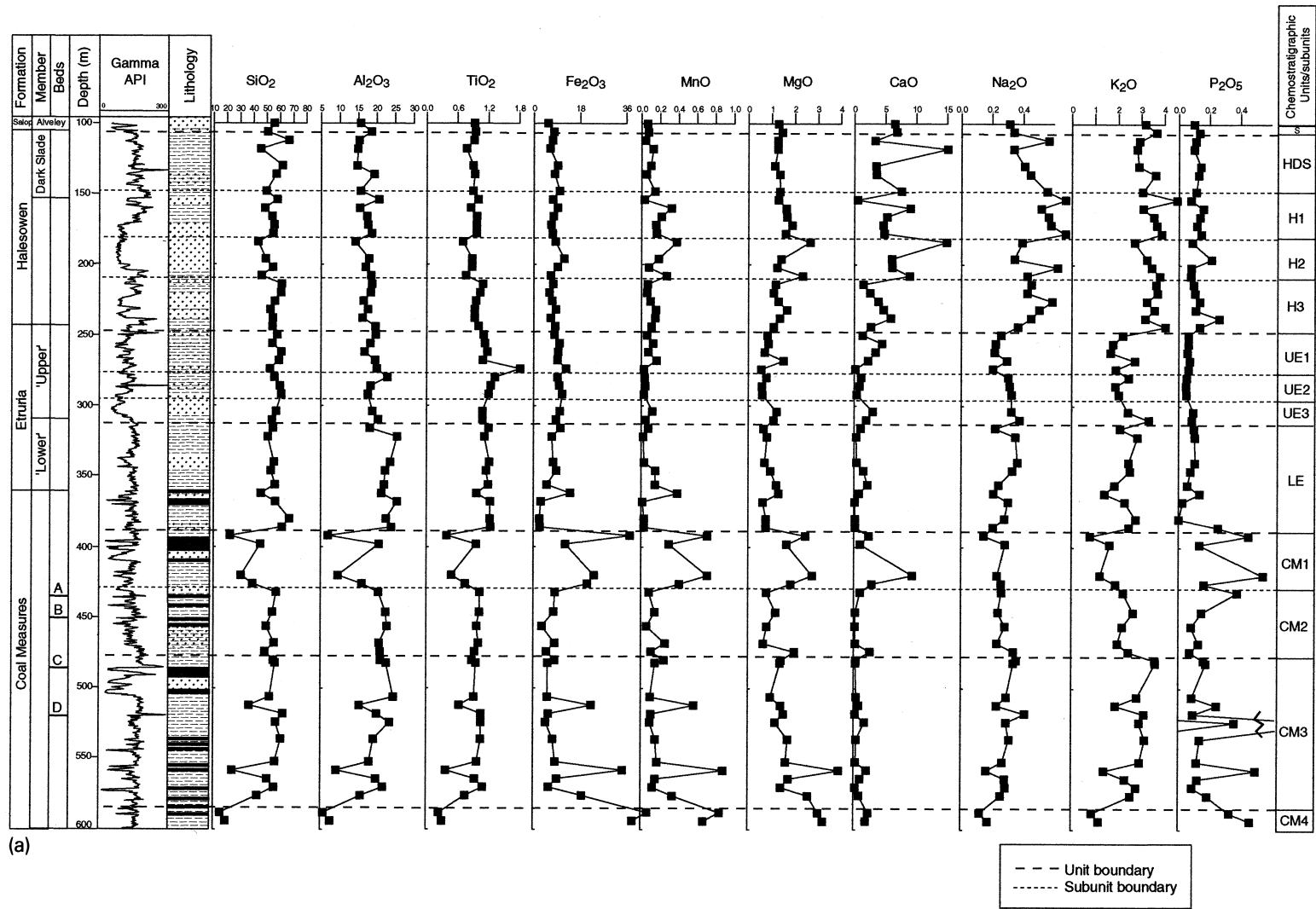


Fig. 2. (a) Major element geochemical profiles for the study interval from the Harts borehole. Data are expressed as weight% oxide. Zig-zag line in the P<sub>2</sub>O<sub>5</sub> profile denotes scale break. Stratigraphic summary for the Harts borehole is based on the scheme of Besly and Cleal (1997). *Dark Sl.* = Dark Slade Member; *Sal.* = Salop Formation; *Alve.* = Alveley Member.

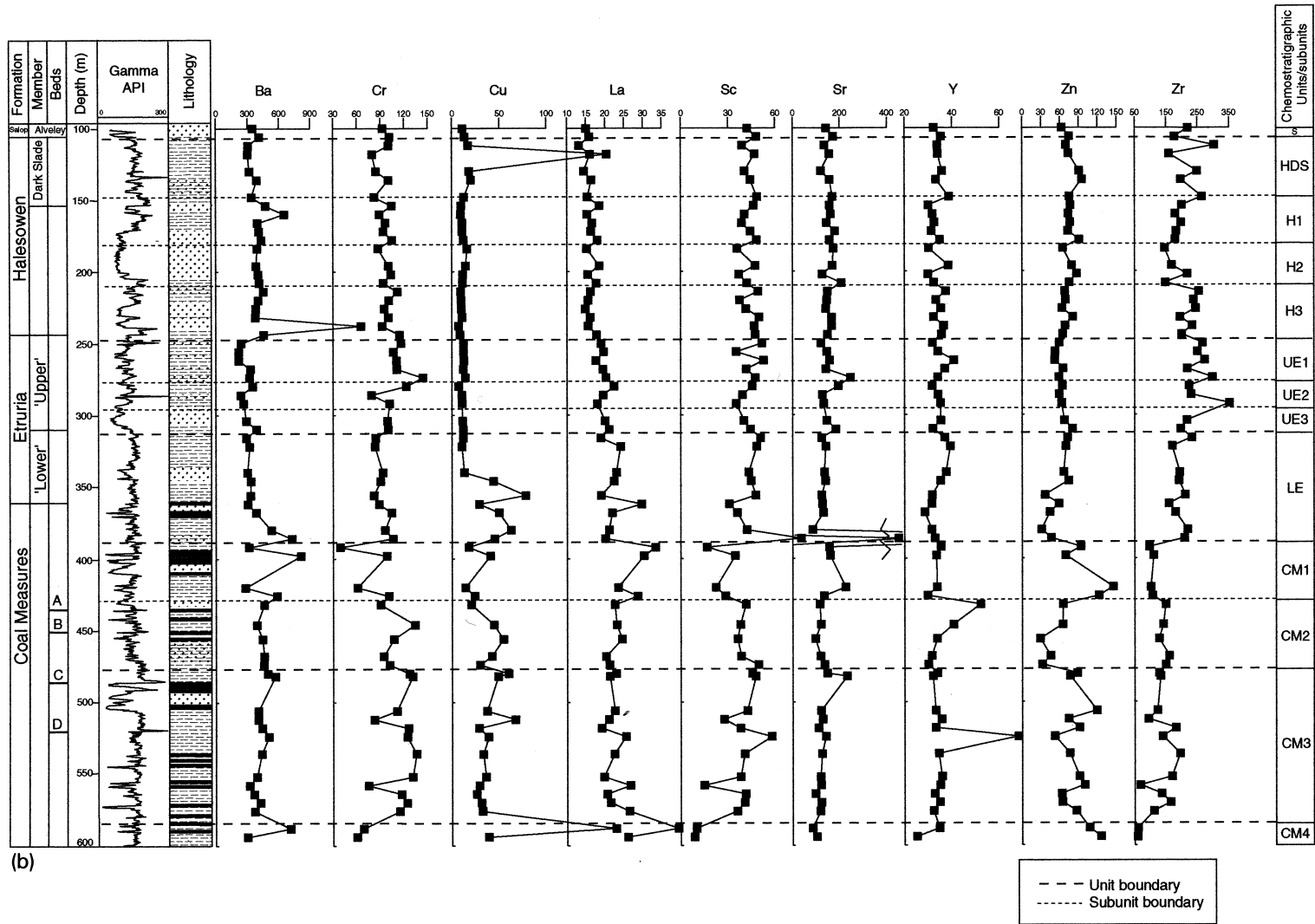


Fig. 2 (continued). (b) Trace element geochemical profiles for the study interval from the Harts borehole. Data are expressed as ppm. Zig-zag line in the Sr profile denotes scale break.

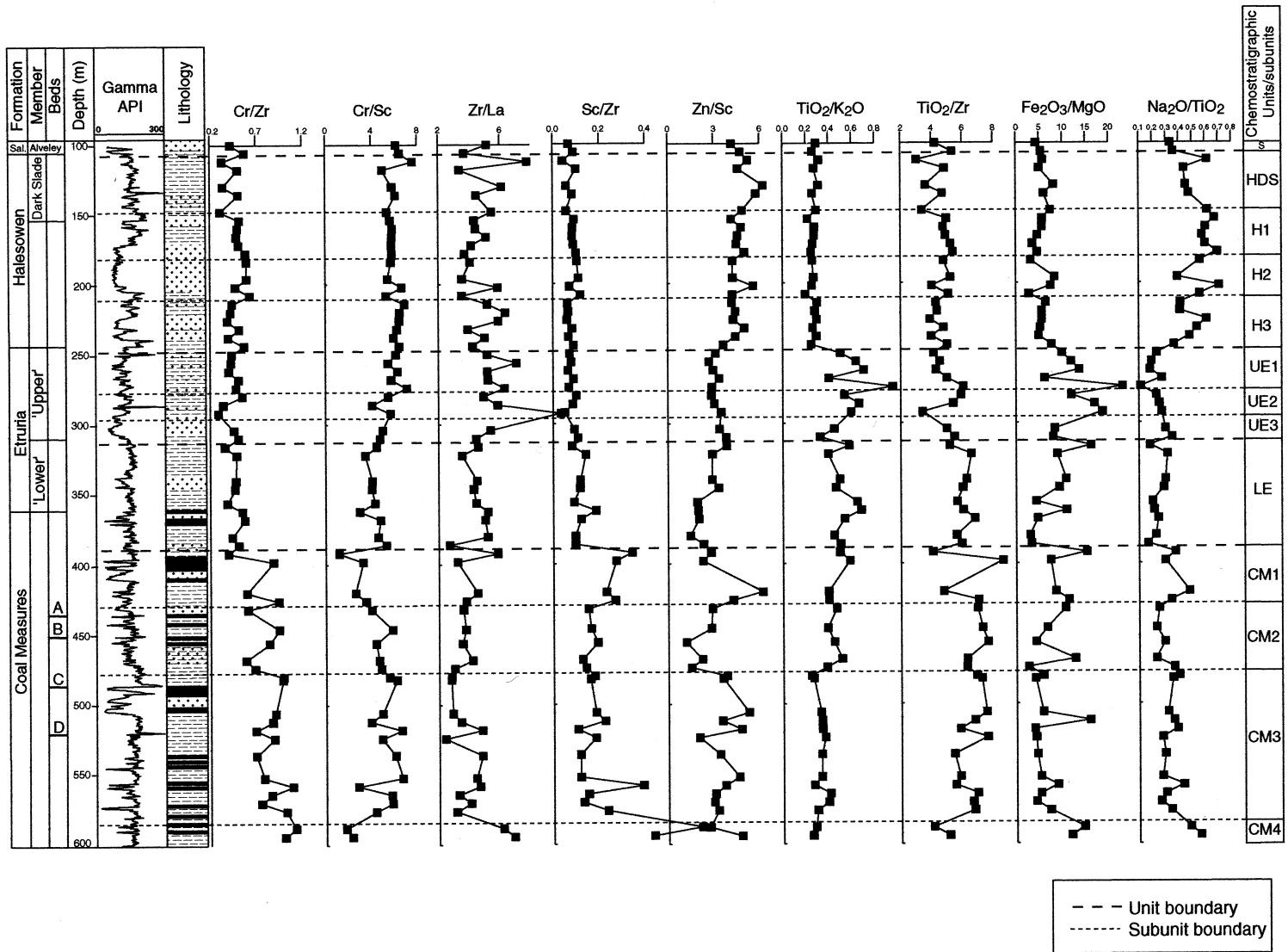


Fig. 3. Ratio geochemical profiles for the study interval from the Harts borehole.



