

CHEMOSTRATIGRAPHY OF UPPER CARBONIFEROUS (PENNSYLVANIAN) SEQUENCES FROM THE SOUTHERN NORTH SEA (UNITED KINGDOM)

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ABSTRACT: Important gas reservoirs occur in the Upper Carboniferous coal measures and red beds of the Southern North Sea. The thick red beds of the Boulton and Ketch formations are difficult to correlate, due to poor internal seismic definition, repetitive e-log signatures, and their barren nature. Although the underlying coal measures of the Westoe, Cleaver, and Caister Formations have better seismic resolution and contain palynomorphs, coals that die out laterally and the lack of diagnostic taxa over certain intervals contribute to their correlation being problematical. However, the application of chemostratigraphy to more than sixty wells from numerous fields in UK Quadrants 44 and 49, as well as from Dutch sector Blocks E, F, and K, allows the establishment of an independent, robust, detailed correlation framework for the aforesaid red beds and coal measures.

Presented in this paper are correlative chemostratigraphic reference sections for the Caister, Westoe, Cleaver, Ketch, Boulton, and Step Graben formations. The chemostratigraphic zonations erected for these formations are based on variations in silty claystone geochemistry that can be tied to changes in provenance, climate, and depositional environment. In addition, the zonations are supported by stratigraphic changes in sandstone and coal geochemistry, the geochemical correlation of tonsteins and marine bands, and the recognition of different types of paleosol in the above formations.

The chemostratigraphic correlation framework enables specific broad intervals ("packages") to be correlated between fields and is also used to constrain seismic correlations with a view to highlighting potential exploration targets. Furthermore, the same framework allows much thinner intervals ("units" and "subunits") to be correlated within fields: these smaller-scale correlations enhance reservoir correlations with respect to the development of fields such as Boulton, Schooner, Tyne, Ketch, and Topaz. In addition to using inorganic geochemical data to characterize and correlate sedimentological packages, data can also be used to identify and correlate marker horizons and surfaces (tonsteins, coals, marine bands, major paleosols), which may be highly correlative low-diachrony surfaces, which greatly enhance the overall validity of the stratigraphic correlation scheme.

KEY WORDS: chemostratigraphy, Upper Carboniferous, correlation, provenance, Ketch Formation, Westoe Formation, southern North Sea, Cleaver Formation

INTRODUCTION

Interwell correlations of most reservoir sequences are usually established using a combination of seismology, petrophysics, biostratigraphy, and sedimentology, though such correlations do not always attain the required resolution for detailed stratigraphic modelling (Stone and Moscariello, 1999; Moscariello, 2000). Furthermore, the aforesaid disciplines are of little or no use if the hydrocarbon reservoirs occur within thick monotonous successions of sandstones and silty claystones with repetitive petrophysical characteristics and no prominent seismic reflectors, as they do in the Upper Carboniferous sequences of the Southern North Sea. However, over the last decade, several stratigraphic techniques (chemostratigraphy, heavy-mineral stratigraphy (Morton et al., 2002), magnetic susceptibility stratigraphy (Ellwood et al., 2001), and cyclostratigraphy (Fischer et al., 2004) have been developed that can be applied to such problematical sequences in the petroleum industry. Chemostratigraphy, the technique employed in this paper, involves the characterization of strata based on variations in inorganic geochemical data, with correlation being achieved by the recognition of compared

geochemical signatures in adjacent sections or wells. There are essentially three types of chemostratigraphy, namely radiometric age isotopic chemostratigraphy (Rollinson, 1993), stable-isotope chemostratigraphy (e.g., McArthur, 1994) and inorganic elemental chemostratigraphy (IEC; Pearce et al., 1999; Pearce et al., 2005a, 2005b). The latter application is now routinely used in the oil industry because large elemental datasets can be rapidly acquired even from small sample volumes but in the laboratory and at wellsite. IEC has been widely used to aid the characterization and correlation of barren or virtually barren sequences (Andrew et al., 1996; Ehrenberg and Siring, 1992; Pearce et al., 1999; Pearce et al., 2005a, 2005b; Preston et al., 1998; Racey et al., 1995; Ratcliffe et al., 2002; Ratcliffe et al., 2004; Ratcliffe et al., in press (a); Ratcliffe et al., in press (b); Ritcey et al., 2005), but it is becoming increasingly utilized to supplement biostratigraphy in fossiliferous sequences (Moothart et al., 2005; Pearce, 1991; Pearce and Jarvis, 1992a, 1992b, 1995; Pearce et al., 2005a; Wright et al., 2004) with equal success.

Most commonly in the petroleum industry, the technique essentially provides a high-resolution, highly refined lithostratigraphic correlation, by identifying changes in whole-rock

geochemistry in sequences that appear otherwise homogeneous. This type of application of chemostratigraphy is demonstrated herein using data from the barren fluvial sequences of the Ketch Formation (colloquially termed the “Barren Red Measures”) and the underlying fossiliferous coal measures of the Caister, Westoe, and Cleaver formations, which are located in the Silver Pit Basin of the Southern North Sea (Besly, 2005). These Upper Carboniferous successions are ideal subjects on which demonstrate chemostratigraphic applications, because the sandstones are significant gas reservoirs, with good well control, yet their correlation remains enigmatic using non-chemostratigraphic methods. Where biostratigraphic control is available, i.e., the coal measures, the chemostratigraphic correlation not only complements the biostratigraphic correlation but also provides higher resolution.

However, the whole-rock geochemical dataset acquired for industry-oriented studies can also be applied to the identification

and correlation of other marker horizons, such as coals, tonsteins, marine bands, and paleosols. Some of these horizons may also be regarded as “low-diachrony surfaces” and provide the potential to extend correlation beyond individual fields to subregional scale. Moreover, the correlation of such horizons provides a means by which chemostratigraphic data can be linked directly to e-log responses and seismology, which in turn can greatly improve integrated stratigraphic modelling.

GEOLOGICAL SETTING AND LITHOSTRATIGRAPHY

The lithostratigraphy of the Upper Carboniferous sequences from the Southern North Sea is summarized in Figure 1 and is discussed in detail by Besly (1995, 2005), McLean et al. (2005), and Pearce et al. (2005a, 2005b). Lithostratigraphic terminology used for the UK successions in this paper follows that proposed

SYSTEM	SERIES	STAGES	West Midlands onshore UK	Quadrant 44 S. North Sea		
PERMIAN	UPPER	SAKMARIAN	Clent Fm.	Silver Pit Claystone		
		ASSELIAN				
CARBONIFEROUS	STEPH.	STEPHANIAN	Salop Fm.	Step Graben		
	WESTPHALIAN	WESTPH. D	Halesowen Fm.	Barren Red Measures	Boulton Fm.	
		BOLSOVIAN	Etruria Fm.		Ketch Fm.	
		DUCKMANTIAN	Coal Measures		Coal Measures	Cleaver Fm.
						Westoe Fm.
		LANGSETTIAN	Coal Measures		Coal Measures	Caister Fm.

FIG. 1.—Stratigraphic summary to the Upper Carboniferous onshore UK and offshore in the southern North Sea. Lithostratigraphy from Besly (2005).

by Besly (2005). Those successions containing hydrocarbons lie mostly within the Conybeare Group (Cameron, 1993), of which the sandy coal measures of the Langsettian and early Duckmantian are restricted to the northern part of the Southern North Sea and are assigned to the Caister Formation, which are overlain by the argillaceous coal measures of the Westoe Formation (Besly, 2005). At the end of Duckmantian times and during the early Bolsovian, gray sandy coal measures were again deposited in the Silver Pit area (Cleave Formation), followed by sandstones and occasional red silty claystones of later Bolsovian age (Ketch Formation; Besley, 2005). The Ketch Formation is locally overlain by red to gray silty claystones and occasional sandstones and limestones of the Boulton Formation (Westphalian D), whereas in a few Dutch sector wells, the Step Graben Formation is encountered, which is of Westphalian D to Stephanian age (van Adrichem Boogaert and Kouwe, 1993). In earlier publications (e.g., Cameron, 1993), those successions now assigned to the Ketch and Boulton formations made up the upper part of the Schooner Formation (Figure 1).

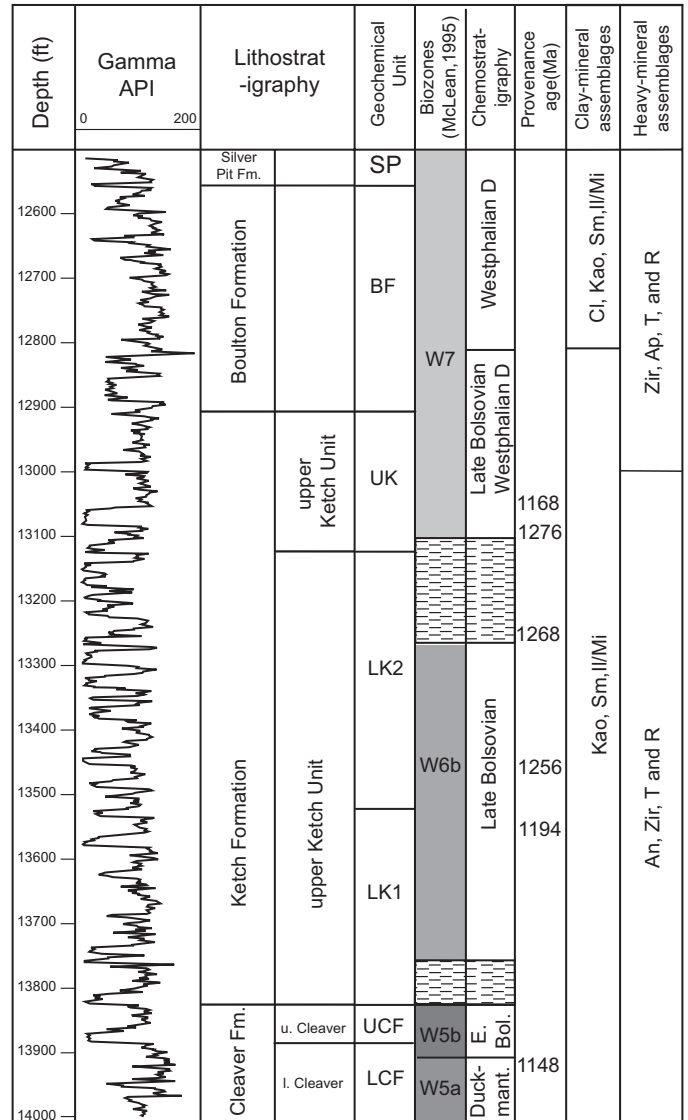
In some cases, significant erosion associated with the Saalian unconformity at the base of the Permian sequences removed either part or all of the Step Graben–Boulton–Ketch Formation section, resulting in the Permian successions resting directly on the coal measures of the Caister, Westoe, or Cleave formations (Cameron et al., 1992; Cameron, 1993; Bailey et al., 1993; Besly, 2005; Pearce et al., 2005b).

