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# Westphalian B marine bands and their subsurface recognition using gamma-ray spectrometry

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**SUMMARY:** Palaeogeographic reconstructions, marine band deposition and the variations of uranium enrichment in sediments enable marine bands to be divided into four types: (1) Namurian marine bands, which represent marine anoxic black shale events, with thick ammonoid acme phases that concentrate uranium; (2) Vanderbeckei marine bands have thin ammonoid acme zones and abundant benthos, resulting from shallower water depths and poorly developed anoxic events with negligible uranium enrichment; (3) Westphalian B/C marine bands are more marginal and have an abundance of land-derived plant fragments with adsorbed uranium, as well as uranium entrapped within phosphatic tests of *Lingula*; (4) brackish water *Lingula* beds with abundant terrigenous matter and negligible uranium response. This classification scheme provides a means of predicting the uranium response of individual marine bands which is attributed primarily to the type and amount of organic matter, and the salinity of the waters responsible for deposition. This approach allows marine bands to be recognized and identified in the subsurface from their gamma ray and spectral gamma response, and together with palynological analysis allows the marine band to be placed more accurately within the regional stratigraphic framework.

The predominantly clastic, non-marine Silesian sediments of north-west Europe were deposited in upper delta plain/coastal alluvial plain environments (Guion & Fielding 1988; Leeder 1988; Besley 1990; Leeder & Hardman 1990). Lateral facies variations within these environments, and vertical stacking of facies, primarily in response to basin subsidence, make lithostratigraphical correlation difficult and unreliable. Although palynological analysis provides a crude biostratigraphic zonation for the Westphalian A–C, recent hydrocarbon exploration interest in the Upper Carboniferous of the southern North Sea requires a higher definition zonal stratigraphy in order to constrain reservoir successions more accurately. However, the Westphalian succession contains up to 19 thin, marine mudstone bands possessing distinctive marine faunas (Calver 1968*a*). These bands are geographically widespread and represent short-lived, regional, marine flooding events when glacially-driven eustatic rises in sea level drowned the low-relief Westphalian upper delta plain/coastal alluvial plain environments (Leeder 1988; Leeder & Hardman 1990). Consequently, marine bands are used as the basis for subdivision and regional correlation of the Westphalian succession, and because of their widespread geographical distribution, short duration, unique faunal character and regular occurrence throughout the succession, they are universally accepted as regional chronostratigraphic markers or time lines (Ramsbottom *et al.* 1978; Besley 1990).

Although recognition of marine bands onshore is relatively easy, offshore it becomes more difficult because the extensive coring or accurate side wall coring necessary to provide biostratigraphically useful fossils is not normally done. Since coring has been used mainly for analysis of hydrocarbon sandstone reservoirs, there is a paucity of mudstone core samples for extraction of ammonoids (goniatites), so that alternative methods of precise marine band identification are necessary. Sometimes the associated marine and brackish water faunas, which tend to be more common, can be used to separate marine bands or simply identify the presence of marine bands. The correct identification of the presence of marine bands may have sequence stratigraphic implications, in that it identifies maximum flooding surfaces and initial flooding surfaces allowing for analysis of systems tracts.

## 1. MARINE BAND IDENTIFICATION

In the Upper Carboniferous, certain marine bands from stratigraphical sections in Yorkshire and Derbyshire have higher radioactivity than associated non-marine sediments (Knowles 1964). Consequently, identification of marine bands in the subsurface using the standard gamma log became a widely used technique in many onshore boreholes, especially in the central Pennines. Marine band identification was based on its abnormally high total gamma response, and its presence has been used to solve correlation problems (Howitt & Brunstrom 1966; Downing & Howitt 1969; Whittaker *et al.* 1985).

Reliance on the total gamma log is not sufficient to confidently identify marine bands in Carboniferous successions, because of the inability of the standard gamma log to differentiate other sources of high radiation such as feldspar, mica-rich non-marine shales, tuffs, tonsteins, zones of mineralization and concentrations of feldspar and heavy minerals in sandstones. A higher than background total gamma signature may be caused by an abundance of any of these radioactive materials. This can lead to miscorrelation of a uranium peak in one well with a potassium peak in another. When the variations in downhole conditions, and the distance removed from stratigraphically well-constrained onshore wells are also taken into account, it is clear that confident identification of marine bands in offshore successions cannot be realistically achieved from total gamma values alone.

### 1.1. Uranium enrichment in marine bands

Adams & Weaver (1958) showed that uranium and thorium concentrations are good indicators of depositional environment. They noted that marine black shales contain higher levels of U than continental shales because the latter were deposited in oxidizing environments where U forms highly soluble and mobile uranyl ions and/or complexes, whereas Th is effectively insoluble in water and behaves as a detrital mineral. Thus, in continental environments U is more readily leached from the sediment than Th. In contrast to this, in marine anoxic environments U is actively removed from solution; a solution in which U is 5000 times more concentrated than Th. Thus, marine anoxic sediments concentrate more U than their continental counterparts due to large amounts of U thought to be concentrated in phosphatic, carbonaceous or bituminous fractions (Ponsford 1955; Knowles 1964; Spears 1964). Certainly, organic matter appears to play an important role in extracting U from solution in anoxic environments (Kochenov *et al.* 1977) and it can be fixed in sediment by oxidising and reducing reactions following sorption of U ions by humic acids (Borovec *et al.* 1979). These reactions are produced by decay of organic matter, (with U adsorbed on to the surface of plant fragments), by substitution of ions in clay and phosphatic minerals, and precipitation in the presence of hydrogen sulphide.