The mineralogy of the Salop Formation is somewhat unusual, being characterized by an influx of angular zircons. This is interpreted in terms of sediment derivation from a local granitic source (Glover and Powell, 1996), although the similarity between the geochemical data and the heavy mineral data from the Salop Formation and the Halesowen Formation suggests that these sediments had the same source. Furthermore, the site of the granitic source is uncertain. Garnet geochemistry and the scarcity of tourmalines in the Salop Formation sediments imply that a Cornubian granite/metasedimentary source to the south is unlikely. Allsop (1987) has postulated the occurrence of Caledonian granites beneath the Wales–Brabant Massif and similar bodies within the western part of this massif may have acted as potential sediment sources for the West Midlands and the Southern Pennines at this time (Glover and Powell, 1996).

The work of Hallsworth (1992) and Lott (1992), both in Glover and Powell (1996), provide excellent clay mineral, heavy mineral and petrographic data from the claystones and sandstones, these data being acquired from core samples and outcrop samples collected from the Etruria, Halesowen and Salop Formations, although none of these samples came from the two study boreholes. Nevertheless, these data provide a firm basis for comparison and enable the interpretation of stratigraphic geochemical variations presented in this paper.

## 5. Methodology

In the Harts borehole, the study interval is 500 m thick and encompasses the Coal Measures and the Etruria, Halesowen and Salop Formations (Fig. 2). The interval is covered by cuttings samples with 10 m spacings, no core being available. In the Allotment-1 borehole, the study interval is 350 m thick, samples being collected only from the Etruria, Halesowen and Salop Formations (Fig. 4). Sample spacings are more variable in this latter borehole; closely spaced samples (1–4 m spacings) have been collected from the cored interval (between borehole depths 445–492 m; Fig. 4), whereas above this interval, only occasional samples are present approximately every 20–30 m. Core sample size varies from ca. 2 cm<sup>3</sup> for the silty claystones to 5 cm<sup>3</sup> for the sandstones.

175 samples were collected, with 90 samples coming from the Harts borehole and 85 samples coming from the Allotment-1 borehole. Of these, most are silty claystones (64 samples — Harts borehole; 56 samples — Allotment-1 borehole), with fewer sandstone samples being collected (26 samples — Harts borehole; 29 samples — Allotment-1 borehole). More silty claystone samples were collected because it is likely that silty claystones deposited in floodplain settings have a wider areal extent. This, in turn, means they will have a greater potential for correlation when compared with the less frequent and probably laterally restricted fluvial channel sandstones.

To avoid contamination, all core and cuttings samples were washed thoroughly prior to preparation for ICP analysis. Each cuttings sample that is analysed is made up of ca. 200 chips that have been extracted by hand-picking from the bulk sample.

All samples were ground in agate and dried prior to preparation. Subsamples (0.250 g) are prepared using a LiBO<sub>2</sub> fusion (Jarvis and Jarvis, 1992). The resultant solutions were analysed by ICP–AES, with the determination of 19 major and trace elements (Si, Al, Ti, Fe, Mn, Mg, Ca, Na, K, P, Ba, Cr, Cu, La, Sc, Sr, Y, Zn and Zr), although most chemostratigraphic studies usually include ICP–AES and ICP–MS analyses. The instrument was calibrated using certificated rock standards, with instrument drift being monitored after every five samples and corrected for by the instrument software. The variability of results from multiple analyses of the reference rocks and the comparison of these results with certified values have enabled the precision and accuracy of the dataset to be assessed. Precision error was measured at <2% for major elements and <4% for trace elements.

## 6. Borehole geochemistry

The geochemical data derived from the silty claystone samples from both boreholes are presented in Figs. 2–5. Figs. 2 and 4 present the geochemical profiles of absolute elemental concentrations against depth. This approach enables the principal geochemical features of the study intervals to be seen. Based on elemental enrichments, depletions and the development of persistent trends recognized from the geo-

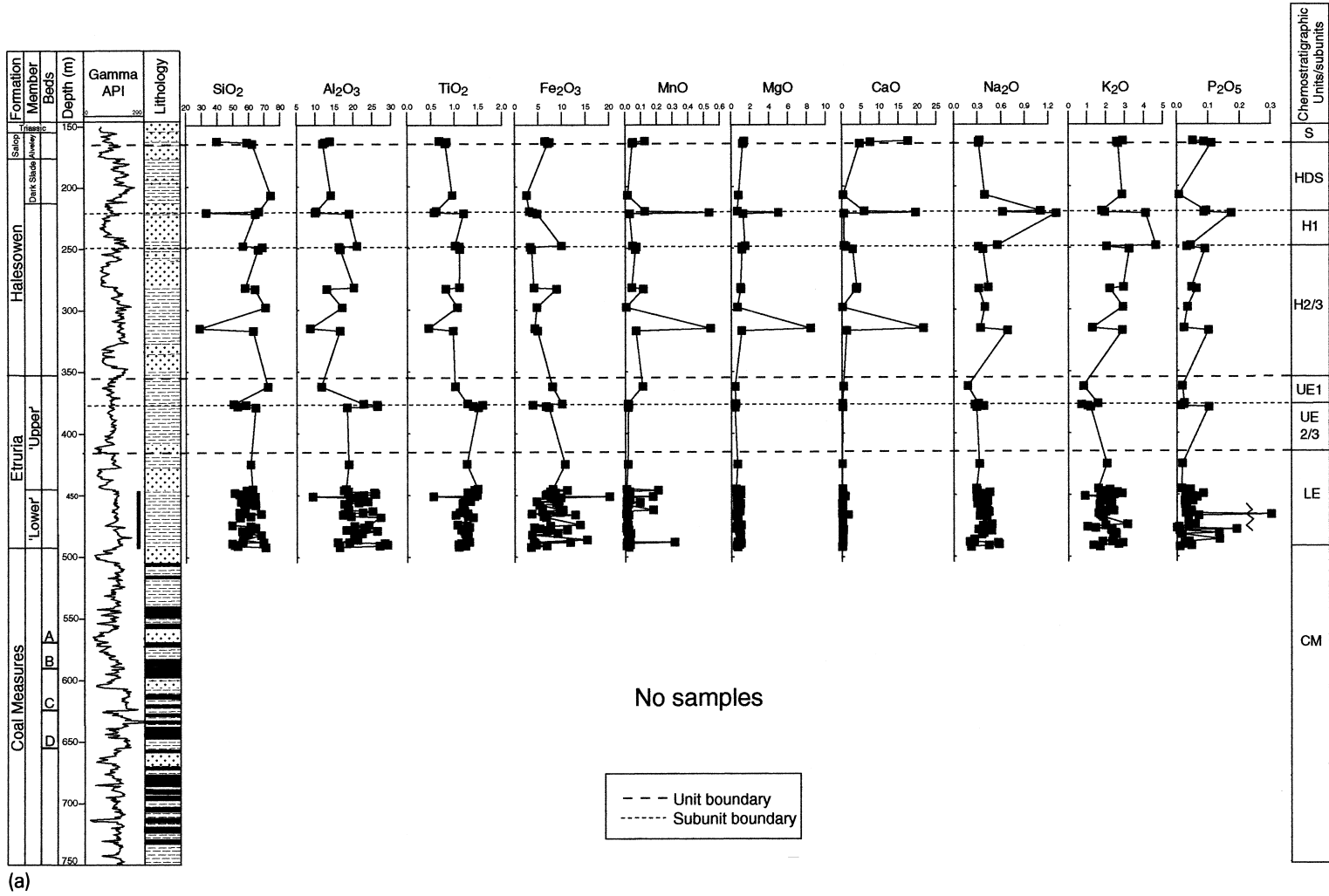
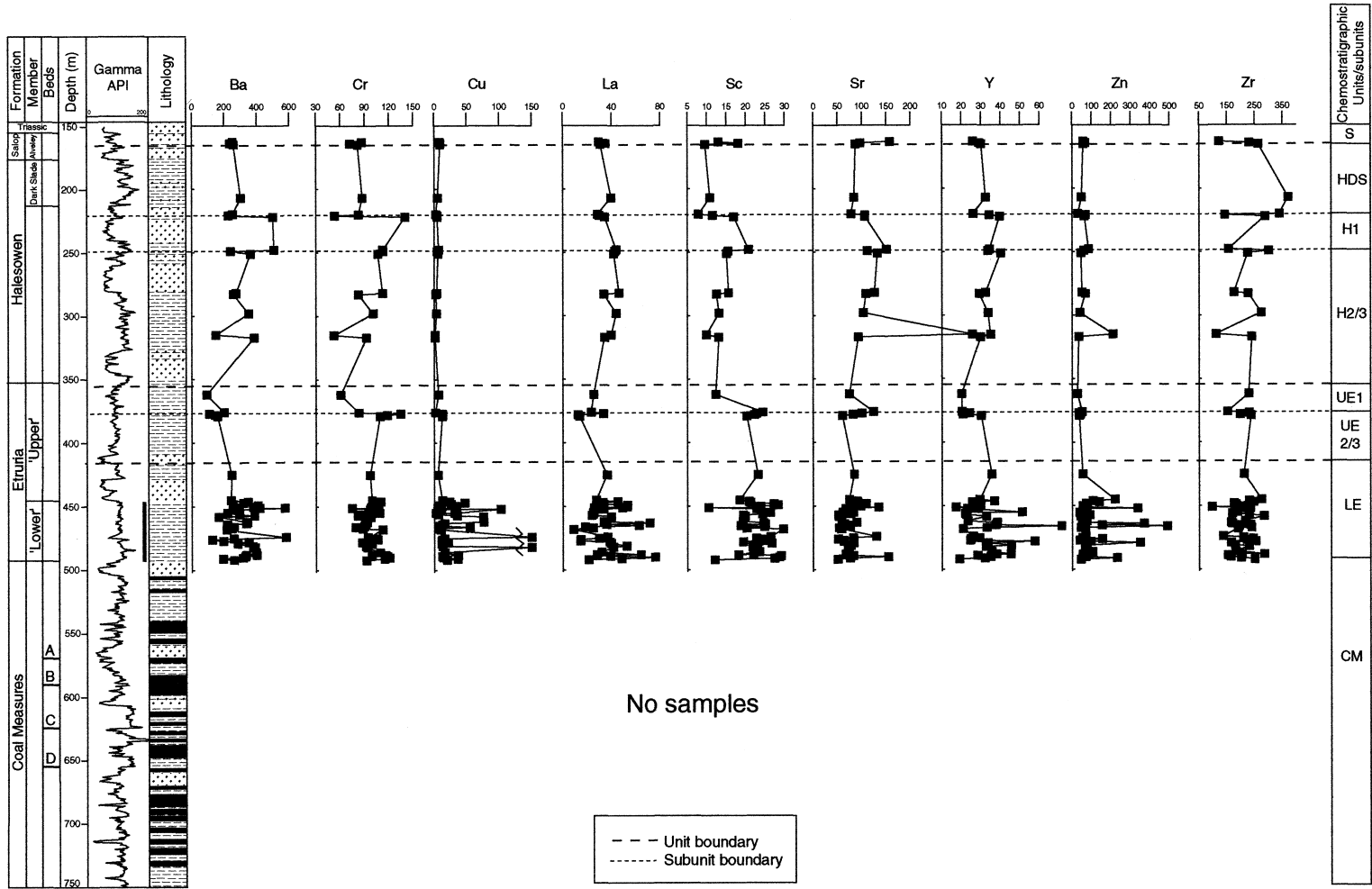


