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ELEMENTS OF A STRATIGRAPHIC FRAMEWORK FOR THE McMURRAY FORMATION IN SOUTH ATHABASCA AREA, ALBERTA

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ABSTRACT

It is a common belief that the sand bodies constituting the potential reservoirs in the McMurray Formation are extremely heterogeneous and almost impossible to correlate. This makes exploration difficult and limits recovery schemes to the few areas that contain thick channel sands.

A new stratigraphic framework is proposed for the McMurray Formation of south Athabasca. Detailed log correlations from 1700 wells demonstrate that stacked, prograding, shoreface parasequence sets that can be regionally correlated over the entire southern Athabasca Oil Sands Deposit. These parasequence sets represent highstand systems tracts. They are best preserved in the south, and are also preferentially preserved towards the top of the McMurray Formation. However, the dominant depositional elements in the basin are lowstand channels incised into the parasequence sets. During sea level rise, these channels are filled with a transgressive estuarine facies complex, consisting dominantly of sandy to muddy estuarine point bars. The basal fill of some of the deeper channel valleys consists of freshwater fluvial point bars.

Statistical facies analysis, using clustering techniques and Markov analysis, differentiates a large database of facies descriptions into three major successions that correspond closely with the proposed stratigraphic framework for the McMurray Formation. These successions are interpreted as: 1) a simple coarsening-upward shoreface succession 2) a complex of interrelated channel fill deposits and 3) rooted paleosols. The top of the McMurray Formation appears to be an erosion surface and may be a sequence boundary.

INTRODUCTION

The consequences of understanding the McMurray Formation of northeastern Alberta cannot be overstated. It is the main reservoir for the Athabasca Oil Sands Deposit and hosts one of the largest hydrocarbon accumulations in the world. Unfortunately, the reality faced by every geologist who undertakes a study of the McMurray Formation is that these Lower Cretaceous sediments appear to be amongst the most complex depositional systems in the Western Canada Basin. Even with good quality cores and geophysical logs from closely spaced wells, which in some cases may be only a few hundred metres apart, lithostratigraphic units within the McMurray Formation are difficult or impossible to correlate for any significant distance (Carrigy, 1971; Mossop, 1980; Flach, 1984).

Most published studies on the facies and stratigraphy of the McMurray Formation in the Athabasca Oil Sands Deposit deal with relatively local areas, typically over a potential production site (e.g. Benthin and Orgnero, 1977; James and Oliver, 1977; Nelson and Glaister, 1978; Knight *et al.*, 1981; Dekker *et al.*, 1984; Rennie, 1987; Beckie and McIntosh, 1989). Almost all of the available data are from the subsurface, although a few excellent outcrop exposures exist in the north-

eastern part of the deposit (Fig. 1).

The main objective of this study was to resolve the stratigraphy and sedimentology of the subsurface McMurray Formation on a regional scale. Given the perceived complexity of the stratigraphy and the apparent difficulties in correlation, it was evident that small study areas supported by only a limited database were inadequate to identify the principal stratigraphic features of the McMurray Formation. It was therefore proposed that the acquisition and analysis of a very large database of well logs and core descriptions could reveal "significant" stratigraphic horizons and sedimentological trends, either through simple observation using advanced digital displays, or through the use of statistical techniques.

In a formal statistical sense, "significance" is partly dependent on the number of samples or observations of a population. With this in mind, data was collected from as many wells as possible (but limited to a maximum density of one well per section), over a wide regional area (Fig. 2). This data density and the size of the regional study area are larger than that of any previous published study, and if it is possible to discern a regional stratigraphic scheme for the McMurray Formation, this approach would seem to have the highest potential for success.

Only one other notable regional study has been published on the Athabasca Oil Sands, that is the work of Flach (1984),

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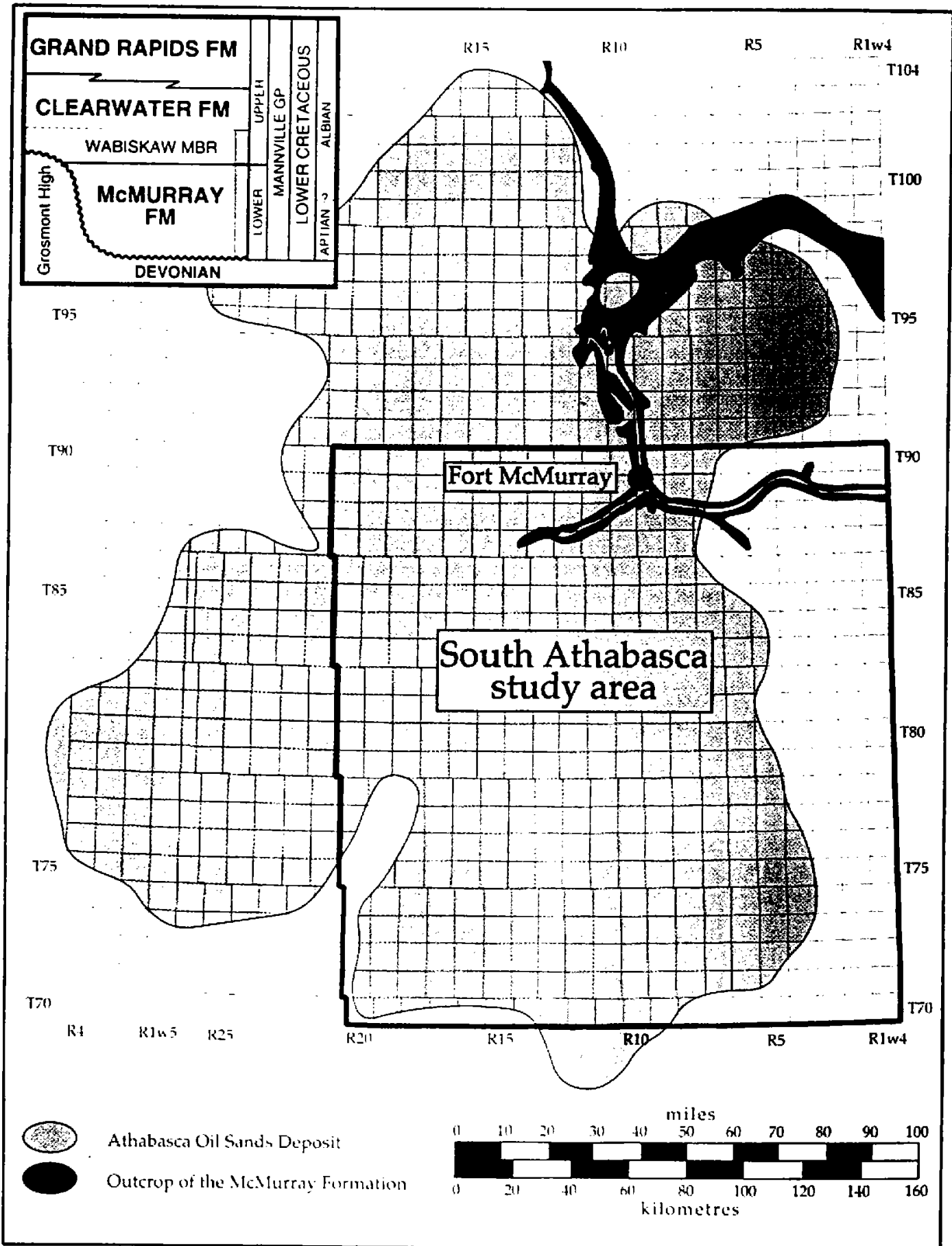


Fig. 1. Aerial distribution of the Athabasca Oil Sands, and the south Athabasca study area.

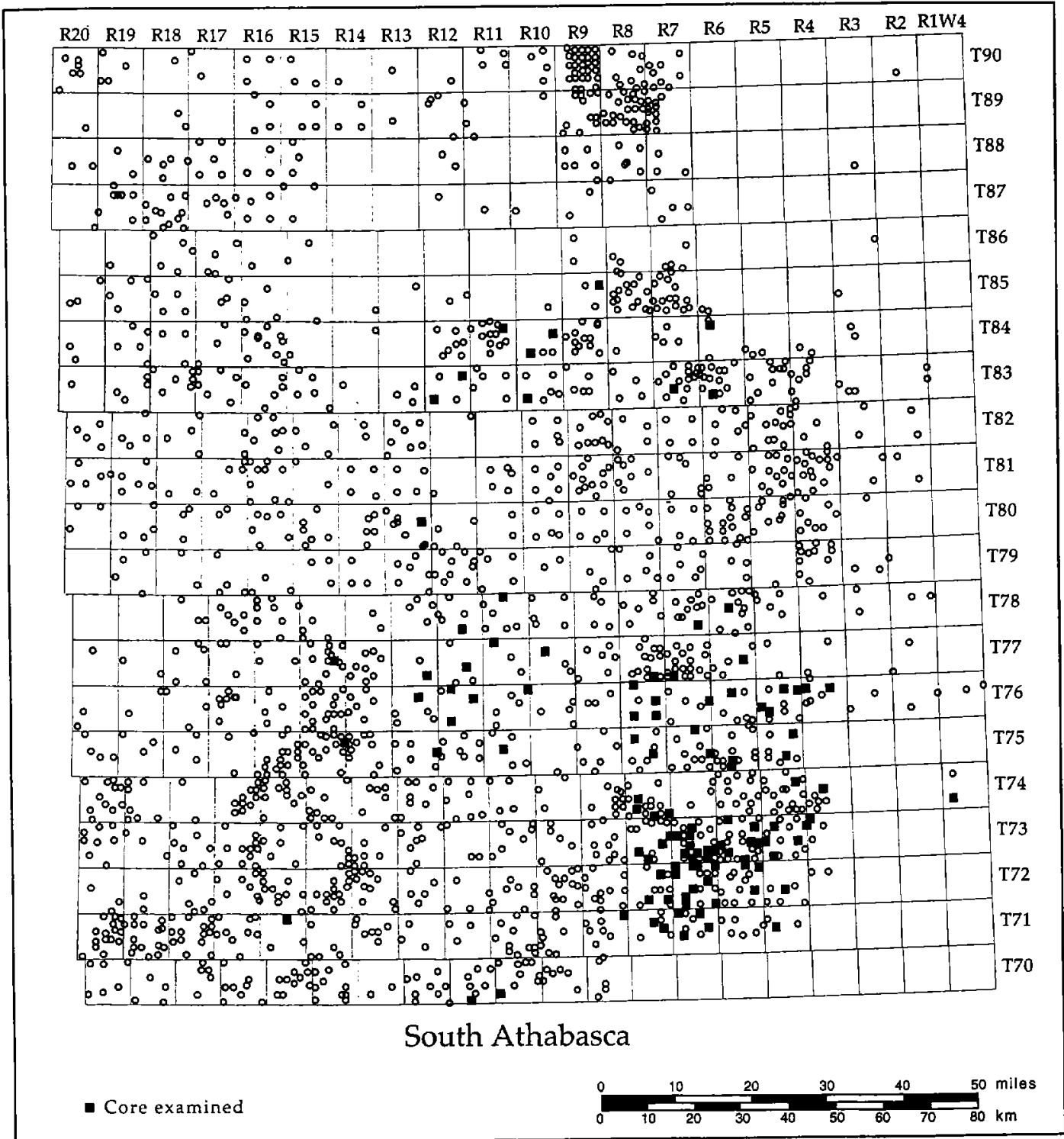


Fig. 2. Distribution of wells used in this study. Geophysical logs from 1699 wells were digitized, and core was examined and digitized from 113 of these wells.

whose economic study of the northern, potentially mineable, part of the Athabasca Deposit stands as a technical model for the characterization of oil sands resources. However regional studies such as this are overwhelmed by the large amount of subsurface data available, primarily geophysical well logs and cores. These data are of many different vintages dating back,

in the earliest cases, to the late 19th century. The vast amount of data began to accumulate quickly in the 1960's, and by 1992, there were upwards of 10,000 wells penetrating the Athabasca Oil Sands, of which perhaps one fifth have been cored. Because of the time that would be required to accumulate and synthesize this amount of data, previous studies have

used only a small sample of the available wells, typically four wells per township, (Flach, 1984; Keith *et al.*, 1988; MacGillivray *et al.*, 1992). The present study was designed to use a database from a much larger sample of data: one well per section (1 section = 1 sq mi. = 2.56 sq km).

Previous studies have typically collected and used digitized geophysical logs to calculate geotechnical properties and reservoir parameters of the Athabasca Deposit (Flach, 1984; Keith *et al.*, 1988; MacGillivray *et al.*, 1992). The present study was designed around development of microcomputer-based graphics software to display the well logs in a standardized manner and produce stratigraphic cross-sections quickly and interactively using any of over 1700 wells digitized from the study area. Above all else, it is this facility that has allowed the new interpretations presented in this study.

Digitized sedimentology of the cores has also proved useful in this study. Statistical techniques have been utilized for facies analysis, resulting in important evidence that complements the interpretations based on the geophysical well logs.

PREVIOUS WORK

The history of sedimentologic studies and interpretations of the Athabasca Deposit has evolved slowly and little advance has been made towards a detailed regional stratigraphic framework. Early sedimentological studies based on modern methods and models are those of Carrigy, who first documented in detail the sedimentological character of the McMurray Formation and the Wabiskaw Member (Carrigy, 1959a, 1959b, 1962, 1963a, 1963b, 1963c, 1966, 1967, 1971). Carrigy established an informal three-fold stratigraphy of the McMurray Formation consisting of lower, middle and upper units (Carrigy, 1959a). This basic stratigraphy has not evolved since then and remains informal, although the units are often referred to as members. Many other workers have also fit their studies into a 3-fold subdivision (James, 1977; Nelson and Glaister, 1978; Stewart and MacCallum, 1978; Flach, 1984). Yet no one has yet been able to reconcile and correlate the stratigraphy observed in the various studies. Given the acknowledged difficulty in correlating beyond a limited area (Mossop, 1980; Flach, 1984), it seems that most workers are reconciled to let McMurray stratigraphy remain on an informal basis. However, one study (Nelson and Glaister, 1978) stands out for recognizing widespread, correlatable, radioactive (gamma ray) signatures from wells in a local subsurface study in the central Athabasca Deposit. Nelson and Glaister point out that within the McMurray Formation there exists at least two correlatable shales, which they believe to be time stratigraphic markers. They use these markers to subdivide the McMurray Formation into three units, each of which can be mapped as a discrete depositional system.