Archard & Trice (1990) were able to recognize the Westphalian/Namurian boundary marine band, Gastrioceras subcrenatum, and the Namurian marine bands, Gastrioceras cumbriense and Gastrioceras cancellatum, from type sections in Yorkshire by their U anomalies, using a hand-held spectrometer (Fig. 1). Similar results were obtained from Namurian outcrops by Leeder *et al.* (1990) who also utilized downhole natural gamma spectrometry logs (NGS) from a subsurface Namurian to Westphalian A section in the southern North Sea to isolate zones of high U within the wellbore, as an indicator of possible marine bands in the succession. However, Leeder *et al.* (1990) emphasize that caution must be exercised in extending correlation to areas remote from the cored boreholes or outcrops where there is a lack of biostratigraphical control. Whittaker *et al.* (1985), for example, state that the Gastrioceras listeri Marine Band in the East Midlands and central Pennines is usually highly radioactive, but in other areas and recently drilled wells within parts of the southern North Sea it cannot be distinguished on gamma ray logs. This

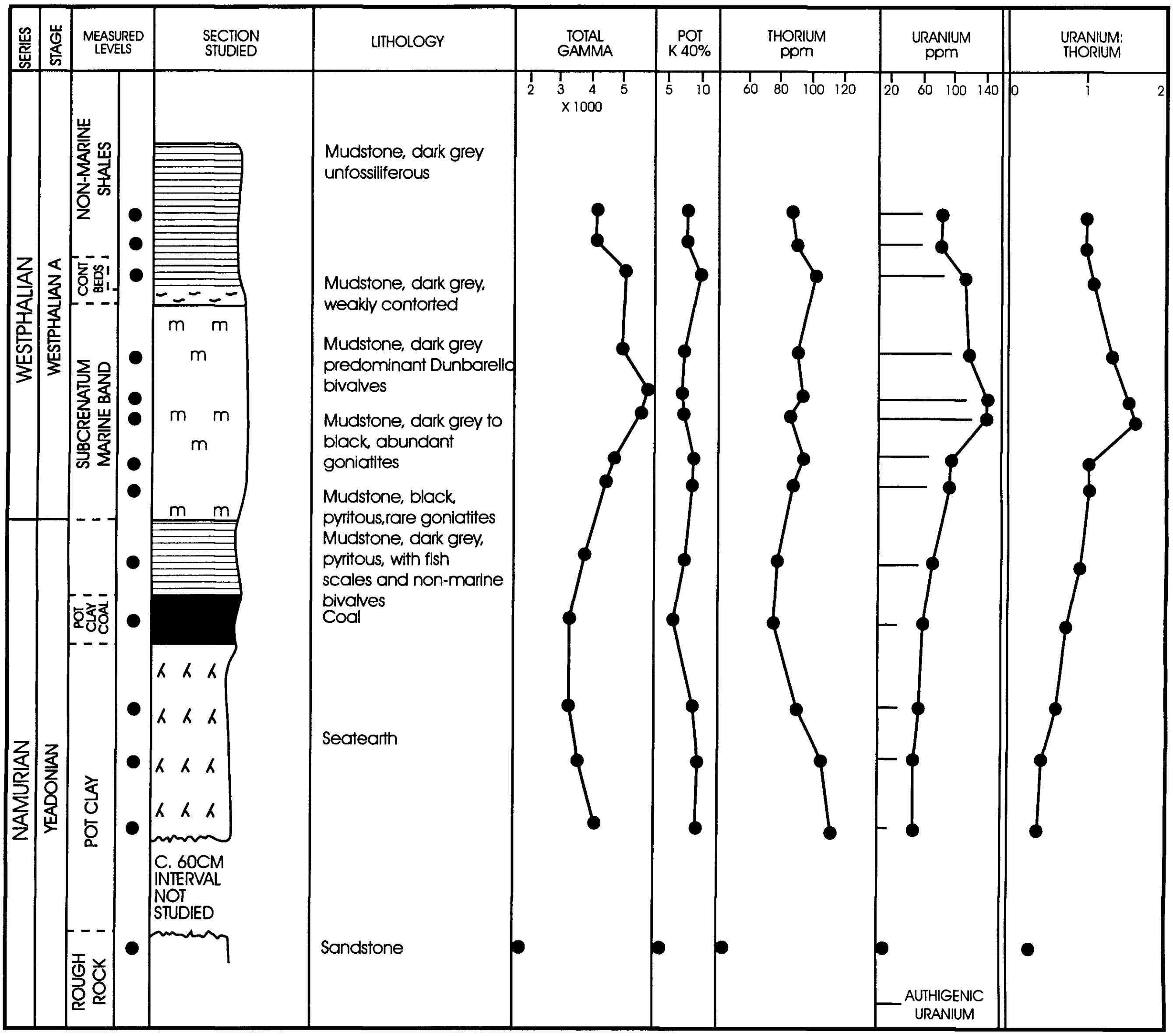


**Fig. 1** Spectral gamma response of the Subcrenatum Marine Band measured in the field by hand-held spectrometer (after Archard & Trice 1990). The total thickness of the section illustrated is about 6 m.

is a major problem in the southern North Sea where well spacing is relatively poor.

Leeder *et al.* (1990) note that significant authigenic U content usually occurs only where black, fissile, pyritous shaly mudrocks are present. These contain the acme fauna of the marine band, dominated by pelagic groups such as ammonoids, but with no benthic fauna (Calver 1968*a*), because of presumed anoxic conditions. They also suggest that increased levels of radioactivity, caused by concentrations of authigenic U, may be related to a slow rate of sedimentation in anoxic bottom waters and the fixation of U by organic tissues (reviewed by Bell 1978). Thus, there is a strong positive correlation between U and the presence of phosphatic and carbonaceous materials (De Voto 1978; Knowles 1964). In the light of the cited faunal evidence, and recent advances in understanding the genesis of black shales in other parts of the geological record (Myers & Wignall 1987), it was considered unlikely by Leeder *et al.* (1990) that the greatly enhanced U contents were mostly authigenic and that they are more directly related to the slow deposition of organic-rich anoxic marine mudrocks. Accordingly, the development of such uraniferous black shales will be related to local or to regional bathymetric conditions during Silesian marine transgressions. Such evidence was reviewed in Maynard *et al.* (1991) and Wignall & Maynard (1993) who noted that U concentration was dependant on sub-regional bathymetric variations. The absence of anoxic bottom waters will lead to normal (oxygenated) marine mudrocks with a benthic fauna and without U enrichment. Thus, no gamma log anomaly is expected from such marine horizons and hence the U content of marine shales should vary widely.

