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Sequence stratigraphy of source rocks applied to the study of the Kimmeridgian/Tithonian in the north-west European shelf (Dorset/UK, Yorkshire/UK and Boulonnais/France)

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In Dorset and Yorkshire (England), the sedimentation of Kimmeridgian/Tithonian age (Mutabilis to Pallasioides zones) shows ordered organic sequences. The distribution of the organic matter content (per cent total organic carbon, petroleum potential, hydrogen indices) is not random, but occurs as widespread primary organic-rich cycles nested within each other. These organic-rich cycles, with thicknesses of about 0.5 m, show regular variations in organic carbon contents, reaching a maximum value midway through the cycle. They formed in response to widespread phenomena and can be correlated over long distances. The cycles were deposited in marine environments mainly below the storm wave base; they show little sedimentological evidence of sea-level fluctuation, either transgression or regression. In the Boulonnais (France), a more proximal setting, the comparable strata show a greater lithological contrast and depositional environments corresponding to bathymetric changes are more easily determined. A comparison of the distribution of organic matter through the sequence dated by ammonites, in the three areas studied, shows a good correlation between the distal (Dorset and Yorkshire) and the proximal (Boulonnais) areas. The main result of the biostratigraphic revision in the Boulonnais (France) concerns the Argiles de Châtillon, which can be subdivided into two members. These belong to the Autissiodorensis Zone (Autissiodorensis Subzone) and the Gigas-Elegans Zone, respectively. Thus the Kimmeridgian–Tithonian boundary is located within this formation. Transgression does not appear to be the main factor determining the accumulation of autochthonous organic matter (type II). Not every major transgressive facies change seen in the Kimmeridgian/Tithonian of the Boulonnais is characterized by an enrichment in organic matter in the basinal area. Good source rocks with high petroleum potentials result from a conjunction between the physiography, the transgression and the climate. This last causes the variations in primary productivity which produce the organic-rich cycles. Transgressions act mostly to reveal the climatic variations. They are a necessary condition for the accumulation of the autochthonous organic matter, but they are not sufficient by themselves, as demonstrated by the transgressions in the Autissiodorensis and Elegans zones. In the first instance, the strata are depleted in organic matter, in both the distal and proximal areas; in the second instance, type II organic matter accumulated in both distal and proximal environments. The vertical fluctuations in the total organic carbon contents, the types of organic matter and the petroleum potentials of the organic-rich cycles, determine the oil potentials of transgressive sequences in sedimentary basins.

Keywords: sequence stratigraphy; source rocks; Kimmeridgian–Tithonian

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The distribution of organic matter in time and space, and consequently that of the main source rocks generating oil and gas, is not a random phenomenon. Several factors contribute to this accumulation, including climate, sea-level change and palaeogeography (Tissot, 1979; Demaison *et al.*, 1983; Fleet *et al.*, 1987). However, the intricate processes that result in major concentrations of organic matter are interdependent (Herbin *et al.*, 1989). Given that the palaeogeography on a global scale can be considered as having been relatively stable during the few million years that correspond to the Kimmeridgian (Cope *et al.*, 1992), it is possible to interpret the vertical and lateral variations in organic content to deduce the contributions of other factors such as climate and sea-level change.

This study focuses on the black shales of the Upper Jurassic of England and northern France, which are a major source unit responsible for much of the oil in the North Sea (Cornford, 1984; Williams, 1986) and even further in Western Siberia. They are Kimmeridgian/Tithonian in age [Kimmeridgian and Tithonian as accepted by the International Subcommission on Jurassic Stratigraphy (1990), on proposition of the working group on the Kimmeridgian/Tithonian boundary].

Owing to the paucity of continuous core resulting from exploration/production boreholes in the North Sea area, the most complete description of these organic facies has been compiled from boreholes, with full recovery, located onshore in England, and from outcrops along the cliffs in Dorset (UK) and Boulonnais (northern France).

An exhaustive study in 1976 by the British Geological Survey (Gallois, 1979) has shown that the organic-rich mudstones in the Kimmeridge Clay, with petroleum potential of up to 20 kg of hydrocarbons per tonne of rock (kg HC/t), are confined to five horizons in the interval between the upper part of the Mutabilis Zone and the lower part of the Rotunda Zone. Subsequently the Institut Français du Pétrole (IFP) carried out a drilling campaign in 1987 to characterize the distribution of organic matter in a 30 km long transect across the Cleveland Basin (Yorkshire) and to extrapolate these observations to the offshore deposits of the Sole Pit Basin in the North Sea (Herbin *et al.*, 1993).

The present paper aims to correlate these facies, deposited below storm wave action in an epeiric sea, with proximal deposits such as those of the Boulonnais (France) which were located in the nearshore vicinity of the London–Brabant Massif during Late Jurassic times. This study summarizes the main geochemical,

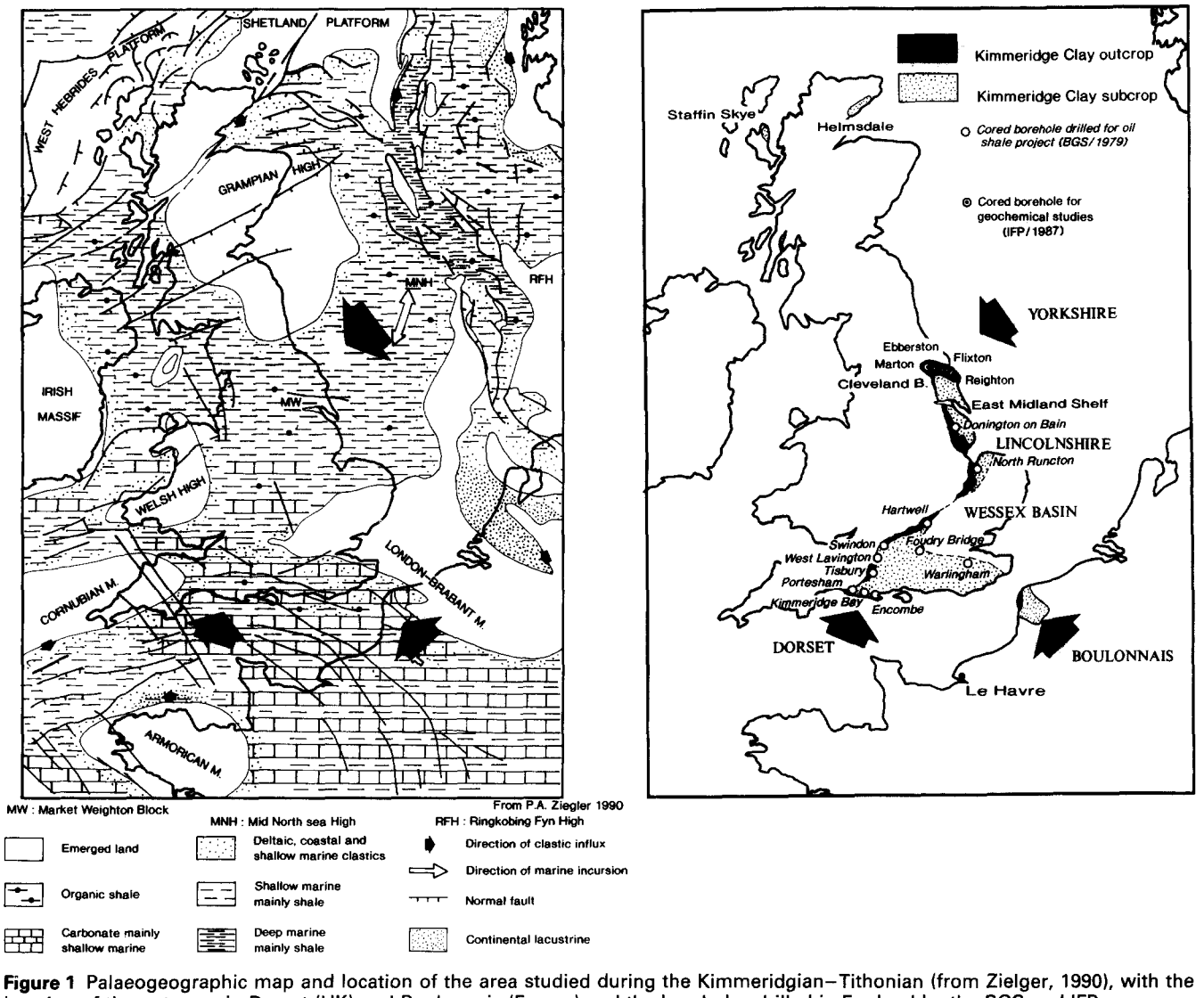

Figure 1 Palaeogeographic map and location of the area studied during the Kimmeridgian–Tithonian (from Zielger, 1990), with the location of the outcrops in Dorset (UK) and Boulonnais (France) and the boreholes drilled in England by the BGS and IFP

sedimentological and biostratigraphic findings from both cores and outcrops and places them in a sequence stratigraphic framework to explore the influences of factors such as climate and sea-level change.

Geological setting of the areas studied

The distribution of the Late Jurassic Kimmeridge Clay in southern and eastern England was mainly controlled by the pre-Permian structure (Penn and Abbott, 1989). Two basins existed: a major basin in southern England (Wessex Basin) and another in the east Yorkshire/Lincolnshire region (North East England Basin) extending seawards to the North East England Platform (Ziegler, 1990; Cope *et al.*, 1992). These two basins were separated by the London Platform, which continued towards the east as the London–Brabant Massif (*Figure 1*). These structural elements were relatively stable, although the North East England Basin became divided by a positive hinge area (the Market Weighton Block) at the end of the Triassic period, and a more northerly Cleveland Basin continued to subside, with some interruptions, into the Cretaceous period. During Late Jurassic time the rapidly subsiding Cleveland Basin was distinguishable from the slowly and intermittently subsiding Market Weighton Block. According to Penn and Abbott (1989) the maximum syn-depositional growth occurred during the early Cretaceous deposition of Speeton Clay.

In England, the Kimmeridge Clay has an outcrop and subcrop that extend from Dorset to North Yorkshire. The Kimmeridge Clay is relatively poorly exposed inland except in scattered brick pits (Cope, 1974; Birkelund *et al.*, 1983) or temporary exposures (Oates, 1981). The best descriptions of the formation come from studies of the coastal cliffs in Dorset and from cores or logs from boreholes elsewhere. Ammonites provide the means for detailed correlations (Cope, 1980), between the type section in Dorset (Cope, 1967; 1978; Cox and Gallois, 1981) and outcrops and boreholes elsewhere in England (Callomon and Cope, 1971; Gallois, 1979; Oates, 1981; Birkelund *et al.*, 1983; Herbin *et al.*, 1991).