Carrigy (1971) observed large inclined bedsets exposed at the Steepbank River, interpreting them as delta foresets. These well-known outcrop exposures are now believed to be inclined heterolithic stratification of point bars in a deep incised channel (Flach and Mossop, 1978). Carrigy (1971, 1973) went on to interpret much of the McMurray Formation in the northern

part of the deposit as deltaic and related deposits. His conclusions are based partly on the interpretation that the McMurray Formation was primarily of freshwater origin, except for a marine wedge at the top that thickens towards the north and west. A deltaic model has been proposed in several other studies, the most detailed being that of Nelson and Glaister (1978). Seminal work on the outcrop exposures around Fort McMurray has contributed greatly to a basic understanding of the sedimentology of the reservoir facies (Mossop, 1980; Mossop and Flach, 1983; Flach, 1984; Flach and Mossop, 1985). Flach and Mossop have demonstrated that the best reservoirs of the Athabasca Deposit are deep, sand-filled, incised channels. This observation is of prime economic importance. However, these channels, or at least their sandy facies, appear to be of relatively limited extent and, while common in outcrop, there has been only limited success in extrapolating the outcrop observations into the subsurface (Mossop, 1980; Flach and Mossop, 1985). It appears that sandy facies of the McMurray Formation are preferentially preserved in outcrop, therefore giving a biased, but highly visible and influential, sample of the reservoir architecture.

The suggestion that much of the McMurray Formation may have been deposited under estuarine conditions was first proposed by Stewart and MacCallum after many years of subsurface and outcrop study (Stewart, 1963, 1981; Stewart and MacCallum, 1978). They put forth the commonly held interpretation that the McMurray Formation consists of a lower fluvial unit, a thick middle estuarine unit and an upper marine unit, and they mapped these facies associations over much of the northern part of the deposit. Their detailed work has survived the test of time, and their basic three-fold subdivision is still generally accepted. In many studies their three-fold facies association model is equated to the informal three-fold stratigraphic framework of Carrigy (1959a).

An on-going debate concerns the extent of marine influence on the accumulation of McMurray sediments. Early studies classified the environments as either marine, normally a thin wedge near the top, or non-marine, making up the bulk of the middle and lower McMurray (Kidd, 1951; Carrigy, 1971). The influence of brackish/estuarine environments, proposed in many subsequent studies, have been based on sedimentological observation, (James, 1977; Stewart and MacCallum, 1978; Knight *et al.*, 1981; Rennie, 1987) and also on the fact that palynological studies reveal that the bulk of the lower and middle McMurray (Singh, 1964; Knight *et al.*, 1981) and in some places virtually the whole of the McMurray Formation (Mossop, 1980) is bereft of marine forms. Flach and Mossop (1985) interpret the deep channel fill successions in outcrops of the McMurray Formation as dominantly fluvial in nature. However, it has been pointed out that nowhere in modern environments is inclined heterolithic stratification associated solely with fluvial environments (Smith, 1988); but it has been documented in many modern and Holocene, tidally influenced, river-dominated estuaries (Smith, 1988, and references therein). Independent detailed studies of ichnofossils both in outcrop (Pemberton *et al.*, 1982) and in the subsurface (Keith *et al.*,

1988; Ranger and Pemberton, 1988) corroborate Smith's conclusions and demonstrate without a doubt that a marine influence exists in the McMurray sediments. This marine signature is imprinted not only on what would be considered the upper McMurray, but the middle McMurray also displays a strong marine influence. This marine signature typically expresses itself as a complex suite of trace fossil forms typical of brackish water conditions with indications of fluctuating salinity. The brackish water ichnofossil suites are recognized in channelized facies (Pemberton *et al.*, 1982; Ranger and Pemberton, 1988) as well as off-channel facies (Keith *et al.*, 1988).

BASIN PALEOTOPOGRAPHY

The McMurray Formation lies directly on a major angular unconformity known as the sub-Cretaceous (or pre-Cretaceous) unconformity. In the Athabasca area, Middle to Upper Devonian carbonates subcrop at the unconformity surface. These carbonate strata dip to the southwest and consequently the subcrop surface exposes successively younger units towards the southwest. The Devonian carbonates are generally somewhat porous and are believed in places to constitute a karst surface (Belyea, 1952). The angular discordance between the Cretaceous and the Devonian is so gentle that in outcrop the contact appears conformable. Only by regional mapping is the angular relationship evident. The unconformity is a hard, indurated surface. It can be considered as the basement for the Lower Cretaceous succession and no doubt had a profound effect on the distribution of facies in the McMurray Formation. The topography on this erosional surface is therefore of vital importance, because it is on this surface that the reservoir rocks of the Athabasca Oil Sands Deposit were deposited.

The sub-Cretaceous unconformity surface can be modelled by mapping the thickness of a suitable interval whose base lies directly on the unconformity surface. If it is assumed that some overlying stratigraphic marker approximated a regionally "flat" surface (relative to paleo-sea level), then an isopach map of the interval between the upper marker and the unconformity forms a mould of the unconformity surface, where the thins represent the highs on the unconformity and the thicks define the lows. Several different intervals have previously been used to map the unconformity topography in various studies, such as: the Base of Fish Scales to the unconformity (Williams, 1963), the top of Mannville Group to the unconformity (Ranger, 1984), or the top of the Wabiskaw Member to the unconformity (Flach, 1984).

REGIONAL PALEOTOPOGRAPHY

During the Early Cretaceous (Neocomian/Aptian) in the Western Canada Sedimentary Basin, the unconformity terrain was an immature, continental, erosional landscape dominated by three major drainage systems (Ranger, 1984). These drainage systems had developed their orientations dominantly due to differential erosion of gently dipping substrate. But tectonic and other structural elements certainly played a role. The subcropping strata dip to the southwest, and thus the erosional surface exposes older strata of the Middle to Upper Devonian

Beaverhill Lake Group in the northeast, and strata as young as Late Jurassic toward the southwest (Leckie and Smith, 1992). Along the western edge of the Western Canada Sedimentary Basin, and underlain dominantly by Jurassic strata, a major southeast to northwest flowing trunk valley system known as the Spirit River Valley drained much of western Alberta. The position and extent of this system is not unexpected since it lay along the axis of the incipient foreland trough of the North American Cordillera.

A central drainage valley system known as the Edmonton Channel valley system had its headwaters in the Swift Current Platform of southeastern Alberta and southwestern Saskatchewan and flowed toward the north-northwest (Williams, 1963; Ranger, 1984). The position of the mouth of the system is not well known, but it may have emptied directly into the Boreal Sea to the north or may have connected with, and thus have been a tributary to, the Spirit River Valley. To the east of the Edmonton Channel valley system was a major axial ridge system of resistant Devonian carbonates known as the Wainwright Ridge in central Alberta and the Grosmont High in northeastern Alberta.

East of the Wainwright Ridge lay the third major drainage valley system, informally referred to here as the McMurray valley system. It is in this valley system that the Athabasca Oil Sands Deposit was localized. The valley system is confined to the northeast by the comparative highlands of the Canadian Shield, and its axis follows a trend parallel to the strike of the outcrop of the Canadian Shield through southern Saskatchewan and Manitoba (Ranger, 1984). The paleotopographic low that forms the axis of the McMurray valley system has been localized by the dissolution of evaporitic facies mainly of the Middle Devonian Prairie Evaporite, but also to some degree the Lower Devonian Cold Lake and Lotsberg formations. This dissolution was responsible for structural subsidence of the overlying drainage basin before, during, and after deposition of the Wabiskaw/McMurray reservoir sediments. The McMurray valley system is eroded into Middle to Upper Devonian carbonates and shales of the Beaverhill Lake Group in the east and Upper Devonian carbonates of the Woodbend Group in the west.

Each of these three trunk drainage systems constitute what may be thought of as depositional sub basins. Certainly this is true as far as deposition of the lowest Mannville is concerned. During the major sea-level transgressions of the Aptian and Albian, much of each valley system would have been flooded and would have reacted independently depending on the topography and dynamics of the sediment supply.

In the Athabasca study area, the top of the Upper Mannville Group is unsuitable as a datum due to erosion in the northeast. In this study, the isopach of the McMurray Formation itself is used as a model for the unconformity paleotopography (Fig. 3). Some thin, patchy, Aptian or Neocomian sediments known as the Deville (Badgley, 1952) or more generally, the Detrital, may lie between the McMurray Formation and the unconformity. However, known occurrences of these are rare and are not readily distinguished on geophysical well logs, which make up the bulk of the subsurface data in this study.

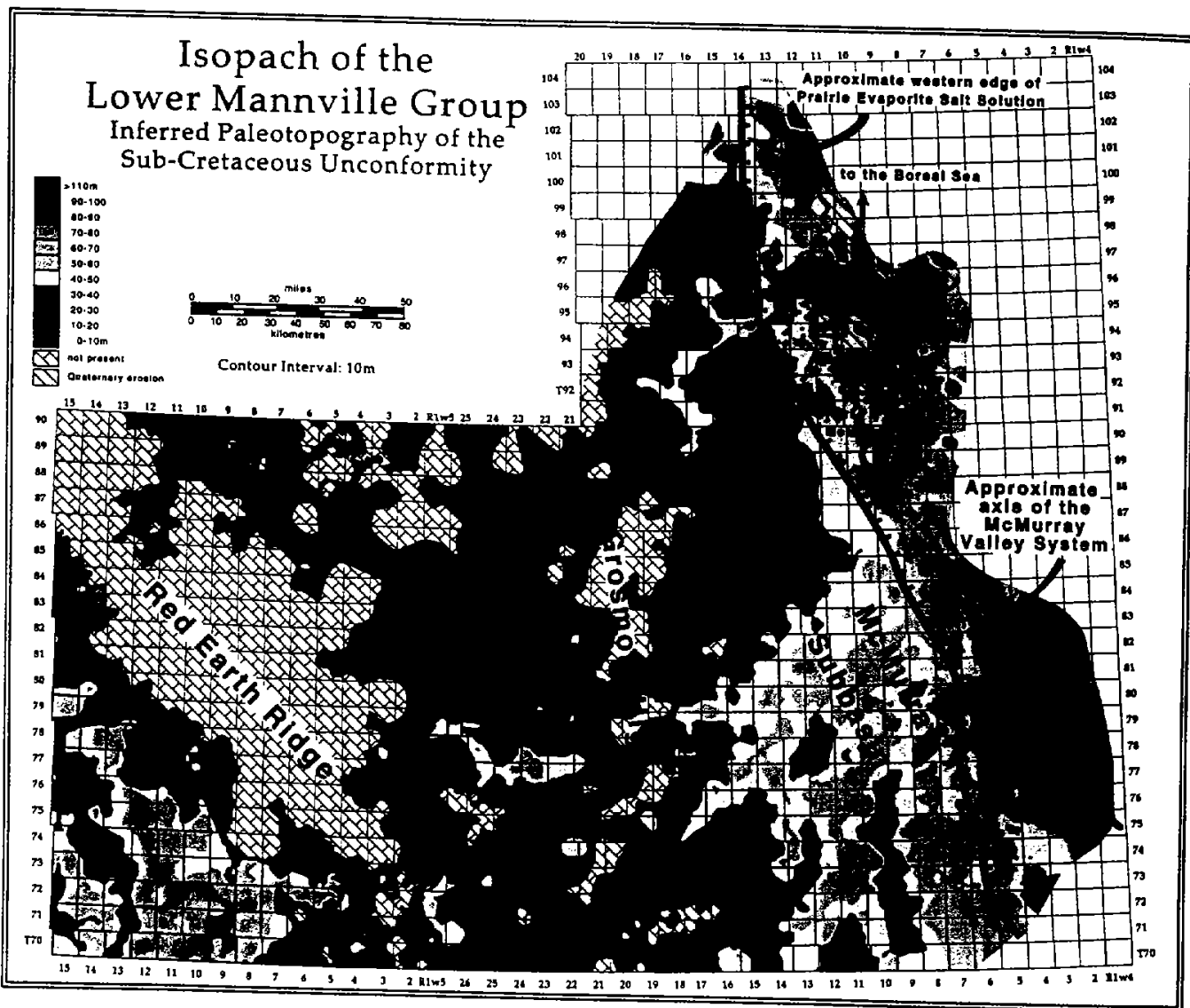


Fig. 3. Paleotopography in earliest Mannville time in northeastern Alberta, inferred from the isopach of the Lower Mannville. The sub-Cretaceous unconformity surface can be modelled by mapping the thickness of a suitable interval whose base lies directly on the unconformity surface. If it is assumed that some overlying stratigraphic marker approximates a regionally "flat" surface (relative to paleo-sea level), then an isopach map of the interval between the upper marker and the unconformity forms a mould of the unconformity surface, where the thins represent the highs on the unconformity and the thicks define the lows. The isopach of the Lower Mannville is used in this study because in the northeast of the Athabasca study area, some portions of the Upper Mannville Group have been eroded. The Wabiskaw "shale marker" is used here as the top of the Lower Mannville although it is actually within the lowermost Upper Mannville, somewhat above the contact with Lower Mannville. It is, however, a reliable regional marker, and is easily picked from resistivity logs.