The regional development of ammonoid-bearing black shale facies in the most widespread onshore Silesian marine bands has been shown by Calver (1968*b*) to be closely related to regional patterns of subsidence, as derived from isopach maps of strata between marine bands. Wignall & Maynard (1993) also noted that U ppm contours follow isopachs. The isopachs describe a 'bull's eye' pattern around the major depocentres in Lancashire and Yorkshire, and a similar situation is believed to have occurred in the southern North Sea where a major depocentre occurs in block 44/26 and to the south (Fig. 2) (O'Mara 1995). This important correlation clearly establishes that anoxia develops most readily in the deepest parts of the basin, after the acme of the marine transgression in an area where Silesian subsidence was at a maximum. The failure of anoxic conditions to develop may be caused by local or regional slow relative water depth increase, probably reflecting proximity to areas of high sediment influx and hence contemporary palaeogeography. This latter point will include the important, but unknown controlling parameter, the slope of the coastal alluvial plain. During marine transgressions the water will shallow progressively as it extends into the more proximal, upslope areas of the alluvial plain, thereby inhibiting the development of anoxia, even when subsidence is still high (Leeder 1988). Evidence of this shallowing northwards is: (1) the presence of a marine fauna in the Vanderbeckei Marine Band in Durham but only a *Lingula* fauna in Northumberland; (2) the presence of Westphalian B marine bands in Durham passing into marginal *Lingula* bands in Northumberland; and (3) cyclothem thickness decreases northwards whereas coal thickness generally increases due to decreasing subsidence, indicating a NNE–SSW palaeoslope.

It should be stressed that previous work on marine bands was mainly concerned with those of Namurian and early Westphalian A age which differ from their Westphalian B counterparts. The former were fully developed marine bands in a lower delta plain setting which had prominent pelagic phases developed with a high organic content, and hence uranium enrichments, far in excess of background levels (Maynard *et al.* 1991; Wignall & Maynard 1993). Furthermore, Namurian delta plain topographic variation was probably greater than that during Westphalian B times when the coastal alluvial plain had a low relief in response to slower, more consistent subsidence (Leeder 1988). As a result Namurian palaeobathymetric variation is more noticeable and uranium concentrations are likely to have been more variable.

Analyses of natural gamma ray spectrometry (NGS) logs from Quadrant 44 wells in the southern North Sea show that palynologically constrained Westphalian B and C marine bands have high U signatures (Fig. 3). A notable exception is the Vanderbeckei Marine Band which, as Figure 4 shows, has negligible U enrichment. Nevertheless, it is easily identifiable, because of its distinctive marine fauna and proximity to the overlying Caister Sandstone (Ritchie & Pratsides 1993) which forms the reservoir in the Murdoch gas field. If one follows the arguments presented above for the Namurian marine bands, then all the Westphalian B marine bands should not be significantly enriched in U, as they do not contain abundant, thick, black, pyritous mudstones with an extensive pelagic fauna; conditions essential for significant U enrichment. (according to the Leeder *et al.* 1990; Maynard *et al.* 1991; Wignall & Maynard 1993 model). Regional palaeogeographic reconstructions show the Westphalian B sediments to have been deposited on a low relief coastal alluvial plain (Guion & Fielding 1988). Thus, Westphalian B transgressive marine bands would be deposited under shallower water depths than comparable Namurian and early Westphalian A marine bands, as reflected in the

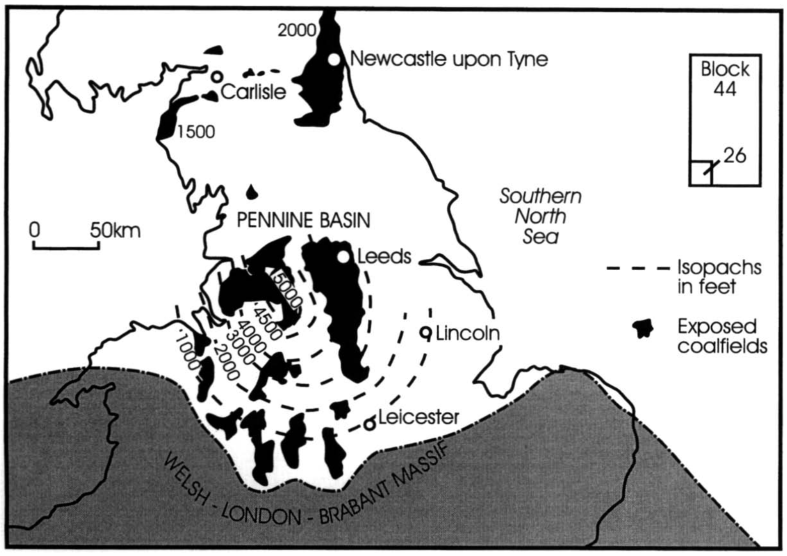


**Fig. 2** Depocentres in the southern part of the Pennine Basin (After Calver 1968*b*), and the southern part of the North Sea south of Quadrant 44/26 for Lower and Middle Coal Measures.