Fig. 4. (a) Major element geochemical profiles for the study interval from the Allotment-1 borehole. Data are expressed as weight% oxide. Zig-zag line in the P<sub>2</sub>O<sub>5</sub> column denotes scale break. Stratigraphic summary for the Allotment-1 borehole is based on the scheme of Besly and Cleal (1997). *Dark Sl.* = Dark Slade Member; *Sal.* = Salop Formation; *Alve.* = Alveley Member.



(b)

Fig. 4 (continued). (b) Trace element geochemical profiles for the study interval from the Allotment-1 borehole. Data are expressed as ppm. Zig-zag line denotes scale break in the Cu profile.

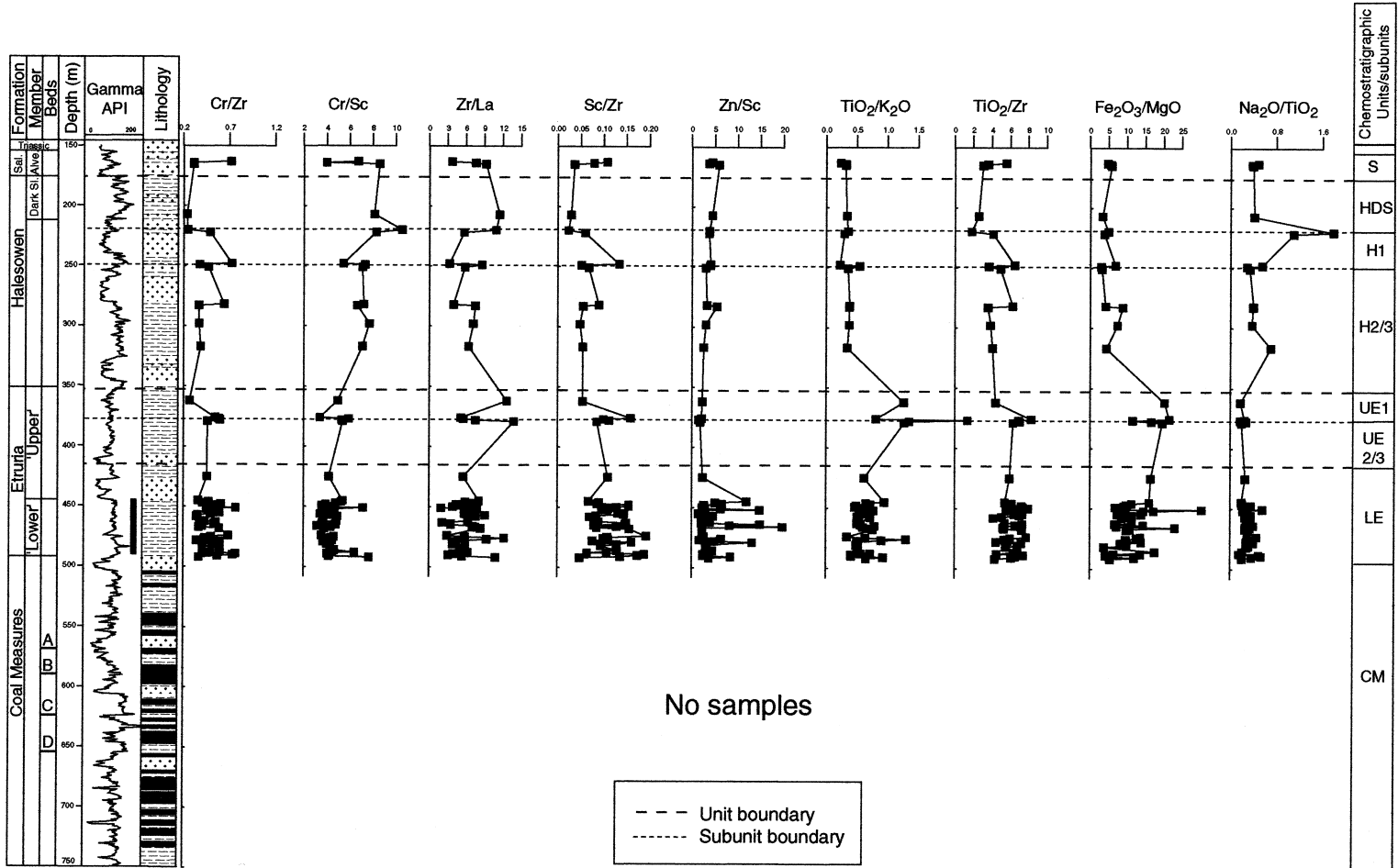


Fig. 5. Ratio geochemical profiles for the study interval from the Allotment-1 borehole.

Table 1

Mean elemental concentrations for each unit and subunit defined in the Harts borehole

Unit	<i>n</i>	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	TiO <sub>2</sub>	Fe <sub>2</sub> O <sub>3</sub>	MnO	MgO	CaO	Na <sub>2</sub> O	K <sub>2</sub> O	P <sub>2</sub> O <sub>5</sub>
<b>S</b>	<b>2</b>	<b>53.1</b>	<b>17.1</b>	<b>0.94</b>	<b>6.7</b>	<b>0.07</b>	<b>1.36</b>	<b>6.65</b>	<b>0.32</b>	<b>3.41</b>	<b>0.116</b>
<b>H</b>	<b>20</b>	<b>54.1</b>	<b>17.2</b>	<b>0.92</b>	<b>8.0</b>	<b>0.14</b>	<b>1.48</b>	<b>5.73</b>	<b>0.49</b>	<b>3.42</b>	<b>0.126</b>
HDS	5	56.1	15.9	0.88	8.2	0.09	1.27	6.61	0.46	3.05	0.117
H1	5	54.1	18.0	0.95	7.6	0.18	1.61	4.87	0.60	3.73	0.126
H2	4	48.3	16.9	0.80	9.0	0.23	1.90	9.00	0.45	3.30	0.114
H3	6	56.5	17.8	0.99	7.3	0.11	1.26	3.52	0.46	3.55	0.141
<b>E</b>	<b>19</b>	<b>56.5</b>	<b>21.0</b>	<b>1.20</b>	<b>8.4</b>	<b>0.08</b>	<b>0.86</b>	<b>1.37</b>	<b>0.28</b>	<b>2.27</b>	<b>0.079</b>
UE1	5	56.8	18.9	1.26	9.9	0.09	0.88	2.36	0.24	2.05	0.063
UE2	3	58.8	19.6	1.26	10.0	0.03	0.65	0.79	0.32	2.12	0.050
UE3	2	55.5	19.7	1.09	9.4	0.08	1.15	2.50	0.35	2.88	0.090
LE	9	55.8	22.8	1.18	6.8	0.10	0.86	0.75	0.28	2.30	0.096
<b>CM</b>	<b>23</b>	<b>45.7</b>	<b>17.7</b>	<b>0.82</b>	<b>15.1</b>	<b>0.32</b>	<b>1.79</b>	<b>1.44</b>	<b>0.26</b>	<b>2.28</b>	<b>0.253</b>
CM1	4	34.5	13.4	0.65	23.6	0.53	2.18	3.94	0.23	1.39	0.325
CM2	5	53.3	21.6	1.00	6.6	0.13	1.09	0.86	0.27	2.30	0.163
CM3	12	51.0	19.3	0.90	11.5	0.26	1.74	0.73	0.29	2.76	0.242
CM4	2	17.1	6.7	0.28	41.4	0.76	3.13	2.17	0.15	1.04	0.397

Unit	<i>n</i>	Ba	Cr	Cu	La	Sc	Sr	Y	Zn	Zr
<b>S</b>	<b>2</b>	<b>381</b>	<b>97</b>	<b>12</b>	<b>15</b>	<b>45</b>	<b>158</b>	<b>34</b>	<b>69</b>	<b>198</b>
<b>H</b>	<b>20</b>	<b>453</b>	<b>97</b>	<b>20</b>	<b>16</b>	<b>44</b>	<b>157</b>	<b>34</b>	<b>76</b>	<b>208</b>
HDS	5	331	89	46	15	44	148	35	81	235
H1	5	472	98	11	17	44	160	32	78	188
H2	4	397	96	13	17	41	169	33	76	170
H3	6	575	103	9	16	45	153	35	69	228
<b>E</b>	<b>19</b>	<b>335</b>	<b>101</b>	<b>24</b>	<b>21</b>	<b>45</b>	<b>211</b>	<b>34</b>	<b>59</b>	<b>226</b>
UE1	5	264	118	13	19	46	163	36	57	261
UE2	3	283	101	9	20	40	151	34	62	268
UE3	2	338	100	11	21	42	165	34	74	207
LE	9	390	92	38	22	47	267	34	55	197
<b>CM</b>	<b>23</b>	<b>448</b>	<b>102</b>	<b>42</b>	<b>24</b>	<b>35</b>	<b>132</b>	<b>36</b>	<b>82</b>	<b>127</b>
CM1	4	497	75	24	29	26	169	33	108	105
CM2	5	441	106	38	22	41	117	38	47	146
CM3	12	425	116	39	22	39	132	37	82	137
CM4	2	506	64	106	33	9	94	30	116	60

Major elements are reported as weight% oxides, and trace element are reported as  $\mu\text{g g}^{-1}$ . Unit mean figures are in bold.

chemical profiles (Fig. 2a–b and Fig. 4a–b), the study intervals are divided into geochemically distinct intervals termed ‘chemostratigraphic units’. Average elemental concentrations for each unit and subunit are presented in Tables 1 and 2. The boundaries between the units are located at steps in the geochemical profiles and, because in most cases the unit boundaries lie between sample locations, they are placed to coincide with marked changes in the gamma trace.