PALEOTOPOGRAPHY OF THE McMURRAY SUB BASIN

The map of the sub-Cretaceous unconformity topography underlying the Athabasca Deposit reveals a north-trending, axial ridge, which effectively divides the area into two sub-basins here termed the McMurray sub basin in the east and the Athabasca sub basin in the west (Fig. 3). This ridge is informally known as the Grosmont High because it apparently results from resistant carbonates of the Grosmont Formation. The Grosmont High is a major north-trending spur off of the Wainwright Ridge. The McMurray Formation is missing, and apparently was not deposited over the crest of the Grosmont

High. These areas are shown in a brickwork pattern (Fig. 3), and would have been highland areas and then islands during marine transgressions. The Wainwright Ridge / Grosmont High complex has numerous minor spurs branching obliquely away from it on both the east and west sides (Fig. 3). On the east side these spurs trend in a northeast direction, and the valleys between them form major northeast flowing tributaries that can be mapped across to the eastern edge of the McMurray sub basin. They drain into the trunk valley of the McMurray valley system. In the south-central portion of the study area is a large ridge that extends along Rges. 9 and 10 from Twp. 77 south to at least Twp. 70. This is the extension

of a major spur from the Wainwright Ridge south of the Athabasca area. To the north another major spur extends at an angle oblique to the main ridge from Twp. 81, Rge. 17 to Twp. 89, Rge. 13. The intervening valley forms another major tributary of the McMurray system, but one that flows dominantly north to approximately Twp. 94, where it abruptly turns to the east and enters the trunk system in the area just south of the Bitumont sub basin.

On the west side of the Grosmont High, in the Wabasca sub basin, resistant spurs appear to be of shorter extent, but are less well defined because of poorer well control. The Wabasca sub basin contains an extension of the Athabasca Oil Sands reservoirs of the McMurray Formation and Wabiskaw Member, but it also hosts the younger Grand Rapids Oil Sand reservoirs of the Wabasca Deposit.

METHODS AND RESULTS

DIGITIZED CORE

One hundred and twenty six cores from the study area in south Athabasca were examined in detail. Preliminary examination and the numerous previous studies discussed above indicated that facies are very complex, and typically vary considerably over only very short distances. Statistical methods for sedimentological analysis have been proposed in the past and have shown significant results in many of those studies (see discussion in Ranger and Pemberton, 1991), but a search of the literature revealed no case studies where these methods were used as the prime method for the analysis and interpretation of facies. If these methods can indeed be useful in a practical study, then the complex sedimentary systems of the McMurray Formation make an ideal candidate, because this complexity has made a qualitative paleoenvironmental interpretation of the McMurray Formation a difficult and, so far, elusive enterprise.

Typically, sedimentological interpretation is a very subjective practice, and consists of classifying distinctive sedimentary units into facies; that is, intervals displaying similar physical and biogenic features. These facies are then interpreted to represent particular depositional environments, based on the sediment type, the physical and biogenic structures characteristic of the facies, and the position of the facies in the vertical succession, as well as thickness and distribution maps. This approach is adequate when dealing with relatively simple sedimentary packages. For the large quantity of complex and highly variable sedimentological data observed in the McMurray Formation, identifying and classifying facies by eye is formidable and liable to be fraught with subjective error. An objective statistical approach seemed appropriate in this case. Using a microcomputer in the core examination lab, all the sedimentological data from the cores were collected directly in digital form. Facies were recorded as intervals identified by a combination of codes representing lithology, grain size, and the simple presence or absence of specific physical sedimentary structures, lithological accessories and ichnofossils. The method demonstrated by Ranger and Pemberton (1991) for

ichnofacies analysis was used for the McMurray analysis, with minor modifications.

STATISTICAL FACIES ANALYSES

Ranger and Pemberton (1991) adopted and refined a two-phased, semi-parametric statistical technique in their ichnological facies analysis. This technique is considered semi-parametric because, although the techniques themselves are non-parametric, the search for outliers and tests of significance, as well as other subsidiary tests, assume the presence of normally distributed statistics.

The technique first classifies measured stratigraphic intervals into groups (*i.e.* facies) using similarity analysis, also known as cluster analysis. Significant "preferred" vertical associations are then determined using Markov transition analysis to produce an idealized model for the vertical ichnofaunal succession. This technique is not limited to ichnofossil analyses, of course, and indeed has its foundations in facies analysis using physical characteristics of stratigraphic intervals (Harbaugh and Bonham-Carter, 1970). In the facies analysis of the McMurray Formation, observations of both biogenic and physical features are given equal weight in the description of facies.

CLUSTER ANALYSIS

Ranger and Pemberton (1991) described in detail the cluster analysis technique for differentiating stratigraphic intervals into facies classes based on physical and biogenic observations. They also conduct empirical trials to see which of several common clustering algorithms is most suitable for stratigraphic analyses. Details of these techniques are described here only briefly, and interested readers are referred to Ranger and Pemberton (1991) and references therein, for a more rigorous treatment.

Cluster analysis is a technique for grouping samples or entities into discrete classes based on recurrent common attributes. The obvious analogue to this in sedimentological studies is the (typically) subjective assignment of units with similar attributes to a certain facies. In the rigorous statistical technique of cluster analysis, the first step is to calculate a matrix of similarity coefficients: between all possible pairs of entities, a coefficient is calculated that represents their distance apart in what can be thought of as multidimensional space. If the attributes are continuous data (rather than binary), then the set of attribute values are an entity's coordinates in this multidimensional space. For binary data, however, this "distance" coefficient is the result of some simple function based on the presence or absence of the attributes. Ranger and Pemberton (1991) used what is known as Euclidian distance, which gives equal weight to the mutual presence or absence of attributes. In the present study, the presence or absence of up to 49 different attributes was recorded. For all of the interval samples, the "absent" attributes far outnumbered those present. It was considered more appropriate to give more significance to the presence of attributes rather than to base the analysis on data that would otherwise be biased toward "absent" attributes. A version of the "Jaccard" coefficient, modified to measure dissimi-

larity (distance) rather than similarity was therefore used in this study. The Jaccard coefficient has been judged to give superior results, on a par with the Euclidian distance method, in empirical trials (Ranger and Pemberton, 1991), but was downgraded because of the possibility of encountering division by zero in the case where all attributes are absent in both of the samples. Although barren intervals may be common in ichnofaunal analysis, none was encountered in this study.

The next step in cluster analysis is the fusion into a single cluster of the two entities that have the greatest similarity. The similarity coefficients are then recalculated based on some transformation function that combines the similarity coefficients of the fused entities. The fusion of entities or clusters of entities is continued until all entities reside in a single cluster. The transformation function used in this study is known as the Error Sum of Squares, which, for each iteration, fuses the two clusters of observations that yield the least increase in the Euclidian sum of squares of the distances of each observation to the centroid of the combined cluster. This method was also judged superior for use with sedimentological data (Ranger and Pemberton, 1991).

Three separate cluster analyses were performed in this study, one each for the sand dominant facies, the shale dominant facies, and the interbedded facies. Complex statistical analysis is not required to reach the obvious conclusion that these three groups represent a basic first order classification, weighted (in a sense) on hydrodynamic conditions. This initial subdivision also breaks down the number of entities (facies intervals) for each analysis into manageable numbers. The number of entities can be a concern, since it should be remembered that the initial matrix of similarity coefficients means that every entity must be compared to all others. This requires a number of iterations that grows exponentially with the number of entities: x^2 , where x is the number of entities.

The resulting cluster scheme is typically displayed as a dendrogram, which displays the hierarchy of similarity relationships. While instructive to examine in the analysis process, the derivation of the dendrogram itself is not the purpose of the technique. The ultimate result is to identify as "similar" all entities residing in each cluster, similarity being defined by the similarity function. These clusters can then be considered to represent an objective classification of the observed sedimentary units into discrete facies.

The cluster analyses of the McMurray Formation resulted in the differentiation of 21 facies: 9 interbedded, 6 sandy and 6 shaly.

CLUSTER ANALYSIS INTERPRETATION

The derived facies are best described by, and interpreted from, a graphic display (Figs. 4, 5, 6) showing the mean facies thickness, dominant sand grain size, dominant bedding thickness of interbedded units and the characteristic physical structures, as well as mean diversity of trace fossil forms, relative abundance of ichnogenera, and relative intensity of bioturbation. The facies interpretation is based on the sedimentology, physical structures and ichnology, as well as position within

the facies succession. Some of the facies successions are complex and the second step in the numerical analysis, Markov analysis, proved invaluable in unravelling the facies relationships.

MARKOV ANALYSIS

Ranger and Pemberton (1991) give a detailed review of the Markov analysis technique used for examining stratigraphic successions in the subsurface, and also point out the potential pitfalls of using the method for analysis of repeated observations over the same stratigraphic interval (i.e. multiple boreholes). Again, details of the analysis are described here only briefly. The technique used in this study is essentially the same as that recommended by Ranger and Pemberton (1991).

Markov analysis measures the probability of transition from one facies to another in a vertical succession of sedimentary intervals. A Markov property or process is one in which the probability of a process being manifest in a given facies at a particular point in time may be deduced from knowledge of the immediately preceding facies. In the variation of the technique most commonly used for stratigraphic studies, the frequency of upward transitions from one facies to another in a vertical sequence is tabulated in a matrix table (Tables 1, 2). Each cell contains the frequency of transitions from the facies states denoted by the rows of the matrix to the facies state denoted by the columns of the matrix. Transitions from one facies state to the same facies state are considered unobservable or undefined and therefore these cells, which make up the principal diagonal of the matrix, are constrained to zeros. In this study the input matrix of transition frequencies was tallied using the facies assigned to the logged intervals by the cluster analyses. Two additional facies were added to the 21 resulting from the cluster analyses. These are actually significant horizons, rather than facies: major erosional scour surfaces (as suggested by Cant and Walker, 1976); and rooted horizons including thin coals and organic black shales (as suggested by Ranger and Pemberton, 1991).

The next step in Markov analysis is to calculate a matrix of "expected" transition frequencies, which provides a model of randomness or independence, i.e. the absence of the Markov property in the data sequence (Table 3). The expected transition frequencies are then subtracted from the observed transition frequencies, yielding a matrix of differences, termed the "residuals" (Table 4). Large residuals can be considered outliers and therefore non-random.

One can test for outliers by first standardising them to a mean of 0.0 and a standard deviation of 1.0. Then, assuming that the residuals are normally distributed, standard two-tailed tests can be applied, whereby 90% of the residuals should lie within ± 1.6 standard deviations of the mean, approximately 95% should lie within ± 2 standard deviations, and approximately 99.5% should lie within ± 3 standard deviations (Table 5). One can thus assign a probability to the occurrence of large residuals. The residuals are then evaluated for significant deviation from randomness using binomial probability tests of significance (Table 6).

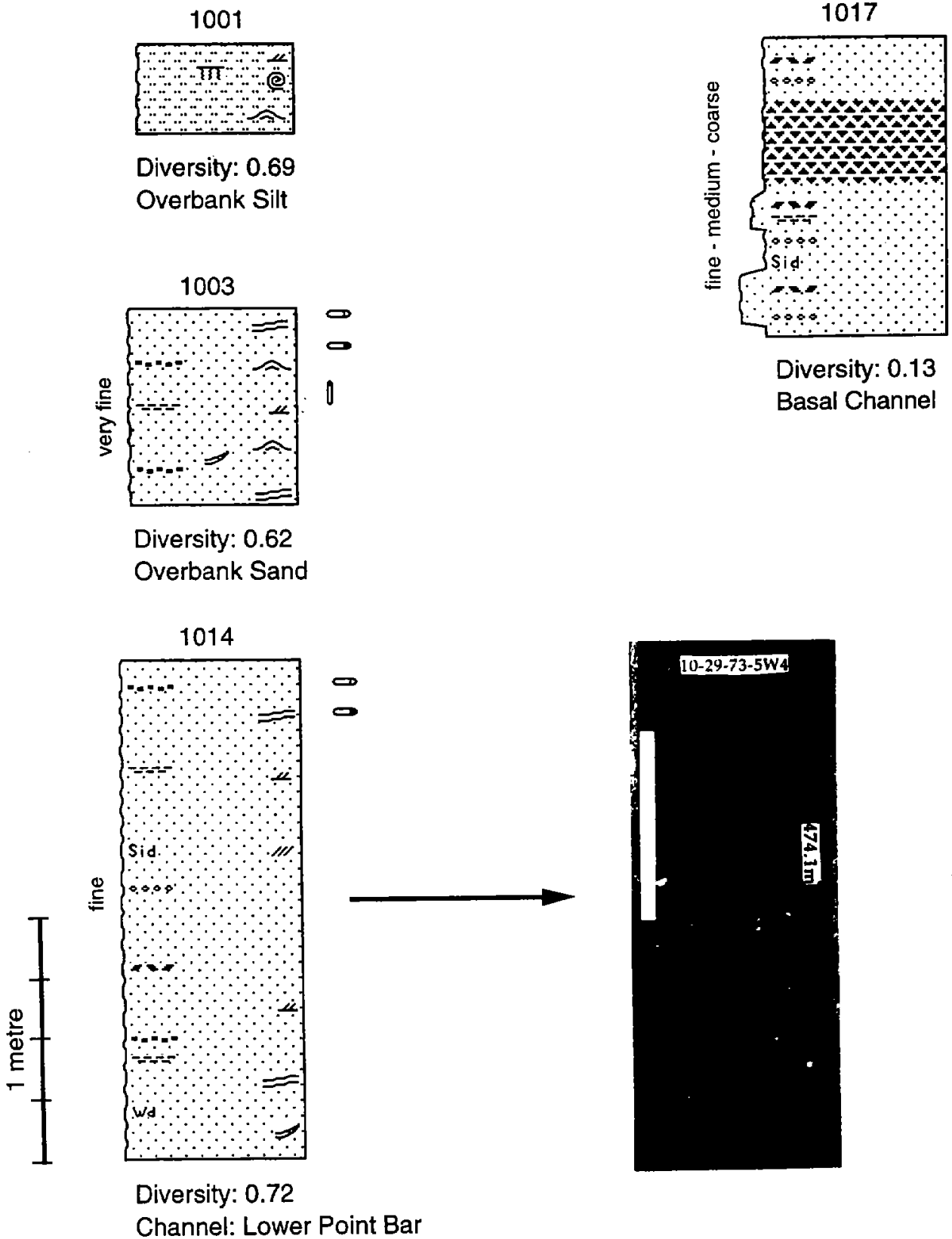


Fig. 4. Sandy facies determined from cluster analysis. Relative length is scaled to the mean thickness. Diversity is the mean number of ichnofossil forms observed in all intervals assigned to the facies. Facies numbers are arbitrarily assigned for identification purposes only. For legend see Figure 15. a) Photo example of facies 1014 is from well 10-29-73-5W4 at 474.1m.