CHEMOSTRATIGRAPHICAL DATASET

The chemostratigraphy of the Ketch and Boulton formations is discussed in Pearce et al. (2005a), well 44/21-3 (Cameron, 1993) providing the geochemical reference sections for these divisions; see Figure 2. Chemostratigraphic studies have also been extended to incorporate well 44/26-4 and well 44/21a-7 (Fig. 3), from which geochemical data are acquired from the Ketch Formation and the underlying Cleave and Westoe formations. A total of four hundred core samples and cuttings have been analyzed, of which two hundred and ninety are silty claystones and the remainder are sandstones. All of these samples have been analyzed by inductively coupled plasma—optical emission spectrometry (ICP-OES) and inductively coupled plasma—mass spectrometry (ICP-MS) (Pearce et al. (2005a), with data being obtained for forty-eight elements. These include the major elements Si, Al, Ti, Fe, Mn, Mg, Ca, Na, K, and P, the trace elements Ba, Co, Cr, Cs, Cu, Ga, Hf, Nb, Rb, Sc, Sr, Ta, U, V, Y, Zn, and Zr and the rare earth elements (REEs) La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Yb, and Lu. The REEs can be further categorized into light rare earths (LREEs), e.g., La to Nd, middle rare earth elements (MREEs), e.g., Sm to Ho, and heavy rare earth elements (HREEs), e.g., Er to Lu.

Silty Claystone Chemostratigraphy

Pearce et al. (2005a) focus primarily on the chemostratigraphy of the silty claystones, inasmuch as the fluvial sandstones of the Ketch Formation probably have shoestring morphologies (Besly et al., 1993) and thus have very poor correlation potential (Besley et al., 1993). In contrast, the overbank silty claystones presumably have a much broader areal extent and thus have a far better potential for correlation. Pearce et al. (2005a) presented a chemostratigraphic correlation for the Ketch Formation between wells 44/21-3 and 44/26c-6, which are some twenty kilometers apart, the correlation being based on systematic stratigraphic variations in silty claystone geochemistry. These variations are related to changes in provenance and depositional environment (Pearce et al., 2005a).



II/Mi = Illite/mica	Zir = Zircon
Kao = Kaolinite	An = Anatase
Cl = Chlorite	Ap = Apatite
Sm = Smectite	R = Rutile
	T = Tourmaline

FIG. 2.—Integrated stratigraphic summary for the Upper Carboniferous interval in well 44/21-3 (modified from Pearce et al., 2005b).

The silty claystone-based chemostratigraphic zonation erected for the Caister Formation–basal Silverpit Formation succession is described with reference to a composite chemostratigraphic reference section using data from four wells. The study intervals are subdivided using a hierarchical zonation scheme based on the recognition of chemostratigraphic sequences, packages, units, and subunits. A chemostratigraphic sequence as used herein is a first-order stratigraphic unit that is broadly equivalent to a lithostratigraphic group and is characterized by a distinct depositional setting. The boundaries of chemostratigraphic sequences typically coincide with unconformities, disconformities, paraconformities, or correlative con-

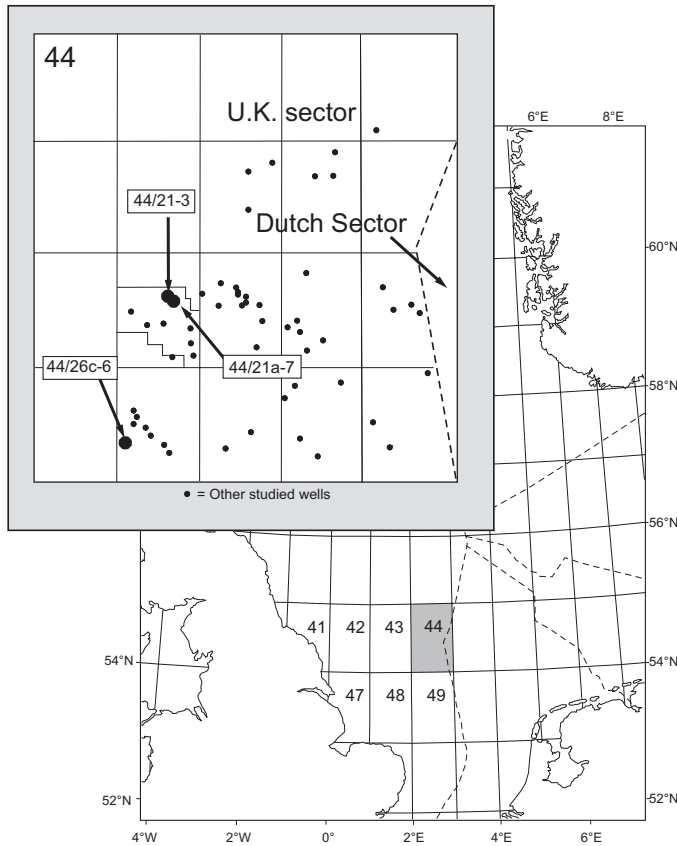


FIG. 3.—Location of wells 44/21-3, 44/21-7, and 44/26c-6. The location of other UK sector wells that have penetrated the Schooner Formation and which have been the subjects of proprietary chemostratigraphic studies are also shown.

formities. Chemostratigraphic packages are broadly comparable to formations and are second-order stratigraphic intervals defined herein. These are usually relatively thick, lithologically distinct, and mappable intervals that can be correlated using comparable characteristics (lithology, depositional environment, and mineralogy). Chemostratigraphic units are third-order intervals defined herein and are generally bounded by lower-order sequence stratigraphic surfaces defined by features such as paleosols, flooding surfaces, omission surfaces, or abrupt facies shifts. Units are broadly equivalent lithostratigraphic members. Chemostratigraphic subunits are the lowest order of interval and often relate to individual sedimentological elements such as beds, channels, or dunes.

In this study the reference section comprises two chemostratigraphic sequences and ten chemostratigraphic packages (Fig. 4) that are defined by significant changes in the values of various elemental ratios. The packages, in ascending order, are as follows:

Chemostratigraphic Sequence S2: Permian
 Package SF—Silverpit Formation
 Chemostratigraphic Sequence S1: Carboniferous
 Package SG—Step Graben Formation
 Package BF—Boulton Formation
 Package UK—upper Ketch Formation
 Package LK2—lower Ketch 2

Package LK1—lower Ketch 1
 Package UCF—upper Cleaver Formation
 Package LCF—lower Cleaver Formation
 Package WF—Westoe Formation
 Package CF—Caister Formation

The packages within Sequence 1 are further divided into lower-order chemostratigraphic units, which can be correlated within a field but not between fields (Pearce et al., 2005a). The main geochemical characteristics of the zonation are illustrated in Figure 4.

- Package SF (Silverpit Formation): has very much higher K/Al (Fig. 4), Cs/Al, and Rb/Al values than Package SG, along with lower Fe/Mg and Cr/Mg values.
- Package SG (Step Graben Formation): K/Al, Rb/Al, and Cs/Al values are higher than those of Package BF but lower than those of Package SP (Silverpit Formation). In addition, Package SG has higher Cr/Mg and Fe/Mg values, plus lower Cr/Th and Nb/Al values, than Package BF.
- Package BF (Boulton Formation): has higher K/Al, K/Ti, Cs/La, and U/Fe values than Packages UK, LK2, and LK1 (Ketch Formation), and is characterized by high U/Fe values, as well as upwardly decreasing Nb/Al and Cr/Th values.
- Package UK (upper Ketch): has higher K/Al and K/Ti values than Packages LK1 and LK2, though its low Cs/La and U/Fe values are comparable to those recorded from the latter two packages. Package UK is also characterized by high Nb/Al, Cr/Th, and Cr/Cs values, especially toward its top, high Fe/Mg and Cr/Mg values midway through the package, and high K/Al and K/Ti values at its base.
- Packages LK1 and LK2 (lower Ketch): have higher Cr/Th and Cr/Cs values than Packages UCF and LCF, as well as much lower U/Fe values than Package UCF. Packages LK1 and LK2 are also characterized by upwardly increasing Fe/Mg and Cr/Mg values.
- Package UCF (upper Cleaver Formation): has lower Cr/Th, Cr/Cs, and Fe/Mg values than Package LK, though all these values increase upwards, in addition to lower U/Fe values than Package LCF.
- Package LCF (lower Cleaver Formation): has higher Nb/Al, Cr/Cs, and Cr/Th values than Packages WF and UCF, and higher U/Fe values than Package WF.
- Package WF (Westoe Formation): characterized by high K/Ti and Cs/La values, as well as low Nb/Al and Cr/Cs values, with very high Nb/Al values occurring close to its base.
- Package CF (Caister Formation): has higher Cr/Mg, U/Fe, Cr/Th, and Cr/Cs values than Package WF, along with lower K/Al and K/Ti values.

While geochemical logs of key elements and element ratios such as those in Figure 4 provide a means to define chemostratigraphic packages and package boundaries, elemental contour plots provide a rapid, visual expression of the geochemical differences between the packages (Fig. 5). An element contour plot such as that in Figure 5 is based on standardized relative concentrations of the elements in silty