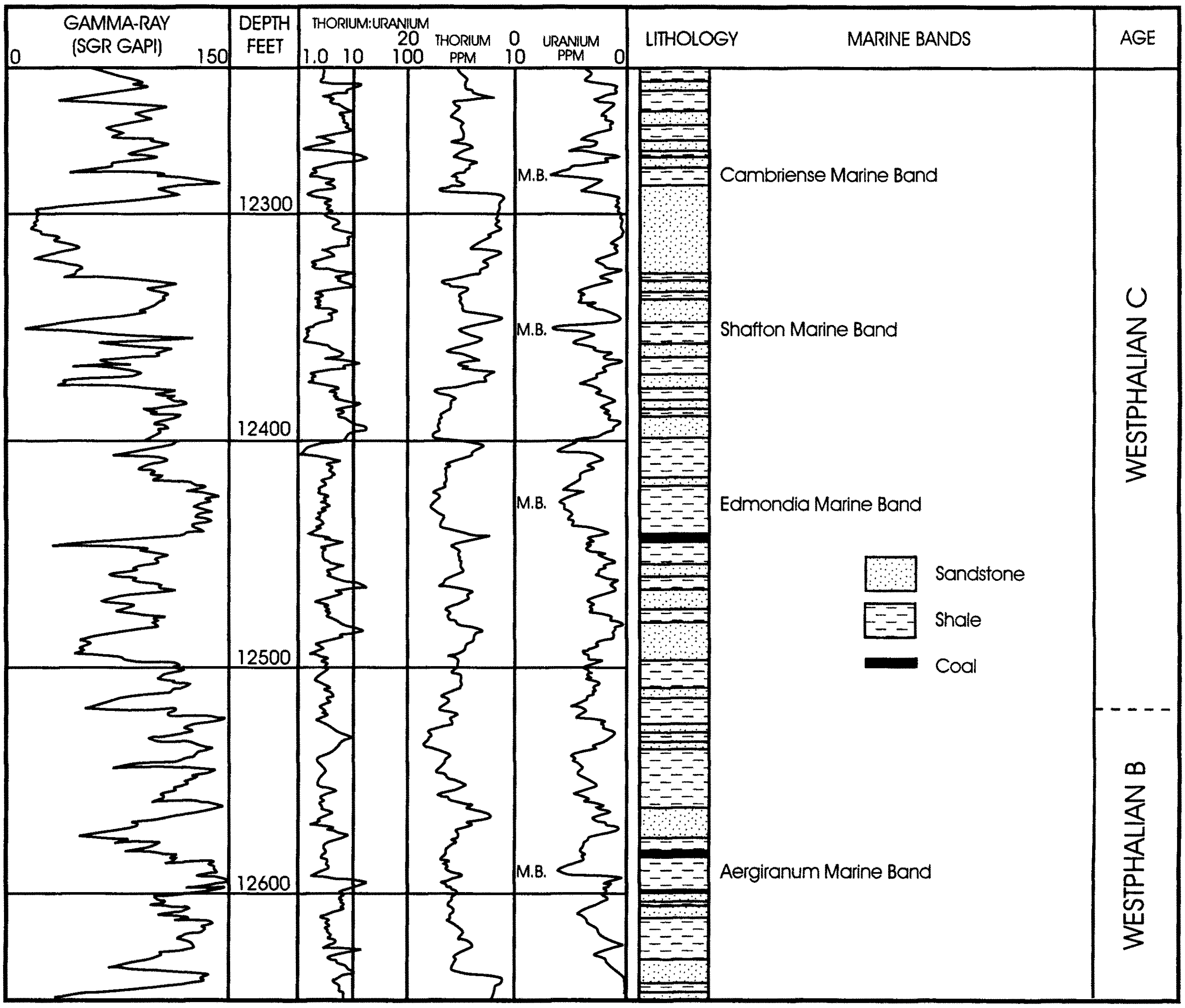


**Fig. 3** Natural gamma ray spectrometry logs from Quadrant 44 in the southern North Sea showing high U signatures of palynologically well constrained Westphalian B and C marine bands.

dominance of benthic faunal phases and the rare development of ammonoid-bearing mudstones. Westphalian B marine bands are commonly indicated by acmes in productid, pectenid and *Myalina* phases with rare lingulid phases (Calver 1968*a*). In addition, palaeocurrent studies indicate flow to the south in Westphalian B times (Guion & Fielding 1988); the occurrence of channel sandstones decreases southwards, whilst that of lacustrine crevasse-splay fed deltas increases; and coal cyclothems are dominated by more muddy sediments in Yorkshire, whereas they are more sandy in Northumberland. The foregoing evidence indicates that the Westphalian B depositional site was more proximal to sediment supply (Fielding 1984; Guion & Fielding 1988), the transgression reaching its limit in Northumberland. Thus it probably spent less time at maximum water depths most conducive to the development of anoxic conditions, as the transgression would withdraw from this area first. Intuitively then one might expect reduced U contents (Leeder *et al.* 1990), whereas the opposite appears to be the case (O'Mara 1995). These U-enriched Westphalian B marine bands could be attributed to significant changes in eustatic water level producing anoxic black shales of Namurian type. By implication these may have formed under conditions of high water depths, high levels of anoxia, slow rates of sedimentation and abundant marine organic matter. Such conditions should produce short-lived, highly uraniferous horizons, a situation refuted by the palaeontological evidence (Calver 1968*a*; O'Mara 1995). Alternatively, there may have been other controls on Westphalian B marine band U enrichment, as discussed below.

## 1.2. Controls on uranium enrichment

The most favourable conditions for U enrichment (De Voto 1978) are: (1) slow rates of marine or lacustrine sedimentation; (2) abundant preserved land plant debris; (3) strongly reducing environments; (4) paucity of terrigenous, non-organic sediment; (5) non-tectonic intracratonic shallow basin, with restricted circulation and low latitude (humid climate); and (6) availability of phosphate. Although the Namurian marine bands satisfy many of the above criteria, especially (1), (3) and (4), the Westphalian B and C marine bands are different in character. Thus, they must satisfy either different criteria than