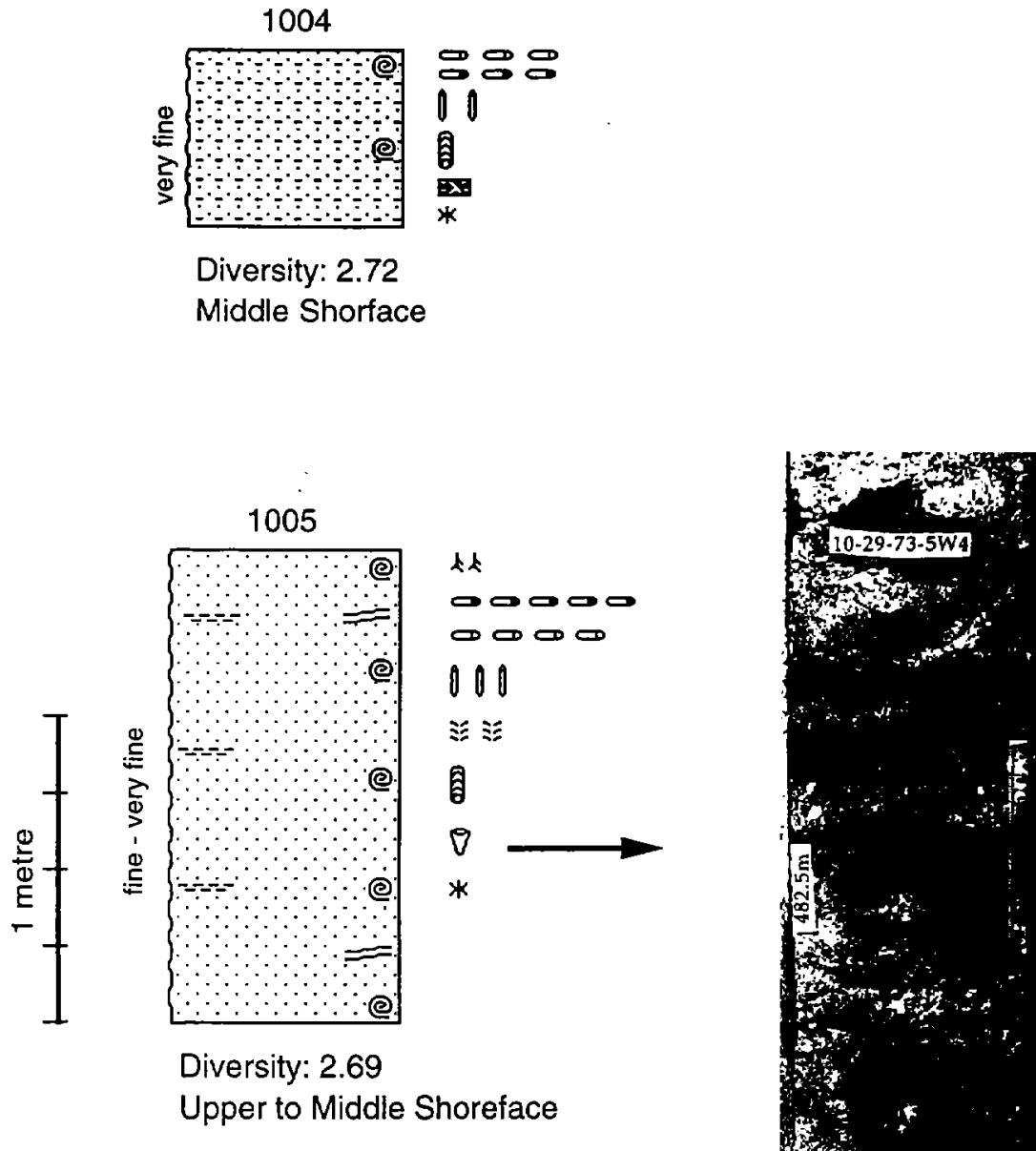


Fig. 4 b) Photo example of facies 1005 is from well 10-29-73-5W4 at 482.5m

Several "preferred" vertical facies successions are resolved by the Markov analysis of the McMurray facies. A discrete vertical facies succession is defined by the fact that it begins with a facies to which no other facies has a significant transition, and it ends with a facies from which there is no significant transition.

One succession consists of a coarsening upward succession of 5 facies (Fig. 7) beginning with intensely bioturbated, silty shale containing a moderately diverse, somewhat stressed *Cruziana* ichnofacies; with elements of a *Skolithos* ichnofacies. The succession develops vertically by becoming coarser and sandier upwards, and may be interbedded with partially preserved, storm sand beds. Although the intensity of bioturbation remains relatively abundant, the ichnocoenoses slowly evolve upwards into an assemblage dominated by the

Skolithos ichnofacies. This succession is interpreted as constituting a fairweather, low energy, shoreface, but the ichnofossil signature indicates a stressed overprint which is typical of brackish conditions: high abundance but low diversity of ichnotaxa; presence of an impoverished marine assemblage; presence of elements of both *Cruziana* and *Skolithos* ichnofacies; morphologically simple structures indicating simple feeding strategies; and a tendency towards dwarfism (Beynon *et al.*, 1988; Pemberton and Wightman, 1992; Ranger and Pemberton, 1992).

The second facies succession resolved by the Markov analysis is somewhat more complex (Fig. 8). The lower unit is a massive, pebbly, fine to coarse-grained sand, which commonly contains brecciated shale clasts. This unit begins a series of significant transitions, almost all of which are indicative of

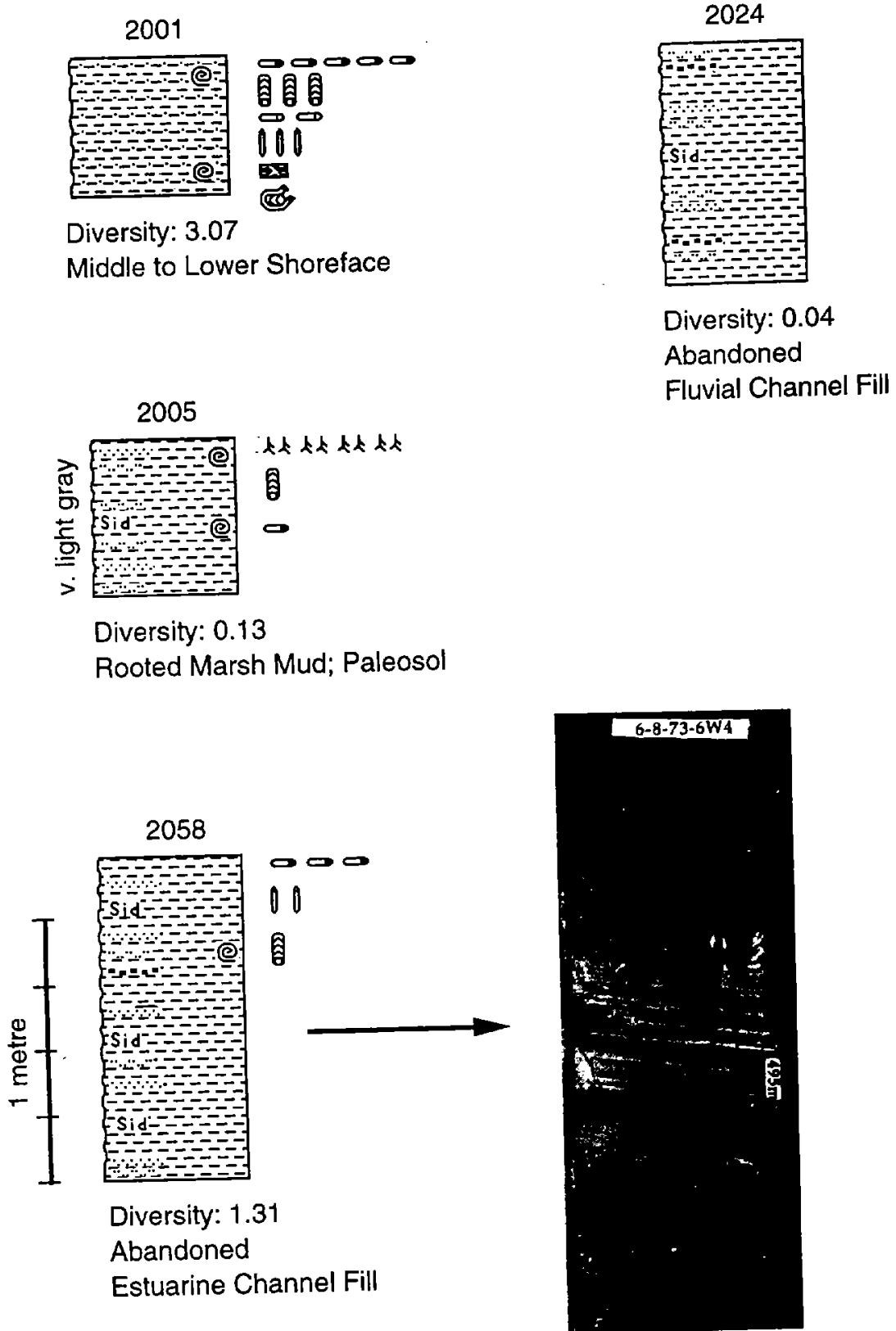


Fig. 5. Muddy facies determined from cluster analysis. Relative length is scaled to the mean thickness. Diversity is the mean number of ichno-fossil forms observed in all intervals assigned to the facies. Facies numbers are arbitrarily assigned for identification purposes only. For legend see Figure 15. a) Photo example of facies 2058 is from well 6-8-73-6W4 at 495.0m.

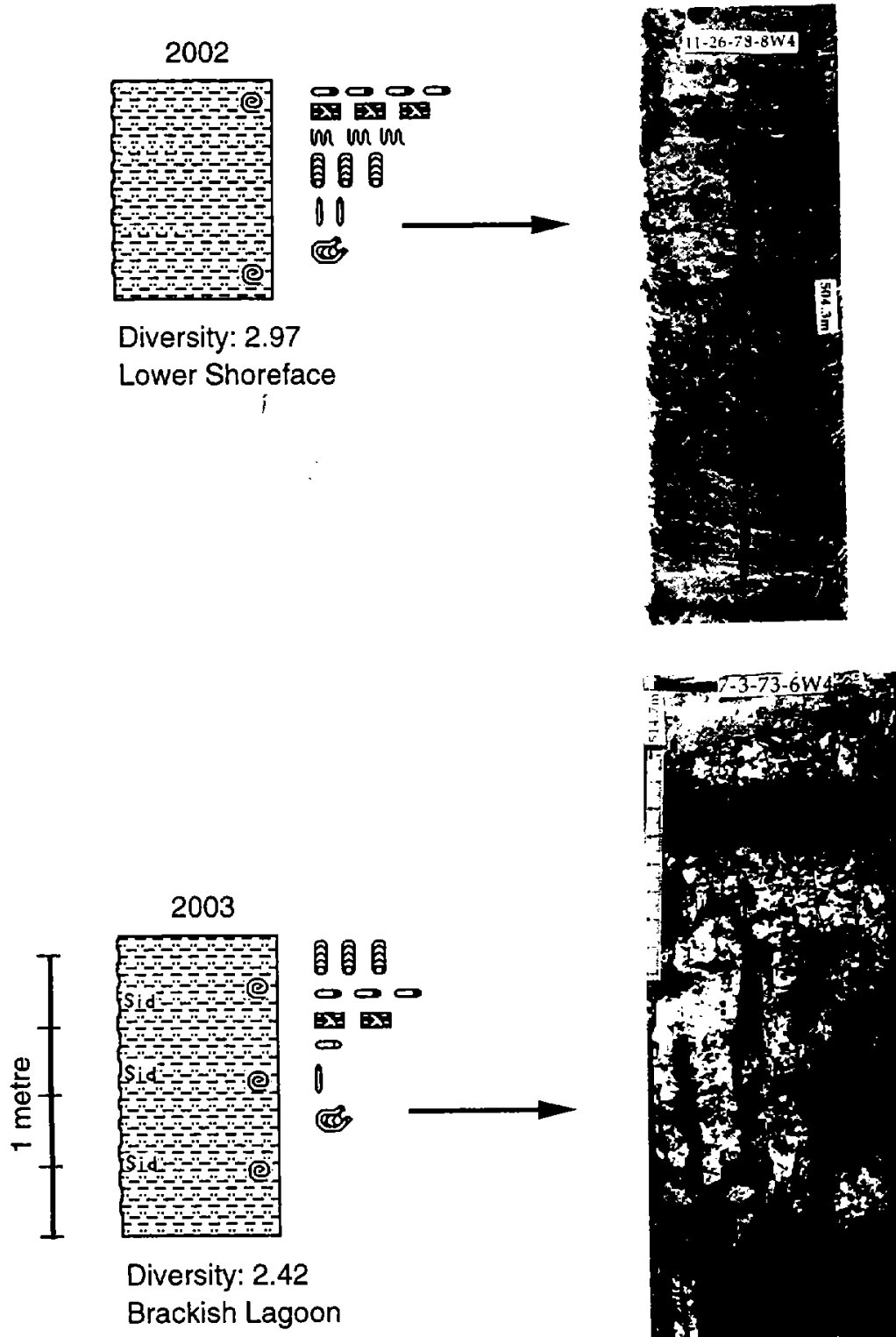


Fig. 5 b) Photo example of facies 2002 is from well 11-26-72-8W4 at 504.3m and facies 2003 is from well 7-3-73-6W4 at 514.7m

channel filling either as active point bars or passive abandonment fills. The succession ends in facies interpreted as brackish estuarine and periodically brackish lacustrine. The facies in the lower part of the succession are all interpreted as freshwater fluvial environments, and the absence of ich-

nofossils supports this conclusion. The upper part of the succession has a brackish overprint, expressed mainly by the distinctive ichnofossil assemblages as described above. The interbedded point bar deposits are interpreted as inclined heterolithic stratification, consistent with an estuarine envi-

