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RECOGNITION AND INTERPRETATION OF PENNSYLVANIAN CYCLOTHEMS IN ILLINOIS, U.S.A.

by P.McL.D. DUFF

ABSTRACT: The problems of defining Illinois cyclothems are discussed. Markovian analysis shows that it is inappropriate to view the whole Pennsylvanian succession in terms of the "idealised" Illinois cyclothem and emphasises the differences between cyclothems of different Formations. It is suggested that eustatic rises in sea level were unnecessary for the formation of most of the cyclothems.

RÉSUMÉ: Les problèmes concernant la description des cyclothèmes d'Illinois font l'objet de cette note. L'analyse de Markov indique qu'il ne convient pas d'envisager la succession entière sous l'angle du cyclothème «idéalisé» de l'Illinois et souligne les différences entre les cyclothèmes des formations différentes. Il est inutile d'invoquer les relèvements eustatiques du niveau de la mer pour la formation de la plupart des cyclothèmes.

Introduction

Beds of Pennsylvanian (Silesian) age in Illinois are among the most quoted in the world when cyylic sedimentation is discussed. Indeed it was following a study of them (WANLESS & WELLER 1932, p. 1003) that the word cyclothem was introduced "to designate a series of beds deposited during a single sedimentary cycle of the type that prevailed during the Pennsylvanian period."

The ensuing forty years of study of coal-bearing cyclothems, both in Illinois and elsewhere, has not, however, resulted in a consensus of opinion favouring any one theory of origin or agreeing on which theory or combinations of theories may be applicable to particular sequences. One of the problems, which has been discussed at length (DUFF *et al.* 1967) is that descriptions of actual sequences are not clearly separated from inferences made about the "models" set up to account for the sequences. The Illinois succession has suffered worse than most in this respect and it is the purpose of this paper to draw special attention to actual sequences in order to clarify the problems they pose.

Regional setting

Table 1 shows the recognised rock-stratigraphic classification of the Pennsylvanian in Illinois (KOSANKE *et al.* 1960) and its relation to the American time-divisions (WANLESS *et al.* 1970), together with two possible correlations with Europe (WANLESS 1969 and EAGAR 1970). (The discovery of *Gastrioceras* aff. *subcrenatum* (FRECH) in Kentucky by EAGAR (*op. cit.*) and GORDON's (1970) work on ammonoids supports the contention that the bulk of Morrowan rocks are Namurian in age).

Pennsylvanian rocks in Illinois comprise the greatest portion of the Eastern Interior Coal Basin (which extends into western Indiana and north-western Kentucky, and covers an area of some 13.8 × $10^9 m^2$.). They rest unconformably on a Mississippian (Dinantian) surface over most of the area, though they overlap on to Devonian, Silurian and Ordovician rocks in the north of Illinois. The sub-Pennsylvanian surface sloped gently to the south-west and a recognisable drainage pattern developed on it. North-east, south-west valleys, ranging in width from 100 to

TABLE 1
Silesian in Illinois

<table>
<tr><th colspan="2">ILLINOIS</th><th rowspan="2">Mid-continent — Illinois correlation (WANLESS et al 1970)</th><th rowspan="2">Mid-continent — European correlation (WANLESS 1969)</th><th rowspan="2">Mid-continent — European correlation (EAGAR 1970)</th></tr>
<tr><th>GROUP</th><th>FORMATION</th></tr>
<tr><td rowspan="5">McLEANBORO</td><td rowspan="2">MATTOON (180 m.+)</td><td>VIRGILIAN</td><td>Stephanian</td><td rowspan="4">Stephanian</td></tr>
<tr><td rowspan="3">MISSOURIAN</td><td rowspan="3">Westphalian D (upper)</td></tr>
<tr><td>BOND (105 m.)</td></tr>
<tr><td rowspan="2">MODESTO (120 m.)</td></tr>
<tr><td rowspan="3">DESMOINESIAN</td><td rowspan="3">Westphalian D (lower) and Westphalian C</td><td rowspan="3">Westphalian C and D</td></tr>
<tr><td rowspan="2">KEWANEE</td><td>CARBONDALE (120 m.)</td></tr>
<tr><td>SPOON (105 m.)</td></tr>
<tr><td rowspan="5">McCORMICK</td><td rowspan="2">ABBOTT (105 m.)</td><td rowspan="2">ATOKAN</td><td rowspan="2">Westphalian B</td><td>Westphalian B</td></tr>
<tr><td rowspan="2">Westphalian A</td></tr>
<tr><td rowspan="3">CASEYVILLE (150 m.)</td><td rowspan="3">MORROWAN</td><td rowspan="3">Westphalian A</td></tr>
<tr><td>Namurian C</td></tr>
<tr><td>Namurian B</td></tr>
</table>

32,000 m., and in depth from 1-150 m, cutting down into underlying Mississippian limestones, can be recognised. (BRISTOL and HOWARD 1971). It appears that, in general, most sediment transport was from the north-east and east to the south-west.

The thickness of the Pennsylvanian sediments varies from south to north. In the south there are some 360 metres of sediments between the Mississippian limestones and the base of the Carbondale Formation; in the north the base of the Carbondale Formation can rest on Ordovician rocks. The thickest complete succession is of the order of 1000 metres and is found in the extreme south where it marks the southern extremity of a central and southern thicker part of the basin of deposition. This is taken to be a more rapidly subsiding portion of the basin than a shelf area found in the west and north of Illinois. Other thickness variations occur due to the presence of positive areas (now marked by anticlinal belts) active during Pennsylvanian deposition.

The sediments are on average predominantly argillaceous (50%) and arenaceous (40%) with carbonates (5%) and coals (1-2%) supplying most of the remaining types (KOSANKE *et al.* 1960, p. 11). The proportions differ slightly in the different formations with e.g. workable coals being found mainly in the Kewanee Group and arenaceous rocks being more abundant in the McCormick Group.

While the "idealised" Illinois cyclothem (Fig. 1) is what is referred to in many text-books as typefying the Pennsylvanian it must be emphasised, as WELLER himself stated (1961, p. 141), it is "only a model, because it is neither ideal nor typical for all parts of the Illinois stratigraphic section nor for the Pennsylvanian sections of other regions". That this is so can be seen very clearly from Fig. 2, which represents a composite section of the Abbott and Spoon Formations in western Illinois. Referring to the Pennsylvanian of this area KOSANKE *et al.* (1960 p. 14) pointed out "In 23 cyclothems present in that area the average cyclothem has only 5 of the 10 most common units ... one cyclothem has nine and four have eight units, (but) many units are known from only a few localities. Including known occurrences elsewhere ... the average completeness is about 7.5 of the 10 units for these 23 cyclothems and all 10 are known for four cyclothems. Because of the local distribution of many units, the completeness of the cyclothems decreases with restriction of area. In any one locality, such as a drill hole, the completeness commonly will be less than half of the standard units".