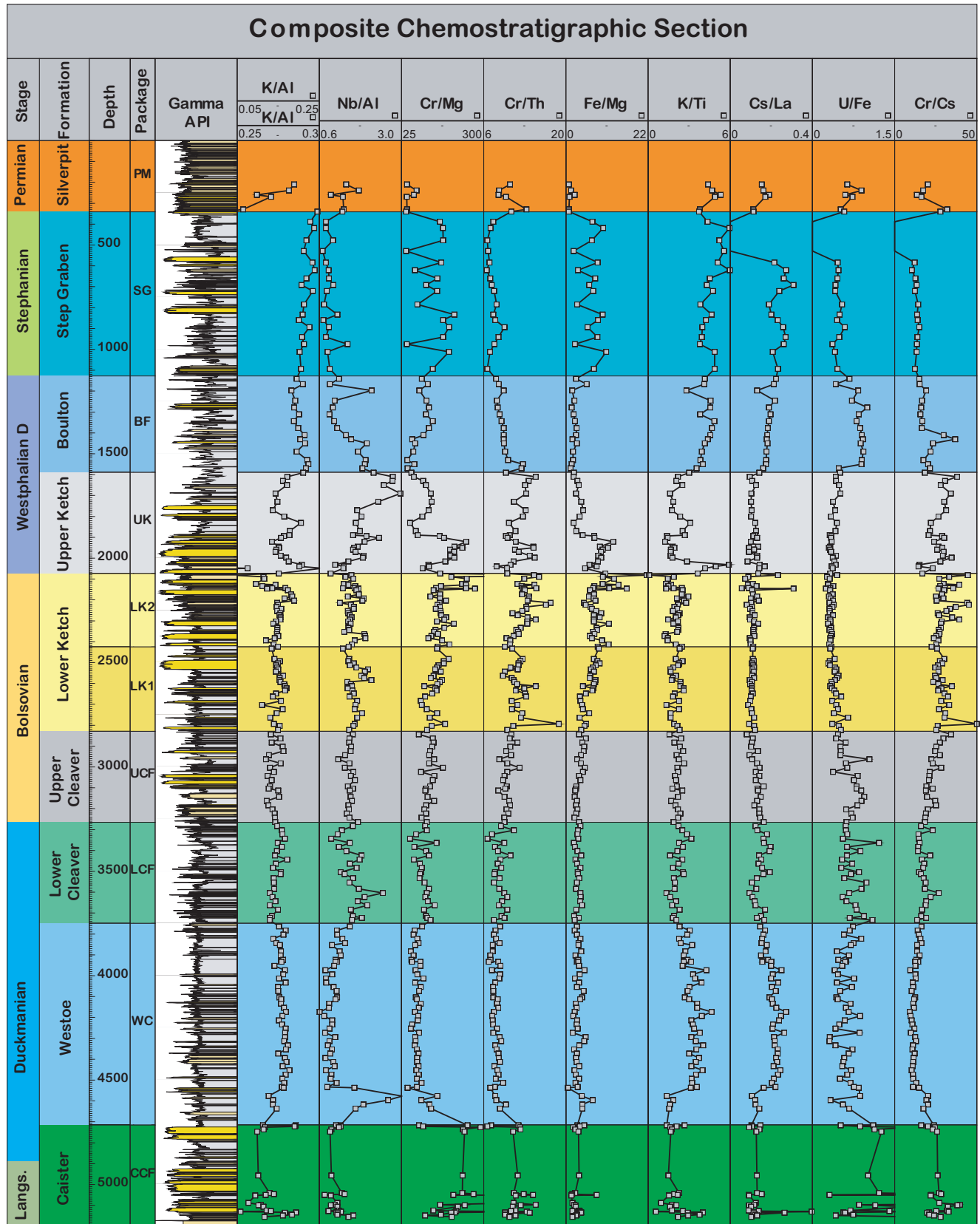
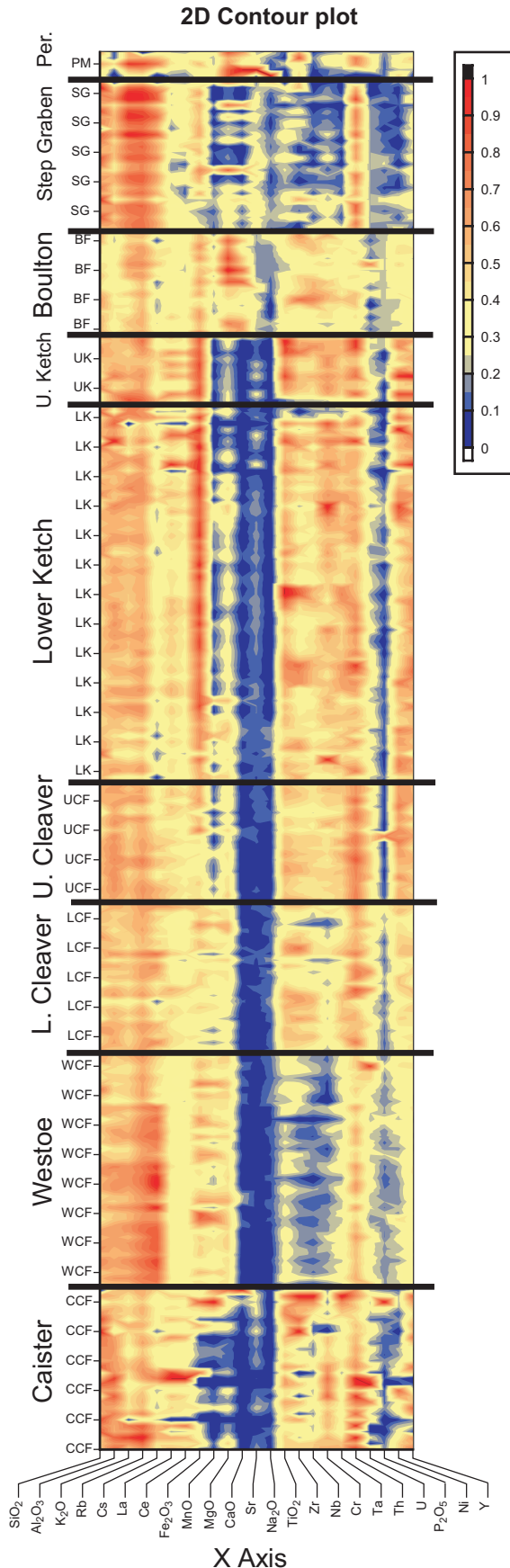


FIG. 4.—Composite chemostratigraphic reference sections for the Caister Formation (Langsetian)–Step Graben Formation (Stephanian) based on variations in silty claystone samples. “Langs.” = Langsetian.



claystone samples through a composite reference section. The plot is constructed using the percentage proportion of each element expressed using a color code, i.e., high concentrations are denoted by red, moderate concentrations by yellow, and orange and blue tones for low concentrations. By sequentially plotting these color fingerprints against depth, a contour plot enables significant chemostratigraphic boundaries to be identified easily. In addition, the color fingerprints provide a rapid means to identify chemostratigraphic affinity for individual samples at wellsite or to aid in the differentiation of faults and missing sections.

GEOCHEMISTRY AND MINERALOGY

Chemostratigraphy is based on the recognition of distinctive characteristics from the geochemical datasets acquired from sedimentary rocks. However, much of the application in the petroleum industry is dependent on establishing mineralogical affinities of the elements used to define stratigraphic correlations. For example, a stratigraphic zonation of a sandstone sequence based solely on the variation in CaO concentrations is equally as valid as a stratigraphic zonation for the same sandstones based on variations in Zr/TiO_2 values. However, the zonation based upon CaO variations is probably reflecting changes in the amount of calcite in the sandstones and as such may have limited potential to provide a field-scale correlation framework. However, changes in Zr/TiO_2 values commonly reflect changes in heavy-mineral suites (Ratcliffe et al., 2004), and, assuming that this can be confirmed by heavy-mineral analysis, changes in the Zr/TiO_2 ratio indicates changes in sediment provenance and therefore is more likely to be a laterally extensive, sub-regional feature that can provide a robust field-scale correlation framework.

For these reasons it is vitally important when applying chemostratigraphic zonations to correlation studies to understand the significance of the elements and element ratios used to define the stratigraphic correlation.

Mineralogical Affinities of Elements

By determining element–mineral affinities, some indication as to whether the abundance and distribution of the elements is influenced by changes in provenance, depositional environment, weathering, or diagenesis can be gained. Pearce et al. (2005a) used principal-component analysis to determine elemental associations from which the mineralogical affinities elements have been inferred (also see Svendsen et al., 2007, for a detailed discussion of use of principal-component analysis and the modeling of geochemical data). The following element–mineral affinities have been deduced for the Upper Carboniferous sequences of the Southern North Sea:

- Si = quartz, but is also associated with other detrital minerals found in siliciclastic rocks.
- Al = clay minerals and mica. Very high Al levels are attributed to the presence of kaolinite, gibbsite, and bauxite, as well as being recorded from paleosols (Pearce et al., 2005b).

←

Fig. 5 (left column).—Elemental 2D contour plot for silty claystone samples from the Upper Carboniferous succession from the Southern North Sea. The plot uses colors to highlight changes in relative concentration of elements within the dataset as a whole (scaled from 0 to 1) from red (high)—yellow (moderate)—blue (low) concentrations.

- Ti, Nb, and Ta = heavy minerals, principally rutile (corroborated by heavy-mineral data; Morton et al., 2005; Pearce et al., 2005b), anatase, and Ti-bearing opaque minerals such as ilmenite and leucoxene.
- Fe = in the red beds of the Ketch Formation, Fe is associated with Fe oxyhydroxides such as hematite and goethite, and with ferroan dolomite cements in the sandstones. In the gray beds and coal measures, Fe is linked with siderite, pyrite, and ferroan dolomite.
- Ca, Mn, Mg, and Sr = carbonate minerals, chiefly siderite, calcite, and dolomite. In the Boulton Formation, thin dolomitized caliches and limestones are encountered. However, carbonates are rare in the Ketch Formation, though sideritic bands are common in the coal measures and calcareous fossils are associated with marine bands. These elements also have subordinate associations with clay minerals, with Mg being linked to chlorite in the Boulton Formation (Pearce et al., 2005b), where this mineral occurs in only minor amounts.
- Na = clay minerals, and the occurrence of halite in formation waters and drilling fluids.
- K, Rb, and Cs = the concentrations of these elements are controlled chiefly by the abundance and distribution of illite + mica (corroborated by XRD data; Pearce et al., 2005b) and, to a lesser extent, by K feldspar, which is, however, relatively rare over the Upper Carboniferous successions.
- P = in the silty claystones, P has an affinity with clay minerals, in particular, illite + mica. However, high P levels are recorded from sideritic horizons, where the element is linked with Fe, Mn, and REEs. Similar P levels are also found together with U, Mo, Ca, and Ce in high-gamma API, dark gray claystones, in which P is associated with biogenic phosphate (fish remains) and calcareous macrofossils.
- Zr and Hf = detrital zircon.
- Co, Ni, Zn, V, and Cu = clay minerals and mica. These elements are also linked to organic material and are released during oxidation of this material, becoming remobilized during diagenesis. In the Upper Carboniferous red beds, Ni is related to the occurrence of Fe oxyhydroxides.
- Th = high Th levels are found with raised Al, Ga, and Sc levels in weathered kaolinitic claystones of the Ketch Formation, where Th probably has an affinity with refractory minerals such as zircon. In the Boulton Formation, Th is linked with other clay minerals, mica, and apatite.
- U = organic material and detrital minerals. In the coal measures, U is linked with organic material, with high U levels being recorded from marine bands. The element is also associated with Th and Zr, all having an affinity with zircon, e.g., in the red beds of the Ketch Formation.
- LREEs = clay minerals and mica. Associated high levels of LREEs and Al point to the presence of abundant kaolinite and gibbsite. LREE enrichments are also good indicators of paleosols (Pearce et al., 2005b).
- MREEs = clay minerals, but they are also abundant in ferruginous paleosols, where they are associated with grain-

coating Fe oxyhydroxides, and in sideritic bands in the coal measures.

- HREEs and Y = heavy minerals such as zircon and garnet. HREEs also occur in clay minerals and mica, where they are not, however, as common as the LREEs and MREEs.
- Sc and Ga = typically associated with Al and LREEs, which suggests that they have an affinity with kaolinitic clay minerals.
- Be, W, and Sn = heavy minerals such as beryl and cassiterite. However, the levels of these elements usually are very low in the Upper Carboniferous silty claystones, which implies that their parent heavy minerals are rare. However, moderate enrichments of Be, W, and Sn can be associated with tonstein horizons (Spears and Zheng, 1997; Spears and Lyons, 1995; Pearce et al., 2005a).
- Ba = clay minerals and sometimes barite-based additives in drilling fluids.

The mineralogy of the succession inferred from the geochemical data has been corroborated with reference to bulk XRD data and heavy-mineral data.

Mineralogical Data

Clay-Mineral Assemblages.—

The principal clay minerals occurring in the Upper Carboniferous sequences and the basal part of the Silverpit Formation are illite, illite/smectite, and kaolinite, along with minor amounts of chlorite (Fig. 6). The abundance of these clay minerals can be used to corroborate stratigraphic variations in the abundance of key chemostratigraphic elements and can provide evidence for changes in environment, provenance, and diagenesis.

Humid tropical conditions persisted during the deposition of the successions assigned to the Caister, Westoe, and Ketch formations, which promoted severe chemical weathering and the consequent formation of kaolinite and Al oxyhydroxides. The Caister and Westoe formations successions were laid down in waterlogged settings, though well-drained oxidized conditions had become established by the time the Ketch Formation sequences were deposited. However, this change in drainage is not mirrored by the clay mineralogy (Fig. 6), though high Fe and Ni levels, along with high Fe/Mg values, reflect the presence of Fe oxyhydroxides in the Ketch Formation.