In Dorset, the Kimmeridge Clay is made up of mudstones, calcareous mudstones and organic-rich mudstones with up to 60% total organic carbon (TOC) in the oil shales and, exceptionally, a petroleum potential of up to 400 kg HC/t rock. The rocks show rhythmic alternations, at a decimetre scale, of dark grey, organic-rich mudstone and pale grey, organic-poor mudstone. Many of these alternations, which form the 'primary cyclicity', can be correlated along the cliffs over long distances. Superimposed on this cyclicity are broader lithological changes in calcareous and organic contents, which can be regarded as longer scale rhythms. They have been labelled and correlated throughout southern England in the study by the British Geological Survey (Gallois and Cox, 1976; Cox and Gallois, 1981). Moreover, decimetre to metre thick bands of dolomite and coccolith-rich cementstones accentuate lithological or stratigraphic boundaries. These prominent hard bands are well displayed in the coastal outcrops where they are used as obvious markers and commonly coincide precisely with zonal boundaries. Examples include the Flats Stone Band (SB) between the Eudoxus and Autissiodorensis zones, Washing Ledge SB, Maple Ledge SB, Blake's Bed 42 between the Autissiodorensis and Elegans zones, Yellow Ledge SB between the Elegans and Scitulus zones, Rope Lake Head SB between the Wheatleyensis and Hudlestoni zones, White SB between the Hudlestoni and Pectinatus zones, and the Freshwater Steps SB (*Figure 2*). Furthermore, these persistent markers can be correlated over large distances in boreholes in Lincolnshire, Norfolk, Surrey, Wiltshire (Gallois and Cox, 1974; Gallois and Medd, 1979) and into Yorkshire (*Figure 4*).

The stratigraphic section of Kimmeridge Clay in the Cleveland Basin is similar to the stratotype section in Dorset. The four boreholes drilled by IFP in this region recovered a complete succession from the Cymodoce to the Pallasioides zones and show increased rates of sediment accumulation from the Eastern England Platform (Reighton 87 borehole) to the basin area (Marton 87) (Herbin *et al.*, 1991; Geyssant, 1994). The Lower Cretaceous Speeton Clay was deposited in a marine environment and is separated from the Kimmeridge Clay by a major disconformity corresponding to the Coprolite Bed (Scott *et al.*, 1987). This thin level (10–20 cm), which is made up of phosphatic pebbles, probably derived from phosphatized hardgrounds and includes internal moulds of bivalves, brachiopods and ammonites, has been identified in two IFP boreholes (Flixton 87 and Reighton 87). This disconformity seals a major erosive phase that occurred after the deposition of the Pallasioides Zone. The ammonite zones of the Tithonian are completely absent in the shelf area near the Eastern England Platform (Reighton 87), but are preserved in the basin (Marton 87, Ebberston 87/87 Bis, Flixton 87) (Figure 10 in Herbin *et al.*, 1991).

The third area included in this study concerns the cliffs of the Boulonnais (northern France) which shows a more proximal facies with nearshore sand bodies (Grès de Châtillon, Grès de la Crèche) close to the edge of the London–Brabant Massif (*Figure 1*). In the Boulonnais, ammonites are less common than in Dorset and Yorkshire because of the proximal setting, but new observations made for this study allow a correlation between the Boulonnais and the English localities. Between Ambleteuse and the Cap Gris Nez, the Argiles de Châtillon outcrop over ten kilometres affected by faults with small apparent throws (2–8 m). In the La Crèche anticline the sequence is folded and affected by larger wrench faults whose apparent throw reaches 35–60 m (*Figure 8*). These Jurassic deposits were folded after the deposition of the Tithonian series and before the first Cretaceous sediments (Pruvost, 1923–1924). The 'Zone de cisaillement Nord Artois' was active at five times (Carboniferous, Permian, Triassic, Early Cretaceous and Eocene), whereas the Late Jurassic appears to have been a more stable time (Colbeaux, 1990). The prevailing lineation in the NNW–SSE direction corresponds to the faults and fold axes in the Palaeozoic basement terranes. During the Tithonian, the facies became more proximal with sandstones. Gravel beds with phosphatic rounded fossils within clay formations have been interpreted as stratigraphic unconformities related to major fluctuations of the sea level (P1, P2, P3, in Pringle and

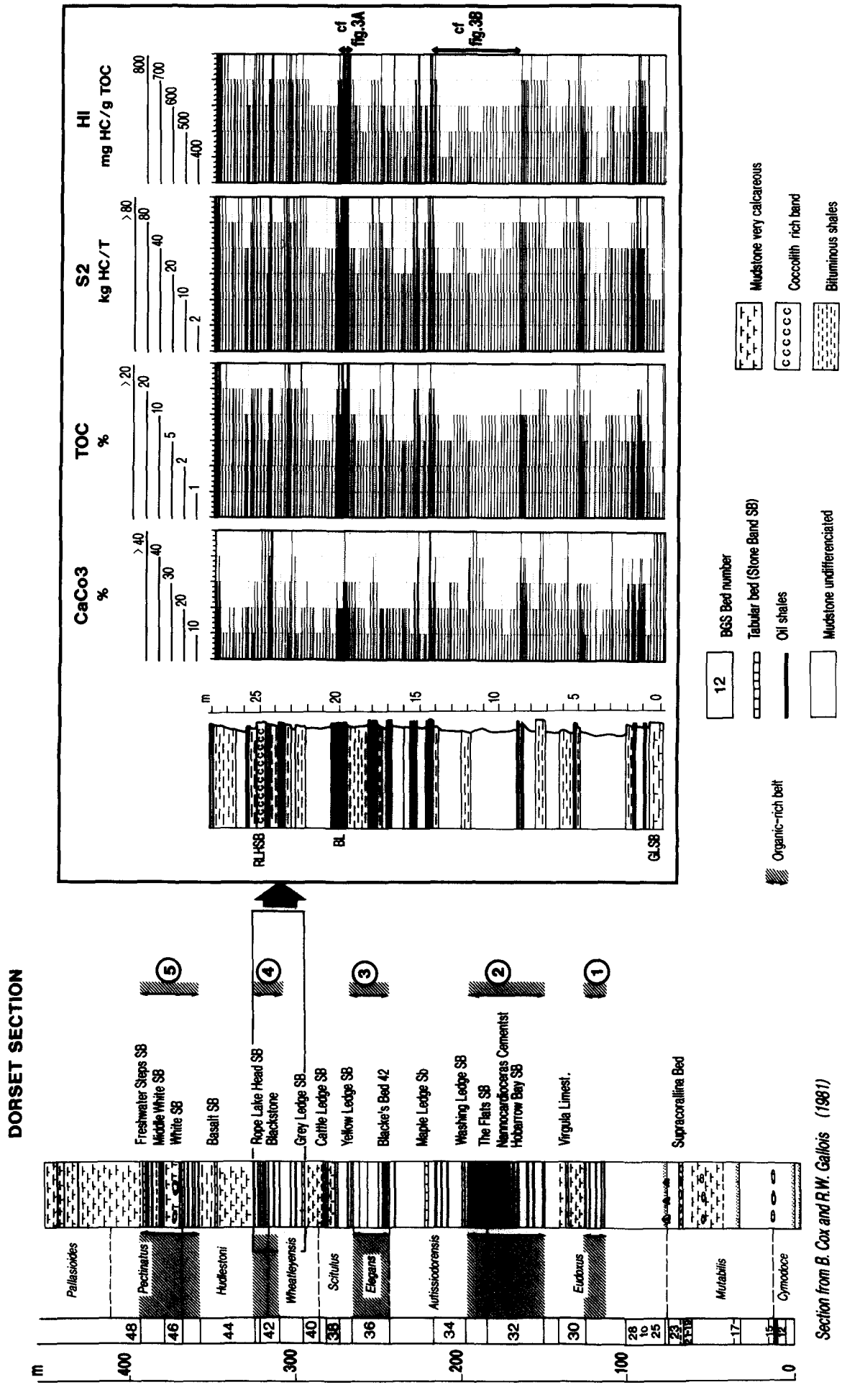

Figure 2 Generalized vertical section of the Kimmeridge Clay Formation in Dorset showing the main concentrations of oil shales with petroleum potential higher than 20 kg HC/t rock stratigraphically condensed in five distinct organic-rich belts corresponding to (1) the middle part of the Eudoxus Zone, (2) the upper part of the Eudoxus Zone and the lower part of the Autissiodorensis Zone, (3) the Elegans Zone, (4) the upper part of the Wheatleyensis Zone and the basal part of the Hudlestoni Zone and (5) the upper part of the Hudlestoni Zone and the *lower part of the Pectinatus Zone. The right-hand panel shows the fluctuation of the main geochemical parametres within the fourth organic-rich belt.* The values are distributed in classes due to their great variability

Pruvost, 1924). At the close of Jurassic time, lacustrine and lagoonal deposits, similar to the so-called 'Purbeck facies' in England, were deposited in the Boulonnais area, but are much thinner, 3 m in the Boulonnais compared with about 120 m at Purbeck in the Wessex Basin. These sediments, which represent the last deposits in the Jurassic period, are equivalent in time to the Spilsby Sandstone of Eastern England whose age is Upper Tithonian.

Organic facies in distal areas of the epeiric basin: Dorset and Yorkshire

The stratigraphic distribution of organic-rich facies is similar in Dorset and Yorkshire although the Dorset succession is considerably thicker (*Figures 2* and *4*). According to Gallois (1979), in Dorset the main concentrations of oil shales with petroleum potential higher than 20 kg HC/t rock are located in five distinct stratigraphic horizons, as shown in *Figure 2*: (1) the middle part of the Eudoxus Zone (BGS bed 29); (2) the upper part of the Eudoxus Zone and the lower part of the Autissiodorensis Zone (BGS beds 32 and 33); (3) the Elegans Zone (BGS bed 36); (4) the upper part of the Wheatleyensis Zone and the basal part of the Hudlestoni Zone (BGS bed 42); and (5) the upper part of the Hudlestoni Zone and the lower part of the Pectinatus Zone (BGS beds 45 to 47). The organic-rich facies are widely distributed along the north-west European margin during these particular periods which correspond to five 'organic-rich belts' (Herbin and Geyssant, 1993).

Detailed sampling along the cliff at Kimmeridge Bay, within the fourth organic-rich belt, located between the upper part of the Wheatleyensis and the basal part of the Hudlestoni zones, shows that the organic-rich facies occur at several discrete intervals. More than 13 levels exhibit a petroleum potential higher than 80 kg HC/t rock, corresponding to a TOC content above 20% (*Figure 2*, enlarged section). The facies interpretation in this particular stratigraphic zone, based on the macrobenthic associations (Wignall and Myers, 1988; Wignall, 1990b; Wignall and Hallam, 1991) suggests variations between aerobic, poikilaerobic and anaerobic benthic environments (Oschmann, 1990; 1991; poikilaerobic = oxygenated environmental conditions during a major part of the year but anoxic to anaerobic for several weeks to a few months). One of the richer organic beds, the so-called Blackstone, is itself heterogeneous, including horizons of lower organic accumulation (TOC $\leqslant$ 10%), between intervals of maximum enrichment (from 40 to 60% TOC corresponding to exceptionally high petroleum potential of up to 400 kg HC/t rock) (*Figure 3A*). These regular and continuous alternations correspond to the primary organic-rich cycles, i.e. the smallest cycles identified on the geochemical log. If we assume that these primary organic-rich cycles have a duration of ca. 25000 years (by reference to the study of the organic-rich cycles in the Kimmeridge Clay of the Yorkshire area, Herbin *et al.*, 1991), the time required for the deposition of the Blackstone would be ca. 75000 years. Within this fourth organic-rich belt, above and below these phenomenal accumulations, there exist the very same type of primary cycles as previously described in the Marton 87, Ebberston 87 or Flixton 87 boreholes in Yorkshire with TOC ranging from 3 to 14% and petroleum potential from 10 to 100 kg HC/t rock (e.g. within the Wheatleyensis Zone, *Figure 3B*).