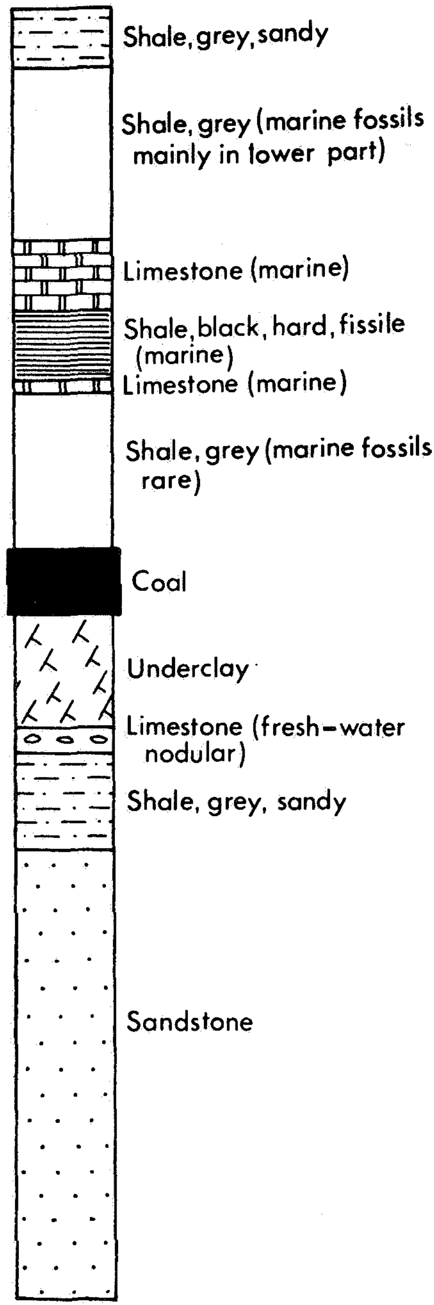

Fig. 1.

The importance of this information has not been fully appreciated. It demonstrates quite unequivocally the considerable lateral and vertical variation of the Illinois succession.

That we have this information is due to the painstaking work of WANLESS (1957) but unfortunately there are few published sequences (as opposed to interpretations) in such detail for other parts of Illinois. The questions therefore remain as to whether there is a typical cyclothem for the Pennsylvanian of Illinois, or part of Illinois, or part of the sequence in Illinois etc. and if so what is it or are they?

Another question is posed in trying to establish the regional significance of the problem. If cyclothems are considered to be due to world-wide events such as eustatic rises of sea level (WANLESS and SHEPARD 1936; WHEELER and MURRAY 1957) or by tectonic events of areal importance (WELLER 1956), an indication of the number of times such events occurred must be relevant to the plausibility of the theories. The difficulty

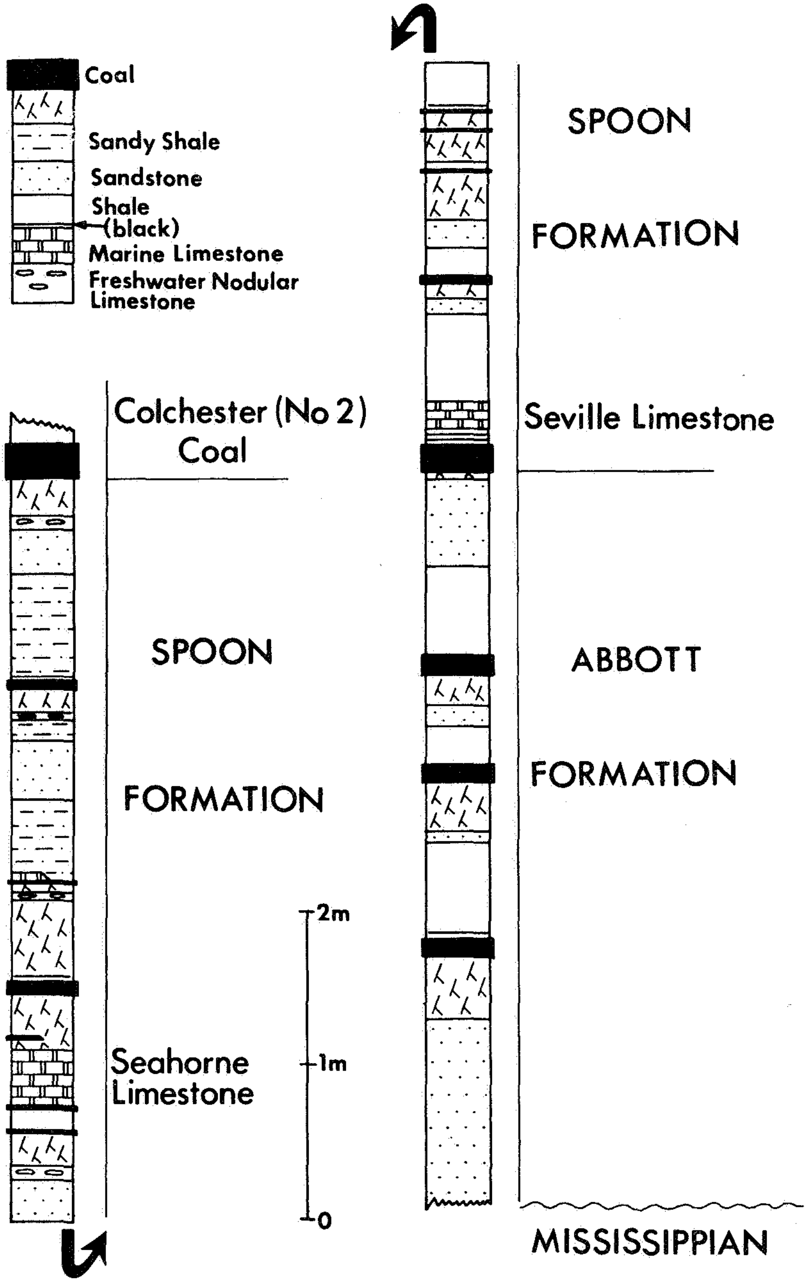

Fig. 2.

in discovering the number of cyclothems present in the Pennsylvanian in the U.S.A. has been gone into in some detail already (DUFF *et al.* 1967). Perhaps here one might simply point out that describing the *identical* sequence from west central Illinois, WANLESS (1957 p. 56) referred to it as being composed of 19 cyclothems, in 1958 (p. 7) of 21 cyclothems while KOSANKE *et al.* (1960) thought it consisted of 23!

Some of the difficulties are due to using the bases of sandstones as the starting points of each cyclothem. On practical grounds this is a problem as "the Pennsylvanian sequence is characterised by great lateral persistence of almost all individual units except the sandstones ..." (KOSANKE *et al.* 1960 p. 13). Further, the base of the sandstone is meant to rest unconformably on the beds of the underlying cyclothem. "The physical evidence for unconformities appears to be present in less than 20% of the area for any cyclothem in Illinois and no unconformities are known for some cyclothems" (KOSANKE *et al.* 1960 p. 13). Theoretically, the choice of the base of the sandstone as being the most significant event in the history of deposition can be criticised (DUFF *et al.* 1967). WELLER (1956) maintained that the base of each sandstone marked a disconformity, and uplift and erosion of the top of each cyclothem occurred before subsidence and deposition of the next. Another line of evidence cited in support of uplift having taken place during the deposition of cyclothems is the occasional occurrence of a seatearth (virtually zero water-depth) immediately, or a few cms., above a marine limestone formed in water the depth of which is considered to be much more than a few cms.