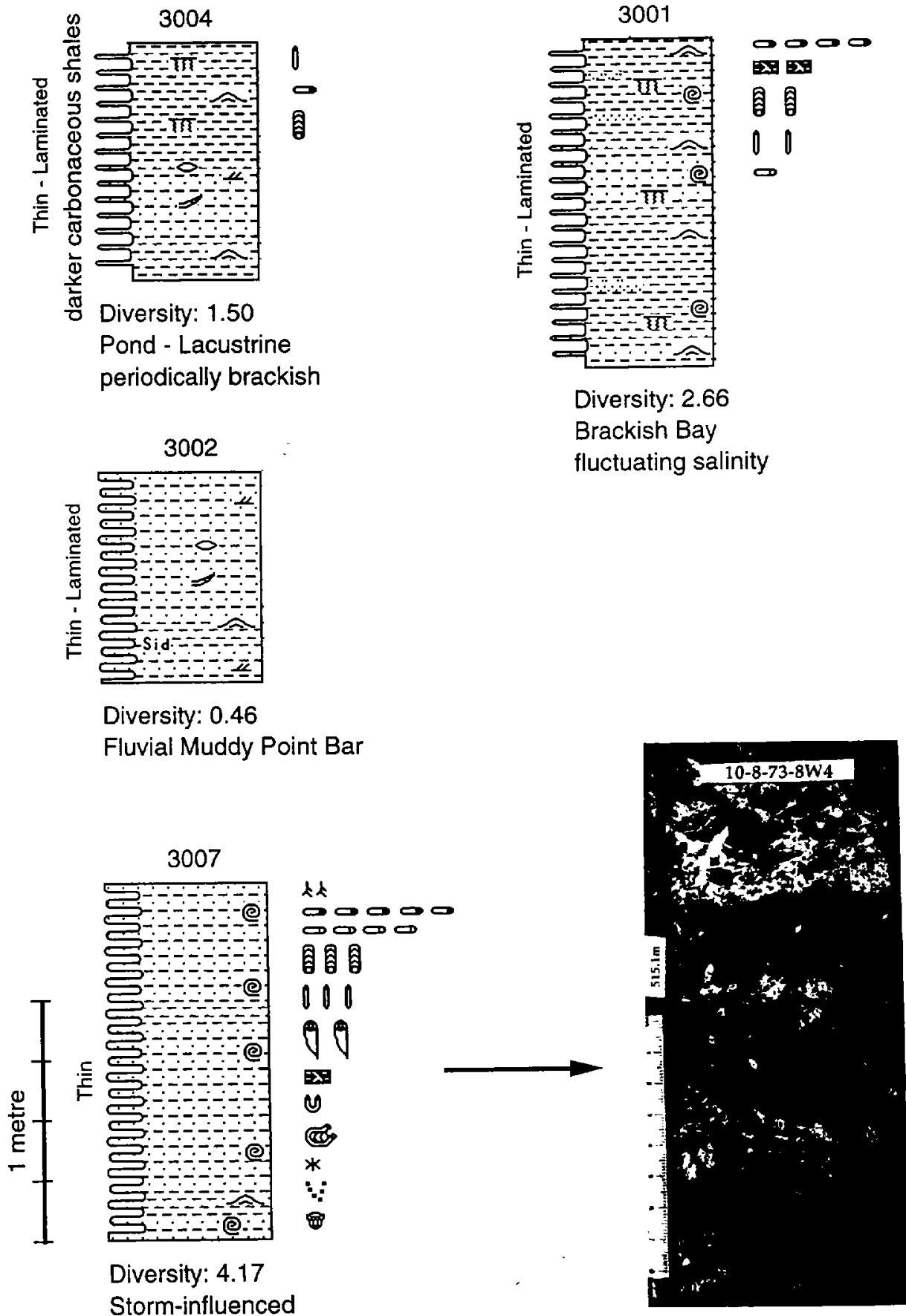


Fig. 6. Interbedded facies determined from cluster analysis. Relative length is scaled to the mean thickness. Diversity is the mean number of ichnofossil forms observed in all intervals assigned to the facies. Facies numbers are arbitrarily assigned for identification purposes only. For legend see figure 15. a) Photo example of facies 3007 is from well 10-8-73-8W4 at 515.1m.

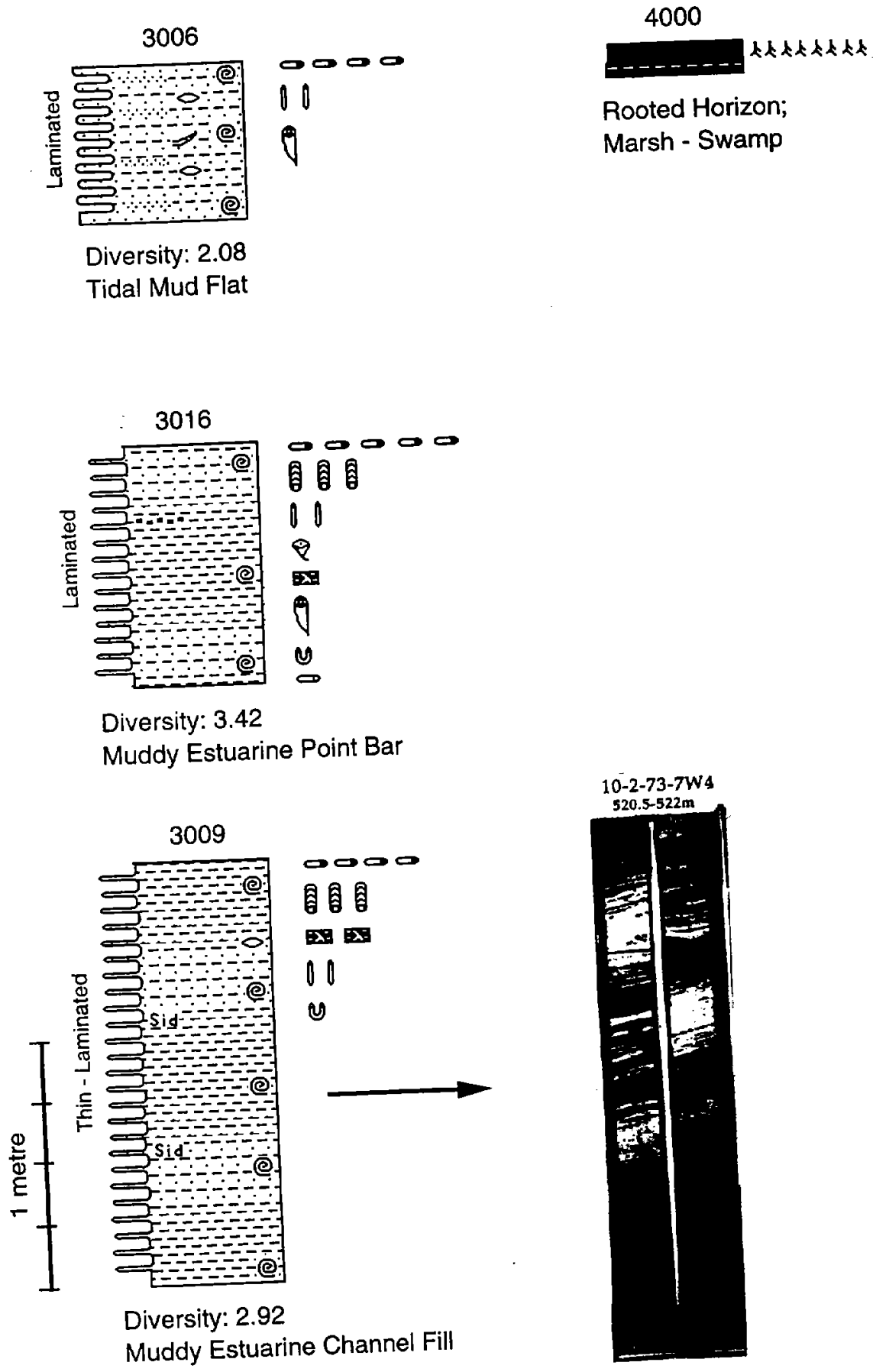
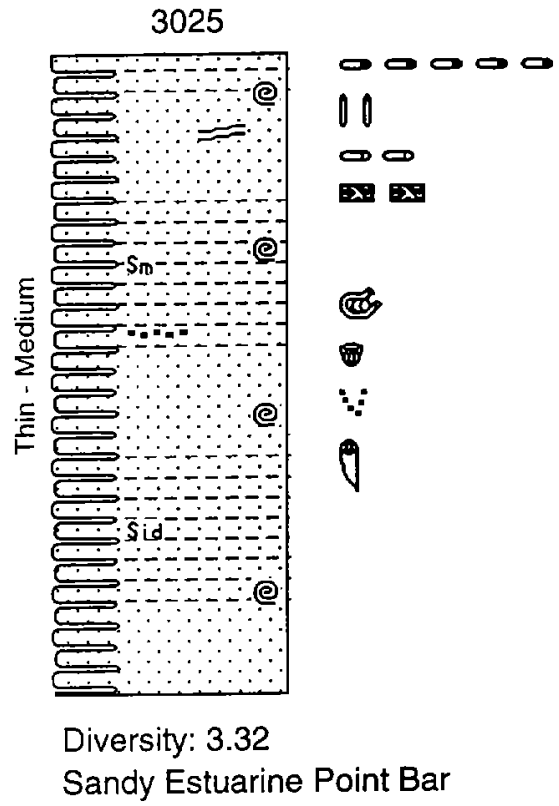
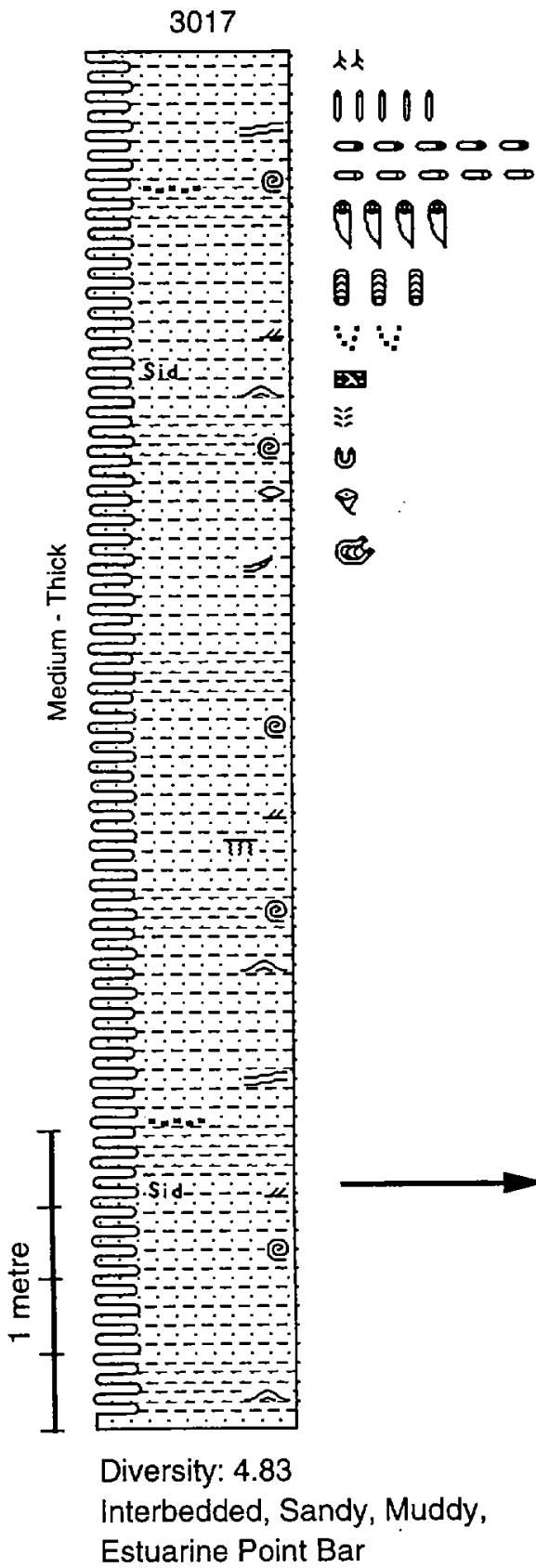


Fig. 6 b) Photo example of facies 3009 is from the interval 522.0m to 523.5m in well 10-2-73-7W4.



10-29-73-5W4
462-465m

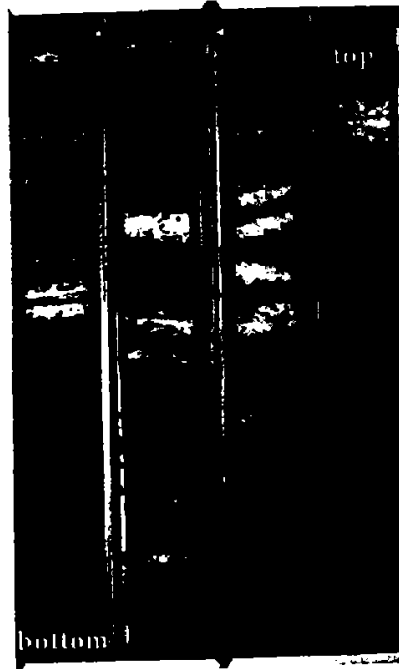


Fig. 6 c) Photo example of facies 3017 is from the interval 460.0m to 463.0m in well 10-29-73-5W4.