On a large scale the five main organic-rich belts correspond to highly favourable periods for the production and preservation of organic matter, and are themselves intercalated with unfavourable periods such as the Autissiodorensis Zone (except for the thin enrichment in organic matter at the lower part, which belongs to the end of the second organic-rich belt), the Scitulus Zone, the middle part of the Hudlestoni Zone and the top of the Pectinatus Zone (Herbin and Geyssant, 1993). The geochemical variations are not random; there is an alternation between long periods of high enrichments (rich in nested cycles) and periods of 'relative' depletion which contain 2–5% TOC and petroleum potential lower than 10 kg HC/t rock.

A similar record exists 400 km northward in York-

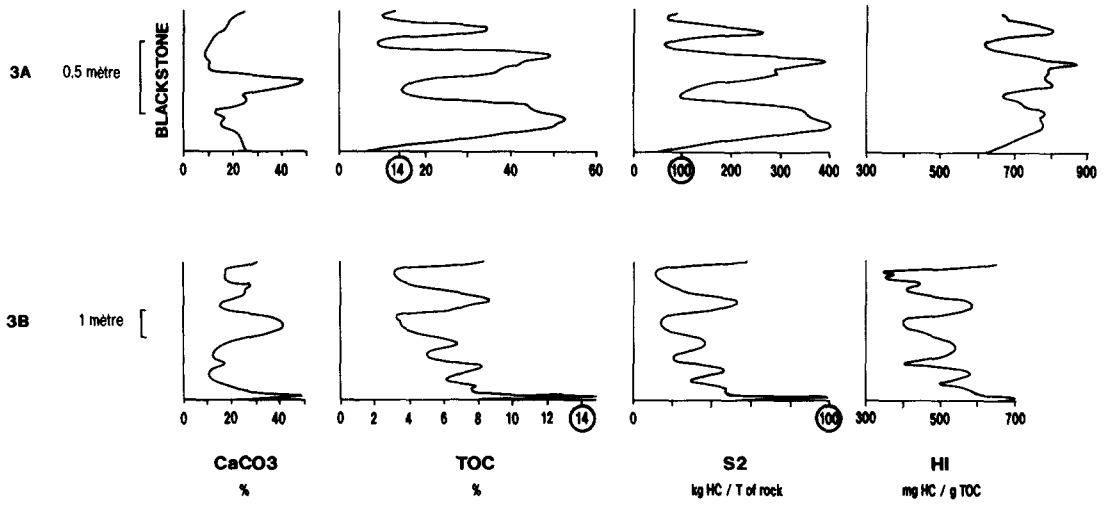

Figure 3 Nature of the organic sedimentation with regular fluctuations of the quantitative and qualitative geochemical parameters. The organic matter distribution shows that all these variations are not random, but are nested within one other. The sections are stratigraphically located on *Figure 2* in the panel corresponding to the fourth organic-rich belt. (A) Period of maximum enrichment: the Blackstone. (B) Period with similar cycles but lower content

shire, where the main concentrations of organic matter have the same age (*Figure 4*). In this area, the study of the organic matter is based on a quantitative analysis performed at a very close spacing (about 10 cm) to obtain a continuous distribution through the Kimmeridgian/Tithonian, i.e. from the Cymodoce to the Pallasioides zones (Herbin *et al.*, 1991). The composite section (*Figure 4*) includes both the results issued from the Reighton 87 Borehole for the Cymodoce to the Mutabilis zones and the Ebberston 87/87 bis Boreholes for the Eudoxus to Pallasioides zones. Owing to the great variability of the parameters (1–40% for the TOC or 2–80 kg HC/t rock for the petroleum potential, for example) these values are distributed in five classes for the carbonates and the hydrogen indices, and six classes for the TOC content and the petroleum potential. This schematic vertical distribution of the main data resulting from Rock–Eval analysis emphasizes the phenomenal qualities of the five major organic-rich belts identified in Dorset, with

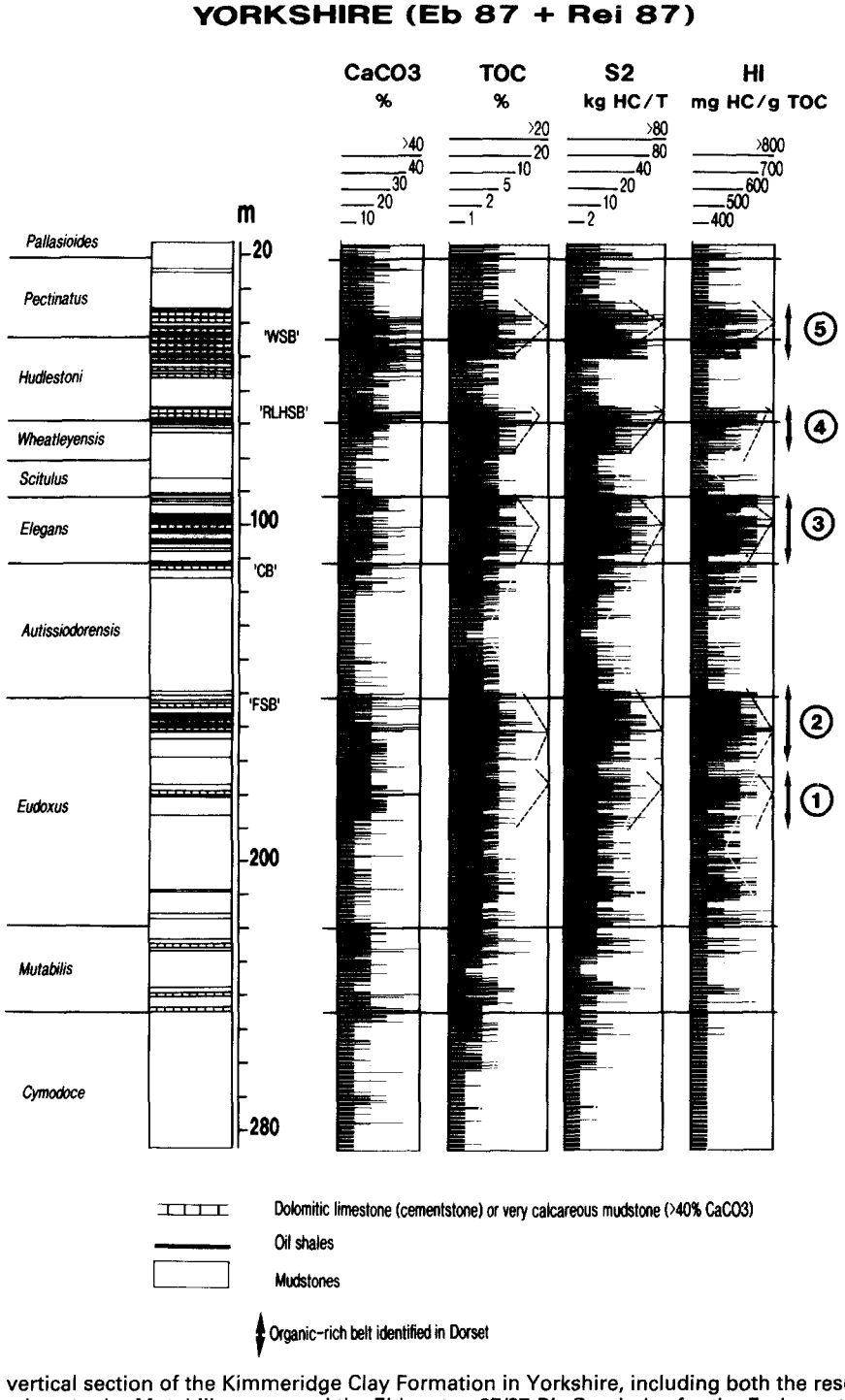

Figure 4 Generalized vertical section of the Kimmeridge Clay Formation in Yorkshire, including both the results from the Reighton 87 Borehole for the Cymodoce to the Mutabilis zones and the Ebberston 87/87 Bis Boreholes for the Eudoxus to Pallasioides zones. The values are distributed in classes due to the great variability of the parameters. They emphasize the qualities of the five major organic-rich belts previously cited in Dorset. The main concentrations of the oil shales with petroleum potential higher than 20 kg HC/t rock are stratigraphically condensed in five distinct organic-rich belts corresponding to (1) the middle part of the Eudoxus Zone, (2) the upper part of the Eudoxus Zone and the lower part of the Autissiodorensis Zone, (3) the Elegans Zone, (4) the upper part of the Wheatleyensis Zone and the basal part of the Hudlestoni Zone and (5) the upper part of the Hudlestoni Zone and the lower part of the Pectinatus Zone

TOC generally fluctuating between 5 and 20% and exceptionally up to 40% at the top of the Eudoxus Zone. Furthermore, the petroleum potential related to these organic-rich belts commonly reaches 80 kg HC/t rock and sometimes even 150–250 kg HC/t rock in the oil shales during the brief period corresponding to the maximum spread of an anoxic environment. In these intervals the organic matter has the highest hydrogen indices, from 600 to 800 mg HC/g TOC. In contrast, depleted strata have a TOC content that fluctuates between 1 and 2%, rarely reaching 5%. The petroleum potential is commonly lower than 10 kg HC/t rock and the hydrogen indices generally less than 400 mg HC/g TOC.

The duration of each of the five long periods that correspond to the organic-rich belts can be estimated at roughly half a million years (*Figure 5*). They themselves include several nested cycles with a secondary periodicity of ca. 280000 years and a third cycle corresponding to an elementary variation of ca. 25000 years (Herbin *et al.*, 1991). These orders of magnitude are based mainly on the stratigraphic scale, the duration of the ammonite zones and the absolute time-scale. They have been calculated from the data (geochemical log and biozonation) obtained in the Cleveland Basin. It is even possible to observe a fourth type of alternation on a millimetre scale, probably related to seasonal fluctuations (fourth-order cycle) (Oschmann, 1991), particularly in the coccolith limestones where the organic-rich laminae alternate with coccolith layers. As noted by Oschmann (1991), burrows are absent in these finely laminated facies, which would have been deposited under an anoxic environment devoid of benthic life. Carbonate beds and organic-rich cycles are often associated. For example, the occurrence of numerous carbonate beds at the bottom and at the top of the Hudlestoni Zone, or at the bottom of the Pectinatus Zone, coincides with the concentration of the petroleum potential (higher than 40 kg HC/t rock) in the fourth and the fifth organic-rich belts (*Figure 4*).

From one locality to another, the thickness of the primary organic-rich cycles is mainly dependent on the average rate of sedimentary accumulation (see, for example, the correlation between the four boreholes in the Cleveland Basin during the Eudoxus Zone; Herbin *et al.*, 1991). These cycles, always expressed in terms of fluctuation of the organic content (% TOC, type of organic matter, petroleum potential), are the consequence of an unstable environment changing with regular frequency. Through Fourier analysis of inorganic geochemical data, Dunn (1974) indicated that several of these superimposed periodicities could be coincident with the duration of astronomical phenomena and consequently be related to climatic fluctuation. House (1986) also argued that the environmental fluctuations responsible for cyclicity within the Kimmeridge Clay could be related to changes in solar radiation and variations in climatic patterns induced by orbital forcing due to the precession of the equinoxes (ca. 21000 year cycle), obliquity of the ecliptic (ca. 40000 year cycle) and eccentricity of the orbit (ca. 96000 year cycle). The hypothesis of climatic fluctuations remains one of the most probable to explain the Kimmeridge Clay cycles because it involves global phenomena spreading over large areas and correlating over long distances with various periodicities. Orbitally forced Milankovitch-type cyclicity may be the main control of this stratification (Waterhouse, 1990). According to Wignall and Rufell (1990) a change from humid style to semiarid style deposition affected the accumulation of the Upper Kimmeridge Clay. Cyclic variations in evaporation and in the influence of meteoric water related to climatic changes have equally been recognized in the uppermost Portlandian to Berriasian of the Prebetic Zone (southern Spain) (Jimenez de Cisneros and Vera, 1993). They confirm and extend the pattern of such repeated phenomena in time and space.