It is doubtful if many sedimentologists would support the assumption that the erosive base of a channel sandstone in a deltaic or fluvial environment implies uplift of the whole sedimentary basin in which it occurs. The second situation poses a more realistic problem, but such a juxtaposition of beds is the exception rather than the rule and in any case the whole argument hinges on assigning with confidence a depth of formation to the particular limestones — a task which is not easy.

Most European geologists define cyclothems in coal-bearing sequences by using the seatearth/coal horizon as the "punctuation mark". The choice can be justified because this is one horizon in the succession where it is known (a) that the depth of water is virtually zero and (b) clastic deposition has ceased for a period of time. If Illinois successions are looked at with European eyes, as it were, some of them obviously contain cyclothems (see e.g. Figs. 2 and 4) that are not at all dissimilar from those in parts of the Carboniferous on Europe — a fact that is not immediately apparent from a study of the "idealised" Illinois cyclothems (Fig. 1). The following is an attempt to study the Illinois sequences using the seatearth/coal horizons as boundaries.

Methods of study of cyclic sequences

During the past decade attempts have been made to study cyclothems in an objective manner with a view to determining as accurately as possible the *actual* order of the beds in them and to pay more regard to the variations. DUFF and WALTON (1962) introduced the concept of the "modal" cycle and the "composite sequence". The first refers to the statistically based most common combination(s) of beds in a cyclic sequence and the second refers to a cycle consisting "of all the rock types investigated in a cyclic succession arranged in the order in which they tend to occur." The method requires a large number of sections and furthermore, ones which are areally and stratigraphically distributed in such a way that a truly representative sample of the area under investigation is examined. While it is possible from published data of successions in Illinois to ensure a reasonably complete stratigraphic coverage, the number of written sections available and their areal distribution renders such a study impracticable. A pilot survey was undertaken on the material mentioned below but no obvious modal cycles emerged after the examination of some 60 cycles. In other words their variability was marked.

However, the sections looked at, which included type and reference sections of the various formations of the Pennsylvanian in Illinois (KOSANKE *et al.* 1960) and two carefully documented deep boreholes. (SMITH and SMITH 1967) in north-west Kentucky, just over the border from Illinois, (Fig. 3) do provide samples for a preliminary study using a different technique.

Markov-chain analysis of sedimentary

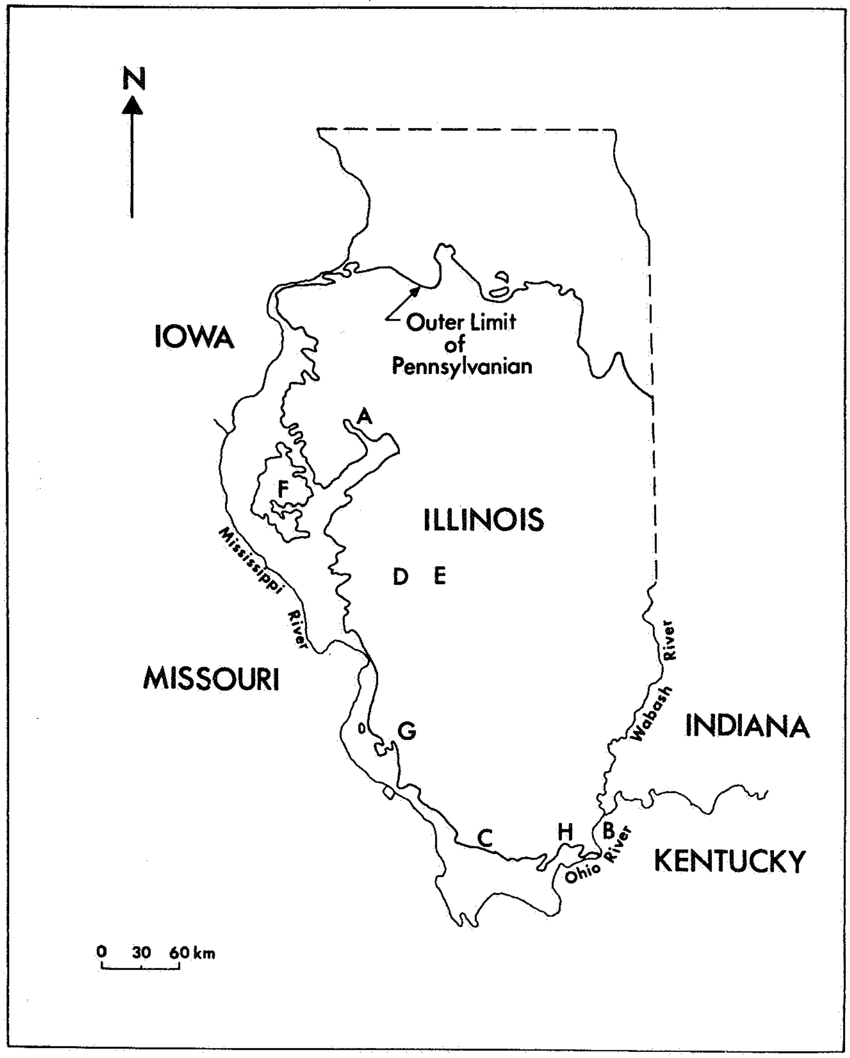

Fig. 3.

successions is a fairly recent development in Britain and America and is proving a useful tool in attempts to quantify information about successions where cyclicity is present (See e.g. READ 1969 and DOVETON 1971 for useful accounts of the technique and an introductory bibliography). Basically each lithological type in a succession is noted, in turn, along with the type that succeeds it. If one recognises, say, six different types one can erect a six-by-six "tally matrix" which will show how many times each rock-type occurs and how many times it is succeeded by each of the five other types in the sequence. From this matrix it is possible to construct a "transition probability matrix" showing the data in the form of probability values rather than as actual figures. (If half of the sandstones in a sequence were followed by shales, for example, this would be represented by 0.5 rather than the actual numbers of the beds). Then if one takes account of the numbers of the different beds in a succession and assumes deposition in random order one can construct an "independent trials matrix" showing the probability of one bed following another when there is no "memory". If one subtracts the values calculated for the independent trials matrix from those of the transition probability matrix a "difference" matrix can be constructed where positive values are taken to indicate that the transition from one bed to another has a higher than random probability of occurring. Statistical tests to validate this assertion are not easy to devise (see discussion by READ 1969) but the original tally matrix and the difference matrix between them provide useful information when an attempt is made to quantify the succession of lithologies so that the reader can judge for himself the validity of the author's reported cyclothems.