Sandstones are less frequent over the Upper Ketch Formation–Boulton Formation successions, which were deposited under poorly drained environments, the climate becoming more arid. Changing drainage conditions and climate are reflected by a decrease in kaolinite and an increase in illite, plus the development of thin coals and gray claystones. Over the upper part of the Boulton Formation and the Step Graben Formation, the effect of climate change becomes readily apparent, with gray measures being progressively replaced by red beds containing thin caliches.

The makeup of the clay-mineral assemblages is also influenced by provenance. For instance, the material making up the Ketch Formation had a northern derivation from the Proterozoic–Caledonian granites and gneisses and ultrabasic rocks of the Ringkjøbing–Fyn High, whereas the Boulton Formation and the Step Graben Formation deposits had a southern derivation from a largely metasedimentary Variscan Rheno-Hercynian source, which contributed abundant illite, mica, and other clay minerals.

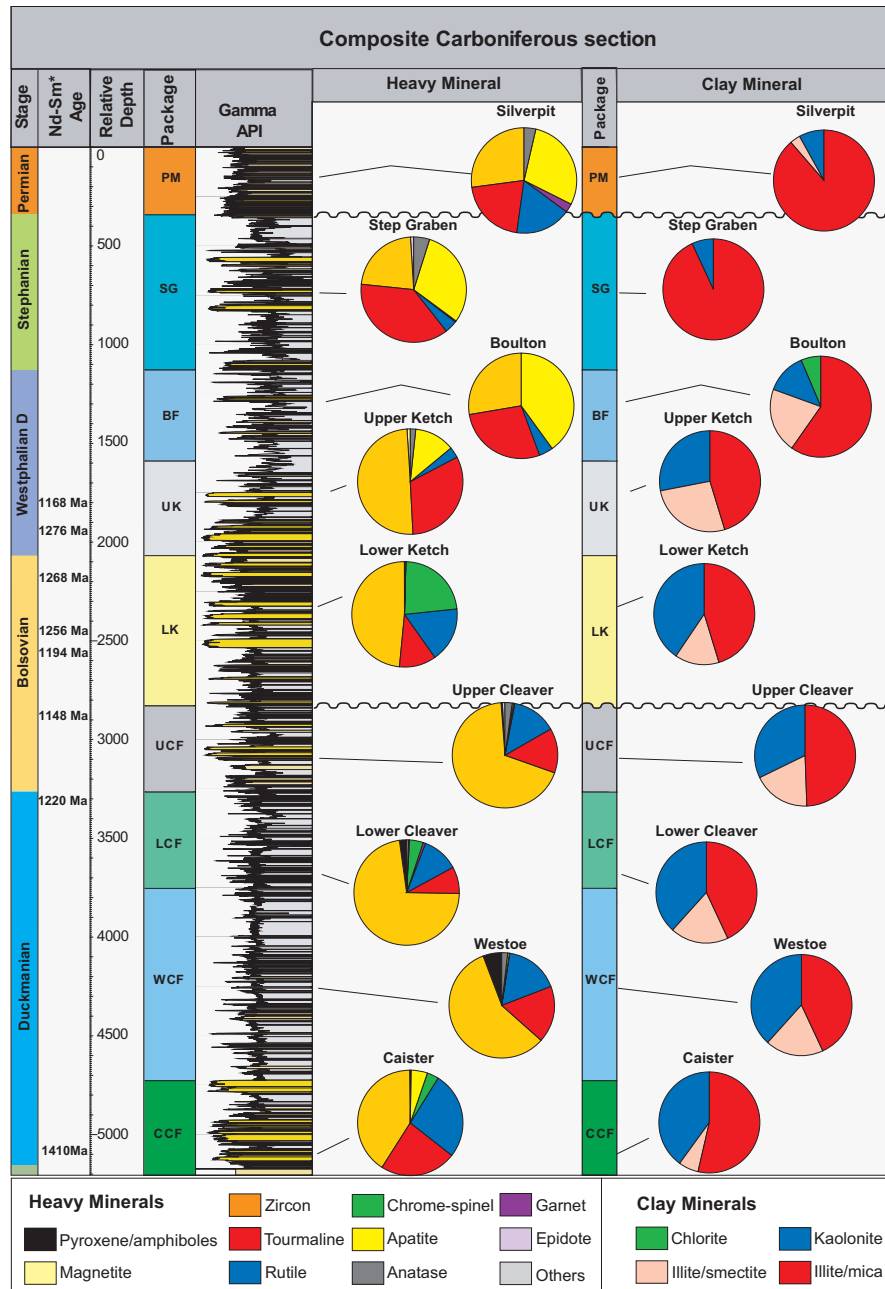


FIG. 6.—A summary of average heavy-mineral and clay-mineral assemblages for each chemostratigraphic package in the composite Upper Carboniferous reference section. All available Nd-Sm age data are also presented (from Pearce et al., 2005b, and Leng et al., 1999).

Moreover, the Silverpit Formation silty claystones contain abundant illite to mica, with minor amounts of kaolinite and illite to smectite—this assemblage consists predominantly of clay minerals reworked from the Upper Carboniferous successions, mostly from the Boulton and Step Graben formations.

Clay-mineral stratigraphy can be highly correlative, and certain chemostratigraphic package boundaries (e.g., UK/BF–Upper Ketch–Boulton Formation and the UK/LK2–Upper and Lower Ketch) exhibit significant changes in clay-mineral assemblages that can be modeled geochemically. However, other chemostratigraphic package boundaries (CF–WCF, Caister–

Westoe, and WCF–LCF Westoe / Lower Cleaver) do not display any notable change in clay mineralogy, and these packages are large defined on changes in heavy-mineral, opaque, and other accessory-mineral phases.

Heavy-Mineral Assemblages.—

Average heavy-mineral assemblages for sandstones for each package are plotted in Figure 6. The principal heavy minerals of the Upper Carboniferous–basal Permian successions are zircon, tourmaline, rutile, apatite, and Cr-spinel, with minor amounts of

anatase, garnet, pyroxene, epidote, monazite, and chloritoid (Morton et al., 2005; Pearce et al., 2005b).

The assemblages of the Caister Formation and Westoe Formation sandstones consist mainly of zircon, tourmaline, and rutile. Their provenance is unresolved at present, though three sources are possible (Morton et al., 2005), e.g., a southern Variscan provenance, the Wales–Brabant High to the west, or the Pennine area to the north. Minor differences do exist, though, between the assemblages of the two sets of sandstones, with the Westoe Formation sandstones containing minor amounts of Cr spinel and traces of fresh pyroxene that might be derived from volcanic ash.

The Cleaver Formation has a mixed provenance, the sandstones containing material of Variscan, Cadomian, and Proterozoic age that possibly came from a southeastern source (northern Germany; Morton et al., 2005), though those sandstones with abundant Cr spinel might have been derived from the Ringkjøbing–Fyn High to the north.

The source for the Ketch Formation is believed to be the Fyn–Fyn High to the north, the detrital material being derived from Paleozoic igneous rocks and Proterozoic gneisses (evidence from limited Nd–Sm data; Pearce et al., 2005b; Moscariello, 2003). Zircon grain-dating data acquired by Morton et al. (2005) confirm this probability by indicating that the above formation contains material from Early Carboniferous, Caledonian, Proterozoic, and Archean sources. Cr spinel becomes common in the Ketch Formation and could have been derived from the Early Carboniferous ophiolitic complex of the Ringkjøbing–Fyn High (Morton et al., 2005), which lies close to the aforementioned Paleozoic igneous rocks and Proterozoic gneisses.

Limited heavy-mineral data obtained by Pearce et al. (2005b) indicate that some Upper Ketch lithic sandstones have a source similar to that of the overlying Boulton Formation, the sandstones of which contain heavy-mineral assemblages characterized by abundant apatite and tourmaline, along with minor amounts of garnet, all of which were derived from a southern Variscan Rheno–Hercynian source. The Step Graben Formation sandstones have heavy-mineral assemblages similar to those of the

Boulton Formation, though the former sandstones are mineralogically more mature.

The sandstones of the Permian Silverpit and Leman Sandstone formations are made up of material mainly reworked from the Upper Carboniferous successions.

Heavy-mineral data and grain-provenance data provide useful evidence that can corroborate the chemostratigraphic interpretations and enhance the confidence of the correlations. However, these analyses are restricted to sandstones, and are costly and are time consuming.

CHEMOSTRATIGRAPHIC CORRELATION

Key geochemical profiles covering the Upper Carboniferous successions of well 44/21-3, well 44/26-4, and well 44/21a-7 are presented in Figures 7 to 9. These profiles can be compared with those for the composite section and then a chemostratigraphic correlation can be constructed, based on changes recognized from the profiles. However, when dealing with profiles constructed from data derived just from cuttings, only major, long-term changes in silty claystone geochemistry, i.e., those related to provenance (Besly, 1995; Morton et al., 2005; Pearce et al., 2005b) and climate change (Pearce et al., 2005b), can be distinguished. These geochemical changes can usually be recognized across an individual field, and nearby blocks (Fig. 10) and can even persist subregionally across Quadrants 44 and 49 and from Dutch quadrants D, E, F, and K.

The correlation highlights the major unconformity at the base of the Ketch Formation. Its presence in well 44/21-3 is supported by palynological data, with samples from the lower part of Package LK1 assigned to Biozone W6b (Late Bolsovian; Pearce et al., 2005b; McLean et al., 2005) overlying samples allocated to Biozone W5b (Early Bolsovian), which shows that most of Package UCF is missing in this well. To the south, considerable thicknesses of section assigned to this package are preserved in well 44/26-4 and well 44/21a-7, though in well 44/26-4 the top of Package UCF is truncated by the Saalian unconformity. Farther northeastwards, the Carboniferous sequences are more exten-

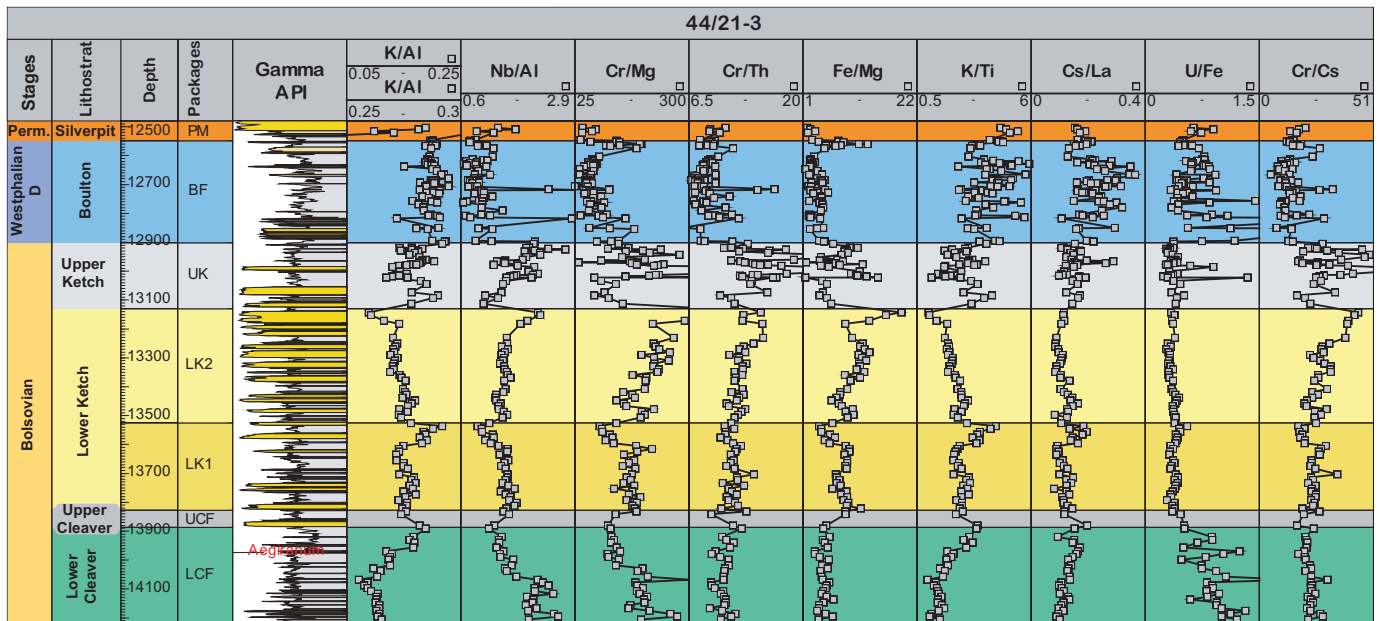


FIG. 7.—Key geochemical profiles based on silty claystone samples used to define the chemostratigraphy in well 44/21-3.