The influence of the variation of sea level is difficult to establish in Dorset and Yorkshire because the observations come mainly from distal environments. Two of the organic-rich belts, the Elegans Zone (third organic-rich belt) and the upper part of the Wheatleyensis/lower part of the Hudlestoni zones (fourth organic-rich belt), would correspond to periods of lower sea level according to the curve of Haq *et al.* (1987) deduced from the study of the facies in the Dorset area. However, there is no clear sedimentological evidence by which individual lithologies could be related to deepening or shallowing. In fact, the sediments deposited in epicontinental seas within epeiric basins remain unchanged during periods of lower sea level at least in the areas unaffected by submarine storm wave erosion (Einsele, 1985). Except for some evidence of distal tempestites which correspond to allochthonous shell pavements of disarticulated bivalves (Aigner, 1980; Oschmann, 1985; 1988; 1991; Wignall, 1989), the sediments deposited in the Cleveland Basin and in Dorset are effectively located in a deep offshore area. They mainly record fluctuations in the oxygen level linked to variations in organic productivity (Tribovillard *et al.*, 1992), which in turn are related to climatic changes (Mann and Myers, 1989). However, a disconformity has been observed in the cores recovered from the boreholes in the Cleveland Basin at the boundary between the Eudoxus and the Autissiodorensis zones. It corresponds to a prominent hard band equivalent to the Flats Stone Band; it has a graded bedding and an erosional base and is interpreted as a distal tempestite sequence (*Figure 6*). This rough surface can be correlated over 30 km from Marton 87 to Reighton 87. It coincides with a shift of about 30° API on the gamma ray log (*Figure 7*). The disconformity suggests that during this period of time the 'wave base razor' (Homewood *et al.*, 1992) began to be effective in the distal environments. The upper part of the Eudoxus Zone must correspond to a lower sea level. However, such changes are rare in Dorset and Yorkshire compared with the lithological changes in Boulonnais.

Organic facies in a proximal area: Boulonnais (northern France)

New information obtained by the ammonite study

Collecting of ammonites, specifically undertaken for this study, assessment of the exact situation of previously reported ammonites (Sauvage and Rigaux, 1872; Loriol and Pellat, 1866; 1874; Pellat, 1880; Rigault, 1891; Leroux, 1929; Pruvost, 1925; Bonte,

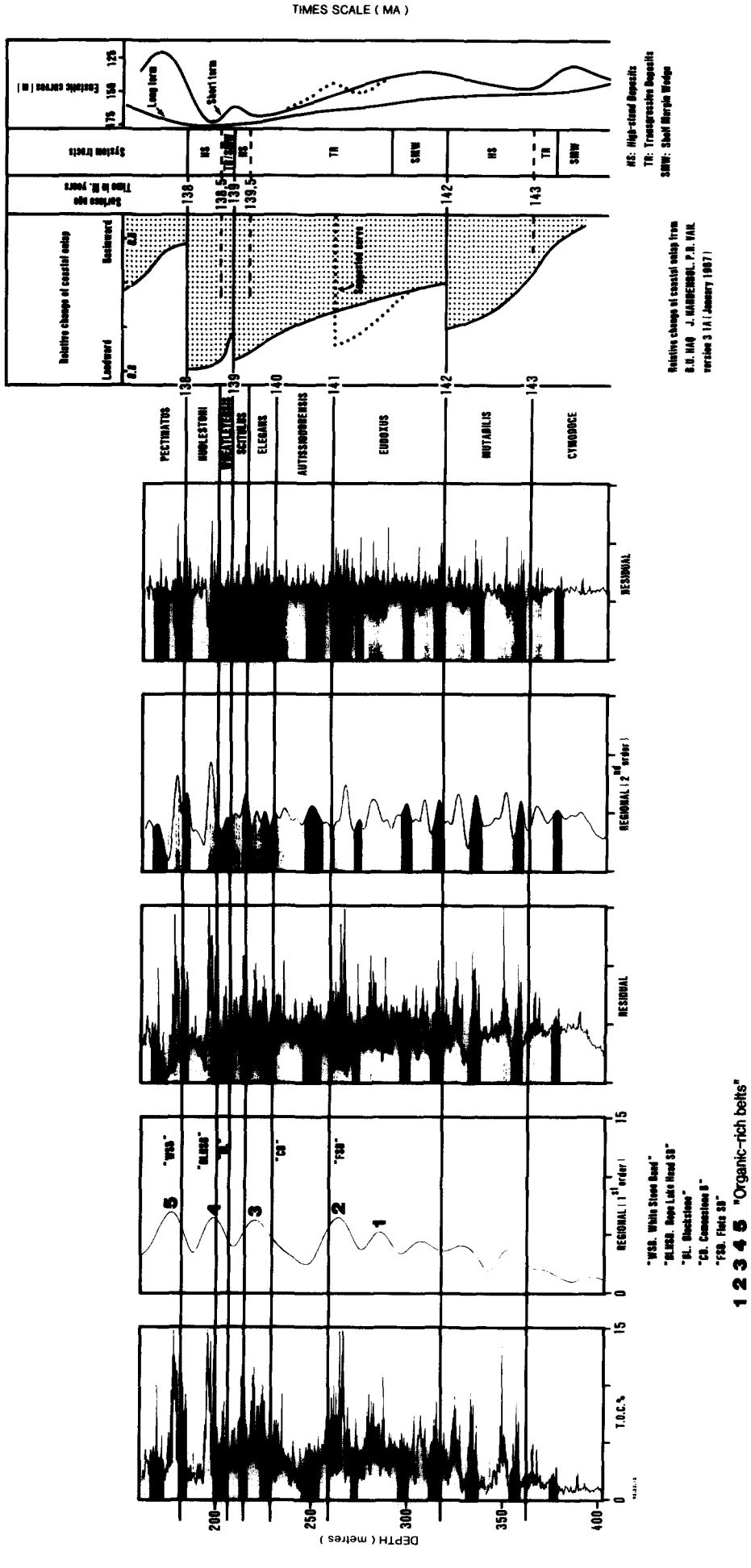

Figure 5 Fourier analysis of the composite log in Yorkshire. The first-order cycles correspond to the organic-rich belts with a periodicity of about half a million years. The second should have a periodicity of a quarter of a million years and the third (the primary organic-rich cycles) a duration of ca. 25000 years, which could fit with the Milankovitch cycles

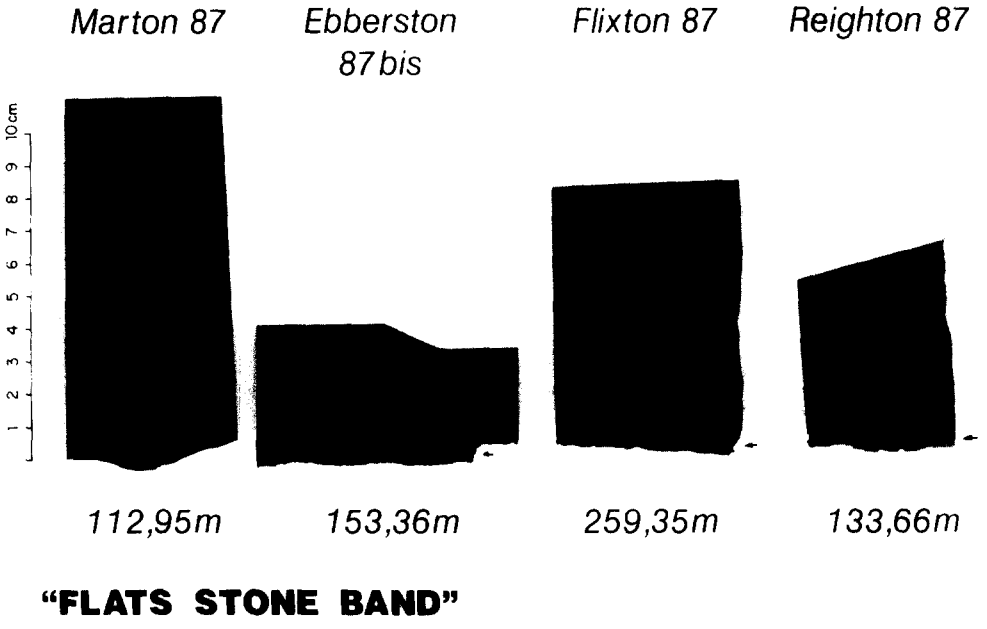

Figure 6 Rough surface at the bottom of the Flats Stone Band with an erosional contact and a graded bedding interpreted as a distal tempestite sequence in the four Yorkshire boreholes

1969; Ziegler, 1962) and recent progress in the understanding of Kimmeridgian and Tithonian biozonation [restatement by the Groupe Français d'Etude du Jurassique, 1991 (pp. 133–134), from works of Cope (1967; 1980), Wimbledon (1980) and Hantzpergue (1989)] leads to new conclusions on the biozonation of the series (Geyssant *et al.*, 1993). The study of other fossil groups (ostracods, foraminifers, bivalves, echinoids) might give information on the palaeoecological and sedimentological conditions of deposition but cannot take the place of ammonites in the biozonation (Kandel, 1969; Barnard and Shipp, 1981; Wignall, 1990a). The best observations on the Kimmeridgian–Tithonian formations in the Boulonnais come from the cliffs, between Equihen (south of Boulogne-sur-Mer) and the Cap Gris Nez, about 20 km apart (*Figure 8*).

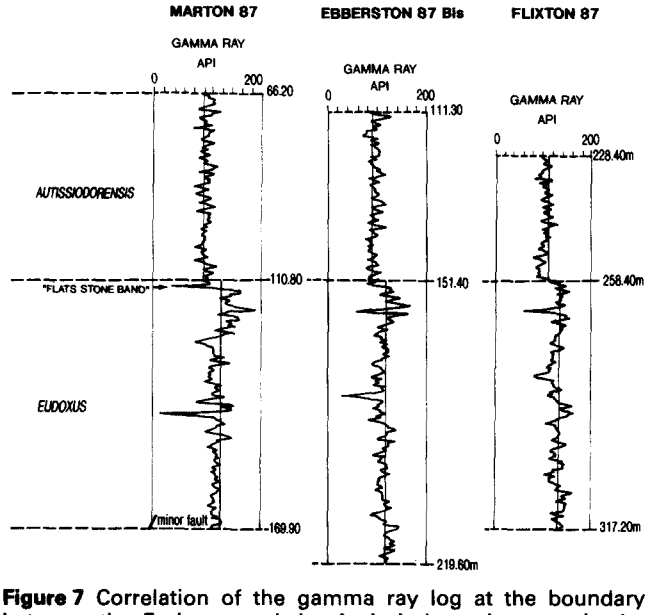

Figure 7 Correlation of the gamma ray log at the boundary between the Eudoxus and the Autissiodorensis zones in the Cleveland Basin (Marton 87, Ebberston 87 Bis, Flixton 87)

Different formations may be identified from the base to the top of the geological section (*Figure 9*).