Analysis of cyclothems in Illinois

Results of the analysis of selected sections of the Pennsylvanian in Illinois are given in the Appendix (pp. 198-203). As in all cases where geological information has to be processed quantitatively certain decisions on classification were necessary. These were based on the quality and quantity of the information available. Generally speaking, it was possible to divide the lithologies into shale, marine shale, marine limestone, "sandstone", seatearth and coal. In certain instances details were sufficient to introduce as separate categories siltstone and mixtures of sandstone and siltstone. When these are not mentioned it is understood that "sandstone" includes them. Fresh-water limestones were not separated out as it was seen from the sections that when they occur they are at the base of seatearths. Decisions also were required on what constituted an individual bed, so as a general rule 0.3 m was regarded as the lower thickness limit for any bed to be recorded separately unless the bed had obviously environmental significance e.g. a seatearth, coal, or a marine shale or limestone. Coals separated only by seatearths, were not recorded individually nor were the intervening seatearths. Such complexes were recorded as one seatearth — coal couplet. Thin marine beds were recorded separately only if it appeared they were within a non-marine sequence. The latter were classified by an absence of fossils so it might be better to consider the division between marine and non-marine shales as one between beds containing marine fossils and beds without marine fossils.

It was possible to compare the results of the adopted classification with a classification used by SMITH & SMITH (1967) in their report on the deep boreholes in Kentucky. They separated the rocks between coals into the following "lithological components" (p. 7): 1) black fissile shale commonly with marine fossils; 2) marine limestone or shale; 3) sandstone and siltstone; 4) gray shale, silty or with siltstone laminations; 5) claystone (including underclay); 6) unfossiliferous limestone; 7) fossiliferous limestone with a freshwater fauna. A comparison of the results (Appendix p. 200-1) shows good agreement.

Taking the stratigraphic groups of the Pennsylvanian in Illinois in order it is possible to make certain observations on cyclic sedimentation within them. It should be noted that the cyclothems taken as representative of the various formations are not modal cyclothems but suggested composite sequences.

McCormick group

This group, which is divided into the Caseyville and Abbott formations, is made up mainly of sandstones (50-60%) and siltstones and sandy shales (40%). Coals, when present, are thin and discontinuous.

The Caseyville beds are characterised by thick (up to 30m.) orthoquartzites, often containing rounded quartz pebbles. Because of the irregular nature of the pre-Pennsylvanian surface local variations in thickness are common. Regionally, thickness can vary from 210m. in the south to zero in the north. The number of coal horizons (and hence cyclothems) also varies, up to seven in some 15 metres of strata being present locally in an area in the extreme north-west (SEARIGHT & SMITH 1969) while in the south 3 or 4 coal horizons in 200 metres or so of beds is not

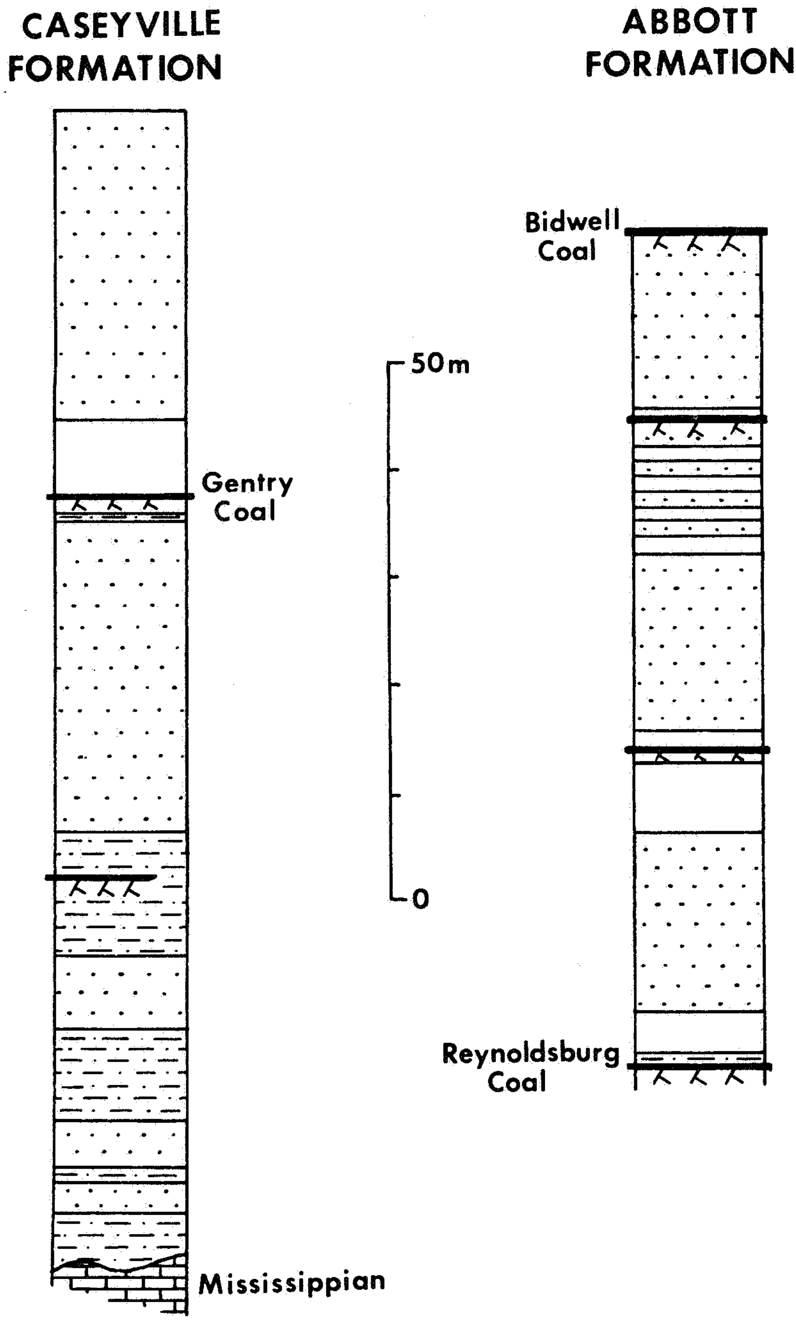
CASEYVILLE FORMATION
ABBOTT FORMATION
Bidwell Coal
50m
Gentry Coal
0
Reynoldsburg Coal
Mississippian

Fig. 4.

atypical. Some fossiliferous sandy beds or sandy limestones have been reported locally but only one geographically-limited marine limestone has been recorded (KOSANKE *et al.* 1960).

The Abbott Formation (maximum thickness 105m) is similar but individual sandstones do not attain great thicknesses. Further, the sandstones are less pure, marking a transition to the typical subgreywackes of the formations above. No limestones have been recorded though fossiliferous sandy beds appear locally. Cyclothems vary in number but four or five are sometimes recorded in western Illinois.

No attempt has been made to subject the McCormick Group to Markov-chain analysis. This is mainly because the type and reference sections are lacking in completeness but luckily the study seems unnecessary. Fig. 1 shows a composite section of the Abbott Formation in west-Central Illinois (WANLESS 1957) and Fig. 4 composite sections of the Caseyville & Abbott Formations for the whole of Illinois (KOSANKE *et al.* 1960). It is obvious the cyclothems bear no resemblance to the "idealised" Illinois type. Rather they are of the shale-sandstone-seatearth-coal type frequently seen in parts of the European Carboniferous.