Table 1. TRANSITION FREQUENCY MATRIX

FACIES	2	3	5	1	2	2	3	4	2	1	3	1	1	3	3	1	2	3	3	3	2	ROW TOTAL		
2001	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
3001	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
5000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
1001	1	1	0	1	2	3	2	0	5	3	4	4	5	6	7	9	4	7	4	6	7	5	8	
2002	18	7	1	5	11	1	11	1	3	3	11	5	2	14	4	2	0	1	4	6	1	1	112	
2003	5	5	3	4	10	1	55	3	9	1	8	7	3	12	12	11	1	4	4	8	3	4	173	
3002	0	0	0	0	0	2	2	1	4	0	1	2	2	0	0	8	2	3	1	1	1	4	34	
4000	10	5	2	3	24	29	5	27	6	2	15	14	3	19	7	8	1	7	8	13	7	2	217	
2005	4	1	0	0	3	0	0	57	2	1	0	0	0	0	1	3	1	0	0	1	0	0	74	
1003	0	9	0	1	4	10	4	2	4	5	3	3	6	9	5	0	0	1	3	3	3	3	78	
3004	1	4	0	0	2	1	0	0	7	0	0	0	2	2	0	4	0	3	0	0	0	5	33	
1004	6	2	0	3	12	12	0	7	3	5	0	15	1	4	1	3	0	2	1	0	0	1	78	
1005	10	5	0	0	9	17	2	13	4	1	1	8	5	13	4	1	1	1	4	6	11	2	118	
3006	0	1	1	0	1	5	1	1	4	0	1	4	2	2	4	2	0	0	0	2	2	3	36	
3007	2	1	0	3	7	16	1	19	6	7	1	8	15	1	1	7	0	0	1	1	2	0	99	
3009	2	3	1	3	7	0	3	0	3	5	0	6	2	2	5	1	3	0	1	0	2	5	52	
1014	1	2	0	1	3	13	7	2	1	0	4	2	2	3	9	4	15	11	2	11	16	4	113	
1017	0	0	2	0	0	4	3	1	1	1	0	1	0	0	0	12	5	0	1	2	0	3	34	
2024	0	4	3	3	1	3	3	5	4	2	8	0	2	0	2	0	6	5	1	1	1	3	57	
3016	2	0	0	0	5	5	0	10	0	0	0	1	6	0	0	0	0	1	1	1	0	3	32	
3017	1	1	0	0	4	8	0	12	2	9	0	0	8	1	2	7	1	5	1	0	2	6	66	
3025	1	0	1	0	2	7	2	1	3	5	0	0	10	0	1	3	8	2	3	0	2	0	51	
2058	1	1	1	1	1	3	1	7	4	2	4	2	0	1	0	4	4	1	2	0	4	1	45	
TOTALS >	66	54	18	28	112	173	34	226	66	85	39	78	116	34	99	53	99	36	56	34	63	54	42	1665

Table 2. OBSERVED TRANSITION PROBABILITY MATRIX

FACIES	2	3	5	1	2	2	3	4	2	1	3	1	1	3	3	1	1	2	3	3	2	
2001	0.0000	0.0299	0.0000	0.1343	0.0745	0.0149	0.2090	0.0149	0.0000	0.0149	0.2090	0.0896	0.0000	0.0597	0.0299	0.0448	0.0000	0.0000	0.0299	0.0299	0.0000	0.0149
3001	0.0392	0.0000	0.0000	0.0196	0.1373	0.1961	0.0000	0.0196	0.0000	0.2157	0.0000	0.0392	0.1176	0.0392	0.0392	0.0196	0.0000	0.0000	0.0196	0.0196	0.0000	0.0784
5000	0.0000	0.1111	0.0000	0.3000	0.1111	0.0000	0.0000	0.0000	0.0556	0.0556	0.0556	0.1111	0.0000	0.0556	0.0000	0.1111	0.1667	0.0000	0.0000	0.0000	0.0556	0.1111
1001	0.0000	0.0370	0.0370	0.1111	0.1481	0.0370	0.1111	0.0000	0.1111	0.0370	0.0370	0.0741	0.0000	0.0370	0.0000	0.0370	0.0000	0.0741	0.0370	0.0000	0.0741	0.0000
2002	0.1607	0.0625	0.0089	0.0445	0.0982	0.0089	0.0982	0.0089	0.0268	0.0268	0.0982	0.0445	0.0179	0.1250	0.0357	0.0179	0.0000	0.0089	0.0357	0.0536	0.0089	0.0089
2003	0.0289	0.0289	0.0173	0.0211	0.0578	0.0058	0.3179	0.0173	0.0520	0.0058	0.0462	0.0405	0.0173	0.0694	0.0694	0.0636	0.0058	0.0231	0.0231	0.0462	0.0173	0.0231
3002	0.0000	0.0000	0.0000	0.0000	0.0588	0.0588	0.0294	0.0000	0.1176	0.0000	0.0294	0.0588	0.0588	0.0000	0.0000	0.2353	0.0588	0.0882	0.0294	0.0294	0.0294	0.1176
4000	0.0461	0.0230	0.0092	0.0118	0.1106	0.1335	0.0230	0.1244	0.0276	0.0092	0.0691	0.0645	0.0138	0.0876	0.0323	0.0369	0.0046	0.0323	0.0369	0.0599	0.0323	0.0092
2005	0.0541	0.0135	0.0000	0.0000	0.0405	0.0000	0.7703	0.0270	0.0135	0.0000	0.0000	0.0000	0.0135	0.0405	0.0135	0.0000	0.0000	0.0000	0.0135	0.0000	0.0000	0.0000
1003	0.0000	0.1154	0.0000	0.0128	0.0513	0.1282	0.0513	0.0256	0.0513	0.0641	0.0000	0.0385	0.0385	0.0769	0.1154	0.0541	0.0000	0.0128	0.0385	0.0385	0.0385	0.0385
3004	0.0303	0.1212	0.0000	0.0000	0.0606	0.0606	0.0303	0.0000	0.0000	0.2121	0.0000	0.0000	0.0606	0.0606	0.0000	0.1212	0.0000	0.0909	0.0000	0.0000	0.0000	0.1515
1004	0.0769	0.0256	0.0000	0.0385	0.1518	0.1518	0.0000	0.0897	0.0385	0.0641	0.0000	0.1923	0.0128	0.0513	0.0128	0.0385	0.0000	0.0256	0.0128	0.0000	0.0000	0.0128
1005	0.0847	0.0424	0.0000	0.0000	0.0763	0.1441	0.0169	0.1102	0.0319	0.0085	0.0085	0.0678	0.0424	0.1102	0.0319	0.0085	0.0085	0.0095	0.0339	0.0508	0.0932	0.0169
3006	0.0000	0.0278	0.0278	0.0900	0.0278	0.1389	0.0278	0.0278	0.1111	0.0000	0.0278	0.1111	0.0556	0.0556	0.1111	0.0556	0.0556	0.0000	0.0000	0.0556	0.0556	0.0556
3007	0.0202	0.0101	0.0000	0.0303	0.0707	0.1616	0.0101	0.1919	0.0606	0.0707	0.0101	0.0808	0.0354	0.0177	0.0265	0.0177	0.0265	0.0177	0.0000	0.0101	0.0101	0.0202
3009	0.0385	0.0577	0.0192	0.0577	0.0577	0.1346	0.0000	0.0577	0.0000	0.0577	0.0362	0.0000	0.1154	0.0385	0.0385	0.0962	0.0192	0.0577	0.0000	0.0192	0.0000	0.0385
1014	0.0088	0.0177	0.0000	0.0088	0.0265	0.1150	0.0619	0.0177	0.0088	0.0000	0.0354	0.0177	0.0177	0.0265	0.0796	0.0354	0.1327	0.0973	0.0177	0.0973	0.1416	0.0354
1017	0.0000	0.0000	0.0588	0.0000	0.0000	0.1176	0.0882	0.0294	0.0294	0.0294	0.0000	0.0294	0.0000	0.0000	0.0000	0.3529	0.1471	0.0000	0.0294	0.0588	0.0000	0.0000
2024	0.0000	0.0702	0.0526	0.0526	0.0175	0.0526	0.0526	0.0877	0.0702	0.0351	0.1404	0.0000	0.0351	0.0000	0.0000	0.1053	0.0877	0.0175	0.0702	0.0175	0.0175	0.0526
3016	0.0625	0.0000	0.0000	0.0000	0.1562	0.1562	0.0000	0.3125	0.0000	0.0000	0.0000	0.0312	0.1875	0.0000	0.0000	0.0000	0.0000	0.0000	0.0312	0.0312	0.0312	0.0000
3017	0.0152	0.0152	0.0000	0.0000	0.0606	0.1212	0.0000	0.1818	0.0303	0.1364	0.0000	0.0000	0.1212	0.0152	0.0303	0.0303	0.1061	0.0152	0.0758	0.0152	0.0000	0.0303
3025	0.0196	0.0000	0.0196	0.0000	0.0392	0.1373	0.0392	0.0196	0.0588	0.0980	0.0000	0.0000	0.1961	0.0000	0.0196	0.0588	0.1569	0.0392	0.0588	0.0000	0.0392	0.0000
2058	0.0222	0.0222	0.0222	0.0222	0.0222	0.0667	0.0222	0.1556	0.0889	0.0444	0.0889	0.0444	0.0000	0.0222	0.0000	0.0889	0.0889	0.0222	0.0444	0.0000	0.0889	0.0222

Table 3. IPF EXPECTED (RANDOM) TRANSITION FREQUENCY MATRIX

ITERATIVE PROPORTIONAL FITTING METHOD WITH TÜRK'S NORMALIZED RESIDUALS

FACIES	2	3	5	1	2	2	3	4	2	1	3	1	1	3	3	1	1	2	3	3	3	2
2001	2.18	0.71	1.11	4.70	7.59	1.36	10.31	2.70	3.48	1.55	3.20	4.88	1.36	4.11	2.14	4.15	1.44	2.26	1.35	2.56	2.18	1.69
3001	2.03	0.54	0.84	3.55	5.73	1.02	7.79	2.04	2.63	1.17	2.41	3.69	1.03	3.11	1.61	3.14	1.08	1.71	1.02	1.94	1.64	1.27
5000	0.70	0.57	0.29	1.23	1.98	0.35	2.69	0.70	0.91	0.41	0.83	1.27	0.35	1.07	0.56	1.08	0.37	0.59	0.35	0.67	0.57	0.44
1001	1.06	0.86	0.28	1.85	2.99	0.53	4.06	1.06	1.37	0.61	1.26	1.92	0.53	1.62	0.84	1.63	0.57	0.89	0.53	1.01	0.86	0.66
2002	4.63	3.75	1.23	3.92	13.08	2.34	17.77	4.65	6.00	2.68	5.51	8.42	2.34	7.09	3.68	7.15	2.47	3.90	2.33	4.41	3.75	2.91
2003	7.48	6.06	1.98	3.10	13.08	3.78	28.72	7.51	9.71	4.33	8.91	13.60	1.78	11.46	5.95	11.56	4.00	6.31	3.77	7.14	6.06	4.70
4000	1.34	1.09	0.35	0.55	2.34	3.78	5.13	1.34	1.73	0.77	1.59	2.43	0.68	2.05	1.06	2.07	0.71	1.13	0.67	1.27	1.08	0.84
2005	9.81	7.95	2.60	4.06	17.16	27.74	4.95	9.86	12.73	5.68	11.68	17.85	4.96	15.03	7.81	15.17	5.25	8.28	4.95			

Table 4. OBSERVED MINUS IPF EXPECTED TRANSITION FREQUENCIES

FACIES	2	3	5	1	2	2	3	4	2	1	3	1	1	3	3	3	1	1	2	3	3	3	2	
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
	1	1	0	1	2	3	2	0	5	3	4	4	5	6	7	9	4	7	4	6	7	5	8	
2001		-2.18	1.29	-1.11	4.30	-2.59	-0.16	3.69	-1.70	-3.48	-0.55	10.80	1.12	-1.36	-0.11	-0.14	-1.15	-1.44	-2.26	0.65	-0.56	-2.18	-0.69	
3001	-0.03		-0.54	0.16	3.45	4.27	-1.02	-6.79	-2.04	8.37	-1.17	-0.41	2.31	0.97	-1.11	-0.61	-3.14	-1.08	-1.71	-0.02	-0.94	-1.64	2.73	
5000	-0.70	1.43		-0.29	0.77	-1.98	-0.35	-2.69	-0.70	0.09	0.59	0.17	0.73	-0.35	-0.07	-0.56	0.92	2.63	-0.59	-0.35	-0.67	0.43	1.56	
1001	-1.06	0.14	0.72		3.08		-2.08	1.01	0.47	-1.06	-1.06	1.63	0.39	-0.26	0.08	-0.53	-0.62	-0.84	-0.63	-0.57	1.11	0.47	-1.01	1.14
2002	13.37	3.25	-0.23	3.08																				
3003	-2.48	-1.06	1.02	0.90	-3.08		-2.78	26.28	-4.51	-0.71	-3.33	-0.91	-6.60	-0.78	0.54	6.05	-0.56	-3.00	-2.31	0.23	0.86	-3.08	3.16	
3002	-1.34	-1.08	-0.38	-0.55	-2.34	-1.78																		
4000	0.19	-2.95	-0.79	-1.23	-2.19	-8.39	-1.50	45.61	17.14	-6.73	-3.68	3.32	-3.85	-1.96	3.97	-0.81	-7.17	-4.25	-1.28	3.95	3.64	-0.98	-0.70	
2005	1.03	-1.40	-0.84	-0.31	-1.53	1.06	2.40	-10.15	0.82															
1003	-3.16	2.95	-0.34	-0.54	-0.27	-1.68	0.34	-4.99	-1.31	5.31														
3004	-0.30	-0.55	-0.83	1.70	6.49	3.09	-1.59	-5.09	-0.16	0.91	-1.82													
1004	2.85	-0.55	-0.83	1.70	6.49	3.09	-1.59	-5.09	-0.16	0.91	-1.82													
1005	5.11	1.04	-1.39	-2.02	0.45	1.18	-0.47	-5.77	-0.91	-5.34	-1.83	2.18												
3006	-1.41	-0.15	0.63	-0.59	-1.47	1.00	0.29	-4.43	-0.42	2.16	-0.82	-0.68	1.43											
3007	-2.05	-2.28	-1.07	1.32	-0.09	4.54	-1.05	3.43	1.93	1.74	-1.35	3.17	7.63	-1.05										
3009	-0.07	1.33	0.45	2.14	-0.51	1.16	-1.04	-4.94	-2.08	0.32	3.80	-2.46	2.24	0.96	-1.17									
1014	-3.63	-1.75	-1.23	-0.92	-1.50	-0.09	4.66	-15.78	-3.65	-6.01	1.32	-3.51	-6.42	0.66	1.91	0.32								
1017	-1.34	-1.08	1.65	-0.55	-2.34	0.22	2.32	-4.14	-1.34	-0.74	0.23	-1.59	-1.43	-0.68	-1.05	-1.06	9.93							
2024	-2.27	2.16	2.40	2.06	-2.97	-3.42	1.85	-3.72	1.72	-0.95	6.69	-2.70	-2.33	-1.15	-1.48	-1.81	2.49	3.79						
3016	0.74	-1.02	-0.33	-0.52	2.80	1.45	-0.63	5.17	-1.26	-1.63	-0.73	-0.50	3.71	-0.64	-1.93	-1.00	-1.94	-0.67	-0.06					
3017	-1.64	-1.14	-0.70	-1.09	-0.62	0.54	-1.33	1.86	-0.65	-5.67	-1.53	-3.14	3.20	-0.33	-2.04	-0.10	2.92	-0.41	2.77	-0.33				
3025	-1.03	-1.64	0.46	-0.84	-1.55	1.27	0.98	-6.79	0.96	2.37	-1.17	-2.41	6.31	-1.03	-2.11	1.39	4.86	0.92	1.29	-1.02	0.06			
2058	-0.78	-0.44	0.53	0.26	-2.11	-2.02	0.10	0.18	2.22	-0.31	2.97	-0.12	-3.23	0.10	-2.72	2.59	1.25	0.65	0.50	-0.90	2.30	-0.44	-1.27	