The absolute concentrations of individual elements are interrelated. For instance, the concentrations of those elements present in detrital minerals

usually found in siliciclastic rocks, such as Si and Al, will be ‘diluted’ in samples that possess carbonate cements. Therefore, it is necessary to compare the geochemical data from the two boreholes by using elemental ratios (Figs. 3 and 5).

## 7. Harts borehole

The Harts borehole is regarded as the reference section because it has good sample coverage. The study interval is divided into six chemostratigraphic

Table 2

Mean elemental concentrations for each unit and subunit defined in the Allotment-1 borehole

Unit	<i>n</i>	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	TiO <sub>2</sub>	Fe <sub>2</sub> O <sub>3</sub>	MnO	MgO	CaO	Na <sub>2</sub> O	K <sub>2</sub> O	P <sub>2</sub> O <sub>5</sub>
<b>S</b>	<b>3</b>	<b>53.5</b>	<b>12.7</b>	<b>0.77</b>	<b>6.9</b>	<b>0.072</b>	<b>1.29</b>	<b>9.85</b>	<b>0.32</b>	<b>2.69</b>	<b>0.083</b>
<b>H</b>	<b>12</b>	<b>59.3</b>	<b>15.2</b>	<b>0.91</b>	<b>4.8</b>	<b>0.137</b>	<b>1.95</b>	<b>5.11</b>	<b>0.57</b>	<b>2.72</b>	<b>0.066</b>
HDS	3	57.8	11.4	0.71	3.1	0.223	2.12	8.56	0.70	2.19	0.062
H1	2	60.1	19.9	1.10	7.3	0.037	1.35	0.56	0.93	4.36	0.108
H2/3	7	59.7	15.4	0.94	4.8	0.129	2.05	4.93	0.41	2.48	0.055
<b>E</b>	<b>43</b>	<b>58.8</b>	<b>21.2</b>	<b>1.25</b>	<b>8.0</b>	<b>0.039</b>	<b>0.69</b>	<b>0.19</b>	<b>0.36</b>	<b>1.94</b>	<b>0.068</b>
UE1	4	58.3	21.7	1.31	7.1	0.041	0.40	0.20	0.28	1.02	0.019
UE2/3	1	64.3	18.4	1.50	7.2	0.019	0.37	0.21	0.29	1.18	0.102
LE	38	58.8	21.2	1.24	8.1	0.039	0.73	0.18	0.36	2.05	0.073

Unit	<i>n</i>	Ba	Cr	Cu	La	Sc	Sr	Y	Zn	Zr
S	3	247	80	9	32	13	113	28	59	204
H	12	316	95	4	38	13	127	33	66	237
HDS	3	259	74	4	33	10	89	31	48	284
H1	2	502	126	6	39	19	128	37	73	221
H2/3	7	287	94	3	40	13	143	33	72	221
<b>E</b>	<b>43</b>	<b>288</b>	<b>99</b>	<b>49</b>	<b>35</b>	<b>23</b>	<b>79</b>	<b>31</b>	<b>106</b>	<b>206</b>
UE1	4	135	99	9	23	20	95	21	38	202
UE2/3	1	159	109	12	14	20	60	30	36	237
LE	38	307	98	54	36	23	78	32	115	205

Major elements are reported as weight % oxides, and trace element are reported as  $\mu\text{g g}^{-1}$ . Unit mean figures are in bold.

units (Fig. 2a–b and Fig. 3), some of which are subdivided into subunits. The boundaries between the chemostratigraphic units coincide broadly with the lithostratigraphic boundaries. The main geochemical characteristics of these units are documented below (also in Table 1, Fig. 2a–b and Fig. 3).

### 7.1. Unit S: (Salop Formation)

Only two samples from a ca. 10 m thick interval assigned to Unit S have been analysed, thus the unit is only poorly characterized geochemically. The geochemical trends developed over Unit H below persist into Unit S, particularly the increased levels of K<sub>2</sub>O, CaO and Zr. In contrast, Na<sub>2</sub>O contents, which are high in Unit H, are lower in Unit S. Compared with the underlying Subunit HDS, Unit S is also differentiated by having lower Na<sub>2</sub>O/TiO<sub>2</sub>, Cr/Sc and TiO<sub>2</sub>/Zr ratios (Fig. 4a).

### 7.2. Unit H: (Halesowen Formation)

Unit H corresponds to the Halesowen Formation, although the base of the unit is placed to coincide with

the gamma 'spike' at borehole depth 248 m (Fig. 2a), which is slightly lower than the lithostratigraphic base of the Halesowen Formation. The principal geochemical features of this unit are very high levels of Na<sub>2</sub>O, K<sub>2</sub>O and CaO, moderately high levels of MnO and MgO and slightly raised P<sub>2</sub>O<sub>5</sub>, Ba and Zn contents. Average SiO<sub>2</sub> and Fe<sub>2</sub>O<sub>3</sub> contents remain relatively constant through Unit H, although locally, SiO<sub>2</sub> contents are depleted by high carbonate contents, e.g., at the top of Subunit H2. In addition, concentrations of Al<sub>2</sub>O<sub>3</sub>, TiO<sub>2</sub>, Cr and La generally are lower than in the underlying Unit E (Etruria Formation) and Unit CM (Coal Measures) and their levels also decline upwards through Unit H. Strong Ba and Cu enrichments are developed in the basal and topmost parts of the unit, respectively. Unit H is characterized by having high Zn/Sc and Na<sub>2</sub>O/TiO<sub>2</sub> ratios and low TiO<sub>2</sub>/K<sub>2</sub>O and Fe<sub>2</sub>O<sub>3</sub>/MgO ratios (Fig. 3).

Unit H is subdivided into four chemostratigraphic subunits, namely, in ascending order, H3, H2, H1 and HDS, with Subunit HDS corresponding to the Dark Slade Member (Besly and Cleal, 1997).

Subunit H3 is equivalent to the basal part of the Halesowen Formation. It has the overall geochem-

ical attributes of Unit H, but is differentiated from Subunit H2 above by having lower CaO, MgO and MnO contents and marginally higher SiO<sub>2</sub>, TiO<sub>2</sub> and Zr contents. In addition, Na<sub>2</sub>O and Zn levels increase upwards through the subunit. Subunit H3 also has variable but high Zr/La ratios and upwardly increasing Na<sub>2</sub>O/TiO<sub>2</sub> ratios (Fig. 3).

Subunit H2 is differentiated by having high CaO, MgO and MnO levels and relatively low SiO<sub>2</sub>, Na<sub>2</sub>O, Al<sub>2</sub>O<sub>3</sub>, TiO<sub>2</sub> and Zr concentrations, particularly in the uppermost sample. The subunit also possesses upwardly increasing Cr/Sc, TiO<sub>2</sub>/Zr and Na<sub>2</sub>O/TiO<sub>2</sub> ratios, the latter being somewhat erratic (Fig. 3).

Subunit H1 has the highest K<sub>2</sub>O and Na<sub>2</sub>O contents and Na<sub>2</sub>O/TiO<sub>2</sub> ratios found in Unit H. It is differentiated from Subunit H2 by having lower CaO, MgO and MnO contents and relatively higher SiO<sub>2</sub>, Na<sub>2</sub>O, Al<sub>2</sub>O<sub>3</sub>, TiO<sub>2</sub> and Zr contents. MgO and Zr contents decrease upwards through the subunit.

Subunit HDS caps the Halesowen Formation. Compared with the other three subunits, Subunit HDS is characterized by upwardly decreasing Na<sub>2</sub>O levels and raised Zr, Y and Cu contents. CaO contents are enriched locally. Furthermore, this subunit possesses low Cr/Zr and TiO<sub>2</sub>/Zr ratios and upwardly decreasing Na<sub>2</sub>O/TiO<sub>2</sub> ratios, as well as increased Zr/La, Zn/Sc and Fe<sub>2</sub>O<sub>3</sub>/MgO ratios (Fig. 3).

### 7.3. Unit E: (Etruria Formation)

Unit E is equivalent to the Etruria Formation, although it does extend down into the top of the Coal Measures. The base of the unit is placed at borehole depth ca. 390 m and incorporates ca. 30 m of grey mudstones, sandstones and coals assigned to the Coal Measures. The unit is characterized by high Al<sub>2</sub>O<sub>3</sub>, TiO<sub>2</sub> and Zr contents and low CaO, MgO, MnO, Na<sub>2</sub>O and K<sub>2</sub>O contents (Fig. 2a–b). In addition, Cr/Sc, Zn/Sc and Fe<sub>2</sub>O<sub>3</sub>/MgO ratios increase upwards, whereas Sc/Zr and TiO<sub>2</sub>/Zr ratios decrease upwards.

Two subunits are recognized, namely subunits UE and LE. Compared with Subunit LE, Subunit UE has high Cr and Zr contents and lower Al<sub>2</sub>O<sub>3</sub> and La contents (Fig. 3a–b). Furthermore, Subunit UE also possesses higher Cr/Sc, Zr/La, Zn/Sc and

Fe<sub>2</sub>O<sub>3</sub>/MgO ratios. The geochemistry of Subunit LE is relatively similar, although Cu contents are enriched in the basal samples. Subunit UE is subdivided into minor units UE1, UE2 and UE3, which are defined primarily by steps in the Cr/Sc, Zr/La, TiO<sub>2</sub>/K<sub>2</sub>O and Fe<sub>2</sub>O<sub>3</sub>/MgO profiles (Fig. 3) and enrichments in these ratios.