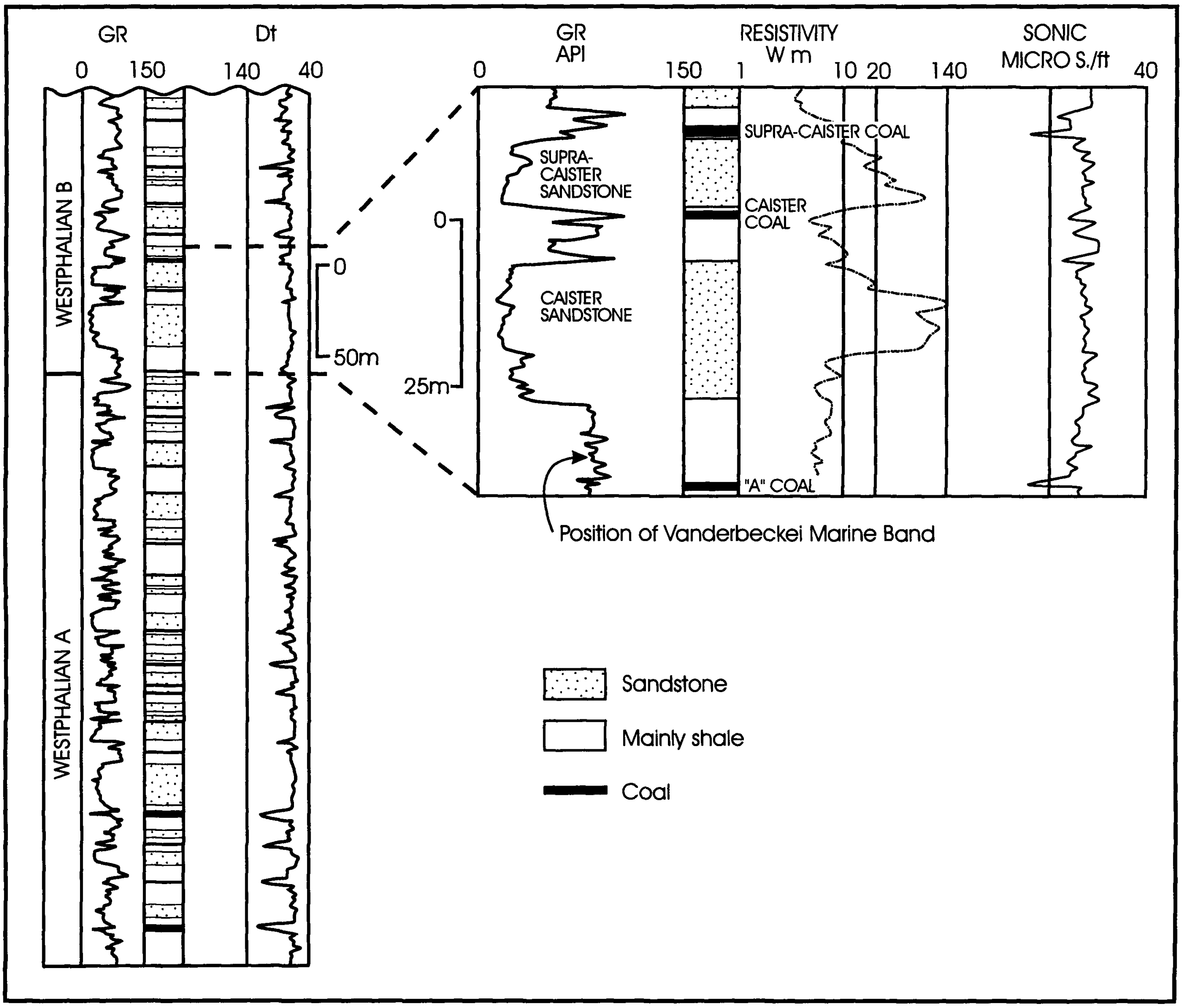


**Fig. 4** Westphalian section in Caister Field, southern North Sea, showing details of the Caister Sandstone wireline log response. The Vanderbeckei Marine Band occurs above the 'A' coal and shows limited U enrichment.

their Namurian counterparts, or the same criteria in different ways, even though the results were the same – U enrichment. Figure 5 shows the ways in which U can be fixed in sediments. In terms of this model the Westphalian marine bands should have a higher proportion of source area detritus, including a significant amount of land plant debris derived from the low-lying, humid, well vegetated humic coastal alluvial plain. The concentration of plant debris would initially increase to a maximum value at an optimum distance offshore before gradually decreasing, as depicted in Figure 6. Plant debris of this type, in the humid low-latitude conditions that prevailed during Westphalian B times, would provide abundant sites for U adsorption. Thus, U concentrations should reflect the abundance of land plant debris.

The terrigenous portion of this land-derived sediment would be at a minimum as erosion was shifted landward by the relative base level high represented by the marine band. The relatively elevated nature of the coastal alluvial plain, compared to the Namurian delta system, suggests that the transgression would be approaching its landward limit, though the waters would be sufficiently saline from their marine provenance to contain a higher U concentration than the surrounding interdistributary lacustrine environments (De Voto 1978). This marginal marine setting allows for the presence of abundant *Lingula*, which Swanson (1960) suggests preferentially concentrates U within its phosphatic test (Fig. 5), probably through passive adsorption.

In conclusion, there does not appear to be any simple direct correlation between water depth and U concentration (Fig. 6) as Leeder *et al.* (1990) and Archard & Trice (1990) postulated. The relationship is probably more complicated; rapid lateral variations in the U response of marine bands over their geographic extent, as noted by Whittaker *et al.* (1985) and Wignall & Maynard (1993), may be caused by the interaction of several interrelated factors. This allows for a fourfold division of marine bands (Figs 6, 7):

- Namurian marine bands represent marine anoxic black shale events, with thick ammonoid acme phases that concentrate U as outlined by Leeder *et al.* (1990).