CHI SQUARE STATISTIC = 1455.08 WITH 483 DEGREES OF FREEDOM

Table 5. STANDARDISED RESIDUALS

FACIES	2	3	5	1	2	2	3	4	2	1	3	1	1	3	3	3	1	1	2	3	3	3	2
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	1	1	0	1	2	3	2	0	5	3	4	4	5	6	7	9	4	7	4	6	7	5	8
2001		-0.51	0.40	-0.23	1.20	-0.62	-0.03	1.04	-0.39	-0.86	-0.29	2.22	0.36	-0.30	0.03	0.03	-0.24	-0.32	-0.54	0.23	-0.09	-0.51	-0.12
3001	0.05		-0.08	0.10	0.97	1.19	-0.21	-1.73	-0.48	2.27	-0.05	0.67	0.32	-0.23	-0.10	-0.77	-0.23	-0.39	0.06	-0.19	-0.37	0.78	
5000	-0.12	0.44		-0.02	0.27	-0.46	-0.03	-0.55	-0.12	0.09	0.22	0.11	0.25	-0.03	0.04	-0.09	0.30	0.76	-0.09	-0.03	-0.12	0.18	0.47
1001	-1.22	0.10	0.25		0.37	0.33	0.18	-0.22	-0.22	0.49	0.16	-0.01	0.08	-0.08	-0.10	-0.16	-0.11	-0.09	0.35	0.18	-0.21	0.36	-0.11
2002	2.80	0.92	0.00	0.88		-0.48	-0.29	-1.73	-0.90	-0.73	0.15	1.51	-0.84	-0.03	1.89	0.15	-1.30	-0.59	-0.71	0.50	0.48	-0.87	-0.44
3003	-0.59	-0.22	0.33	0.30	-0.75		-0.67	7.01	-1.13	-0.13	-0.82	-1.18	-1.68	-0.15	0.20	1.66	-0.09	-0.73	-0.55	0.12	0.29	-0.75	-0.12
3002	-0.29	-0.22	-0.03	-0.09	-0.56	-0.41		-0.77	-0.03	0.66	-0.14	-0.09	-0.05	0.41	-0.48	-0.22	1.63	0.40	0.56	0.15	-0.01	0.04	0.90
4000	0.11	-0.72	-0.10	-0.22	1.87	0.39	0.07	4.32	-1.72	-0.91	0.94	-0.96	-0.46	1.11	-0.15	-1.83	-1.06	-0.28	0.87	1.02	-0.19	-1.04	
2005	0.33	-0.31	-0.15	-0.26	-0.52	-2.15	-0.33	12.12	-0.43	-0.13	-0.87	-1.36	-0.34	-1.14	-0.30	-0.36	-0.09	-0.60	-0.33	-0.42	-0.57	-0.43	
1003	-0.77	1.76	-0.16	-0.02	-0.34	0.34	0.70	-2.62	0.28														
3004	-0.02	0.84	-0.03	-0.08	-0.01	-0.38	0.15	-1.26	-0.28	1.47													
1004	0.81	-0.08	-0.16	0.51	1.78	0.88	-0.36	-1.29	0.02	0.30	-0.42												
1005	1.41	0.34	-0.28	-0.47	0.18	0.90	-0.06	-1.46	-0.18	-1.35	-0.42	0.64											
3006	-0.31	0.02	0.23	-0.09	-0.33	0.33	0.14	-1.13	-0.05	0.63	-0.16	-0.12	0.44										
3007	-0.48	-0.54	-0.22	0.41	0.04	1.26	-0.22	0.97	0.57	0.52	-0.29	0.90	2.08	-0.22									
3009	0.04	0.41	0.18	0.63	-0.10	0.37	-0.21	-1.24	-0.49	0.15	1.07	-0.59	0.65	0.31	-0.25								
1014	-0.90	-0.40	-0.26	-0.18	-1.29	0.04	1.29	-4.11	-0.90	-1.53	0.41	-0.87	-1.64	0.24	0.57	0.14							
1017	-0.29	-0.23	0.50	-0.09	-0.56	0.12	0.68	-1.03	-0.03	-0.12	-0.36	-0.32	-0.12	-0.48	-0.22	0.48							
2024	-0.54	0.63	0.70	0.61	-0.72	-0.84	0.55	-0.92	0.52	-0.19	1.83	-0.65	-0.50	-0.24	-0.33	-0.42	0.72	1.06					
3016	0.26	-0.21	-0.03	-0.08	0.80	0.64	-0.11	1.43	-0.27	-0.37	-0.13	-0.07	1.04	-0.11	-0.45	-0.20	-0.45	-0.12	0.05				
3017	-0.37	-0.24	-0.12	-0.23	-0.10	0.20	-0.29	0.55	-0.11	1.53	-0.34	-0.77	0.91	-0.03	-0.48	0.03	0.83	-0.05	0.79	-0.03			
3025	-0.21	-0.37	0.18	-0.16	-0.35	0.40	0.32	-1.73	0.32	0.69	-0.25	-0.58	1.73	-0.21	-0.50	0.43	1.35	0.30	0.40	-0.21	0.08		
2058	-0.14	-0.05	0.20	0.13	-0.50	-0.47	0.09	0.11	0.65	-0.02	0.85	0.03	-0.79	0.09	-0.66	0.74	0.39	0.07	0.19	-0.18	0.67	-0.05	

Non-random residuals significant at 5% level or better: @90% confidence: Bold @95% confidence: Bold and Underlined

Table 6. SIGNIFICANCE

PROBABILITY OF OBSERVED OR GREATER NUMBER OF TRANSITIONS OCCURRING AT RANDOM

FACIES	2	3	5	1	2	2	3	4	2	1	3	1	1	3	3	3	1	1	2	3	3	3	2
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	1	1	0	1	2	3	2	0	5	3	4	4	5	6	7	9	4	7	4	6	7	5	8
2001		-0.1095	0.1591	-0.3259	0.0437	-0.2152	-0.6059	0.1408	-0.2429	-0.0279	-0.5377	0.0000	0.3627	-0.2538	-0.6060	-0.6392	-0.3977	-0.2343	-0.0999	0.3915	-0.5253	-0.1095	-0.4949
3001	-0.6688		-0.5828	0.5711	0.0619	0.0554	-0.3554	-0.0022	-0.1250	0.0000	-0.3049	-0.5633	0.1612	0.2737	-0.3920	-0.5172	-0.0393	-0.3342	-0.1755	-0.7272	-0.4188	-0.1881	0.0384
5000	-0.4893	0.1091		-0.7464	0.3493	-0.1226	-0.6995	-0.0543	-0.4877	0.6066	0.3165	0.5743	0.3676	-0.6993	-0.7080	-0.5676	0.2957	0.0058	-0.5483	-0.6998	-0.5060	0.4384	0.0706
1001	-0.3401	0.5813	0.2453		0.2809	-0.3499	0.4168	-0.4053	-0.3385	0.1557	0.4615	-0.6394	0.5822	-0.5829	-0.5125	-0.4254	-0.5976	0.5648	0.2237	0.4164	-0.3577	0.2108	-0.5107
2002	0.0000	0.0827	-0.6530	0.0439		-0.3313	-0.3194	-0.0464	-0.0508	-0.1436	0.5031	0.0223	-0.1458	-0.5848	0.0113	0.5045	-0.0232	-0.0820	-0.0950	0.2061	0.2805	-0.1077	-0.2098
3003	-0.2374	-0.4329	0.3181	0.3749	-0.2345		-0.1067	0.0000	-0.0548	-0.4925	-0.0678												

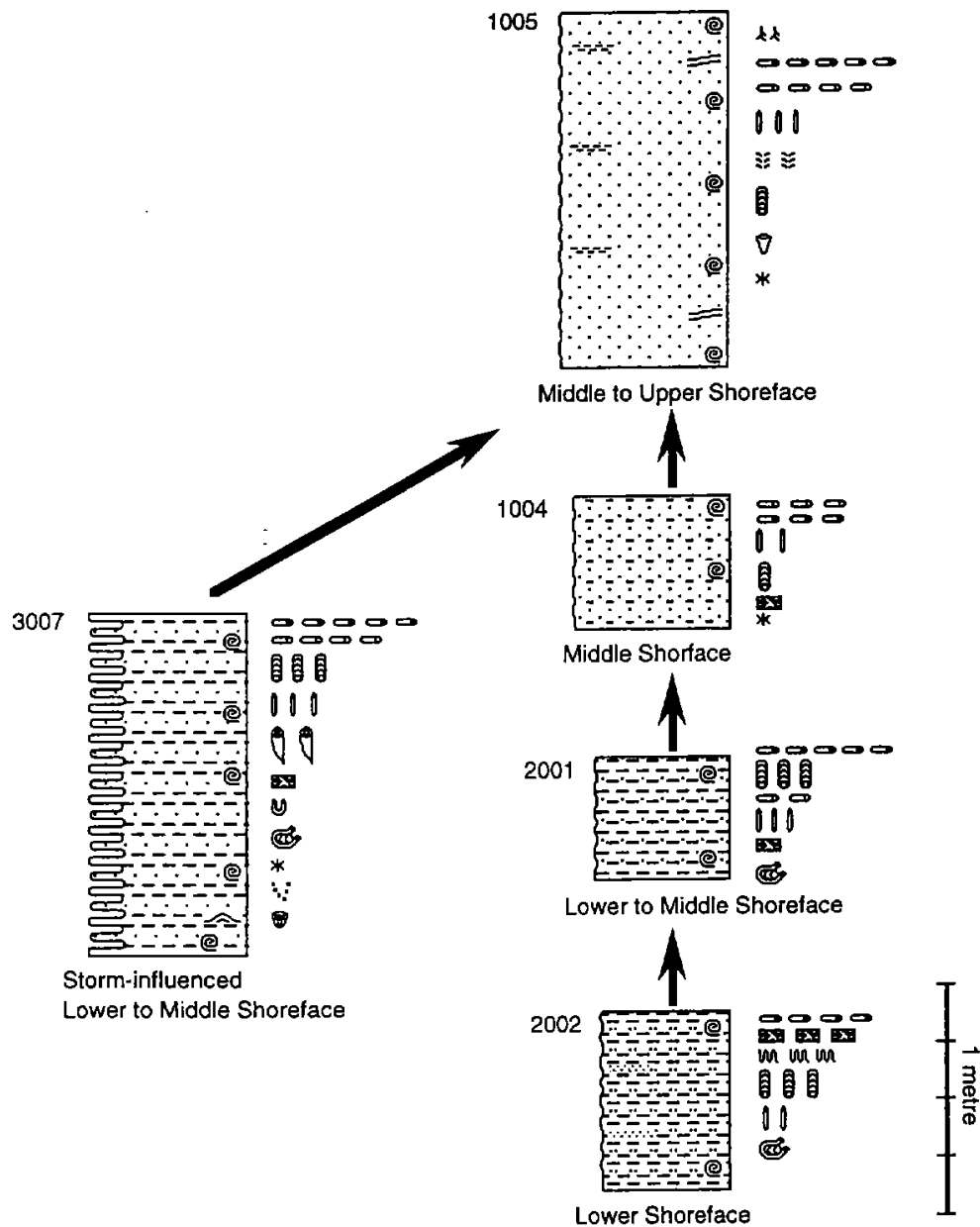


Fig. 7. Significant facies succession resolved from Markov analysis with 95% confidence, and interpreted as a low energy prograding shoreface. For legend see Figure 15.

ronment (Thomas *et al.*, 1987; Smith, 1988; Ranger and Pemberton, 1992)

A third significant facies succession from the Markov analysis (Fig. 9) is a simple system interpreted as marsh/lagoon overlain by rooted horizons, coal swamps, rooted marsh mud and oxidized muddy paleosols.

CROSS SECTIONS FROM DIGITIZED GEOPHYSICAL LOGS

Statistical facies analysis requires a regional context. This can be done using geophysical well logs or seismic data, which provide much greater coverage of the subsurface than core alone. For lithofacies detection, the gamma-ray log is the preferred tool in this study. The other commonly available logs, the SP and resistivity logs, are both influenced by the

bitumen saturation in the sand and also by extreme variability in formation water salinity, which is common in the shallow Mannville Group of northeast Alberta. Working cross-sections were produced in both east-west (Township) and north-south (Range) orientations over the whole of the south Athabasca study area. The unique digital display of gamma-ray logs for a given well as twinned mirror images allowed rapid visual correlation of stratigraphic units within the McMurray Formation.