Kewanee group

This is the part of the succession where virtually all of the mineable coals in Illinois occur. Sandstones only account for some 25% of the total thickness, with argillaceous rocks being the more important. Marine limestones and coals, while thin relative to the succession as a whole, become important nevertheless as horizons that can sometimes be widely traced. Again two formations are recognised.

Spoon Formation

In its reference section (KOSANKE *et al.* 1960, pp. 63-65) this formation includes seven cyclothems, two of which contain marine limestones. No marine fossils are recorded elsewhere. Variations in thickness of the formation and the numbers of cyclothems, as shown in published generalised sections, are considerable, e.g. 4 in 30 m. in the north (SMITH 1968); 8 in 23 m. in the west (REINERTSEN 1964) 5 in 24 m. (SMITH 1958) or 7 in 120 m. (BAXTER *et al.* 1963) in the south. (See Fig. 2 for generalised section.)

From the statistical analysis (Appendix p. 198) of the summing of the transitions recorded in the type and reference sections it is possible to infer that a cyclothem representative of the Spoon Formation would be as follows: —

Seatearth
*Sandstone (including beds and intercalations of siltstone)
Shale (with occasional marine limestones at or near the base) Coal

*In cyclothems that appear later in this paper noted as "sandstone".

Carbondale Formation

This formation is characterised by the presence of thick widespread workable coals (0.6 — 2.1 m., occasionally 4.5 m) and laterally persistent limestones (0.3 — 1.5 m. thick) in a predominantly argillaceous succession. Sandstones may be prominent locally and frequently appear to fill channels (sometimes 30 m. deep).

Thickness variation again is mainly one of decrease from the south to the north and west. Commonly about 60-90 m. the formation attains 120 m. on the south-east but can thin to 30 m. in the west. Cyclothems can vary from 4 in 48 m. in the type section, in the west, to 8 in 78 m. in the east (CLEGG 1965). Generally speaking there appear to be between 5 and 6. Figure 5 illustrates some of the lateral variation that may occur in the Carbondale Formation.

In the type section the number of transitions recorded is only 24 and the number of cyclothems 4. In an attempt to make the analyses more meaningful transitions from nearby sections covering the whole formation (see Appendix p. 199) were added.

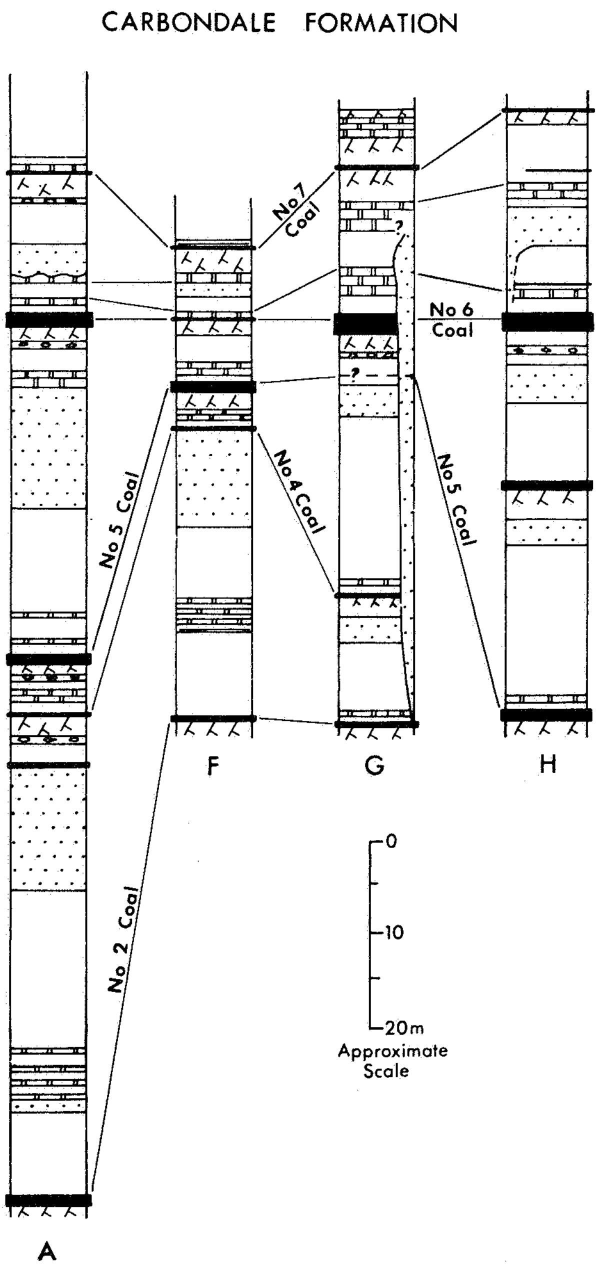
CARBONDALE FORMATION
No 7 Coal
No 6 Coal
No 5 Coal
No 4 Coal
No 5 Coal
No 2 Coal
A
F
G
H
0
10
20m
Approximate Scale

Fig. 5.

The Carbondale cyclothem resulting from the analysis can be represented as:

Seatearth
"Sandstone"
Shale
Marine limestone (often above marine shale if latter present)
Shale (sometimes with Marine Shale)
Coal

McLeansboro group

Comprising, in upward order, the Modesto, Bond and Mattoon Formations, this group has more and thicker limestones but thinner (usually < 0.3 m., occasionally 1 m.) coals than the underlying Kewanee Group.

As these formations have been recorded in detail in the report of the north Kentucky boreholes (SMITH and SMITH 1967) the borehole sections and type sections will be discussed together.

Modesto Formation

Some 120 m. thick in the borehole, and in southern Illinois, it can be as little as 60 m. in thickness in the north. There are 5 cycles in 120 m in the borehole and 6 in 62 m. in the type section in the west. (CLEGG 1965) records 8 in 80 m in the east. The type section yields a cyclothem as follows:

Seatearth
"Sandstone"
Shale
Marine Limestone
Shale
Marine Shale
Coal

The borehole data (based on the lithological classification of SMITH & SMITH 1967) yields the following:

Clay (i.e. seatearth)
Sandstone/siltstone
Shale
Marine Shale or Limestone
Marine black shale
Coal

Bond Formation

Predominantly argillaceous, the formation is nevertheless characterised by the thickness of some of its limestones and in particular those that delineate it stratigraphically. The basal member (Shoal Creek Limestone) can attain 4.5 m. in thickness, the top limestone (Millersville) 15 m. Coals are thin (0.3 m). In the type area in western Illinois (Fig. 3) the thickness of the formation is about 90 m. though in the east and north it can thin to 23 m. The Kentucky boreholes recorded 108 m. with 4 cyclothems present in the lowermost 54 m. In the type and reference sections 3 cyclothems appear in the equivalent lower part.

The Millersville limestone is *part* of a thick cyclothem (by our definition) which is "topped" by a coal in the overlying Mattoon Formation.