### 7.4. Unit CM: (Coal Measures)

Unit CM corresponds to an interval of Coal Measures sediments which extends from the base of the study interval at borehole depth 600 m to just above the major coal seams at borehole depth ca. 400 m. Within this unit lies the Aegiranum Marine Band and the U/N Coal (= ?Cambriense Marine Band) (Fig. 2a). Unit CM has similar Al<sub>2</sub>O<sub>3</sub>, Na<sub>2</sub>O, CaO and TiO<sub>2</sub> contents to those of Unit E above, but in contrast, has higher P<sub>2</sub>O<sub>5</sub>, Ba, Cu and Zn contents and lower Zr contents (Fig. 2a–b). The unit is subdivided into four subunits, namely CM4–CM1 (in ascending order).

Subunit CM4 corresponds to the basal part of Unit CM and is defined only tentatively on the basis of two samples that have very distinctive geochemical characteristics. The subunit is differentiated from the overlying Subunit CM3 by having very high Fe<sub>2</sub>O<sub>3</sub>, MgO, CaO, P<sub>2</sub>O<sub>5</sub>, Cu and Zn concentrations (Fig. 2a–b) and high Zr/La and Sc/Zr ratios (Fig. 3).

Subunit CM3 comprises an interval that incorporates the Aegiranum Marine Band and the Bottom Robins Coal (Edmondia Marine Band). Gamma API values increase upwards through the subunit and are higher overall than elsewhere in Unit CM3. This is reflected by higher and upwardly increasing K<sub>2</sub>O contents. When compared with Subunit CM2, Subunit CM3 has higher Cr, Zn and Sc contents (Fig. 2b), as well as higher Cr/Sc and Zn/Sc ratios and slightly higher Na<sub>2</sub>O/TiO<sub>2</sub> ratios. A sample from immediately below the Aegiranum Marine Band is enriched in P<sub>2</sub>O<sub>5</sub> and Y; as such enrichments usually point to the presence of a marine band, it may be that either some slight caving has occurred or that there is a small difference (<5 m) between the cuttings depths and the log depths.

Subunit CM2 is equivalent to a succession including the U/N Coal (= ?Cambriense Marine Band) and the Top Robins Coal (Shafton Marine Band). The

subunit has lower gamma API values than Subunit CM3, and this is reflected by lower  $K_2O$  contents. Major element concentrations for Subunit CM2 are comparable to those of Subunit CM3, but their trace element contents are different. In Subunit CM2, Cu contents decrease upwards, Y contents increase upwards and Zn contents are depleted significantly. The subunit is also defined by low Zn/Sc ratios and high  $TiO_2/K_2O$  ratios, as well as by upwardly increasing  $Fe_2O_3/MgO$  ratios and upwardly decreasing Cr/Sc ratios (Fig. 4a). No significant anomalies are recognized in the geochemical data derived from those samples associated with the U/N Coal and the Top Robins Coal.

Subunit CM1 comprises the uppermost part of Unit CM that overlies the U/N Coal. The subunit is distinct geochemically, largely because of very high  $Fe_2O_3$ , MnO, MgO, CaO and  $P_2O_5$  contents (Fig. 2b) and depleted  $SiO_2$ ,  $Al_2O_3$ ,  $TiO_2$  and  $K_2O$  levels. In addition, Ba, La, Sr and Zn levels are all enriched, whereas Cr, Sc and Zr levels are depleted (Fig. 2b). Subunit CM1 is recognized quite clearly from the ratio profiles (Fig. 3) and the boundary with Unit E represents one of the most obvious changes in sediment geochemistry over the entire section, being marked by distinct steps in virtually all of the geochemical profiles (Fig. 2a–b and Fig. 3).

## 8. Allotment-1 borehole

The study interval from this borehole has been divided into three chemostratigraphic units and five subunits (Fig. 3a–b and Fig. 5). The morphology of the geochemical profiles covering this interval are much more erratic than those covering the study interval of the Harts borehole. This is because the composited cuttings samples of silty claystones from the Harts borehole are more homogeneous lithologically and geochemically than the core samples from the Allotment-1 borehole. Because the cuttings samples are composited, any lithological and geochemical variability that may be present is reduced, whereas such variability is preserved in core samples. Therefore geochemical profiles constructed from core sample data always tend to be relatively erratic (cf. Figs. 2 and 3 with Figs. 4 and 5). The geochemical profiles are also influenced by vari-

able sample spacing, as in the Allotment-1 borehole; such spacing produces erratic profiles and hampers the accurate placement of the boundaries of the chemostratigraphic units, the designation of the subunits being purely subjective. Despite these problems, several key geochemical features are recognized in the study interval of the Allotment-1 borehole, which are comparable to those from the Harts borehole. Consequently, Units S, H and E are recognized in the Allotment-1 borehole.

### 8.1. Unit S: (*Salop Formation*)

Three samples from the interval assigned to Unit S have been analysed. They have low  $Al_2O_3$  and  $Na_2O$  contents and high CaO contents, although the levels of other elements are variable (Fig. 4a–b). Elemental ratios likewise are variable, but as in the Harts borehole,  $Na_2O/TiO_2$  and Zr/La ratios tend to be lower than in Unit H below (Fig. 6).

### 8.2. Unit H: (*Halesowen Formation*)

As in the Harts borehole, Unit H corresponds to the Halesowen Formation and is characterized by high  $K_2O$  and  $Na_2O$  levels and lower  $Al_2O_3$ ,  $TiO_2$  and La contents when compared with Unit E below. In addition, localized enrichments of CaO, MnO and MgO contents are only found in Unit H.  $Fe_2O_3$  contents are slightly lower in this unit and along with  $TiO_2$  contents decrease upwards (Fig. 4a–b). Unit H is also differentiated from Unit E by possessing higher Cr/Sc and  $Na_2O/TiO_2$  ratios, lower  $TiO_2/K_2O$  and  $Fe_2O_3/MgO$  ratios and marginally lower  $TiO_2/Zr$  ratios (Fig. 5).

Unit H is subdivided, albeit tentatively, into three subunits (HDS, H1 and H2/3), which are comparable to those in the Harts borehole. Subunit HDS has high Zr levels and upwardly decreasing  $Na_2O$  contents. The correlation of Subunit HDS between the two boreholes is based on high Zr/La ratios, depleted  $TiO_2/Zr$  ratios and upwardly decreasing  $Na_2O/TiO_2$  ratios (Fig. 5).

Subunit H1 has high  $K_2O$ ,  $Na_2O$ , Ba and Cr contents and high  $Na_2O/TiO_2$  ratios. The underlying Subunit H2/H3 is characterized by general upward increases in  $K_2O$ , Cr and Ba levels. The high CaO, MnO and MgO contents that typify Subunit H2



in the Harts borehole are not recognized in the Allotment-1 borehole, although one Subunit H2/3 sample is enriched in these three elements. Because of this, subunits H2 and H3 are not separated in the Allotment-1 borehole.

### 8.3. Unit E: (Etruria Formation)

Unit E is equivalent to the Etruria Formation. Whether the base of the unit lies within the top of the Coal Measures, as it does in the Harts borehole, cannot be assessed, as samples are not available from below the base of the Etruria Formation. When compared with Unit H, Unit E is characterized by high  $\text{Al}_2\text{O}_3$  and  $\text{TiO}_2$  contents, slightly higher  $\text{Fe}_2\text{O}_3$  contents and lower CaO, MgO, MnO,  $\text{K}_2\text{O}$  and  $\text{Na}_2\text{O}$  contents (Fig. 4a–b). Unit E is differentiated quite clearly from Unit H by having lower Cr/Sc and  $\text{Na}_2\text{O}/\text{TiO}_2$  ratios, higher  $\text{TiO}_2/\text{K}_2\text{O}$  and  $\text{Fe}_2\text{O}_3/\text{MgO}$  ratios and marginally higher  $\text{TiO}_2/\text{Zr}$  ratios (Fig. 5).

Unit E is subdivided into subunits UE and LE. Despite the geochemical variability found in the analysed samples from these subunits, they have comparable geochemical characteristics to the equivalent subunits in the Harts borehole. Subunit UE possesses high Zr/La,  $\text{TiO}_2/\text{K}_2\text{O}$  and  $\text{Fe}_2\text{O}_3/\text{MgO}$  ratios when compared with Unit LE. Subunit UE is subdivided further into minor units UE1 and UE2/3 based on variations in the Zr/La,  $\text{TiO}_2/\text{K}_2\text{O}$  and  $\text{Fe}_2\text{O}_3/\text{MgO}$  ratios, the base of UE1 corresponding with a maximum value of the  $\text{Fe}_2\text{O}_3/\text{MgO}$  ratio

(Fig. 5). Minor units UE2 and UE3 cannot be differentiated with any confidence in the Allotment-1 borehole, although this may be due simply to the low numbers of samples that have been analysed.

### 9. Chemostratigraphic correlation summary

On the basis of the geochemical data outlined above, a chemostratigraphic correlation framework is constructed for the two boreholes (Fig. 6).

The geochemical characteristics of the Etruria Formation are similar in both boreholes, and the same is true for the Salop and Halesowen Formations. Discriminant function analysis (DFA) has been applied to the geochemical dataset derived from the analysed silty claystone samples (107 in all) from the two boreholes (Table 3) and the correlation of Units S, H and CM and subunits UE and LE are assessed. Not enough samples are available from some of the subunits, e.g., H1–H3, to enable any valid statistical correlations to be made for them. The overall correlation of samples from the Allotment-1 and the Harts borehole is measured at 92.5%. It is significant that Units S, H and CM are distinct geochemically from subunits UE and LE in both boreholes. In addition, DFA confirms the subdivision of Unit E (Etruria Formation) into subunits UE and LE, although sample numbers from these subunits are low.

For the Harts borehole, the boundaries of the principal chemostratigraphic units coincide closely with existing lithostratigraphic boundaries, although mi-

Table 3

Discriminant function analysis correlation confidence of geochemical samples from units S and H (Salop and Halesowen Formations), Upper Etruria, Lower Etruria and Coal Measures from the Harts and Allotment-1 boreholes

Actual		Salop and Halesowen	Upper Etruria	Lower Etruria	Coal Measures
Salop and Halesowen	<i>n</i>	32	0	0	0
	% cor. conf.	100.00	0.00	0.00	0.00
Upper Etruria	<i>n</i>	1	11	3	0
	% cor. conf.	6.70	73.30	20.00	0.00
Lower Etruria	<i>n</i>	0	4	32	0
	% cor. conf.	0.00	11.10	88.90	0.00
Coal Measures	<i>n</i>	0	0	0	23
	% cor. conf.	0.00	0.00	0.00	100.00
Correctly classified 92.5%					

Total dataset of 19 elements and 106 silty claystone samples (sandstone samples not included). ‘% cor conf.’ = % correlation confidence, *n* = no. of samples.