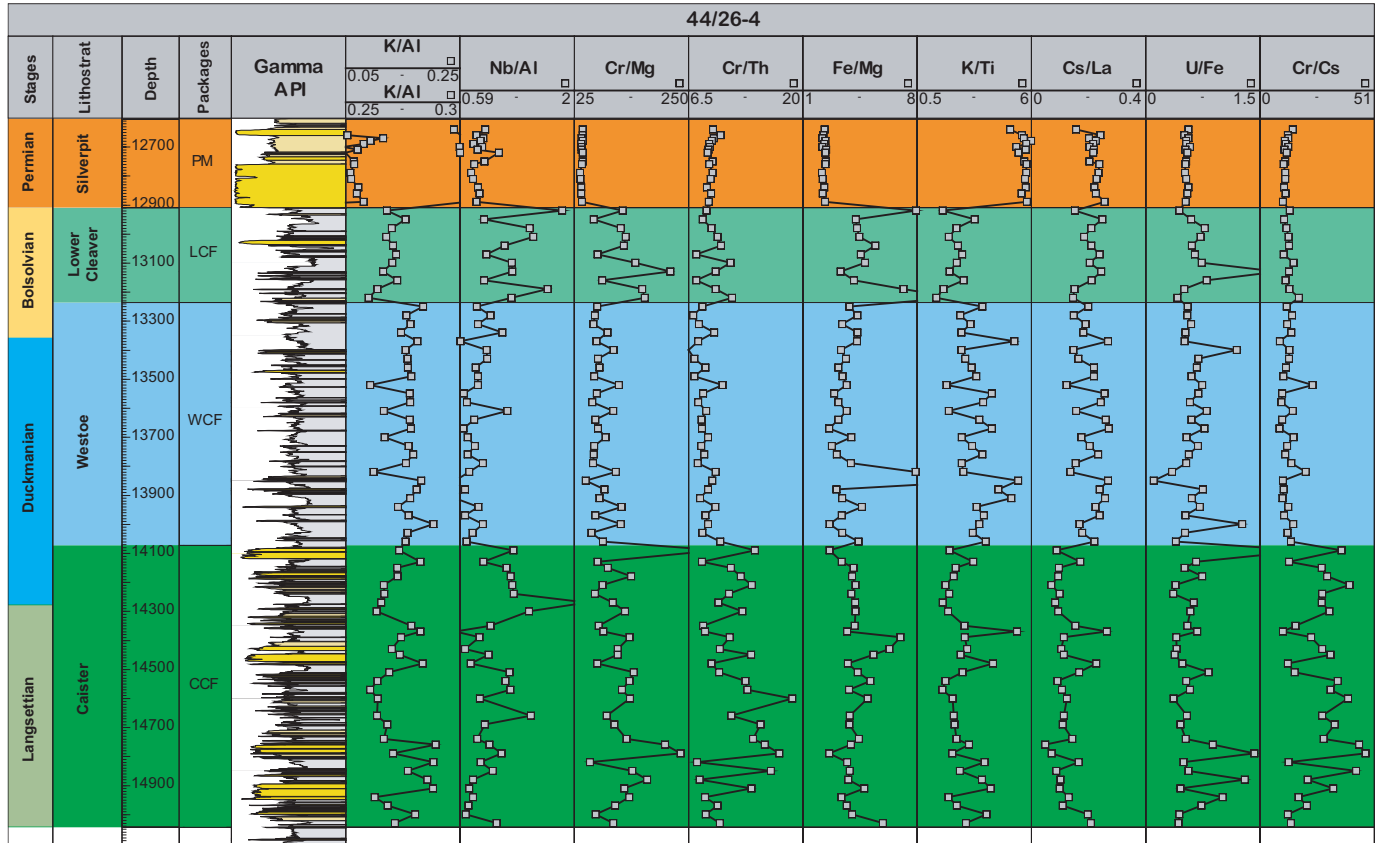


FIG. 8.—Key geochemical profiles based on silty claystone samples used to define the chemostratigraphy in well 44/26-4.

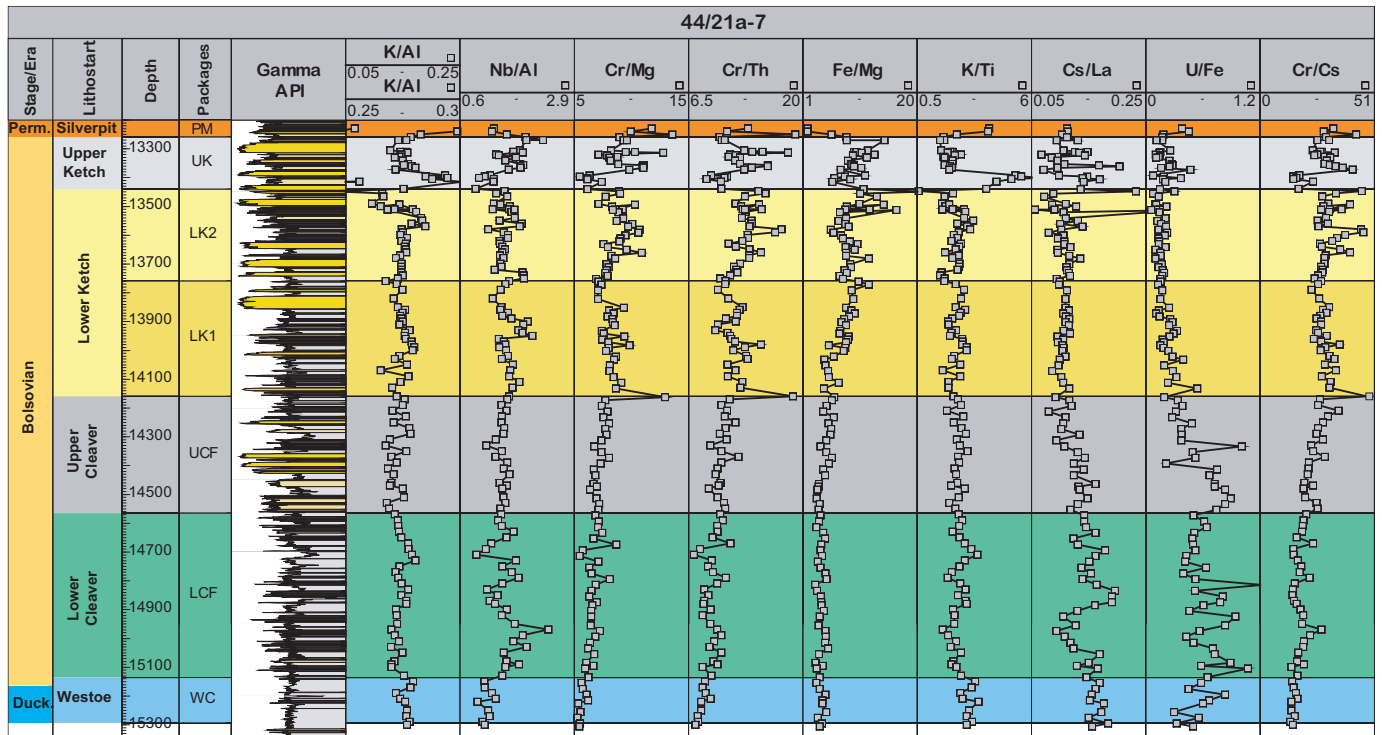


FIG. 9.—Key geochemical profiles based on silty claystone samples used to define the chemostratigraphy in well 44/21a-7.

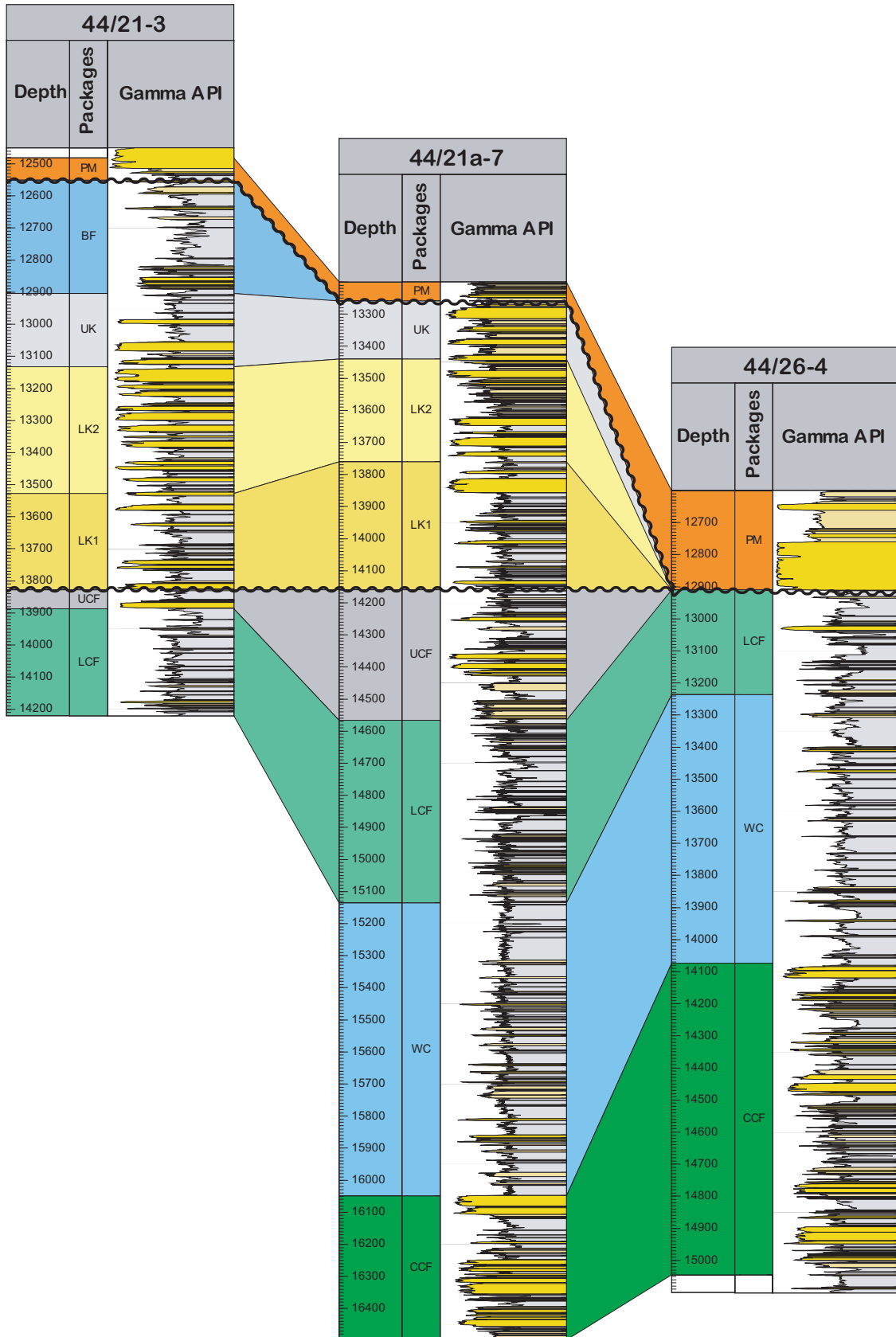


FIG. 10.—Chemostratigraphic correlation: wells 4421-3, 44/26-4, and 44/21a-7

sively eroded and Permian rocks rest directly on Langsettian or older deposits (Jones et al., 2005).