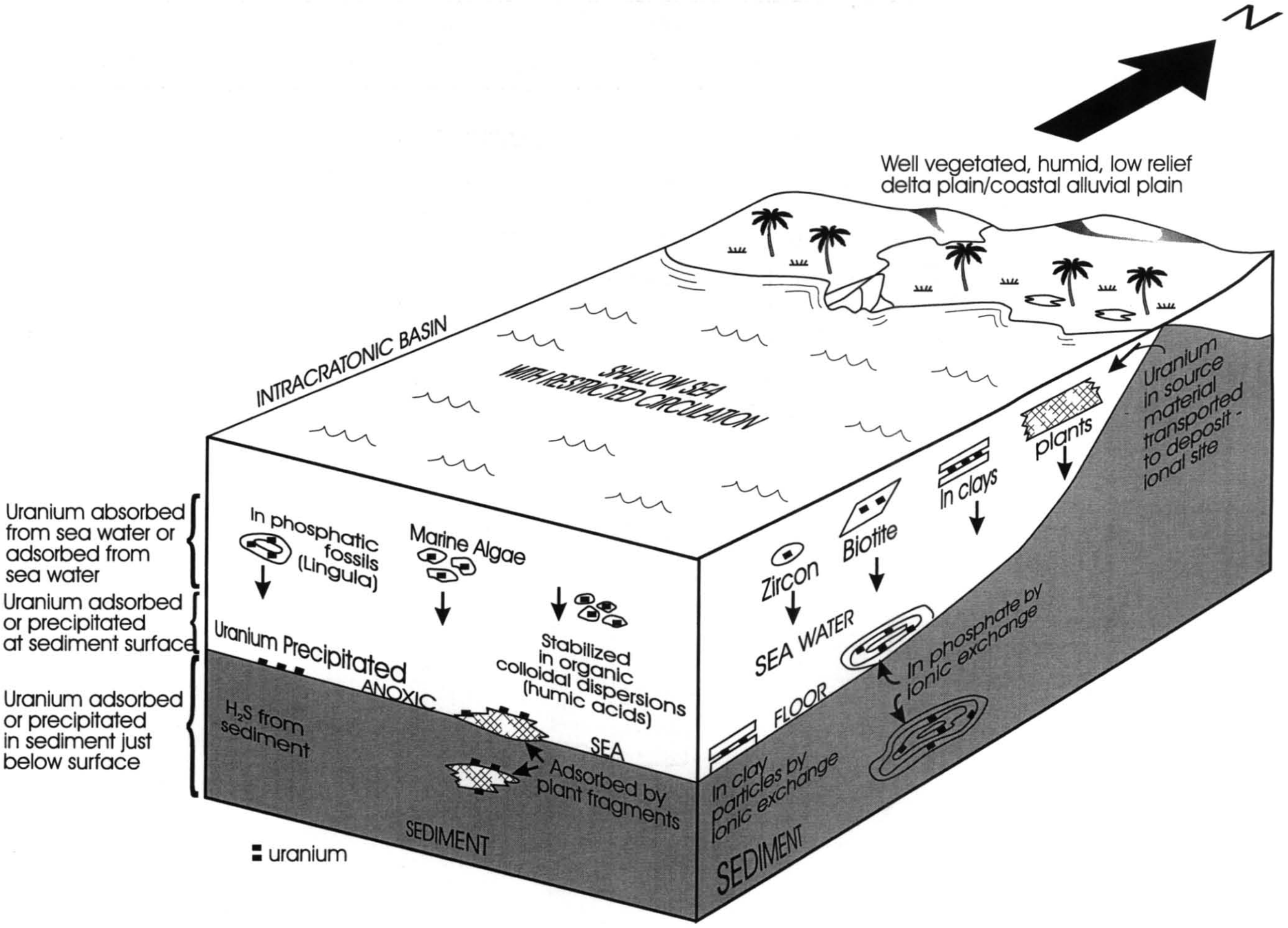
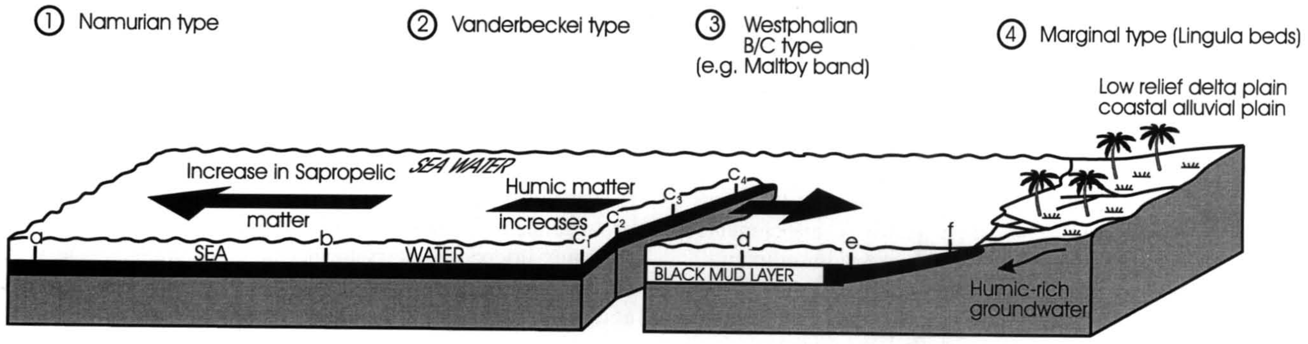


**Fig. 5** Sites of U fixation in black shales (data from Swanson 1960).



| | a | b | $C_1$ | $C_2$ | $C_3$ | $C_4$ | d | e | f |
|---|---|---|---|---|---|---|---|---|---|
| Organic matter % | 30 | 25 | 20 | 17 | 15 | 10 | 15 | 10 | 5 |
| Humic % | 15 | 25 | 50 | 50 | 50 | 50 | 75 | 85 | 95 |
| Sapropelic % | 85 | 75 | 50 | 50 | 50 | 50 | 25 | 15 | 5 |
| Uranium % | 0.0030 | 0.0041 | 0.0063 | 0.0054 | 0.0048 | 0.0031 | 0.0070 | 0.0054 | 0.0031 |

**Fig. 6** Conceptual model showing the theoretical distribution of humic and sapropelic materials in a shallow sea in which organic-rich, anoxic black muds are accumulating, estimated U concentrations (after Swanson 1960) and location of the four types of marine band recognized in this study (see text for details). Seaward increase in total organics reflects seaward decrease in detrital terrigenous sediment.

- Vanderbeckei-type marine bands are weakly anoxic, have thin ammonoid acme phases and abundant benthos, resulting from shallower water depth compared to Namurian marine bands, and consequently negligible U enrichment. They contain a lower proportion of humic material from land-derived organic debris, compared to Westphalian B/C marine bands, as the distance to the contemporary shoreline was greater.
- Westphalian B/C marine bands, such as the Maltby, are more marginal but have an abundance of land-derived plant

fragments with adsorbed uranium, as well as U entrapped within the phosphatic tests of *Lingula* which are more abundant in these types of marine bands. Consequently they have high levels of U enrichment (Fig. 7).

Brackish water *Lingula* beds with high proportions of locally derived terrigenous sediment give a negligible U response (Fig. 7). The increase in silty detritus negates the effects of *Lingula* in concentrating U.

The above subdivision of marine bands supplements the ideas of previous workers and attempts to explain the differing U responses for different types of marine band and within the same marine band (Fig. 8) encountered within Westphalian B sediments (O'Mara 1995). Most probably, a transition exists between the offshore Namurian type, through the Vanderbeckei type to the marginal Westphalian B/C type marine bands in response to the relationship between anoxia, organic land-derived detritus, sediment supply and marginality (water depth and faunal content). This, in turn, produces the variations in U concentration between and within individual marine bands. A common feature that promotes U concentrations in all these marine bands is the intracratonic relatively shallow water nature of the basin, characterized by restricted access and circulation of marine water leading to a dominance of reducing conditions.