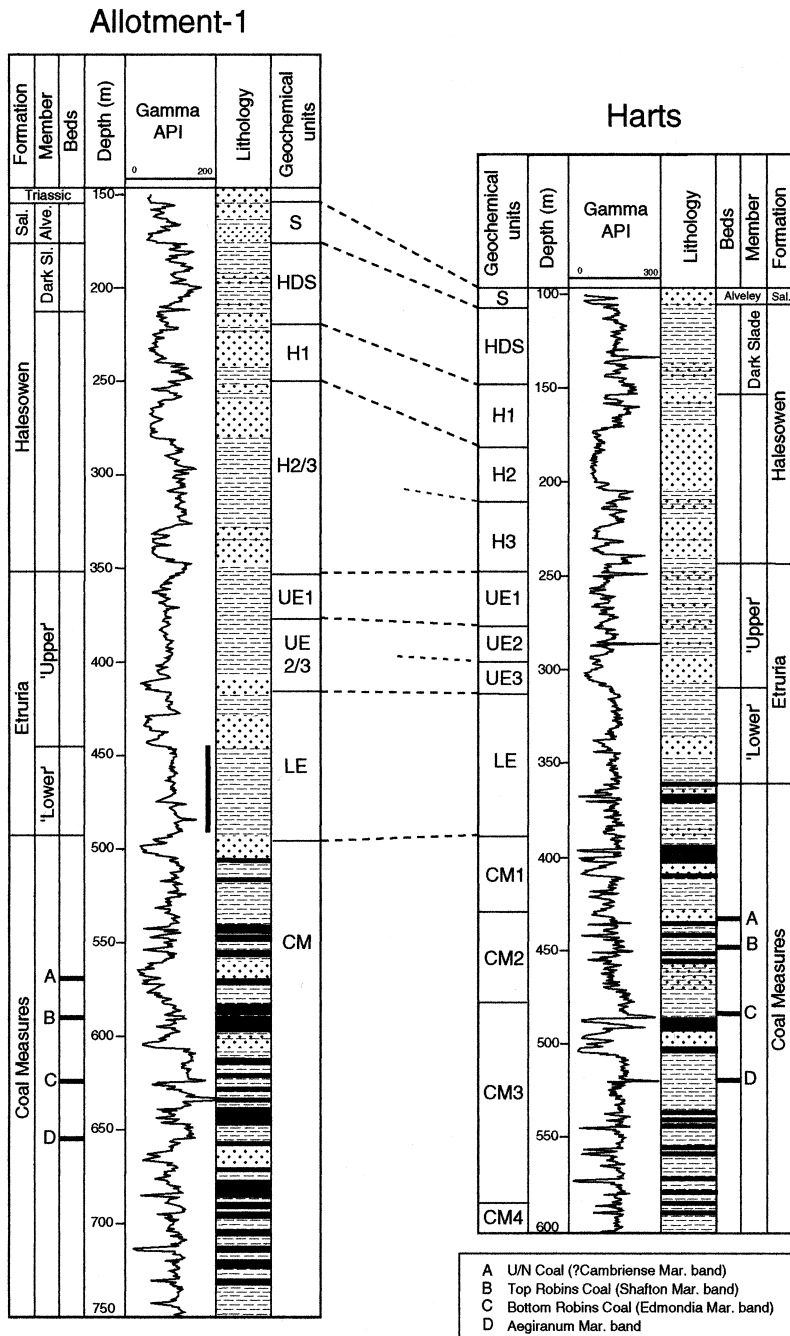


Fig. 6. Chemostratigraphic correlation for the Allotment-1 and Harts boreholes.

nor differences are found associated with the bases of the Halesowen Formation and Unit H and more importantly with the bases of the Etruria Forma-

tion and Unit E. Furthermore, subunits HDS, UE and LE correspond closely to recognised lithostratigraphic subdivisions (Besly and Cleal, 1997). The

coincidence between the geochemical and lithostratigraphic boundaries appears to suggest that the cuttings from the Harts borehole are representative of the lithologies penetrated and that they have not been affected adversely by caving. In contrast, poor sample coverage in the Allotment-1 borehole prevents the accurate placement of the boundaries between the chemostratigraphic units.

Where sample frequencies are consistent and relatively high in the Harts borehole, the subunits and minor units such as H1-3, UE1-3 and CM1-4 are recognized and they probably represent locally correlative intervals. Although they are defined on the basis of the geochemical data from only 4 or 5 samples and therefore their validity may be questioned on statistical grounds, it should be remembered that the geochemical data for each sample represent the composited signature of ca. 200 silty claystone chips per sample and therefore if the individual subunits and minor units possess distinctive geochemical signatures, then they certainly represent significant stratigraphic features. Conversely, in the Allotment-1 borehole, the recognition of the Unit H subunits is purely subjective.

## 10. Discussion

The mineralogy of the late Carboniferous sequences in the West Midlands has been discussed briefly by Glover and Powell (1996) and Besly and Cleal (1997). Some knowledge of the mineralogy provides a means by which to relate stratigraphic variations in mineralogy to changes in sediment geochemistry. It is significant that sandstones and silty claystones from the same units and subunits often can be differentiated using the same geochemical criteria, which demonstrates that in these instances, sediment geochemistry is mostly affected by variations in provenance rather than by differences in grain size. A number of key features are recognized, as follows.

(1) The high K, Rb, Cs and Zn levels found in the Halesowen Formation (subunits H1-3 and HDS) and, to a lesser extent, in the Salop Formation (Unit S) probably are due to increases in detrital illite and white mica. This interpretation is consistent with the observations of Hallsworth (1992, in Glover and Powell, 1996) who reports illite to be the predom-

inant clay mineral (e.g., illite 50%, kaolinite 30% and chlorite 20%). Fig. 7a–b illustrate that subunits CM1-4, LE and UE1-3 are characterized by significantly higher  $Al_2O_3/K_2O$  ratios than subunits H1-3 and HDS and Unit S; this is believed to reflect higher kaolinite/illite ratios in the former subunits. Besly and Cleal (1997) report high kaolinite contents typify the Etruria Formation silty claystones, whereas illite/mica levels are considerably higher in the Halesowen Formation sediments.

(2) Using the geochemical sandstone classification scheme of Herron (1988), the sandstones from the Halesowen Formation classify geochemically as Litharenites. A similar classification is derived from petrography (Lott, 1992, in Glover and Powell, 1996), which reflects the occurrence of abundant micaceous metasedimentary lithic clasts (Association B: metasediment-dominated litharenite; Besly and Cleal, 1997).

(3) The high Na contents of the Halesowen Formation and, to a lesser extent, of the Salop Formation probably are linked to the presence of sodic plagioclase. These higher Na contents produce high  $Na_2O/TiO_2$  ratios for the silty claystones and sandstones (Fig. 7c–d and Fig. 8a–b) and enable the samples from these formations in both boreholes to be differentiated from the samples collected from the Coal Measures and the Etruria Formation.

(4) The generally higher background contents of Ca, Mn and Mg in the Halesowen and Salop Formations, along with localized enrichments in these elements, are attributed partly to the presence of caliche horizons (ferroan calcite and ferroan dolomite cements) and peloidal limestones, and partly to the occurrence of carbonate lithic clasts in the sandstones, these clasts being reworked from the Carboniferous Limestone (Lott, 1992, in Glover and Powell, 1996; Association C: sublitharenite containing detrital limestone grains — Besly and Cleal, 1997). In addition, carbonate lithic content increases upwards through these two formations at the expense of micaceous lithic clasts (Lott, 1992, in Glover and Powell, 1996; Besly and Cleal, 1997). This trend may be mirrored by increased Ca contents found in samples from the Salop Formation and from the upper part of the Halesowen Formation.

(5) Raised Cr and P levels in the Halesowen Formation coincide with increases in chromian spinel

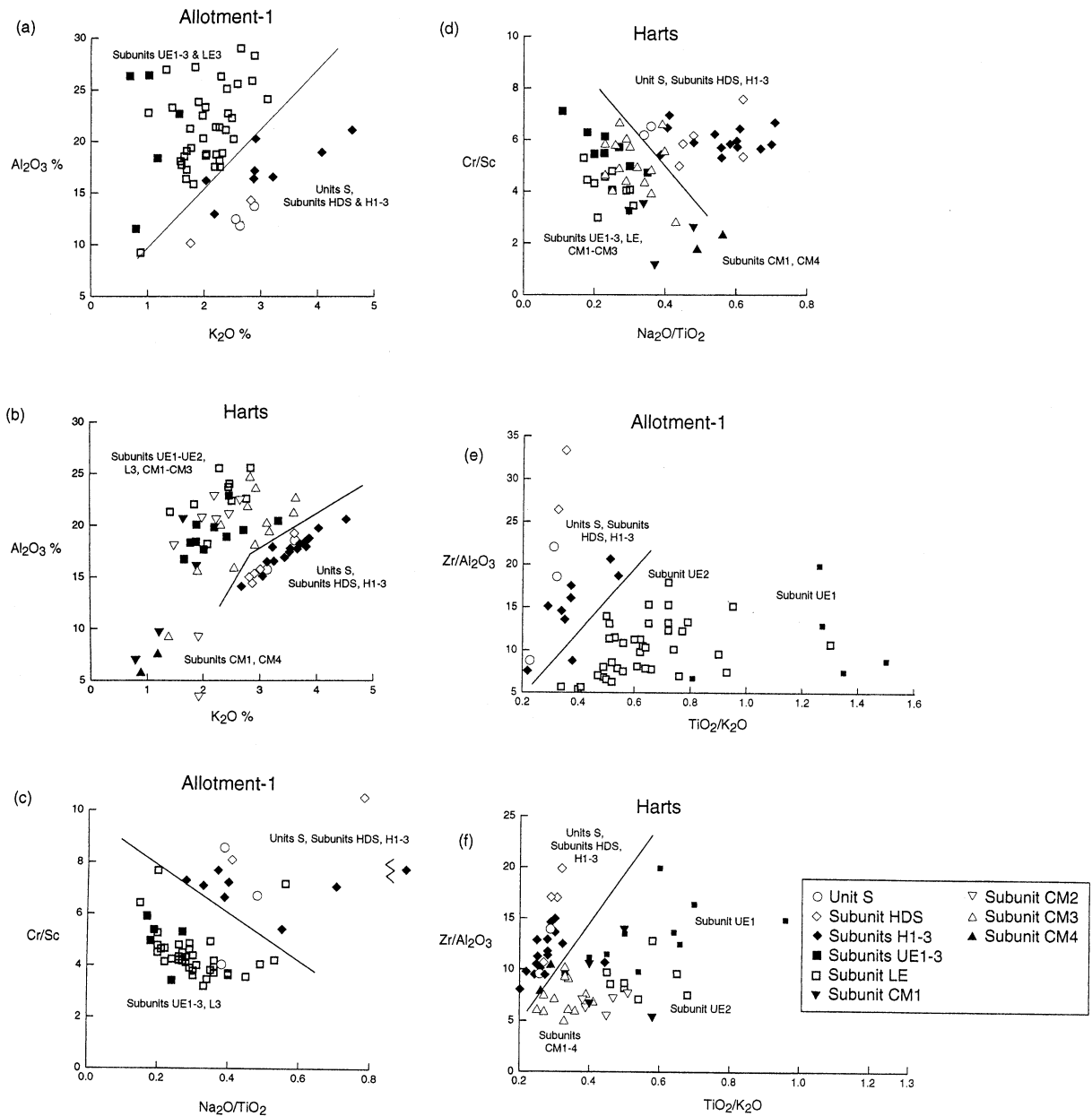


Fig. 7. (a–b) Binary diagrams illustrating variations in  $\text{Al}_2\text{O}_3$  and  $\text{TiO}_2$  contents in silty claystone samples from the Allotment-1 and Harts boreholes. (c–d) Binary diagrams illustrating variations in Cr/Sc and  $\text{Na}_2\text{O}/\text{TiO}_2$  ratios in silty claystone samples from the Allotment-1 and Harts boreholes. (e–f) Binary diagrams illustrating variations in  $\text{Zr}/\text{Al}_2\text{O}_3$  and  $\text{TiO}_2/\text{K}_2\text{O}$  ratios in silty claystone samples from the Allotment-1 and Harts boreholes.