SANDSTONE CHEMOSTRATIGRAPHY AND MINERALOGY

So far, only small geochemical datasets have been acquired for the sandstones from each chemostratigraphic package, though they provide additional useful evidence that reinforces the correlations and corroborates proposed provenance changes. Figure 11 highlights the broad geochemical differences in sandstone geochemistry.

Sandstones from the Boulton and Step Graben formations have much higher Al, K, Rb, Cs, Ca, Mg, and P concentrations than the other sandstones, which shows they contain relatively abundant amounts of clay (predominantly illite), claystone lithic clasts, mica, feldspar, carbonate (in the form of cement and clasts), and apatite. The Package LK1 and LK2 sandstones are mineralogically more mature and are characterized by high Si levels, along with relatively high Cr, Nb, Zr, Th, and U contents that are attributed to heavy minerals (Fig. 6). In contrast, the Cleaver Formation and Westoe Formation sandstones lack the high Cr, Nb, and Th levels of the Ketch Formation sandstones, whereas the Caister Formation sandstones have high Al, Si, Ti, Sr, Nb, Th, U, and Zr concentrations.

The above changes in sandstone geochemistry not only reinforce the changes in provenance deduced from the heavy-mineral data and petrographic data (Pearce et al., 2005b; Morton et al., 2005) but also refine the silty claystone-based chemostratigraphic correlation.

COAL CHEMOSTRATIGRAPHY

Coals have long been used as a means for correlation (Weller, 1930; Wadsworth et al., 2002), inasmuch as they are often laterally

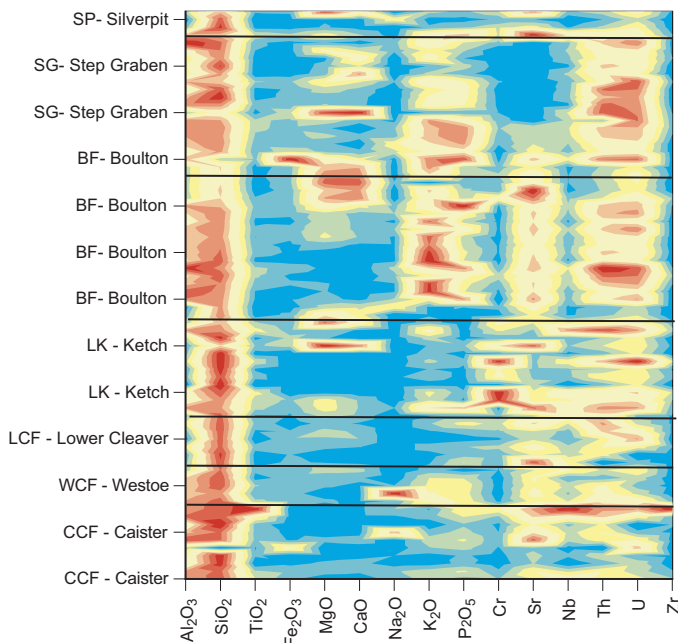


FIG. 11.—Elemental 2D contour plot for the Upper Carboniferous sandstones from the Southern North Sea. The plot uses colors to highlight changes in relative concentration from red (high)—yellow (moderate)—blue (low) concentrations.

persistent, provide material suitable for dating, can potentially be identified on seismic sections, and provide a means for identifying T-R cycles in the terrestrial environment (Wadsworth, this volume). Coals are common in the Cleaver and Westoe formations, where they routinely aid seismic correlations (Cooper et al., 2005), though even here, washouts, lateral impersistence, and seam splitting all serve to cause complications. Because coal is often well preserved in cuttings, a coal-based chemostratigraphy could provide an additional means for stratigraphic zonation and correlation in the oil industry.

Knowledge of the abundance and distribution of elements in coals is vital from an economic and environmental point of view. According to Spears and Zheng (1997), the major elements occur in the minerals rather than the organic matter, so the major-element geochemistry might provide some insight into trace-element–mineral associations in most of the UK coals. Si and Al are linked chiefly to kaolinite and illite, Ca and Mg are associated mainly with carbonate minerals, and Fe is linked to pyrite. With respect to the trace elements, Rb, Cr, Th, Ce, Zr, Y, Sn, Be, Ga, La, Ta, Nb, and V all occur chiefly in clay minerals and volcanic ash, whereas As, Mo, Sb, Tl, and Se are associated with Fe and are associated with pyrite in coals. If clear inorganic geochemical variations can be identified in either individual coals or groups of coals, they may form the basis for a coal chemostratigraphy that can supplement the silty claystone-based framework.

Clear differences are found between the inorganic geochemical signatures of selected coals from the Caister, Westoe, and Lower Cleaver formations (Fig. 12). Coals from the lower part of the Caister Formation typically have low Ti, Cr, Cs, La, and Nb contents and thus differ markedly from the Westoe Formation coals (note that the basal coal of the Westoe corresponds to the C3 seismic marker—Cooper et al., 2005, thereby providing an important stratigraphy-to-seismic tiepoint). The basal coal of the Lower Cleaver Formation is very distinctive geochemically, in that it has very high Ti, Cr, Nb, V, Yb, and Zr contents, and as a result its geochemical fingerprint can be used to a good marker for interwell correlation. The abundance of these elements is probably due to the presence of airfall volcanic ash (see later discussion on tonsteins; also see Spears and Zheng, 1997). Coal seams represent considerable periods of time, and air-fall ash tends to be preserved, whereas ash falling in areas where active sedimentation was occurring would quickly be reworked and its geochemical signature would not be easily recognized.

The establishment of a coal-based chemostratigraphy provides an additional and important means by which to refine the silty claystone-based chemostratigraphic correlation (Fig. 13). In addition, the recognition of certain key coal seams also enables the chemostratigraphic correlations to be integrated with seismic sections and potentially into transgressive–regressive correlation schemes such as those proposed by Wadsworth et al. (2002).

TONSTEINS AND ASH LAYERS

Explosive volcanic eruptions generate large amounts of fine-grained pyroclastic material, which is distributed at tropospheric and stratospheric altitudes by wind. Characteristic features of the resulting volcanic ash-fall deposits are their lateral continuity, broad areal distribution, time equivalence, and distinctive geochemistry (Spears and Lyons, 1995).

Königer and Lorenz (2002) studied airfall tuff deposits within complex fluvio-lacustrine, Carboniferous to Permian successions in the Saar–Nahe Basin (southwestern Germany). They found that each of the tuffs has a unique geochemical fingerprint, which probably reflect differences in the original composition of the

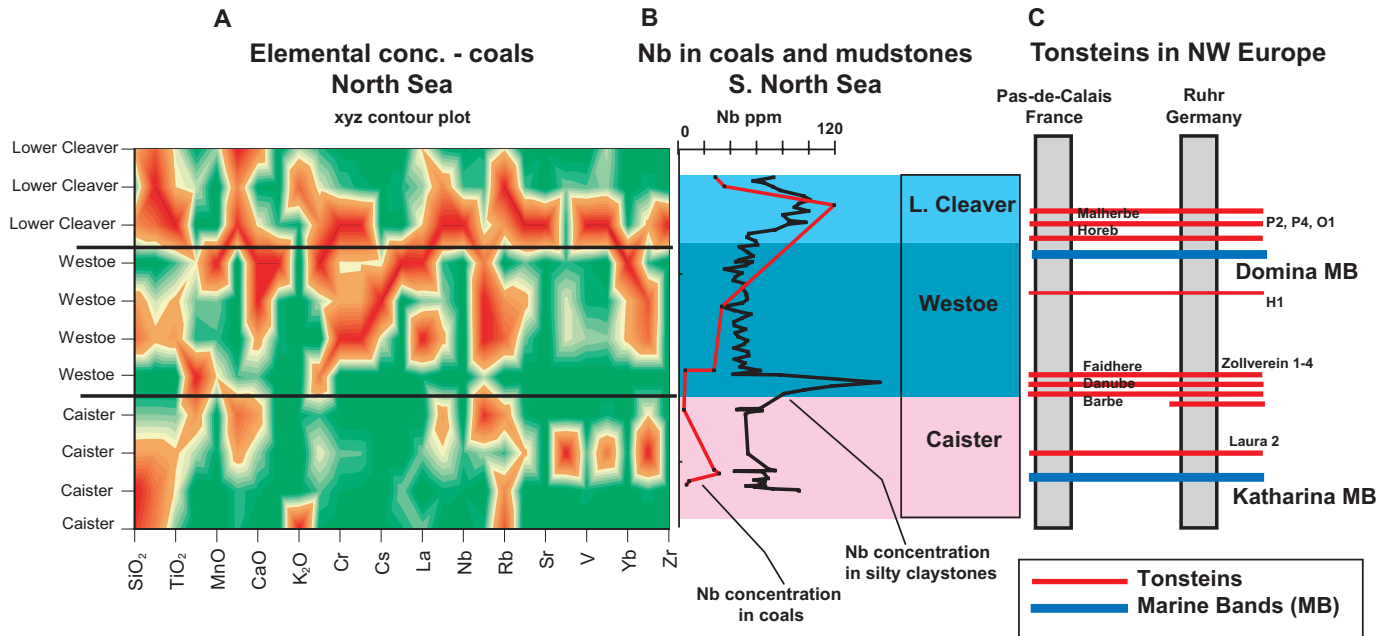


FIG. 12.—Variations in and controls on coal inorganic geochemistry. **A)** Elemental 2D contour plot for the Upper Carboniferous coals from the Caister–Lower Cleaver interval. The plot uses colors to highlight changes in relative concentration from red (high)—yellow (moderate)—blue (low) concentrations. **B)** A comparison between Nb / Al ratios exhibited by coal and silty claystones. **C)** The stratigraphic distribution of tonsteins in continental NW Europe.

parent magma. These geochemical differences between the various tuffs are significant and thus provide a powerful tool for recognizing and correlating individual tuffs within the complex sedimentary sequences of the Saar–Nahe Basin.