The Argiles du Moulin Wibert (20 m) consists of black pyritic marls with some micritic or coquina limestone beds. At the base of this formation, the first metre belongs to the Mutabilis Zone (Lallierianum Subzone p.p.) with *Aulacostephanus peregrinus* Ziegler present. The rest of this formation contains ammonites from the Lower Eudoxus Zone (Orthocera Subzone) with *Orthaspidoceras orthocera* (d'Orb.), *Aulacostephanus* cf. *calvescens* Ziegler and *Aulacostephanus eudoxus eudoxus* (d'Orb.).

The Sables et Grès de Connincthun (1–5 m) is a sandstone containing no ammonites.

The Calcaires du Moulin Wibert (14 m) is composed of decimetre-scale limestone beds alternating with black marls. Common *Aspidoceras caletanum* (Opp.) associated with uncommon *Sutneria eumela* (d'Orb.) and *Amoeboceras beaugrandi* (Sauvage) indicate the Caletanum Subzone of the Eudoxus Zone.

The Grès de Châtillon (about 5 m) consists of yellow sands and sandstones with spheroidal weathering. They belong to the top of the Eudoxus Zone (Contejeani Subzone) [*Aulacostephanus yo* (d'Orb.) present].

The Argiles de Châtillon (18–25 m) has been investigated in detail during this study and may be divided into two parts. The lower member (8 m) is composed of more or less massive, black, pyritic mudstones with decimetre-scale biodetrital intercalations. At the base is a disconformity, and above there are 15 cm of mudstone enclosing a rich fauna with frequent *Propectinatites* sp. and rarer *Aulacostephanus autissiodorensis* (Cott.), *Aulacostephanus volgensis* (Vischn.), *Tolvericeras* (*T.*) *murogense* Hantz. and *Aspidoceras catalaunicum* (Loriol). This fauna indicates the Autissiodorensis Zone (Autissiodorensis Subzone). Notable at this level is the predominance of ammonites with a subserpenticone morphology (evolute, slow whorl-growing in height and thickness), corresponding to a fast rise in relative sea level (deduced from facies

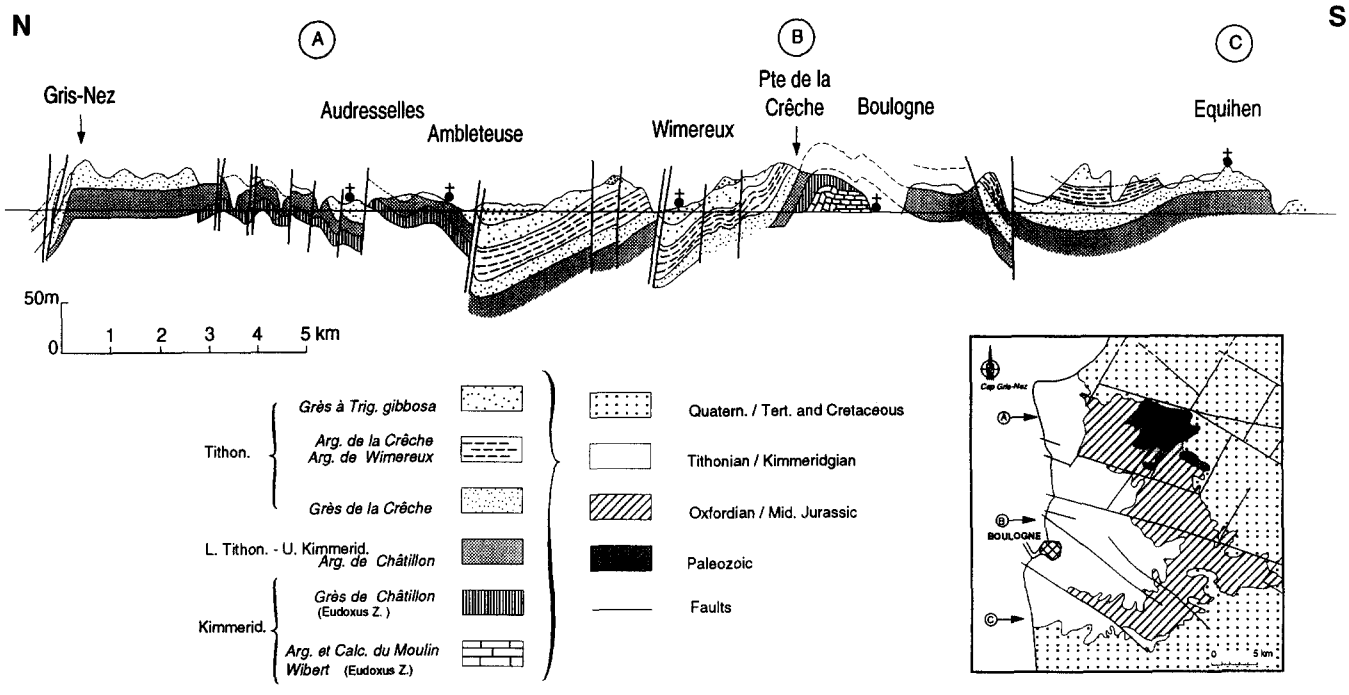

Figure 8 Simplified geological map with the location of the section studied in the Boulonnais: A, Audresselles; B, La Crèche; C, Equihen (Pruvost and Pringle, 1924; modified from Colbeaux, 1990). Cross-section along the cliffs of the Boulonnais with the location of the areas studied. Vertical exaggeration ×20

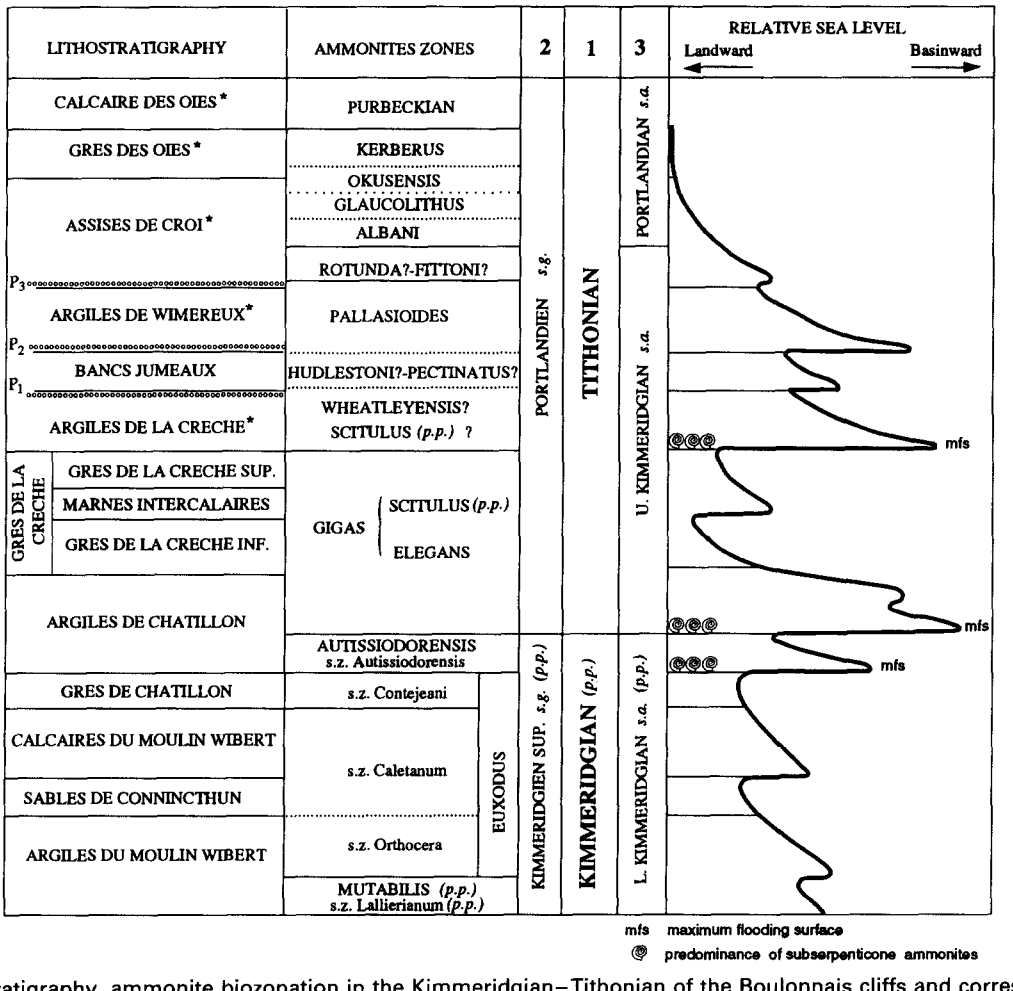

Figure 9 Lithostratigraphy, ammonite biozonation in the Kimmeridgian–Tithonian of the Boulonnais cliffs and correspondence with the variation of the relative sea level. Lithostratigraphy was gradually established in France since 1863 until 1969: ★, new determinations proposed by Ager and Wallace (1966). (**1**) Kimmeridgian–Tithonian as accepted by the International Subcommission on Jurassic Stratigraphy (1990) on a proposal from the Working Group on the Kimmeridgian–Tithonian boundary. (**2**) As a reminder, extension of the Kimmeridgian *sensu gallico* and Portlandian *sensu gallico*. (**3**) As a reminder, extension of the Kimmeridgian *sensu anglico* and Portlandian *sensu anglico*

analysis interpreted in terms of depositional environments) (Proust *et al.*, 1993; Geyssant *et al.*, 1993). Two limestone beds (15–20 cm each) are present in the middle of this member, the lower one with frequent *Aspidoceras catalaunicum* (Loriol) showing a globulous morphology, very different from the subserpenticones present at the base. At the top of this member, a limestone bed (50 cm) contains *Aulacostephanus autissiodorensis* (Cott.), *Gravesia lafauriana* Hantz., *Tolvericeras* (*T.*) n.sp. and *Aspidoceras catalaunicum* (Loriol) (Autissiodorensis Zone, Autissiodorensis Subzone). Ammonites with a globulous morphology, evolute, with thick whorl are present, whereas subserpenticone ammonites are absent. This lower member belongs to the Autissiodorensis Zone (Autissiodorensis Subzone). The upper member (11–15 m) consists of black shales with coquina beds. At its base a disconformity occurs and above there are 15 cm of phosphatic mudstone with frequent *Pectinatites* (*Arkellites*) sp. and *Propectinatites* sp. and rarer, fragmentary *Gravesia* cf. *gigas* (Zieten). Ammonites with subserpenticone morphology are also present in this level corresponding to a fast rise in relative sea level (Proust *et al.*, 1993; Geyssant *et al.*, 1993). In the shales of this upper member *Pectinatites* (*Arkellites*) *bleicheri* (Loriol) (subserpenticone) is present, and *Gravesia gigas* (globulous morphology) is common at the top. The upper member belongs to the Gigas–Elegans Zone, the basal zone of the Tithonian. The upper part of the Autissiodorensis Zone (Irius Subzone) is missing. The Kimmeridgian–Tithonian boundary is located within the Argiles de Châtillon, at the boundary between the two members of this formation, and is represented by a disconformity.

The Grès de la Crèche is composed of several members: Grès de la Crèche inférieurs (10 m) with *Gravesia gigas* (Zieten) and *Pectinatites* (*Arkellites*) *bleicheri* (Loriol); Marnes intercalaires (3–5 m) with *Gravesia* sp.; Grès de la Crèche supérieurs (5 m) with *Gravesia* sp. and *Pectinatites* sp.

The ammonite fauna indicates that Gigas Zone which is the equivalent of the Elegans Zone and the basal part of the Scitulus Zone (Cope, 1967).