Adding the type and reference sections together to obtain a reasonable number of transitions (Appendix p. 201) a new feature emerges in the cyclothem. Marine limestone appears above the "sandstone": —

Seatearth
Shale
Marine limestone
"Sandstone"
Marine Shale
Coal

The new position of the limestone is due to the Bunje and Millersville Limestones. It appears that in this part of the succession (where the marine influence is becoming marked) conditions for plant life could not always be established on top of the sand and silt which generally shallowed the area of deposition. Presumably deposition did not overtake subsidence and the sea invaded the area — hence the limestones.

The presence of marine limestones out of place, as it were, does not emerge from a study of the Bond Formation in the boreholes (Appendix p. 201): —

Clay (i.e. seatearth)
Shale
"Sandstone"
Marine Limestone or Shale

Marine black shale
Coal
being the composite sequence.

Mattoon Formation

Published detailed information about the Mattoon successions is scant apart from that given by SMITH and SMITH (1967) so that no attempt was made to analyse data other than theirs.

In general thicknesses have been reported varying from 150 to 220 metres and emphasis has been placed on the fact that sandstones become more prominent than in the lower formations of the McLeansboro Group (KOSANKE *et al.* 1960). Lateral persistence of named units has not yet been demonstrated in many cases and this is borne out by the reluctance of SMITH and SMITH (1967) on the evidence available to them to correlate in detail the Mattoon of the deep boreholes with that in other parts of the Illinois Basin.

In the boreholes some 246 metres of beds are assigned to the Mattoon Formation and 17 cyclothems identified.

Using the lithological types chosen by SMITH and SMITH (1967) a composite sequence as follows can be constructed:

Clay (with fresh-water limestones below)
"Sandstone"
Shale
Marine black shale (with marine limestone or shale above or below)
Coal

Because of the detail of the recorded information it was possible to construct a 9 × 9 tally matrix showing 122 transitions (Appendix p. 203) — using a slightly different classification from that of SMITH and SMITH (1967 p. 7) and one similar to that used in analysing the Spoon — Bond Formations reference and type sections. This analysis resulted in the following:

Seatearth (with fresh-water limestone at base)
Siltstone
Sandstone
Sandstone/siltstone mixture
Shale
Limestone
Marine shale
Coal

As stated earlier similar comparisons were made between the analyses of all the transitions recorded in the boreholes (i.e. taking the McLeansboro Group as a whole) and the results compared well. The above cyclothem for the Mattoon also serves for the McLeansboro Group.

Discussion

A study of the analyses and the text-figures make it obvious that both the order and number of the units in the Illinois cyclothems are variable — and while the sample is limited it is based mainly on type and reference sections. With the exception of those in the McCormick Group and Spoon Formation the cyclothems described in the previous pages certainly bear a resemblance to the idealised Illinois cyclothem. But it must be emphasised they too are composites — and in fact compromises portraying considerable variations on a theme. A study of tally and difference matrices in the Appendix demonstrates the difficulties encountered in creating a composite sequence. Taking the Carbondale Formation as an example (p. 199), the tally matrix shows nine marine limestones, followed in four instances by shale, twice by "sandstone", twice by seatearth and once by marine shale. Attempts to construct more formalised "facies-relationships" from the difference matrix (see e.g. MIALL 1973) emphasise the variability of the order of the units.

Despite all this, however, with the Carbondale Formation and McLeansboro Group cyclothems, there is still a recognisable pattern of events. Peat-forming conditions tend to be followed closely, though not necessarily immediately, by marine conditions. These change in that chemical and argillaceous sediments tend to give way to arenaceous deposits — which are probably not marine though this cannot be entirely ruled out. Finally argillaceous material accumulates again with the water being shallow enough for plant life to establish itself. The cycle begins again with plant-life ceasing, peat no longer accumulating and sedimentation recommencing. The only essential repetitive element in this sequence of events is that periodically the area of accumulation must be shallow enough to allow plants to root, live and die.

In detail it is possible to cast doubts on the real value of idealised Illinois cyclothem when the suggested superposition of the various marine beds above the coal is considered. The analyses and sections do not support two distinct limestone bands (see Fig. 1) and WELLER (1957) expressed difficulty in the identification of the "middle" limestone. (i.e. the one above the marine black shale). In this connection it is perhaps significant that SMITH and SMITH (1967, p. 7) grouped certain marine shales with the limestones as one of their single "major lithologic components". They separated out, however, the marine black shale and there is justification for this because it is most distinctive lithologically and palaeontologically. (To European eyes it is identical in appearance with many of the widespread Namurian and Westphalian marine bands). Environmentally of course, the marine black shales are, to quote MOORE (1964, p. 344), "the most puzzling of all". The other marine shales and limestones, as they appear in many sections, seem to grade into one another both laterally and vertically. Attempts to force different looking types into a preferred vertical order may not therefore be very meaningful. Studies on Pennsylvanian and Permian limestones in Kansas by HARBAUGH (1964) and LAPORTE and IMBRIE (1964) emphasise the lateral variations that occur in them and in modern environments. They point out the difficulty in modern carbonate environments of correlating lithological and biological facies differences with parameters such as depth, distance from shore etc. and consequently the dangers of making incorrect environmental inferences from variations in limestones, etc.

The sandstones have been studied exhaustively (POTTER 1963) and fit well into the delta model of Pennsylvanian sedimentation summarised by WANLESS et al. (1970). The case against sandstones being used to mark the beginning ot each cycle has been argued here (p. 187) and elsewhere (DUFF *et al.* 1967). As SWANN (1964) and WANLESS *et al.* (1970) point out, if many ot them are delta distributaries then they are part ot the same sequence of events that laid down the underlying muds. Division of a succession into cyclothems at that point, therefore, seems illogical.

Many problems concerning other aspects of the sedimentation and sediments of the cyclothems remain. If, however, it is conceded that different parts of the succession and different areas may have different types of cyclothems then perhaps attention can be diverted from the actual order of the beds to the factor most cyclothems have in common — and this applies to European examples as well. Basically we have a situation where zero water-level conditions (coals) alternate within the main (we assume) shallow-water conditions. On available evidence the shallow-water is certainly sometimes marine but in many areas evidence of this is conspicuous by its absence. A deltaic environment seems applicable for most sequences (with of course alluvial conditions pertaining on parts of the delta top). The real question is whether or not the marine incursions represent large scale events, or local events, or both.

Of relevance to this last question is the number of cyclothems present in a succession. It is obvious from the evidence in the preceding pages that the number of cyclothems in the succession varies from place to place. To say then that there are about 50 cyclothems in the Pennsylvanian of Illinois may not be very helpful — least of all if it is assumed that each cyclothem is like all the others and all were formed in the same way. If eustatic rise in sea level were the cause of each, presumably one would have to account for 50 rises in Illinois and 90 in West Virginia (90 cyclothems were reported in W. Virginia (KAY & COLBERT 1965 p. 248)) or decide that the evidence for 40 eustatic rises in sea level is missing in the Illinois succession. Perhaps it is too in West Virginia and we are dealing with say 130 rises in sea level! This argument is patently absurd and one can only postulate that cyclothems are probably not all formed in the same way. There seems no need for instance with the McCormick Group and probably the Spoon Formation, to require any other mechanism for producing the cyclothems than a sedimentary one — the normal sequence of events inherent in the growth of a delta complex.