Wray et al. (1996) use rare-earth-element data to determine whether Middle and Upper Turonian argillaceous beds from northern Germany are composed of either bentonitic clay (altered volcanic ash) or detrital clay. In addition, chemostratigraphy has been employed to correlate tuffs found in the Permian Newcastle and Wollombi Coal Measures in New South Wales, Australia, these correlations enabling existing lithostratigraphic correlations to be refined (Andrew et al., 1996). Furthermore, Pearce et al. (this volume) recognize the Stafford Tonstein in onshore UK Carboniferous coal-measures successions on the basis of its characteristic high Sn, Y, Th, Ti, and Be levels enrichments, the geochemical data being acquired from cuttings.

Burger and Damburger (1985) discuss the correlation of marine bands and tonsteins in northwest Europe, in particular, between the Pas-de-Calais in France and the Ruhr in Germany. High Nb, Ta, Ti, Th, and Sn levels are recorded from silty claystones and coals at the base of the Lower Cleaver Formation and probably reflect the presence of volcanic ash, which might be time-equivalent to regionally extensive tonsteins (Burger and Damburger, 1985) that possibly extend into the Southern North Sea. Comparable high levels are also encountered in silty claystones at the base of the Westoe Formation and are broadly time-equivalent to another series of laterally persistent tonsteins reported in northwest Europe (Fig. 12). As an allied point, heavy-mineral analysis has reported traces of angular pyroxene grains from the Westoe Formation and the basal part of the Lower Cleaver Formation (Fig. 6), corroborating the presence of volcanic material in this part of the succession.

Whilst tonsteins obviously have an important place in correlation, their usefulness is sometimes limited, because they are

thin and thus may be missed when sampling core intervals. Moreover, when dealing with cuttings, their geochemical signature may become extremely “diluted” by the presence of more abundant lithologies occurring over the collection interval of these samples. Nevertheless, Figure 12 shows that where tonsteins are relatively frequent, their trace-element signatures can be recognized in the silty claystone geochemical datasets, even when dealing with datasets acquired solely from cuttings.

PALEOSOLS

Paleosols are an established means of interpreting paleoenvironments, determining facies, and constructing correlations; however, the correlation of individual paleosols is often unreliable, due to the lack of unique pedogenetic characteristics. Inorganic geochemical data can provide a means to refine their characterization and strengthen their use for correlation.

Pearce et al. (2005a) and Besly (2005) recognize different types of paleosols over the Upper Carboniferous successions discussed in this paper. These authors demonstrate that ferruginous ultisols are well developed over the upper parts of Package LK, being defined by high Fe contents, high Fe/Mn values, and high values of $Al_2O_3 / (MgO + CaO + Na_2O + K_2O)$ (the “alumina/bases” ratio of Retallack, 1997). The presence of these ultisols reflects periods of extensive hydrolytic weathering. Caliches, which form under semiarid climatic conditions, occur in Packages BF (Boulton Formation) and SG (Step Graben Formation). These paleosols are readily detected by their high CaO contents (10% to 30%) and high $(CaO + MgO) / Al_2O_3$ values (Pearce et al., 2005b). Illitic gley soils are present at the top of Package LK1 (Unit S1c; Pearce et al., 2005b), and their development appears to be laterally persistent in many of the proprietary wells analyzed.

Paleosols are potentially important features when considering sequence stratigraphic frameworks of terrestrial environ-

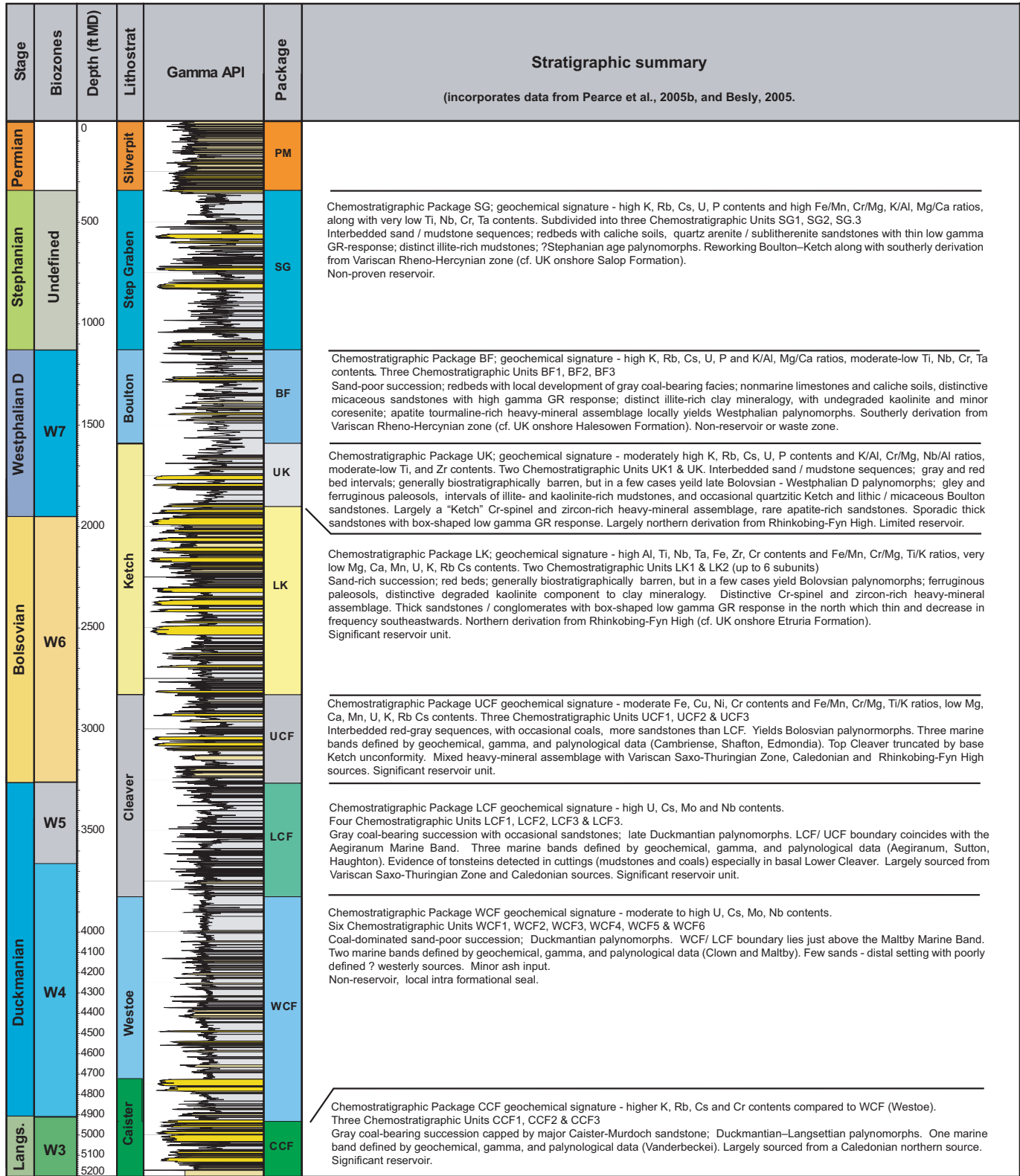


FIG. 13.—Integrated stratigraphic summary for the Upper Carboniferous interval Caister Formation–Step Graben Formation.

ments (Wright, 1990). Therefore, by enabling not only the identification but also the characterization of paleosols in samples from well bores, inorganic geochemical data can be used an important primary data source when establishing a basinwide correlation in continental sequences.

MARINE BANDS

For many years, marine bands have been used for correlating Upper Carboniferous successions, inasmuch as they are usually laterally persistent, they provide material suitable for dating, and their presence can often be detected on E-logs (Adams and Weaver, 1958; Archard and Trice, 1990; Leeder et al., 1990; Davies and McLean, 1996; O'Mara and Turner, 1997). However, marine bands do not always display high U and resultant high GR responses.

Pearce et al. (this volume) propose an integrated geochemical and palynological methodology for the detection of marine bands. The geochemical component can also be applied independently and is based on cumulative scores for a series of elements including U, P, Mo, Th, P, Cu, V, Ni, and Co. Using geochemistry in this way, seven marine bands have been detected over the Westoe and Cleaver formations using data acquired from core samples and cuttings (Fig. 14), the presence of these bands subsequently being corroborated by palynological data. Furthermore, the

geochemical data are used to recognize marine silty claystones, brackish-water to marginal-marine silty claystones, and freshwater silty claystones to be differentiated, as well as facies-based interwell correlation schemes to be constructed. In addition, the identification and correlation of the marine bands adds a further level of refinement to the chemostratigraphic correlation framework (Figs. 13, 15).

DISCUSSION

Chemostratigraphy, using whole-rock inorganic geochemical data, has really developed as a stratigraphic technique over the past decade, and it is suggested herein that this reflects its increased application in the petroleum industry. The application in the oil industry is primarily to aid with interwell correlation of reservoir sandstones or clay permeability barriers or baffles, and is most often undertaken within reservoir intervals and between closely spaced wells. When applied in this manner, the technique mostly defines boundaries between chemostratigraphic packages and units that reflect subtle changes in mineralogy such as clay minerals, detrital feldspars, or heavy-mineral suites. As such, these boundaries are highly diachronous surfaces, resulting in chemostratigraphy being used to define high-resolution lithostratigraphic frameworks to improve reservoir modelling (Ratcliffe et al., 2002), rather than being used to define a chrono-