The Argiles de la Crèche (8–9 m) contain black shales. Subserpenticone ammonites (*Pectinatites* sp.) are located at their base, still within a level corresponding to a fast rise in relative sea level (Proust *et al.*, 1993; Geyssant *et al.*, 1993).

The Bancs-jumeaux (1 m) include two limestone beds enclosed by two phosphatic horizons P1 and P2. The lower (P1) yielded reworked specimens of *Pectinatites* (*Virgatosphinctoides*) *pringlei* (Pruvost). This species is comparable to *P.* (*V.*) *wheatleyensis* Neaverson group and might indicate the Wheatleyensis Zone, so that the underlying Argiles de la Crèche might also correspond to the Wheatleyensis Zone pars. No ammonites have been found in the upper phosphatic level (P2). The Hudlestoni and Pectinatus zones are not documented and might correspond to the interval between the two phosphatic horizons P1 and P2.

The Argiles de Wimereux (8–9 m) contain grey mudstone with *Pectinatites* (*Pectinatites*) *devillei* (Loriol) and *P.*(*P.*) *boidini* (Loriol) of the Pallasioides Zone.

The Niveau phosphaté de la Tour de Croi (=P3) (some centimetres) also contains many phosphatic fossils, reworked from the underlying levels; among them are *Pectinatites* (*Pectinatites*) *devillei* (Loriol), *P.*(*P.*) *boidini* (Loriol) and *Pavlovia pallasioides* (Neaverson) of the Pallasioides Zone and indigenous specimens of *Pavlovia* sp.

In the Assises de Croi (10 m) and Grès des Oies (12 m), the biozonation was revised by Townson and Wimbledon (1979). They identified the Albani, Glaucolithus, Okusensis and Kerberus zones.

The Calcaire des Oies (2 m) is the last Jurassic level of the geological section and corresponds to the 'Purbeckian' facies of the Tithonian.

Correlations between shell morphology in ammonite populations and fluctuations in relative sea level have been considered in recent years (Hantzpergue, 1991; 1993; El Hariri *et al.*, 1992; Marchand, 1992). In the Kimmeridgian–Tithonian of the Boulonnais, there is a clear relationship between shell morphology in ammonite populations and palaeodepth. In the levels corresponding to a fast rise in relative sea level as deduced from sedimentological evidence and the distribution of organic matter (i.e. at the base of the Autissiodorensis Zone, at the base of the Gigas–Elegans Zone and at the base of the Argiles de la Crèche), ammonites with evolute, subserpenticone shells dominate (*Propectinatites*, *Pectinatites*). They originate from subboreal seas, in the basin axis particularly from Dorset, where they are abundant and diversified. In contrast, in the deposits intercalated between these transgressive levels, palaeodepth decreases and West European Platform ammonites with globulous morphology (*Aspidoceras*, *Gravesia*) replace the former ones. Subboreal species with subserpenticone morphology invade the West European Platform during transgressive phases, but become rarer when palaeodepth becomes unfavourable for them (Geyssant *et al.*, 1993; Geyssant, 1994).

Furthermore, it is possible to suggest some correlations between beds in the Boulonnais and the Dorset stone band markers that correspond to the boundaries between the ammonite zones. For instance, at the Eudoxus–Autissiodorensis boundary the Flats Stone Band, defined in Dorset and identified in Yorkshire as a regressive horizon, with its erosional base and graded bedding (*Figure 6*) might correspond to a period of time when the Grès de Châtillon in the Boulonnais was being deposited.

Distribution of organic matter during Kimmeridgian–Tithonian times

Two main organic-rich intervals exist in the section. The lower interval is in the Argiles de Châtillon, sometimes described as 'bituminous shales', and the upper interval is in the Argiles de la Crèche. The organic matter in the Argiles de Châtillon has been studied through detailed sampling of unweathered outcrop (after deep scraping) taken precisely every 10 cm along a decametre-scale and using a special hand held piston corer driven into the sediments. This light easy to handle tool can be used on a rope ladder and can recover plugs about 7 cm long, giving about 40 g of material. In the other argillaceous formations, samples were also taken to assay the organic content. Three sites have been investigated along the shore: (A)

Audresselles, (B) La Crèche and (C) Equihen (*Figure 8*). Sampling in sites (A) and (C) served to characterize the lateral extension of the organic facies within the Argiles de Châtillon for comparison with the reference site near La Crèche anticline (B).

At the base of the succession, and belonging to the Eudoxus Zone (Argiles du Moulin Wibert and Calcaires du Moulin Wibert), are two transgressive cycles (Proust *et al.*, 1993) separated by the Sables et Grès de Conniincthun. These contain very little organic matter, generally less than 0.5% TOC on average, with a petroleum potential (S_2) lower than 0.5 kg HC/t rock (*Figure 10*). The origin of the organic matter can be deduced from the Rock–Eval analysis (Espitalié *et al.*, 1985/1986). The type II/type III mixture or alteration of type II during sedimentation indicates that the environment was not dysaerobic on the platform during this period. Furthermore, these sediments are very calcareous. The limestones (70–80% $CaCO_3$) have a TOC of less than 0.2%, although the clays or the calcareous clays (<20% $CaCO_3$) can reach 1–1.5% TOC. This regular alternation between more and less calcareous facies indicates changes of the environment over short periods of time, i.e. similar to those observed in organic-rich cycles in more argillaceous facies.

Above the Grès de Châtillon, which marks a regressive phase at the top of the Eudoxus Zone, the deposition of the Argiles de Châtillon represents a major transgression. The organic matter content within this formation varies through the section (*Figure 11*). At the base of the Autissiodorensis Zone, just above the disconformity, the TOC reaches 3–7% (17 $<S_2<46$ kg HC/t rock) with hydrogen indices typical of type II origin (HI up to 600 mg HC/g TOC). However, this thin accumulation (20 cm thickness) abruptly disappears upsection with the TOC content falling to 2% on average, corresponding to petroleum potential of about 5 kg HC/t rock and HI around 300 mg HC/g TOC. The TOC content shows a progressive upward decrease, with less than 1% TOC, $S_2<2$ kg HC/t rock and HI close to 150 mg HC/g TOC. The Argiles de Châtillon belonging to the Autissiodorensis

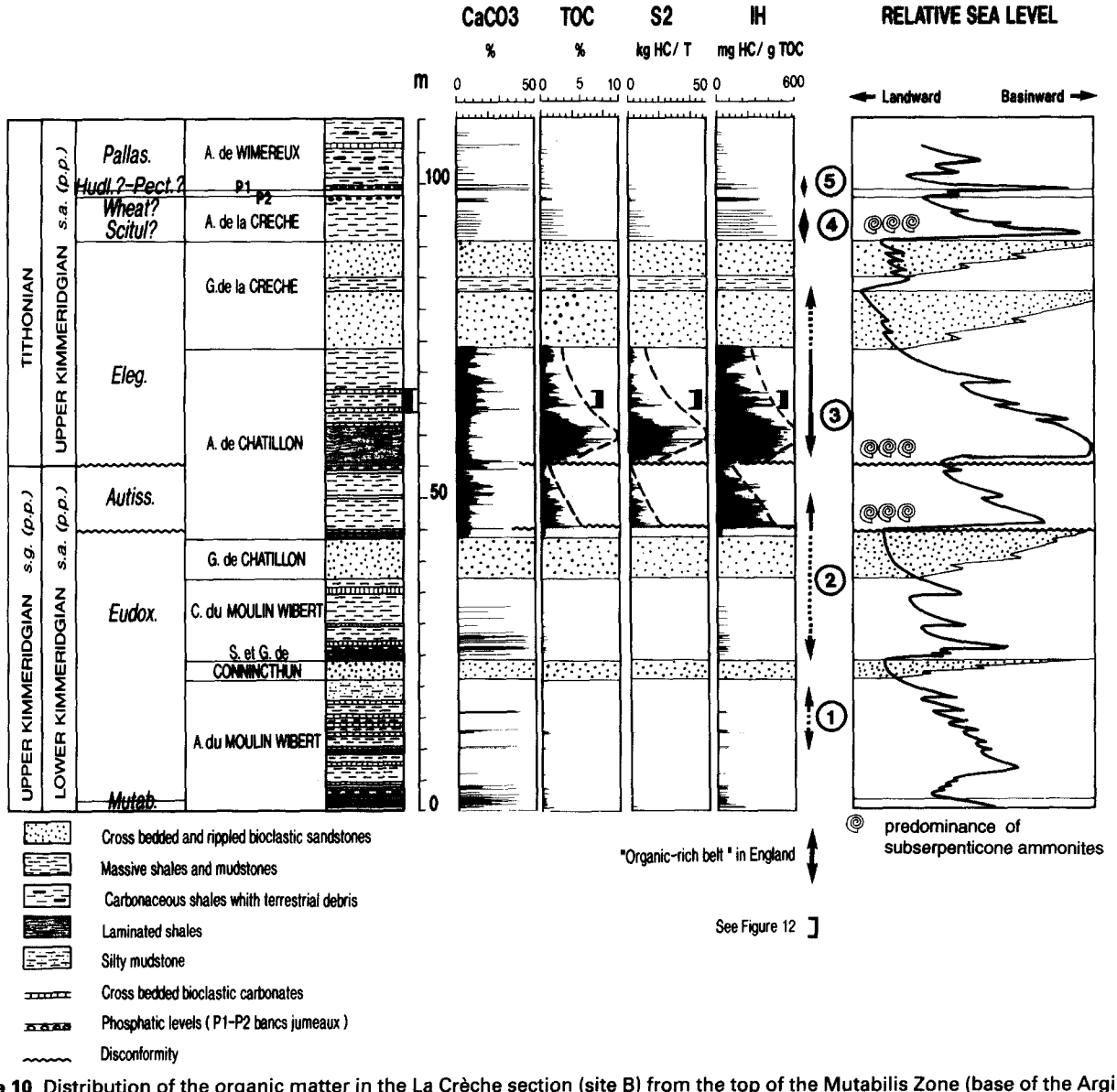

Figure 10 Distribution of the organic matter in the La Crèche section (site B) from the top of the Mutabilis Zone (base of the Argiles du Moulin Wibert) to the Pallasioides Zone (Argiles de Wimereux). A deepening occurs after the deposition of the Grès de Châtillon and corresponds to the Argiles de Châtillon. Correlation with the main regression and transgression deduced from the depositional environments in Proust *et al.* (1993)