The situation is further confused by the high background levels of U in Westphalian B environments. These are caused firstly by the abundance of land plant debris which adsorbs U, and secondly by the high water table leading to reducing conditions, favouring the formation of uranium-bearing siderite. Furthermore, lacustrine environments, which are common throughout Westphalian B facies associations (Fielding 1984; O'Mara 1995), appear to be sites of U enrichment. Some of

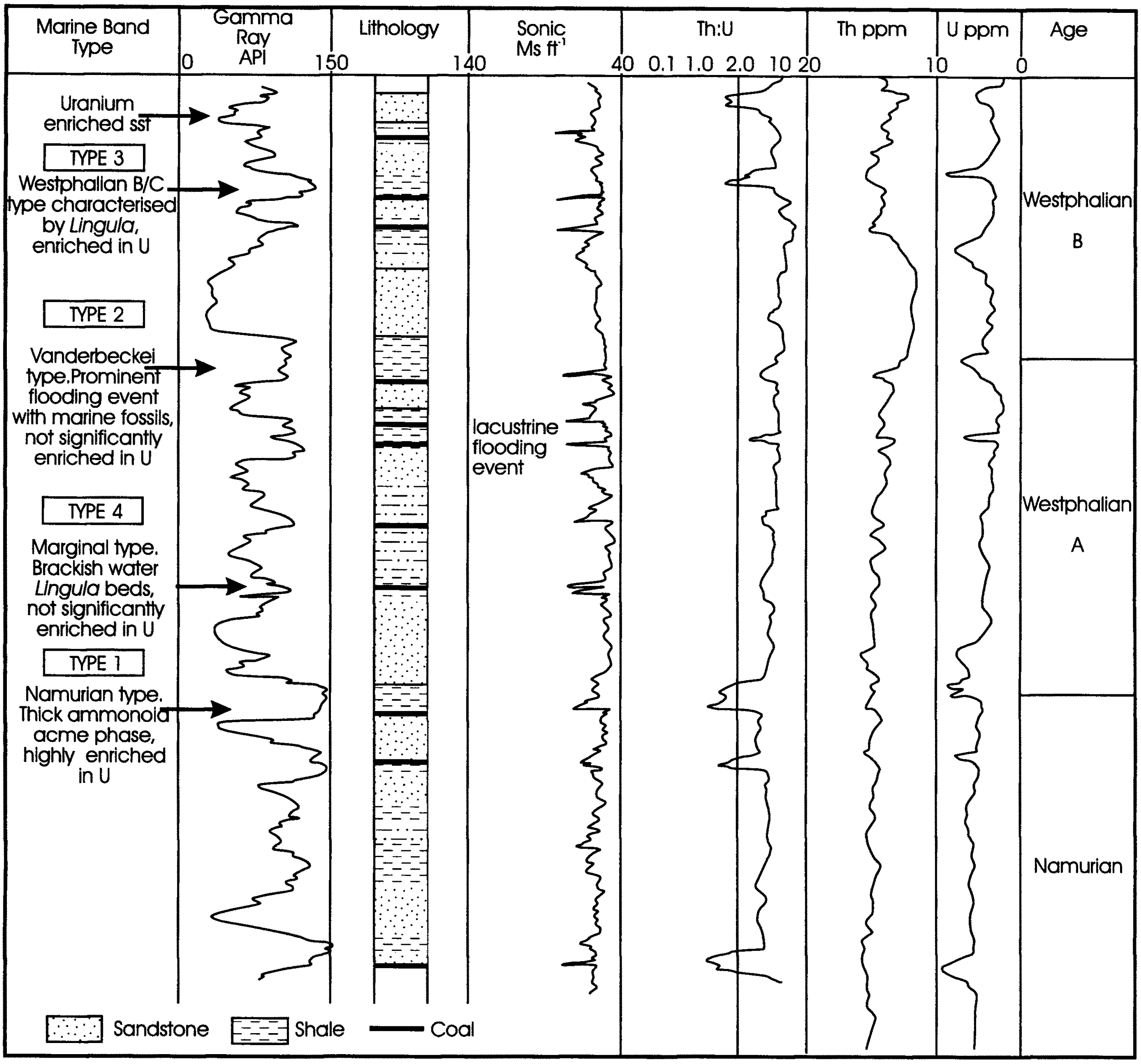


**Fig. 7** Log response for the Namurian to Westphalian B succession in Quadrant 44 of the southern North Sea showing characteristic log response for different marine band types recognized in this study.