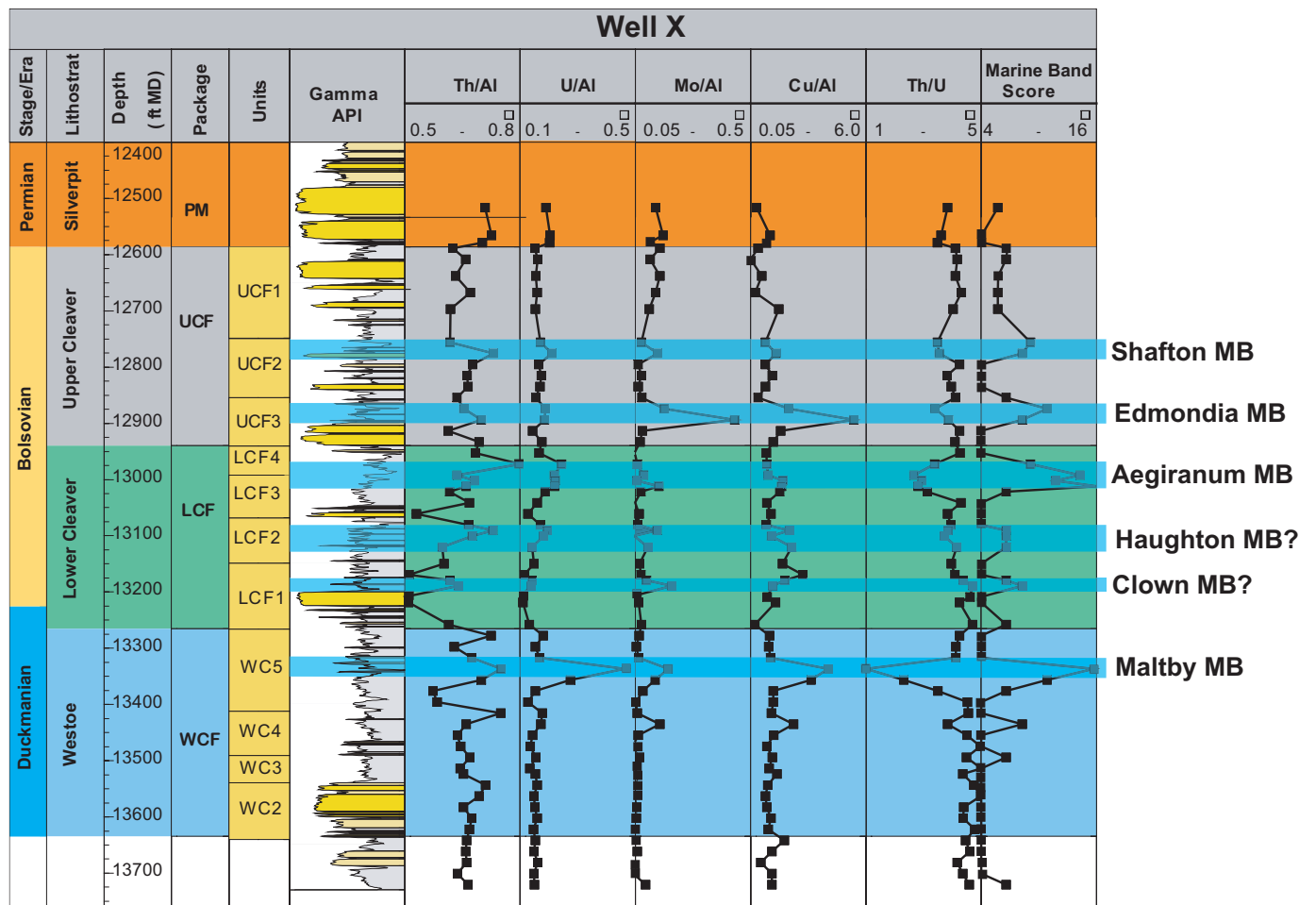


FIG. 14.—Geochemical classification of marine bands (Pearce et al., this volume).

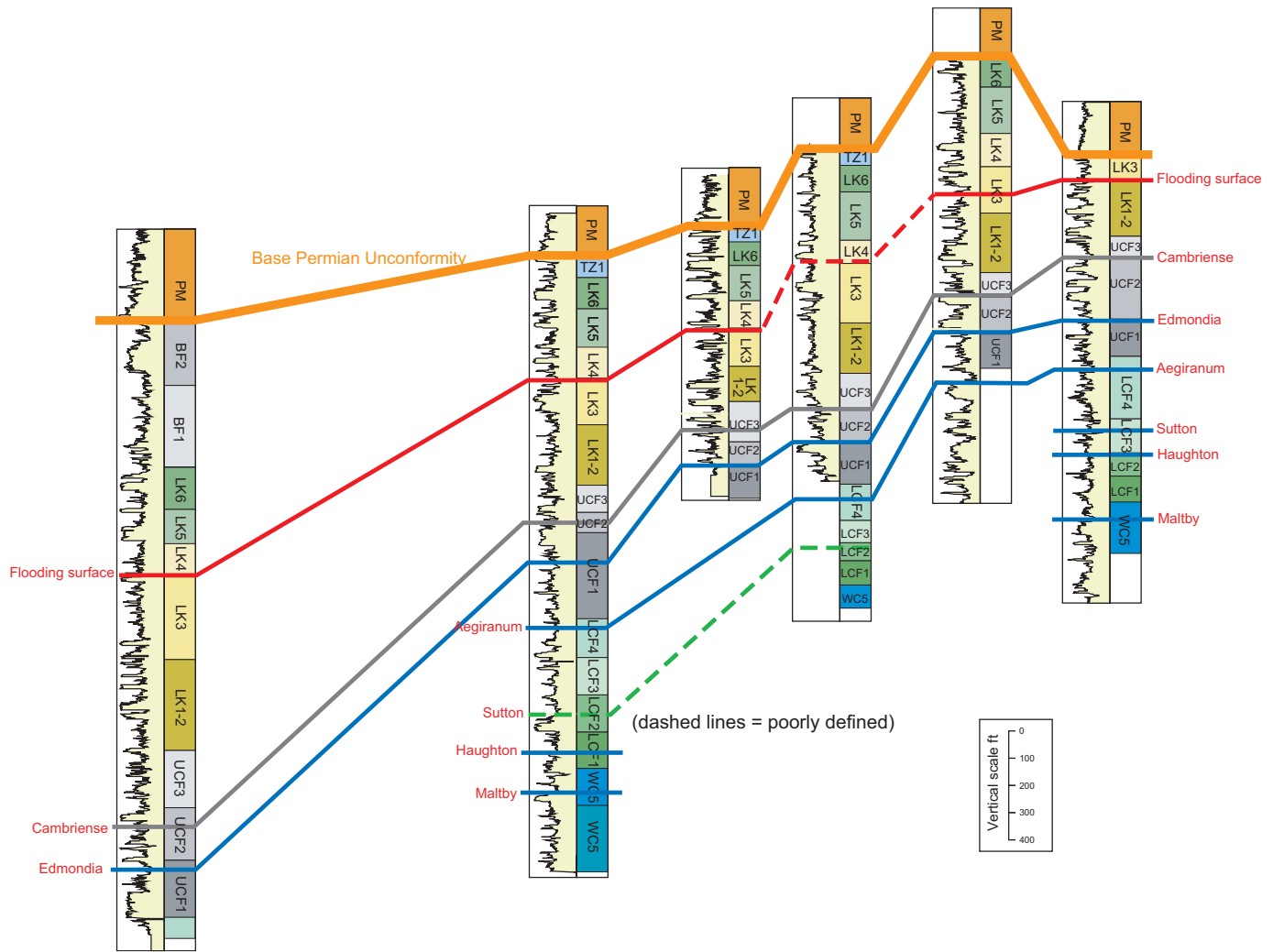


FIG. 15.—Correlation of marine bands within the Westoe and Cleaver Formations, which refine the resolution defined from variations in silty claystone geochemistry. “Langs.” = Langsettian.

stratigraphic correlation. The pragmatic commercial application of chemostratigraphy is demonstrated above by the correlation of both barren and fossiliferous sequences of the Ketch and Boulton formations. The usefulness of the chemostratigraphic correlation schemes is testified to by the number of wells (> 60 wells) analyzed by a variety of oil companies in the Southern Gas Basin.

However, chemostratigraphy can be used to focus on identifying time-omission surfaces such as unconformities and hiatuses, condensed intervals such as paleosols and coal seams, sequence stratigraphic-related surfaces such as flooding surfaces and marine bands, and low-diachrony surfaces such as the bases of ash bands and coal seams. It can also aid in recognizing these features in well-bore sections, avoiding the problems typified by ash-bed correlation, where one ash bed can appear superficially very similar to another. As such, chemostratigraphy, when integrated with other stratigraphic disciplines, such as biostratigraphy or lithostratigraphy, can add to the definition of chronostratigraphic frameworks.

Whilst the surface-recognition approach has proved very successful (Kramer et al., 2001; Wray et al., 1996; Königer and

Lorenz, 2002; Burger and Damberger, 1985), there are associated problems when dealing with the petroleum-based applications. Recognition of surfaces depends on continuous core coverage or outcrop samples being available to ensure that each important feature is sampled at each locality. Unfortunately, core material is limited with respect to most reservoir sequences, and as development drilling continues, the primary source of geological data is cuttings. In these instances, the geochemical signatures of the aforesaid surfaces, which are usually easily recognized when dealing with core-sample and outcrop-sample datasets, often become either “diluted” or even obliterated by the collective geochemical signature of the lithologies present over the composited sample depths. As a result, the potential for surface-based correlations is to some extent lost when dealing with petroleum applications. The consequence of this loss is that relatively few attempts have been published whereby whole-rock inorganic geochemical data have been rigorously employed for surface recognition and correlation.

As demonstrated in this study, chemostratigraphy (IEC) has application to the petroleum industry by providing a detailed

reservoir-to-field-scale correlation framework. It can also be used to establish subregional correlation schemes, but it must be tied to a chronostratigraphic scheme to assess the extent of diachrony. In some instances IEC can be tied to chronostratigraphic events such as tuffs, marine bands, and changes in climatic and seawater conditions and therefore can be used to establish by more regionally extensive or even global correlations.

Chemostratigraphy, using chiefly cuttings data, is now routinely employed to constrain the subregional stratigraphy of the Upper Carboniferous in the Southern North Sea. This paper has presented the results and conclusions from only a small selection of the entire dataset that has been released for publication. The entire geochemical database encompasses over sixty wells from Quadrants 44 and 49 (UK sector), as well as in Blocks E, F, and K of the Dutch sector. Interpretation of these data has led to the establishment of a robust, independent, high-resolution chemostratigraphic correlation scheme for the Upper Carboniferous successions in the aforesaid areas. Chemostratigraphic packages can be correlated between fields, their correlation being used to constrain seismic correlations, which in turn highlight potential exploration targets (Cameron et al., 2005). On the other hand, chemostratigraphic units more often are correlated within an individual field, where their correlation enhances reservoir correlations, e.g., in fields such as Boulton, Schooner, Tyne, Ketch, and Topaz (Stone and Moscariello, 1999; Moscariello, 2000; Cooper et al., 2005; Jones et al., 2005). Increasingly, the ability to consistently define chemostratigraphic units subunits is leading to well-site application, where picking well TD (Conway et al., 2002) and aiding when geosteering is carried out in real time at well site.

CONCLUSIONS

Well sections through the hydrocarbon-bearing Upper Carboniferous Boulton and Ketch formations in UK Quadrants 44 and 49 are difficult to correlate, because they have poor internal seismic definition, repetitive E-log signatures, and a barren nature. Moreover, even though the underlying coal-measures sequences assigned to the Cleaver and Westoe formations have better seismic resolution and contain palynomorphs, their correlation still proves challenging due to coals that die out laterally and the lack of diagnostic taxa over certain intervals. Correlative chemostratigraphic reference zonations have been constructed for the Caister, Westoe, Cleaver, Ketch, and Boulton formations, based on silty claystone geochemical data acquired from cuttings and core samples. The zonations are founded on changes in silty claystone geochemistry, which reflect changes in provenance, climate, and depositional environment, and the subsequent corroboration of this zonation by biostratigraphic data, enables the chemostratigraphy to be tied to chronostratigraphy.

This paper summarizes a pragmatic application of chemostratigraphy to the correlation of both barren and fossiliferous sequences, and demonstrates how the chemostratigraphic zonations and correlations can be established from the geochemistry of the predominant lithology, which in the case of the Upper Carboniferous sequences is silty claystone. The zonations provide a framework into which other stratigraphic components can be added, ultimately resulting in a comprehensive chemostratigraphic correlation scheme. With respect to the Upper Carboniferous sequences, supplementary information takes the form of sandstone geochemistry, geochemical evidence for the presence of coals, tonsteins, paleosols, and marine bands, clay-mineral data, and heavy-mineral data. In addition, the correlation has been integrated with available biostratigraphic data, and the recognition of unconformities and coals enables the chemostratigraphic correlation to be tied to seismic correlations,

thereby producing a comprehensive methodology for reservoir-field-subregional correlations that can be applied not only to the Upper Carboniferous clastic reservoirs of the Southern North Sea but also to other clastic reservoirs worldwide.

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