With the cyclothems higher in the Pennsylvanian the alternations of deltaic and marine conditions complicate the simpler picture of the earlier cyclothems. Here lateral continuity and scale are important factors to be taken into consideration. Firstly lateral continuity of all the marine horizons over Illinois has not been proved. In fact the work of WANLESS and his co-workers (e.g. WANLESS *et al.*, 1963, 1970) demonstrates excellently the extent of the extreme lateral variation in Illinois apart from certain horizons. Correlation of specific horizons of the Pennsylvanian from Kansas into Illinois and thence into Pennsylvania is still limited to a very few. Even if many more marine horizons should prove to be continuous would it necessarily follow that each one required a rise in sea level throughout the world? (a marine incursion co-vering Kansas, Missouri, Illinois, Indiana, Ohio, Pennsylvania, Kentucky and West Virginia represents a change in sea level affecting $\frac{1}{500}$ of the surface area of the earth!)

If such extensive marine invasions were proved (and as yet the evidence is not available) and they could be linked with similar extensive invasions on other continents then it would be obvious to think of eustatic rises in sea level. At present we have evidence for very extensive marine invasions in Europe with certain of the marine bands of the Westphalian and Namurian. Their number is small and an order of magnitude less than the number postulated for the Pennsylvanian of the U.S.A. They are, however, the horizons that should provide the key. The problem in Illinois (and the U.S.A.) is that it is still not possible to separate easily the local cyclothems from the regional ones (see e.g. discussion by WANLESS (1964) on this problem). It will eventually be solved as more knowledge of the detailed stratigraphic palaeontology becomes available. It is to be hoped that the drilling that must be done in the near future in the U.S.A. to assess more accurately its coal reserves will provide the same stimulus to detailed correlation that the post-war drilling in Europe did at this side of the Atlantic.

Acknowledgements

This work arose out of an exercise performed by graduate students in the Geology Department, Syracuse University, N.Y. in 1972 when we attempted to analyse published sections of Illinois Pennsylvanian rocks with a view to defining as objectively as possible the cyclicity present. The enthusiasm and interest of the class and the problems the exercise raised, rather than solved, led me to look into the matter further.

The work is of course based on the meticulous recording of data by the late H.R. WANLESS and the Illinois Geological Survey — they are in no way responsible for my interpretation of their data.

I am particularly grateful to Dr. W.B. HEPTONSTALL of the Grant Institute of Geology, Edinburgh University for writing a computer program to process the data and for his general interest in the project.

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APPENDIX *

Spoon Formation

Type section — KOSANKE *et al.* 1960 pp. 62-63
Reference Section — KOSANKE *et al.* 1960 pp. 63-65

Tally Matrix (Type and reference sections combined)

	Shale	"Sandstone"	Seatearth	Coal	Limestone
Shale	0	6	6	0	2
"Sandstone"	1	0	6	0	0
Seatearth	1	0	0	14	0
Coal	9	2	0	0	2
Limestone	3	0	1	0	0

(53 transitions)

Difference Matrix

	Shale	"Sandstone"	Seatearth	Coal	Limestone
Shale	0.00	*0.23*	0.10	−0.35	0.04
"Sandstone"	−0.16	0.00	*0.58*	−0.30	−0.09
Seatearth	−0.29	−0.21	0.00	*0.57*	−0.10
Coal	*0.35*	−0.04	−0.32	0.00	0.06
Limestone	*0.47*	−0.16	−0.01	−0.28	0.00

* For details on the construction of tally, transition probability, independent trials and difference matrices see e.g. GINGERICH 1969. For reasons of space only the tally and difference matrices are given in the Appendix.

Carbondale Formation

Type section — KOSANKE *et al.* 1960 pp. 65-67
Sections 3 & 4 — WANLESS 1957 pp. 189-191

Tally Matrix (combined sections above)

	Shale	"Sandstone"	Marine Shale	Seatearth	Coal	Limestone
Shale	0	3	2	3	0	5
"Sandstone"	1	0	0	3	0	1
Marine Shale	2	0	0	0	0	3
Seatearth	1	0	0	0	7	0
Coal	5	0	2	0	0	0
Limestone	4	2	1	2	0	0

(47 transitions)

Difference Matrix

	Shale	"Sandstone"	Marine Shale	Seatearth	Coal	Limestone
Shale	0.00	0.09	0.01	0.00	−0.20	*0.13*
"Sandstone"	−0.10	0.00	−0.12	*0.41*	−0.16	−0.01
Marine Shale	0.10	−0.12	0.00	−0.19	−0.16	*0.39*
Seatearth	−0.20	−0.13	−0.13	0.00	*0.70*	−0.23
Coal	*0.40*	−0.12	*0.16*	−0.20	0.00	−0.22
Limestone	*0.11*	0.09	−0.02	0.02	−0.18	0.00

Modesto Formation (a)

Type section — KOSANKE *et al.* 1960 pp. 67-70

Tally Matrix

	Shale	"Sandstone"	Marine Shale	Seatearth	Coal	Limestone
Shale	0	3	1	3	0	3
"Sandstone"	3	2	0	2	0	0
Marine Shale	3	1	0	0	0	1
Seatearth	0	0	0	0	6	0
Coal	2	0	4	0	0	0
Limestone	2	1	1	1	0	0

(39 transitions)

Difference Matrix

	Shale	"Sandstone"	Marine Shale	Seatearth	Coal	Limestone
Shale	0.00	0.07	−0.10	0.10	−0.20	*0.17*
"Sandstone"	*0.13*	0.00	−0.18	0.10	−0.18	−0.12
Marine Shale	*0.31*	0.00	0.00	−0.17	−0.17	0.09
Seatearth	−0.29	−0.21	−0.18	0.00	*0.82*	−0.12
Coal	0.04	−0.21	*0.49*	−0.18	0.00	−0.12
Limestone	*0.11*	0.00	0.03	0.03	−0.17	0.00

Modesto Formation (b)

Drill core, southern part of Illinois Basin (Kentucky) — Smith and Smith 1967 p. 8. (*their lithologic classification*, p. 7.)

Tally Matrix

	Marine black shale	Marine Limestone or Shale	"Sandstone"	Shale	Clay	Coal
Marine black Shale	0	2	0	2	0	0
Marine Limestone or Shale	2	0	2	6	0	0
"Sandstone"	0	2	0	2	3	1
Shale	0	2	6	0	2	1
Clay	0	1	0	0	0	4
Coal	2	3	0	0	0	0

(43 transitions)

Difference Matrix

	Marine black shale	Marine Limestone or Shale	"Sandstone"	Shale	Clay	Coal
Marine black Shale	0.00	*0.25*	−0.20	*0.25*	−0.13	−0.15
Marine Limestone or Shale	0.08	0.00	−0.04	*0.31*	−0.15	−0.18
"Sandstone"	−0.11	−0.03	0.00	−0.03	*0.24*	−0.04
Shale	−0.12	−0.12	*0.30*	0.00	0.03	−0.09
Clay	−0.10	−0.06	−0.21	−0.26	0.00	*0.65*
Coal	*0.30*	*0.34*	−0.21	−0.26	−0.13	0.00

Bond Formation (a)

Type section — KOSANKE *et al.* 1960 pp. 71-73
Reference section — KOSANKE *et al.* 1960 pp. 73-77.