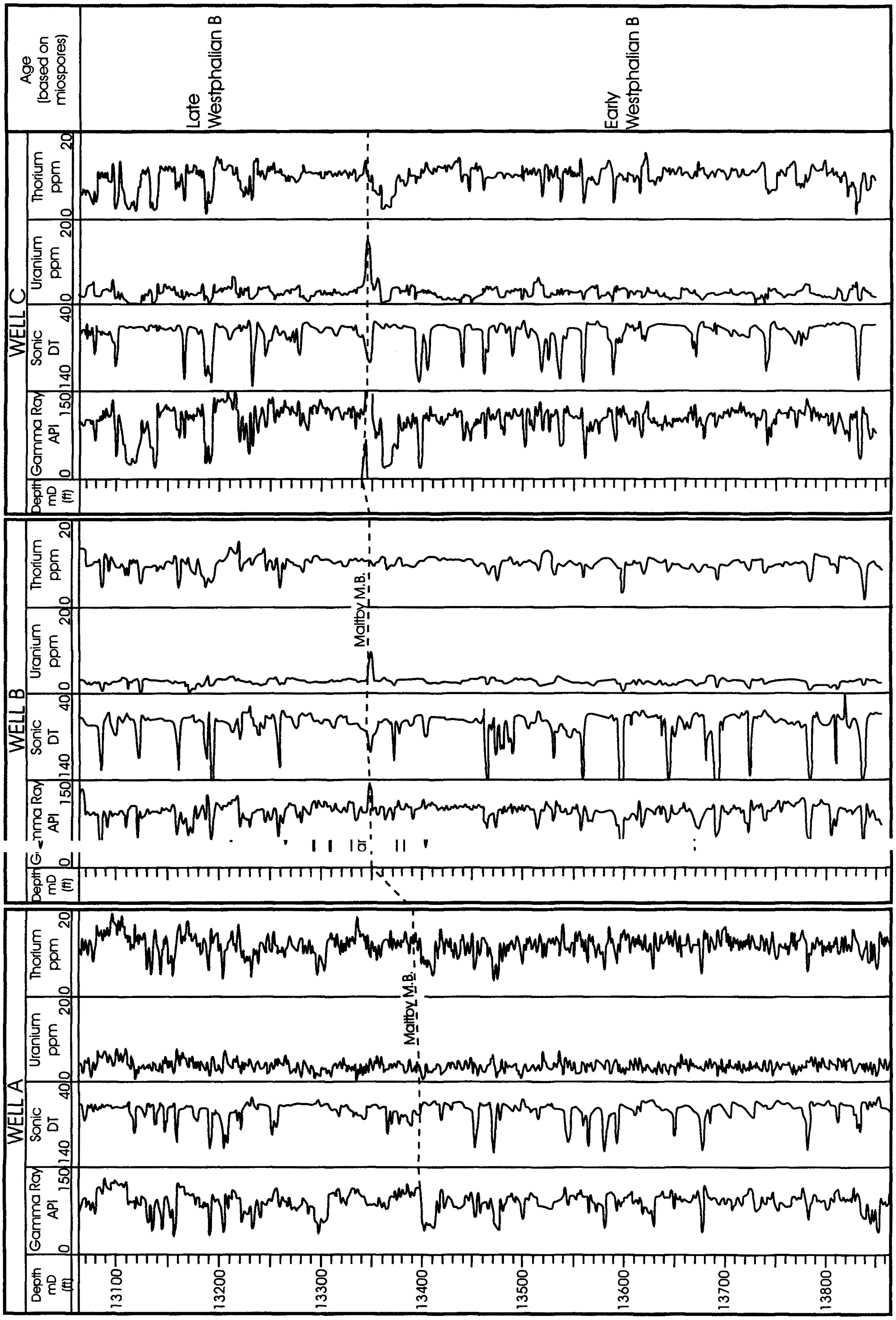


**Fig. 8** Cross section showing three wells in the southern part of Quadrant 44 in the southern North Sea, and variation of U response of the Maltby marine band.

these lakes were stratified and anoxic (Haszeldine 1981) with poor current mixing leading to the development of highly reducing bottom waters. This, combined with land plant debris, suggests that they may have had U levels approaching those of some marine bands. However, their waters were initially less enriched in U, and the terrigenous clastic input was high with the result that the marine bands, particularly enriched in U, can still be distinguished. Extreme care in correlation is required when marine bands of the Vanderbeckei type are intercalated with lacustrine black shales with a similar degree of uranium enrichment, as is commonly the case in the Westphalian B succession.

## 2. MARINE BAND IDENTIFICATION IN THE SUBSURFACE

In many subsurface well sections U and Th levels can be measured directly using the natural gamma spectrometry log (NGS of Schlumberger, Spectrolog of Western Atlas Wireline). Modern tools have the ability to measure the spectrum ranging from 0–3MeV which takes into account both high and low radiation energy. Archard & Trice (1990) illustrate how high U and U:Th values occur at the same level as the Subcrenatum Marine Band (Fig. 1) and its associated marine fauna.

High U levels are not exclusively restricted to marine bands. Other possible sources of high U concentrations in Westphalian sediments are: (1) detrital heavy minerals such as zircon and magnetite (containing U) in sandstones; (2) tonsteins; (3) tuffaceous material; and (4) zones of mineralization. In order to try and eliminate these potential causes of high U concentrations it is important to establish lithology accurately, as marine bands almost exclusively occur in mudstones. The application of depth matched gamma, lithodensity, sonic and any cuttings information usually proves satisfactory in eliminating these non-mudstone anomalies. Once lithology has been determined, comparison with the spectral gamma log allows U peaks to be highlighted. Leeder *et al.* (1990) suggests a threshold for significant enrichment of 6ppm, although this is borehole dependent, as documented below. The next step is to calculate Th:U ratios, and according to Adams & Weaver (1958), values of less than two are taken as diagnostic of anoxic marine depositional environments. Hollywood & Whorlow (1993) propose a slightly higher cut-off of 3 to account for variations in log quality and the extent to which fully marine conditions are established in different areas. More importantly, appreciation of the individual borehole conditions is required (see below).

### 2.1. Effects of borehole conditions on uranium concentration

Excessive rugosity or hole roughness can cause severe interpretational problems and it is essential to evaluate hole conditions by reference to the caliper log. Problems are particularly acute where gamma peaks occur as the tool sticks during connections if wireline is run on drill pipe. Oil-based mud systems tend to yield good U capture and environmental corrections are required when using excessive barite or potassium chloride in such systems. Running speed of the tool can also significantly affect the U concentrations recorded, and increased tool recovery rates above recommended speeds severely reduce U levels and the accuracy of the measurements, so that anomalies do not appear significantly higher than background levels.

The above borehole variations preclude the use of any absolute values. When picking marine bands from spectral gamma ray data, a background non-marine shale U and Th:U level can be established, although this may not be constant throughout the wellbore. Frequently the high U values experienced with marine bands are accompanied by Th levels which are either constant or falling. Both produce a pronounced ‘kick’ in the Th:U ratio. Positive U anomalies accompanied by collective positive Th and K are more likely to represent tool sticking events (check cable tension) though U peaks with Th peaks alone may still be caused by marine bands if the U peak is relatively insignificant. Distinct corresponding U and Th peaks are most probably tonsteins, especially the thicker tonsteins. Some of these have a distinctive gamma response and are geographically widespread, and as such they provide a useful correlateable ‘time line’ independent of palynology (O’Mara 1995).

## 3. CONCLUSIONS

Outcrop recognition of marine bands is based on their ammonoid content and associated marine macrofaunal phases. Although recognition in the subsurface is more difficult due to the lack of adequate borehole samples for biostratigraphic determinations, it is nevertheless crucial for calibration of log response. The U log response of marine bands, commonly used to identify marine bands in the subsurface, varies markedly due to the complex controls on U enrichment. Palaeogeographic reconstructions, marine band deposition and the controls on U sediment enrichment provide a means of dividing marine bands into four types.

(1) Namurian marine bands represent marine anoxic black shale events, containing thick ammonoid acme phases, which concentrate U as outlined by Leeder *et al.* (1990).

(2) Vanderbeckei-type marine bands are weakly anoxic, have thin ammonoid acme phases and abundant benthos due to shallower water depths, and thus they have negligible U enrichment. They also contain a low proportion of land-derived humic material due to the significant distance to the contemporary shoreline.

(3) Westphalian B/C marine bands contain an abundance of land-derived plant material with adsorbed U, in addition to the U associated with the phosphatic tests of *Lingula* which are particularly abundant in these marine bands. As a result they have a high level of U enrichment.

(4) Brackish water *Lingula* beds contain a high proportion of terrigenous clastic input and negligible U response.

This classification of marine bands allows for prediction of the possible U response of individual marine bands within a new data set, and is thought to reflect primarily the organic content and salinity conditions under which the bands were deposited. Marine bands can be recognised in the subsurface from their gamma ray and spectral gamma ray log response, which together with palynological analysis enables them to be successfully incorporated in the regional stratigraphical framework where they provide important tie lines and surfaces for correlation.

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