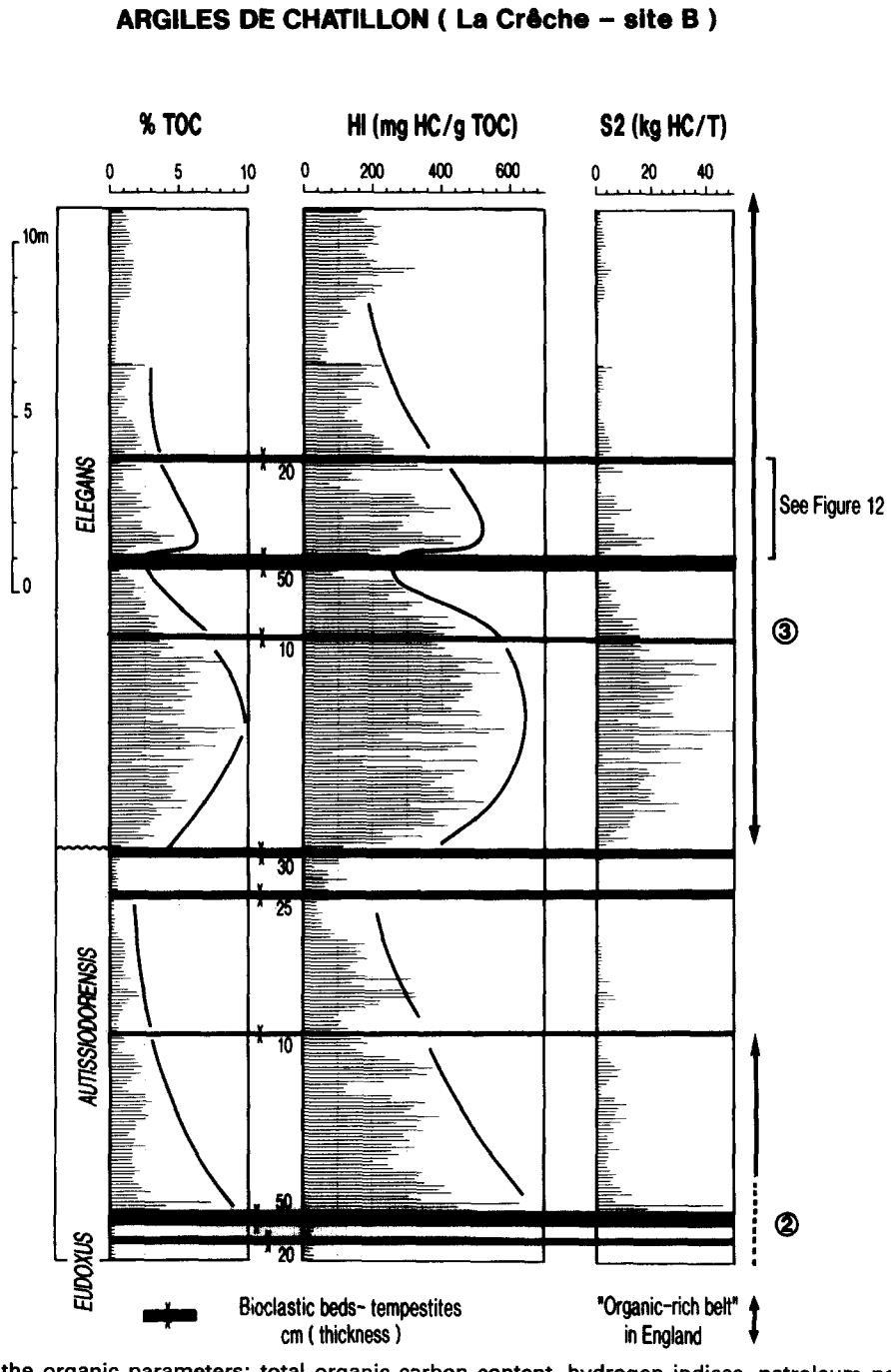

Figure 11 Distribution of the organic parameters: total organic carbon content, hydrogen indices, petroleum potential, within the Argiles de Châtillon (Autissiodorensis and Gigas–Elegans zones). The landmark limestones and distal storm shell beds occur mainly in the trough of the primary organic cycles

Zone whose total thickness is about 10 m are consequently characterized by a general loss in the quantity (TOC, petroleum potential) and the quality of organic matter.

The boundary between the Autissiodorensis and the Gigas–Elegans Zone is coincident with a disconformity corresponding to the top of a distinctive sandy limestone (*Figure 11*). The distribution of organic matter within the Gigas–Elegans Zone shows a Gaussian distribution, with a positive trend up to a maximum enrichment of about 9% TOC, including a group of cycles with numerous fluctuations and several maxima, and then a large negative trend with a minimum toward the base of the Grès de la Crèche. The petroleum potential is high, about 20 kg HC/t rock, reaching more than 50 kg HC/t rock in the richer levels. All the hydrogen indices are typical of a type II origin (400–600 mg HC/g TOC) and confirm the occurrence of a dysaerobic environment. The positive trend at the base of the Gigas–Elegans Zone extends over 5 m, whereas the general decrease spreads over about 10 m, giving an asymmetrical pattern to the general curve. This thick sequence includes secondary fluctuations similar to the nested cycles already observed in the boreholes in the Yorkshire area and in the cliffs in Dorset. The variation of the sedimentary record appears similar in the three areas studied (Dorset, Yorkshire and Boulonnais). However, in the Boulonnais, the occurrence of distal storm shell beds deposited on a nearshore shallow shelf can be used to estimate the oscillation of the sea level curve (Fürsich and Oschmann, 1986; Proust *et al.*, 1993). These shell beds

are characterized by near-monospecific accumulations of the bivalve *Nanogyra virgula*. They reflect different degrees of proximality and can be arranged along an onshore–offshore gradient. The environment of the Argiles de Châtillon generally corresponds to a shallow shelf below the storm wave base, with low general energy conditions, and showing evidence of tidal influences in some beds (Fürsich and Oschmann, 1986). The high energy environments corresponding to the shell beds are characterized by an erosive base and prominent grading. Distal storm beds consist of very thin layers (5 cm), whereas proximal storm beds are commonly thicker (up to 50 cm). Rare and thin distal storm beds occur in the strata with maximum organic matter content. More common and thicker beds generally occur in the parts of the succession containing little organic matter (*Figure 11*), which suggests that the lower organic content beds were deposited during a lower relative sea level. These primary organic-rich cycles are commonly asymmetrical, forming part of a general upward decrease in organic matter along the flank of a higher order cycle (*Figure 12*), which suggests that they are the result of variation with different periodicities (the combination of at least two frequencies).

The distribution of the organic matter within the Argiles de Châtillon is similar at all the three localities examined (*Figure 8*). Using the distinctive limestone beds it is possible to locate the primary organic-rich cycles and to follow them over long distances (*Figure 12*). All the organic geochemical parameters show regular variations: the total organic carbon content, the petroleum potential and the hydrogen indices are strongly affected by the position within the sequence. The primary organic-rich cycles in the La Crèche section (Site B) shows a variation of the petroleum potential from 1 to 20 kg HC/t rock along on a decimetre to metre scale (60–100 cm).

In Audresselles (Site A) and Equihen (Site C) the maximum in organic content, which occurs at the base of the Gigas–Elegans Zone, is thinner and less strongly developed (TOC 6%). This could indicate that the depocentre was near La Crèche, the maximum subsidence correlating with the higher accumulation of organic matter.

Above the Grès de la Crèche, the Argiles de la Crèche contain organic matter of type II origin (400<HI<500) with up to 3% TOC and a petroleum potential reaching 16 kg HC/t rock (*Figure 10*). These contents, which occur mainly at the base of the formation, progressively disappear toward the top, and within the Argiles de Wimereux the organic matter content is generally lower than 1%, except for the occurrence of dispersed terrestrial plant debris, which is of centimetre- and sometimes decimetre-scale size and has up to 60% TOC. The abundance of terrestrial plant debris is indicative of a major regression.

Comparison between the three areas: Dorset, Yorkshire and Boulonnais

The generalized section of the Boulonnais can be

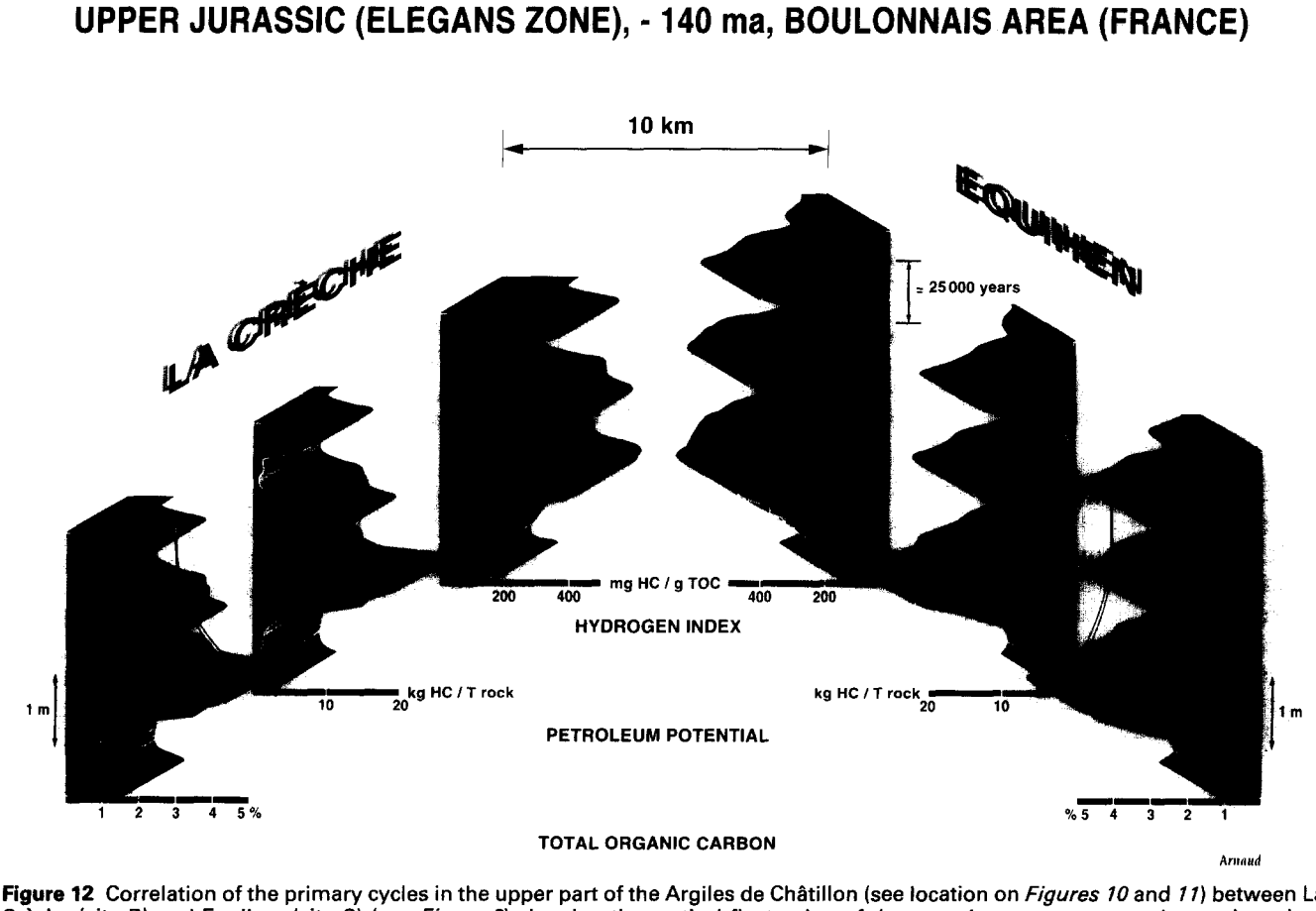

Figure 12 Correlation of the primary cycles in the upper part of the Argiles de Châtillon (see location on *Figures 10* and *11*) between La Crèche (site B) and Equihen (site C) (see *Figure 8*) showing the vertical fluctuation of the organic parameters: total organic carbon content, hydrogen indices and petroleum potential

compared with the information collected in Dorset and Yorkshire (*Figure 13*). In the Boulonnais the Eudoxus Zone is separated into two units corresponding to two major transgressive/regressive cycles (Proust *et al.*, 1993). However, these deposits, which contain numerous bioclastic beds, are not so rich in organic matter as the first and the second organic-rich belts in Dorset or Yorkshire with which they correlate. This is interpreted to be a consequence of the local configuration, which allowed insufficient palaeodepth for the preservation of organic matter on the shelf during this period. About 100 km southward, near Le Havre (*Figure 1*), in a more distal and deeper environment, the content in organic matter of the Eudoxus Zone in the Argiles de Octeville reaches a peak with up to 4% TOC (Baudin, 1992). Thus the preservation of organic matter was certainly widespread, except towards the shelf, where the water was shallow. The regressive facies, which marks the top of the Eudoxus Zone, was previously suggested from the generalized section in Yorkshire, on the basis of tempestite evidence at the base of the Flats Stone Band (Figure 16 in Herbin *et al.*, 1991). The sandstones (Grès de Châtillon) and the disconformity are equivalent phenomena in the Boulonnais. However, this obvious regression does not correspond to the upper boundary of the second organic-rich belt, which occurs at the base of the Autissiodorensis Zone (*Figures 2* and *4*). In the basin, the seaward shift of facies corresponds to a temporary cutoff of organic matter within the upper part of the second organic-rich belt (Figure 17 in Herbin *et al.*, 1991).