and apatite. The heavy mineral assemblages of this formation are characterized by relatively high garnet contents, although garnet levels are lower in the basal and topmost samples (see also Hallsworth,

1992, in Glover and Powell, 1996). Unfortunately, the distribution of garnet is very difficult to model from bulk geochemistry as this mineral has a diverse geochemistry. Varieties of garnet typically are

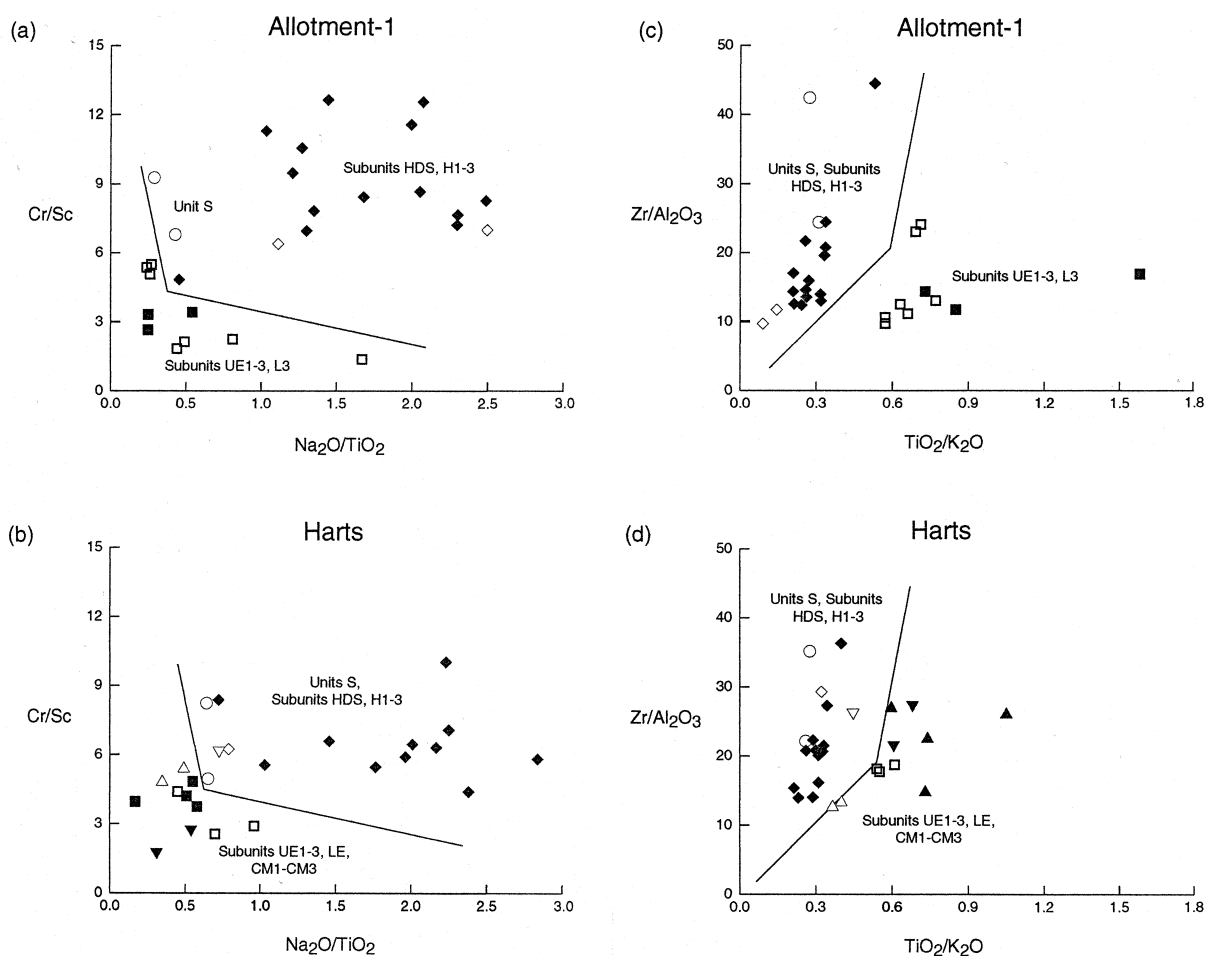


Fig. 8. (a–b) Binary diagrams illustrating variations in Cr/Sc and Na<sub>2</sub>O/TiO<sub>2</sub> ratios in sandstone samples from the Allotment-1 and Harts boreholes. (c–d) Binary diagrams illustrating variations in Zr/Al<sub>2</sub>O<sub>3</sub> and TiO<sub>2</sub>/K<sub>2</sub>O ratios in sandstone samples from the Allotment-1 and Harts boreholes.

characterized by major elements such as Ca, Fe, Mg and Mn. These elements are major constituents in the abundant mineral phases such as carbonates and clay minerals and therefore, any garnet-related geochemical signature will be suppressed by the elemental concentrations associated with the more abundant minerals. Associated with the high garnet levels are increases in chrome-spinel and chloritoid (Hallsworth, 1992, in Glover and Powell, 1996). Cr contents in subunits H1–3 and HDS and Unit S may be linked to illite contents, but as there is no clear relationship between Cr and K, this suggests that the presence or absence of illite has little or no influence on Cr concentrations.

(6) Silty claystone and sandstone samples show the distinct linear Zr relationship developed over the Salop Formation and in some Halesowen Formation samples (Fig. 7e–f and Fig. 8c–d). The increase in Zr contents in the Halesowen and Salop Formations coincide with influxes of angular zircon grains. Hallsworth (1992), in Glover and Powell (1996), reports a sudden increase in euhedral zircon grains in some of the Salop Formation sandstones.

(7) High Ti and Fe contents found in the Etruria Formation reflect relatively abundant haematite and anatase, although relatively high levels of rutile are partly responsible for increased Ti contents. Subunits CM1-4, LE and UE1-3 can be differentiated from

subunits H1–H3 and HDS and Unit S on the basis of their lower  $\text{Na}_2\text{O}/\text{TiO}_2$  ratios (Fig. 7c–d). These ratios reflect higher  $\text{TiO}_2$  contents that are linked with rutile and anatase abundance in the Coal Measures samples and especially in the Etruria Formation samples.

(8) High levels of Al and La in the Coal Measures and in the Etruria Formation indicate high kaolinite/illite ratios (Besly and Cleal, 1997).

(9) Depleted levels of Mg, Mn and Ca in the Etruria Formation suggest leaching of these elements has occurred, which may have been particularly strong towards the top of the formation in subunit UE.

(10) High P contents found in the Coal Measures, which, in the Harts borehole, occur in association with raised Y levels in those samples associated with marine bands, are attributed to enrichments in marine phosphate.

The bulk geochemistry is not as sensitive an indicator of sediment provenance as studies based on the chemical characteristics of their constituent grains. Therefore the geochemical data presented herein do not necessarily enhance our understanding of the provenance of the Duckmantian–Stephanian sediments in the West Midlands. What is confirmed, however, is that the geochemical data can be related to changes in the bulk mineralogy, the clay mineralogy and the heavy mineral suites and that reliable data can be obtained from core and cuttings samples. Furthermore, changes in the heavy mineral assemblages as recognized from the sandstone core samples can also be recognized in the silty claystones, based on changes in the concentrations of certain elements. This demonstrates that in some circumstances, changes in sediment provenance can be deduced in sequences for which core and good quality sandstone cuttings are unavailable.

The geochemical data presented herein are consistent with the mineralogical and provenance models of Glover and Powell (1996). These authors propose that following a period of Hercynian uplift, folding and erosion, the present-day West Midlands area became covered by ‘Pennant-type’ sediments that prograded from the south, which led to the deposition of the Halesowen Formation. However, slightly later, the influence of the southern provenance area became diminished. This possibly reflected increasing

aridity, coupled with tectonic activity which compartmentalized the area into small isolated basins, thus cutting off the main sediment pathways from the south. Consequently, the Salop Formation sediments may have had a relatively local source lying to the south west and west, being derived from erosion of the rejuvenated Mercian Highlands, which formed part of the Wales Brabant Massif, and also from reworking of the Halesowen Formation.

## 11. Conclusions

(1) The study demonstrates that changes in the heavy mineral assemblages, and in the clay mineralogy, which can be linked to provenance changes, can be inferred from variations in elemental concentrations. These chemical variations are recognized in the data from both the silty claystones and the sandstones.

(2) By using ICP analytical techniques, reliable geochemical data can be obtained from very small samples picked from cuttings. Such small samples would not be suitable for analysis by either XRF, XRD or isotopic techniques, nor would they be suitable for heavy mineral analysis. This therefore highlights the potential of chemostratigraphy as an independent correlation technique, which works equally well regardless of whether core or cuttings samples are analysed. Ideally, however, chemostratigraphy should be employed in conjunction with other stratigraphic techniques such as biostratigraphy, E-log stratigraphy and stratigraphies based on clay mineralogy and heavy minerals, which would then produce a fully integrated, robust stratigraphic correlation framework.