Tally Matrix (Type and reference sections combined)

	Shale	"Sandstone"	Seatearth	Coal	Marine Shale	Limestone
Shale	0	4	4	0	4	3
"Sandstone"	1	0	0	0	0	3
Seatearth	0	0	0	6	0	0
Coal	1	0	0	0	4	1
Marine Shale	9	0	0	0	0	1
Limestone	4	0	1	0	2	0

(48 transitions)

Difference Matrix

	Shale	"Sandstone"	Seatearth	Coal	Marine Shale	Limestone
Shale	0.00	*0.15*	*0.12*	−0.18	−0.03	−0.04
"Sandstone"	−0.08	0.00	−0.11	−0.13	−0.22	*0.57*
Seatearth	−0.35	−0.09	0.00	*0.86*	−0.23	−0.19
Coal	−0.18	−0.09	−0.12	0.00	*0.43*	−0.02
Marine Shale	*0.52*	−0.10	−0.13	−0.15	0.00	−0.11
Limestone	*0.21*	−0.10	0.02	−0.14	0.05	0.00

Bond Formation (b)

Drill core, southern part of Illinois Basin (Kentucky) — SMITH and SMITH 1967 p. 8 (*their classification*).

Tally Matrix

	Marine Black Shale	Marine Limestone or Shale	"Sandstone"	Shale	Clay	Freshwater Limestone	Coal
Marine black Shale	0	2	1	0	0	0	0
Marine Limestone or Shale	0	0	0	5	0	0	0
"Sandstone"	0	1	0	2	1	1	0
Shale	0	2	4	0	0	1	1
Clay	0	0	0	0	0	1	3
Freshwater Limestone	0	0	0	0	3	0	0
Coal	2	1	0	1	0	0	0

(32 transitions)

Difference Matrix

	Marine Black Shale	Marine Limestone or Shale	"Sandstone"	Shale	Clay	Freshwater Limestone	Coal
Marine black Shale	0.00	*0.47*	*0.17*	−0.27	−0.13	−0.10	−0.13
Marine Limestone or Shale	−0.07	0.00	−0.18	*0.71*	−0.14	−0.11	−0.14
"Sandstone"	−0.07	−0.01	0.00	*0.11*	0.06	0.09	−0.14
Shale	−0.08	0.01	*0.30*	0.00	−0.16	0.01	−0.04
Clay	−0.07	−0.21	−0.17	−0.28	0.00	*0.15*	*0.61*
Freshwater Limestone	−0.07	−0.20	−0.17	−0.27	*0.87*	0.00	−0.13
Coal	*0.43*	0.04	−0.17	−0.27	−0.14	−0.10	0.00

Mattoon Formation (a)

Drill core, southern part of Illinois Basin (Kentucky) — SMITH and SMITH (1967 p. 8) (their classification)

Tally Matrix

	(a) Marine Black Shale	(b) Marine Limestone or Shale	(c) "Sand-stone"	(d) Shale	(e) Clay	(f) Freshwater Limestone	(g) Freshwater Limestone (fossiliferous)	(h) Coal
Marine black Shale	0	2	1	3	0	0	0	1
Marine Limestone or Shale	3	0	1	4	0	0	0	0
"Sandstone"	1	2	0	2	9	2	1	2
Shale	0	0	9	0	2	0	0	2
Clay	0	2	2	0	0	1	1	11
Freshwater Limestone	0	0	0	0	3	0	0	1
Freshwater Limestone (fossilife-rous)	0	0	0	0	3	0	0	0
Coal	3	2	5	4	0	0	2	0

(87 transitions)

Difference Matrix

	(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)
(a)	0.00	*0.19*	−0.08	*0.27*	−0.21	−0.04	−0.05	−0.07
(b)	*0.29*	0.00	−0.10	*0.34*	−0.21	−0.04	−0.05	−0.21
(c)	−0.05	−0.01	0.00	−0.08	*0.23*	0.06	−0.01	−0.14
(d)	−0.09	−0.11	*0.45*	0.00	−0.07	−0.04	−0.05	−0.07
(e)	−0.10	0.01	−0.14	−0.18	0.00	0.02	0.00	*0.41*
(f)	−0.08	−0.10	−0.21	−0.16	*0.55*	0.00	−0.05	0.05
(g)	−0.08	−0.09	−0.21	−0.15	*0.80*	0.04	0.00	−0.20
(h)	*0.09*	0.01	0.06	0.07	−0.24	−0.04	0.07	0.00

Mattoon Formation (b)
Core description, southern part of Illinois Basin (Kentucky) — Smith and Smith 1967 pp. 14-21 (classified as type sections except that sandstone and siltstone are differentiated where possible).

Tally Matrix

	Shale (r)	Siltstone (s)	Sandstone (t)	Sandstone/ Siltstone mixtures (u)	Marine Shale (v)	Seatearth (w)	Coal (x)	Marine Limestone (y)	Freshwater Limestone (z)
(r)	0	8	0	7	3	2	3	2	1
(s)	4	0	1	5	0	12	0	0	0
(t)	3	4	0	1	0	0	1	0	0
(u)	2	7	4	0	0	0	0	0	0
(v)	7	1	0	0	0	0	0	1	0
(w)	0	0	1	0	1	0	13	1	1
(x)	5	2	3	0	5	0	0	0	2
(y)	5	0	0	0	0	0	0	0	0
(z)	1	0	0	0	0	3	0	0	0

(122 transitions)

Difference Matrix

	(r)	(s)	(t)	(u)	(v)	(w)	(x)	(y)	(z)
(r)	0.00	0.08	−0.09	*0.14*	0.02	−0.10	−0.06	0.04	0.00
(s)	−0.09	0.00	−0.04	0.01	−0.09	*0.38*	−0.17	−0.04	−0.04
(t)	0.10	*0.25*	0.00	0.00	−0.08	−0.15	−0.04	−0.04	−0.04
(u)	−0.09	*0.34*	*0.23*	0.00	−0.08	−0.16	−0.16	−0.04	−0.04
(v)	*0.54*	−0.08	−0.08	−0.11	0.00	−0.15	−0.15	0.08	−0.04
(w)	−0.26	−0.21	−0.03	−0.12	−0.03	0.00	*0.60*	0.02	0.02
(x)	0.04	−0.09	0.09	−0.12	*0.21*	−0.16	0.00	−0.04	0.08
(y)	*0.77*	−0.19	−0.08	−0.11	−0.08	−0.14	−0.14	0.00	−0.03
(z)	0.02	−0.19	−0.08	−0.11	−0.08	*0.61*	−0.14	−0.03	0.00