On the shelf (Boulonnais) the basal part of the Argiles de Châtillon, including the first sediments belonging to the Autissiodorensis Zone, is characterized by a slight accumulation in organic matter. Similar enrichments occur during the same stratigraphic interval, at the base of the Autissiodorensis Zone, in Dorset and Yorkshire. They have been recorded by R. W. Gallois from numerous boreholes in southern England (Portesham, Tisbury, West Lavington, Foudry Bridge) and north of the London Platform (North Runcton, Donington on Bain) (*Figure 1*). They correspond to the top of the second organic-rich belt, which occurs from the upper part of the Eudoxus Zone to the lower part of the Autissiodorensis Zone (*Figures 2* and *4*). As a result of the overall deepening evident from the base of the Autissiodorensis Zone, the shelf became more favourable to the deposition of claystones. This transgression allowed the organic signal previously existing in the basin from the upper part of the Eudoxus Zone to be expressed briefly in the Boulonnais. Owing to the transgression, during a brief period of time, the Boulonnais was thus subjected to the same dysaerobic environment as was present in Dorset and Yorkshire. However, these last references to the second organic-rich belt soon disappeared, and the major part of the Autissiodorensis Zone then underwent a regular decrease in the TOC content, both in the distal (Dorset and Yorkshire) and in the proximal (Boulonnais) areas. So, except for this very thin enrichment, which marks the end of the second organic-rich belt, the Autissiodorensis Zone represents a depleted organic period corresponding to the interval of time between the second and the third organic-rich belts, and is characterized by a low TOC whatever the area, on the shelf as well as in the basin (trough in the TOC distribution; *Figures 2*, *4* and *5*).

Consequently, there is a paradox: although the transgression was much greater during the Autissiodorensis Zone than during the Eudoxus Zone, with deposition of claystones on the shelf area, the preservation of organic matter was less effective during the Autissiodorensis Zone, irrespective of the palaeodepth. This suggests that the transgression may not have been the main factor producing *in fine* the major accumulation of autochthonous organic matter.

The upper part of the Autissiodorensis Zone in the Boulonnais corresponds to a disconformity, with ammonites concentrated into a kind of hardground. A similar disconformity has also been identified near the London–Brabant Massif in the Swindon Borehole (Gallois, 1979). In the Boulonnais, above this disconformity, in the Gigas–Elegans Zone, the sea level was still high, with deposition of microlaminated organic shales corresponding to a deep ramp floor. This coincides with great accumulations of organic matter of type II origin, which progressively increase in quantity

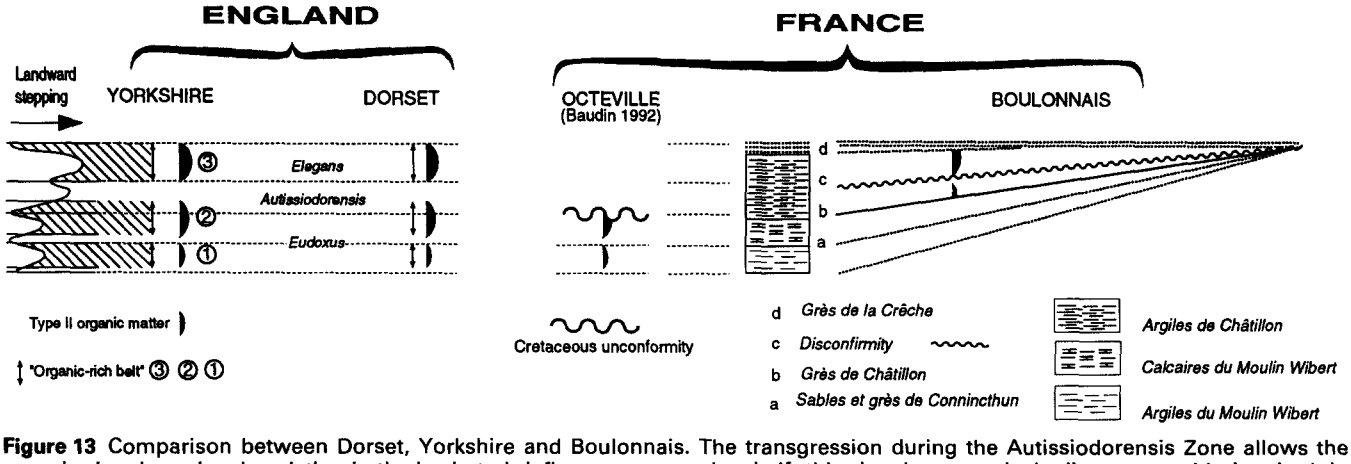

Figure 13 Comparison between Dorset, Yorkshire and Boulonnais. The transgression during the Autissiodorensis Zone allows the organic signal previously existing in the basin to briefly reappear on the shelf; this signal progressively disappears with time both in the distal and in the proximal areas. Although the transgression was greater during the Autissiodorensis Zone than the Eudoxus Zone, the preservation of organic matter was less effective whatever the area may be, even in the basin, which means that the phenomenon of the generalized transgression might consequently not have been the main parameter producing *in fine* the major accumulation of autochthonous organic matter

and in quality, reach a maximum and then regularly decrease. This period of sedimentation in the Boulonnais is equivalent to the third organic-rich belt in Dorset and Yorkshire. The groups of cycles and the primary organic-rich cyclicity illustrated by the geochemical parameters (%TOC, petroleum potential, hydrogen indices) within the organic-rich periods could have resulted from minor eustatic variations in phase with oscillations of climatic change, which would explain the occurrence of storm shell beds right at the base of the organic cycles. The duration of these primary organic-rich cycles is roughly estimated at ca. 25000 years, by comparison with the similar cycles studied in Yorkshire.

The precise dating given by the ammonite zonation reveals that there is no simple relation or synchronism between the transgressive periods and the presence of marine organic matter, or between the regressive periods and the disappearance of marine organic matter. At the top of the Gigas–Elegans Zone the accumulation of type II organic matter still extends in the distal areas (Dorset, Yorkshire), whereas the deposition of sandstones devoid of organic matter within the Grès de la Crèche corresponds to a major regression. As noted by Creaney and Passey (1993), source rock accumulation persists longer in the distal environments than in shelfward time-equivalent rocks.

Above the Grès de la Crèche, stratigraphic interpretation is complicated because the succession is condensed. The Argiles de la Crèche, which contain up to 4% organic matter of type II origin (HI between 400 and 500 mg HC/g TOC) are included in a new transgressive sequence. They correspond to the fourth organic-rich belt. The Hudlestoni–Pectinatus zones, reduced to a very condensed section with two phosphatic levels, can be correlated with the fifth organic-rich belt. This is also interpreted as a transgressive period, expressed here by phosphatic nodules. At the top of the succession in the Boulonnais, the Pallasioides Zone is devoid of organic matter and similar to the Dorset or Yorkshire section. It marks the end of organic sedimentation and the beginning of a major regressive trend, which culminated with the Purbeckian facies.

Conclusions

A comparison of the organic sequences in the three areas studied shows good correlation between the distal areas (Dorset, Yorkshire) and the proximal area (Boulonnais). Whatever the area considered, the distribution of organic matter follows similar rules, with regular fluctuations of the TOC contents and maximum accumulation, related to transgressions. However, every major transgression does not correspond to an organic enrichment.

During the two transgressions within the Eudoxus Zone, organic matter was fully preserved (first and second organic-rich belts) in the depocentre of the Cleveland Basin (Marton 87) and in the Dorset area (Kimmeridge Bay), half preserved on the East England Platform (the TOC content and the thickness of the primary organic-rich cycles is half in Reighton 87, Herbin *et al.*, 1991; 1993) and absent in the proximal facies of the Boulonnais, which was well oxygenated at this time. The regressive phase at the top of this ammonite zone temporarily interrupts the enrichment in organic matter. Renewed extension of the area of organic matter preservation occurred at the base of the Autissiodorensis Zone, i.e. at the beginning of the following major transgressive phase (Dorset, Yorkshire, Boulonnais). In none of these areas was preservation of organic matter sustained, although the transgression was greater than the earlier ones. This suggests that the transgression was not sufficient by itself to produce or to preserve organic accumulation if the external conditions (for example, the climatic changes promoting organic productivity) were not favourable. In contrast, during the Gigas–Elegans Zone, which also corresponds to a transgressive phase, the conditions were optimal and led to maximum enrichment, and at the top of this ammonite zone a regressive phase produced a disappearance of the organic matter in the nearshore facies, but not in the distal area.

The deposition of the source rocks within epeiric basins during a period of major transgressions such as the Kimmeridgian was mainly due to the physiographic framework and was linked to a specific palaeogeography (Cope *et al.*, 1992). A typical landscape consisted of a large aquatic area with shallow water (only a few hundred metres deep), and rare emerged areas with mainly low relief diversified by channels with estuarine environments. There were no large-scale erosive processes or coarse detrital inputs in the distal areas, which were dominated by the deposition of clay minerals, some of which are of diagenetic origin (see Mélières in Herbin *et al.*, 1991). As these conditions existed for a few million years and governed the balance of exchange within the silled basin (particularly the renewal of dissolved oxygen), the main fluctuations of organic matter recorded in the sediments illustrate changes brought about by external and ubiquitous phenomena such as the climate which, through alternating periods, governed the productivity of aquatic biomass and its preservation.

A transgression is certainly not sufficient by itself to produce an accumulation of organic matter, but the occurrence of source rocks (type II) is the result of positive interactions between three main parameters: (1) physiography (concerning the shape of the basin and the volume of sediments available); (2) transgression (influencing the size of the area producing the organic material and the water depths); (3) climate (governing the quality of the organic matter and the variation of primary productivity). The rate of accumulation of organic matter increases when all three parameters are in conjunction, but ceases when any one of them is unfavourable. The thickness and areal spread of valuable storage volumes of organic carbon depend on the continuity of such a conjunction. This explains why less organic matter accumulated during the Autissiodorensis Zone than during the Elegans Zone, although both sequences are transgressive. Prediction of the occurrence of source rocks in quality and quantity requires knowledge of each of these interdependent parameters.

Transgressions commonly generate silled basins which are favourable for the preservation of the organic matter. However, other things being equal, climate is

the most important parameter that influences the amount of organic matter produced and preserved. This is illustrated by the scale of variation of the organic parameters within the nested cycles [petroleum potential (S_2) varies by a factor of 10 within a few decimetres in the primary organic-rich cycles].

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