(3) The occurrence of systematic stratigraphic variations in geochemistry within the Duckmantian–Stephanian successions has led to the recognition of a series of geochemically distinct intervals termed chemostratigraphic units. These units correspond closely with the principal divisions of the revised Upper Carboniferous lithostratigraphy of the West Midlands as presented by Besly and Cleal (1997). Clear geochemical differences are present between the Coal Measures and the Etruria, Halesowen and Salop Formations. Furthermore, the Coal Measures and the Etruria and Halesowen Formations can be

divided into several geochemically distinct subunits, which, for the Etruria and Halesowen Formations, are correlated reasonably successfully between the Harts and Allotment-1 boreholes. The geochemically distinct Subunit HDS is believed to be equivalent to the Dark Slade Member (Besly and Cleal, 1997) that caps the Halesowen Formation in both boreholes. The distinctive geochemistry of this subunit seems to support the designation of its proposed lithostratigraphic counterpart as a member.

(4) Geochemical variations can be linked to changes in bulk mineralogy, clay mineralogy and heavy mineral assemblages. This, in turn, enables elements to be assigned to groups which reflect sediment provenance, diagenesis and weathering. A major change in sediment geochemistry is recognized in the upper part of the Coal Measures and not, as might be expected, at the base of the Etruria Formation, which is composed predominantly of reddened sediments. This indicates that reddening is not a primary control on sediment geochemistry. Another major variation in sediment geochemistry occurs at the unconformable boundary between the Halesowen Formation and the Etruria Formation. This variation presumably reflects a change in sediment provenance and significantly, it is recognized in the geochemical data from both the silty claystones and the sandstones, proving that the different provenance geochemical signatures have not been modified due to differences in grain size. Most of the Coal Measures sediments were derived from the north west and west, whereas the Etruria Formation sediments came from the Wales Brabant Massif. Eventually these sediments were replaced by the sediments of the Halesowen Formation, which had a metasedimentary source to the south. Towards the end of deposition of the Halesowen Formation sediments, the climate became increasingly arid and the importance of the southern provenance area diminished. The Salop Formation deposits originated from more localized sources in the Wales Brabant Massif area and possibly also from reworking of the Halesowen Formation deposits.

(5) The good chemostratigraphic correlation established between the Harts and Allotment-1 boreholes, which is based on geochemical characteristics and ultimately on changes in provenance, is likely to be broadly consistent over a relatively wide area. It

is probable that similar geochemical features will be developed in nearby sections of equivalent age and thus chemostratigraphy will be an additional and important stratigraphic and correlation tool which can be applied to these problematical sequences.

The paper shows that chemostratigraphy can be used as a stratigraphic tool, and is able to provide new insights into the correlation of barren sequences. Work is continuing on Upper Carboniferous successions from the West Midlands in order to test the chemostratigraphic correlation proposed herein. Case studies in which chemostratigraphy has been applied to sequences in the Schooner Formation (Cameron, 1993), in part equivalent to the 'Barren Red Measures', as penetrated by numerous wells in the Southern North Sea, has and will form the subject of other papers (Besly and Pearce, 1997).

### Acknowledgements

The authors wish to thank the British Coal Authority for access to the sample material. In addition, the work of Lorna Dyer, Department of Earth Sciences, University of Greenwich, is greatly appreciated. Constructive reviews of this manuscript by two reviewers are gratefully acknowledged, although the views expressed in this paper are those of the authors alone. The paper is published with the permission of the British Coal Authority.

### References

- Allsop, J.M., 1987. Patterns of late Caledonian intrusive activity in eastern and northern England from geophysics, radiometric dating and basement geology. *Proc. Yorkshire Geol. Soc.* 46, 335–353.
- Besly, B.M., 1988. Palaeogeographic implications of late Westphalian to early Permian red-beds, Central England. In: Besly, B.M., Kelling, G. (Eds.), *Sedimentation in a Synorogenic Basin Complex: the Upper Carboniferous of Northwest Europe*. Blackie, Glasgow, pp. 200–221.
- Besly, B.M., Cleal, C.J., 1997. Upper Carboniferous stratigraphy of the West Midlands (UK) revised in the light of borehole geophysical logs and detrital compositional suites. *Geol. J.* 32, 85–118.
- Besly, B.M., Pearce, T.J., 1997. Enhanced reservoir correlation of the Schooner Field. 5th Conference on Petroleum Geology of NW Europe (abstract).

- Besly, B.M., Burley, S.D., Turner, P., 1993. The late Carboniferous 'Barren Red Bed' play of the Silver Pit area, Southern North Sea. In: Parker, J.R. (Ed.), *Petrology Geology of Northwest Europe: Proceedings of the 4th Conference*. The Geological Society, London, pp. 727–740.
- Bhatia, M.R., Crook, K.A.W., 1986. Trace element characteristics of graywackes and tectonic setting discrimination of sedimentary basins. *Contrib. Mineral. Petrol.* 92, 181–193.
- Cameron, T.D.J., 1993. 5. Carboniferous and Devonian of the Southern North Sea. In: Knox, R.W.O'B., Cordey, W.G. (Eds.) *Lithostratigraphic Nomenclature of the UK North Sea*. British Geological Survey, Nottingham, 93 pp.
- Cullers, R.L., 1995. The controls on the major- and trace-element evolution of shales, siltstones and sandstones of Ordovician to Tertiary age in the West Mountains region, Colorado, U.S.A. *Chem. Geol.* 123, 107–131.
- Floyd, P.A., Shail, R., Leveridge, B.L., Franke, W., 1991. Geochemistry and provenance of Rhenohercynian synorogenic sandstones: implications for tectonic environment discrimination. In: Morton, A.C., Todd, S.P., Haughton, P.D.W. (Eds.), *Developments in Sedimentary Provenance Studies*. Spec. Publ. Geol. Soc. London 57, 173–189.
- Glover, B.W., Powell, J.H., 1996. Interaction of climate and tectonics upon alluvial architecture: Late Carboniferous–Early Permian sequences at the southern margin of the Permian Basin, UK. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 121, 13–34.
- Glover, B.W., Leng, M.J., Chisholm, J.I., 1996. A second major fluvial source for the Silesian Pennine Basin of northern England. *J. Geol. Soc. London* 153, 901–906.
- Hallsworth, C.R., 1992. Stratigraphic variations in the heavy minerals and clay mineralogy of the Westphalian to ?Early Permian succession from the Daleswood Farm borehole, and the implications for sand provenance. *Br. Geol. Surv. Tech. Rep.*, WH/92/185R.
- Herron, M.M., 1988. Geochemical classification of terrigenous sediments using log or core data. *J. Sediment. Petrol.* 58, 820–829.
- Hertzog, R., Colson, L., Seeman, B., O'Brien, M., Scott, H., McKeon, D., Wraight, P., Garu, J., Ellis, D., Schweitzer, J., Herron, M., 1987. Geochemical logging with spectrometry tools. SPE Paper 16792.
- Jarvis, I., Jarvis, K., 1992. Inductively coupled plasma-atomic emission spectrometry in exploration geochemistry. In: Hall G.E.M., Vaughlin, B. (Eds.), *Analytical Methods in Geochemical Exploration*. *J. Geochem. Explor. Spec. Issue*.
- Jarvis, I., Jarvis, K., 1995. Plasma spectrometry in earth sciences: techniques, applications and future trends. In: Jarvis, I., Jarvis, K.E. (Eds.), *Plasma Spectrometry in Earth Sciences*. *Chem. Geol.* 95, 1–33.
- Kelling, G., 1974. Upper Carboniferous sedimentation in South Wales. In: Owen, T.R. (Ed.), *The Upper Palaeozoic and Post-Palaeozoic Rocks of Wales*. University of Wales Press, Cardiff, pp. 185–224.
- Lott, G.K., 1992. Petrology and diagenesis of the Upper Carboniferous sandstones from the Daleswood Farm borehole, South Staffordshire. *Br. Geol. Surv. Tech. Rep.*, WH/92/182R.
- Pearce, T.J., Jarvis, I., 1992a. The composition and provenance of turbidite sands: Late Quaternary Madeira Abyssal Plain. *Mar. Geol.* 109, 21–51.
- Pearce, T.J., Jarvis, I., 1992b. Applications of geochemical data to modelling sediment dispersal patterns in distal turbidites: Late Quaternary of the Madeira Abyssal Plain. *J. Sediment. Petrol.* 62, 1112–1129.
- Pearce, T.J., Jarvis, I., 1995. High-resolution chemostratigraphy of Quaternary distal turbidites: a case study of new methods for the correlation of barren strata. In: Dunay, R.E., Hailwood, E.A. (Eds.), *Non-biostratigraphical Methods of Dating and Correlation*. *Spec. Publ. Geol. Soc. London* 89, 107–143.
- Pettijohn, F.J., 1975. *Sedimentary Rocks*, 3rd ed. Harper Row, New York.
- Potts, P.J., 1987. *A Handbook of Silicate Rock Analysis*. Blackie, 620 pp.
- Preston, J., Hartley, A., Hole, M., Buck, S., Bond, J., Mange, M., Still, J., 1998. Integrated whole-rock trace element geochemistry and heavy mineral chemistry studies: aids to correlation of continental red-bed reservoirs in the Beryl Field, UK North Sea. *Pet. Geosci.* 4, 7–16.
- Primmer, T.J., Kerr, S.S., Myers, K.J., 1990. Feasibility of in-situ elemental analysis in mudrock evaluation. In: Hurst, A., Lovell, M.A., Morton, A.C. (Eds.), *Geological Applications of Wireline Logs*. *Spec. Publ. Geol. Soc. London* 48, 203–210.
- Racey, A., Love, M.A., Bobolecki, R.M., Walsh, J.N., 1995. The use of chemical element analysis in the study of biostratigraphically barren sequences: an example from the Triassic of the central North Sea (UKCS). In: Dunay, R.E., Hailwood, E.A. (Eds.), *Non-biostratigraphical Methods of Dating and Correlation*. *Spec. Publ. Geol. Soc. London* 89, 69–250.
- Rippon, J.H., 1996. Sand body orientation, palaeoslope analysis and basin-fill implications in the Westphalian A–C of Great Britain. *J. Geol. Soc. London* 153, 881–900.
- Shail, R.D., Floyd, P.A., 1988. An evaluation of flysch provenance — example from the Gramscatho Group of southern Cornwall. *Proc. Ussher Soc.* 7, 62–66.
- Spears, D.A., Amin, M.A., 1981. A mineralogical and geochemical study of turbidite sandstones and interbedded shales, Mam Tor, Derbyshire, UK. *Clay Miner.* 16, 333–345.
- Taylor, S.R., McLennan, S.M., 1985. *The Continental Crust, its Composition and Evaluation*. Blackwell, Oxford.
- Waters, C.N., Glover, B.W., Powell, J.H., 1994. Structural synthesis of S. Staffordshire, UK; implications for the Hercynian evolution of the Pennine Basin. *J. Geol. Soc. London* 150, 697–713.