The resistivity log is useful for determining the top of the Wabiskaw Member, which is a basin-wide shale with a distinct resistivity signature, and probably indicates a condensed section. The contact between the top of the McMurray Formation and the Wabiskaw Member is not obvious on the gamma-ray

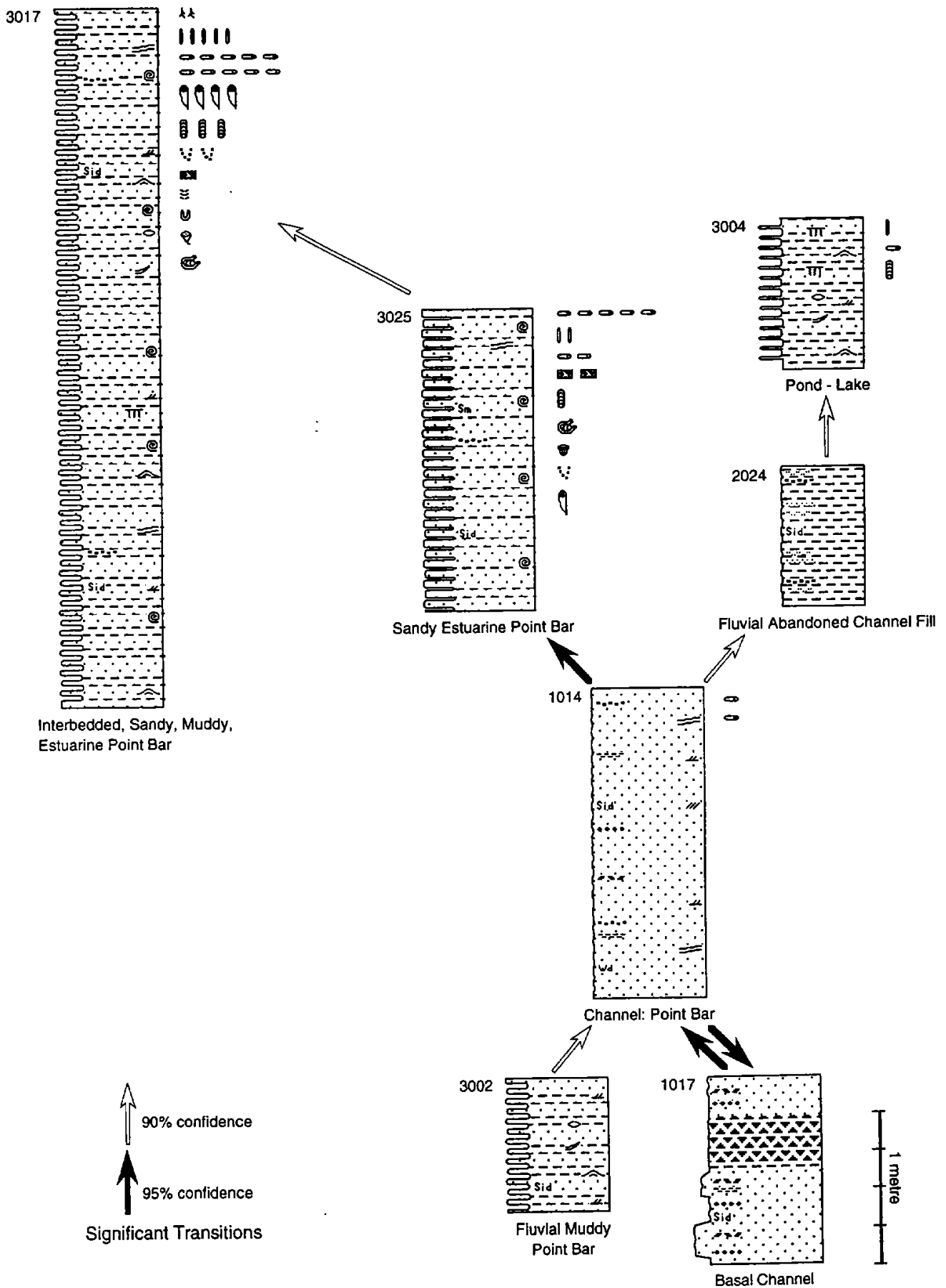


Fig. 8. Succession of facies resolved from Markov analysis, and interpreted as complex channel fills. Significant transitions are shown for both 90 and 95% confidence level. Succession is freshwater fluvial towards the base, becoming brackish estuarine towards the top. For legend see Figure 15.

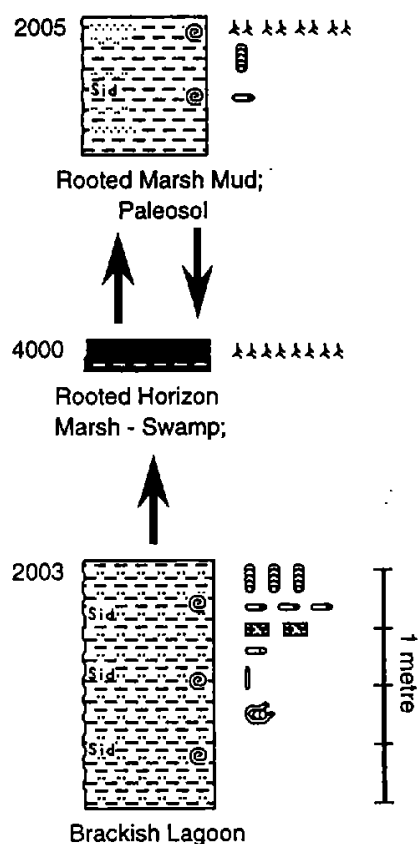


Fig. 9. Significant succession of facies resolved from Markov analysis with 95% confidence, and interpreted as marsh/lagoon overlain by rooted horizons, coal swamps, rooted marsh mud and oxidized muddy paleosols. For legend see Figure 15.

and the Wabiskaw Member is not obvious on the gamma-ray logs or any other log, and this horizon had to be tied into the core observations. The contact is almost always distinctive in core, being characterized by a change in mineralogy from the quartz arenite of the McMurray Formation to the glauconitic litharenite of the Wabiskaw Member. There is also a distinct change in ichnofossil assemblages from a stressed, apparently brackish assemblage in the McMurray Formation to a robust, apparently more fully marine assemblage in the Wabiskaw Member. The sub-Cretaceous unconformity also is rarely recognisable on the gamma-ray logs, but is distinctive on density logs.

Despite the commonly held belief that there are no regionally correlatable horizons in the McMurray Formation, the processed, standardized, digital log displays reveal that several regional shale units are readily discerned (Fig. 10). Furthermore, these shales bound stratigraphic units whose log signatures are distinct and relatively persistent over a wide area, in both an east-west (Fig. 10a) and north-south direction (Fig. 10b). The three upper stratigraphic units are especially obvious. These are here termed the "red", "green" and "blue" intervals from top to bottom, rather than assigning rank designation because additional study may allow further subdivision. These intervals can be correlated over much of the south

Athabasca area. Both the upper "red" and the lower "blue" units have a distinct gamma ray signature indicating that they constitute, for the most part, a simple coarsening upward interval, 8 to 12 metres in thickness. The middle "green" interval has a more complex log signature, and may represent amalgamated units. The upper "red" interval, which constitutes the top of the McMurray Formation, appears to have an erosional upper boundary (see Fig. 10b, well 14-18-74-12W4).

The distinct signatures of the three units cannot, however, be correlated through all wells without fail. There are many areas where the signature is anomalous, suggesting that the correlatable unit has been eroded. Maps of the distribution and thickness of the three intervals demonstrate this (Figs. 11, 12, 13). The areas in black are areas where the gamma ray signature is anomalous. These anomalous signatures indicate a wide variety of fining upwards, sandy, shaly or heterogeneous fills with no discernible pattern. Many of the wells with anomalous signatures form contiguous linear areas suggestive of incised valleys a few kilometres wide and up to 75 kilometres long (e.g. Fig. 1 along Twp. 77).

DISCUSSION

The results of the facies analysis and the regional gamma-ray log correlations complement each other and suggest a new, comprehensive, stratigraphic framework for the McMurray Formation. The McMurray Formation did aggrade due to Early Cretaceous sea-level rise, but the standard belief that the overall vertical record reflects a transition from fluvial through estuarine to marine is a gross over-simplification.

The McMurray Formation accumulated as a series of thin parasequences, 8 to 12 metres in thickness, consisting of prograding shoreface deposits that are probably the result of eustatic sea-level fluctuation. The McMurray sub basin developed near the craton at the eastern edge of the foreland basin, on the opposite side of the basin from the actively subsiding foreland trough, and underwent relatively little subsidence. Given little accommodation space during each sea-level rise, shoreface deposits probably prograded rapidly and over long distances. Little is known of the rates and volumes of sediment input, but the McMurray valley system did drain a major part of west-central Canada, which included large tracts of Jurassic siliciclastic sediments, and all of the southwestern Canadian Shield during late Aptian to early Albian time (Ranger, 1984). One may thus surmise that the basin was not starved.

Ichnofossil evidence indicates that the basin never reached fully marine conditions during aggradation of the McMurray Formation. This is probably due to the restricted nature of the northern part of the basin caused by the convergence of the Grosmont High in the west and the Canadian Shield in the east. The continued influx of fresh water from the McMurray valley system even during highstand sea level induced brackish conditions, and the constriction in the basin prevented rapid dispersion into the Boreal Sea to the north.

Additionally, because of the low rate of subsidence, even a minor sea-level drop would have wide-reaching effects, expos-

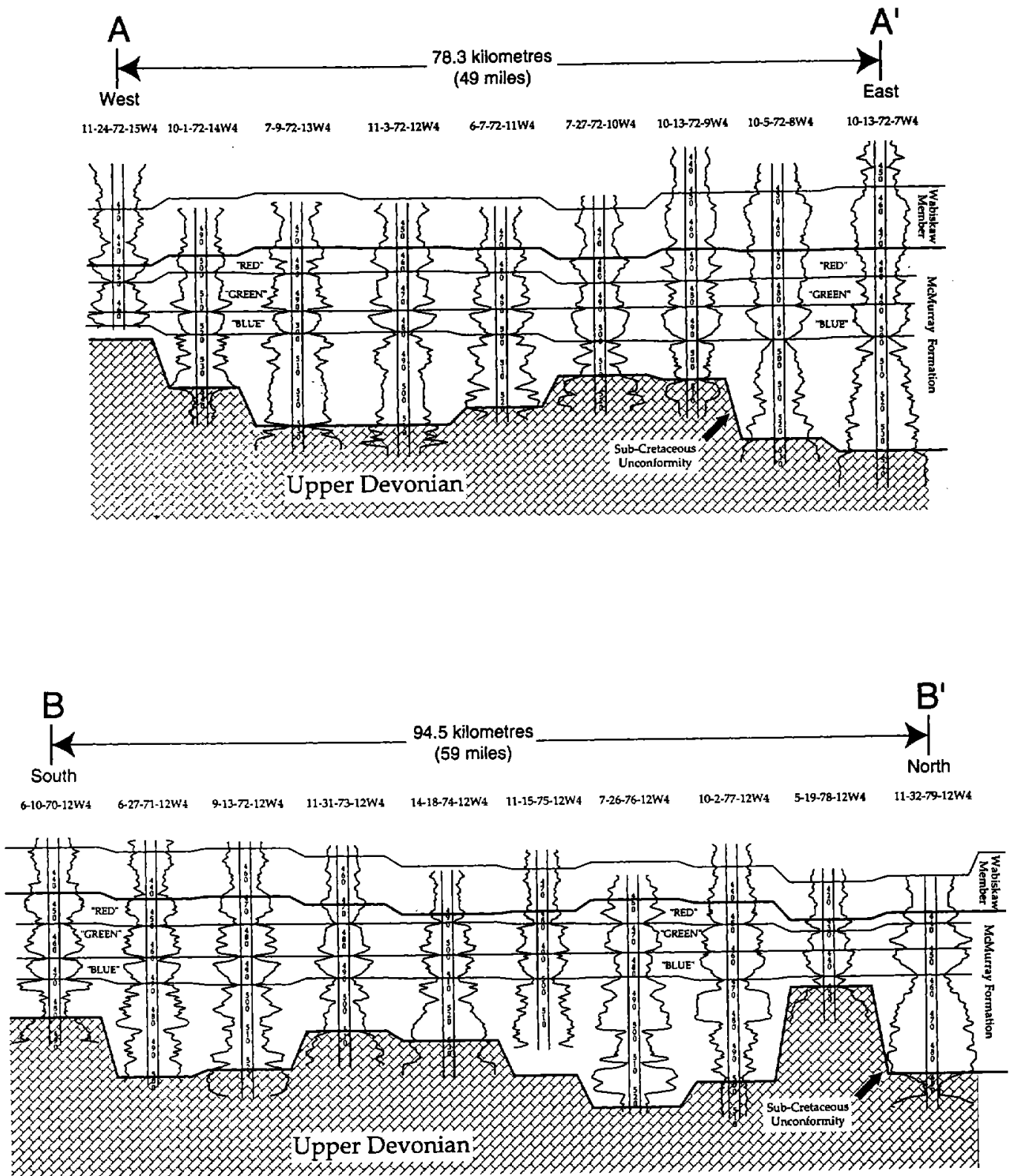


Fig. 10. These cross-sections demonstrate the existence of regional, correlatable parasequences or parasequence sets in the McMurray Formation. Three are shown here designated "Red", "Green" and "Blue", which have been mapped over the entire South Athabasca area (Figures 11, 12 and 13). For convenience, the datum is the top of the "Blue" parasequence. The log curves are twinned gamma-ray plots in mirror image, which greatly facilitates the visual correlation of the shapes. For locations, see A-A', and B-B' in Figures 11, 12 and 13. A-A' East-west cross-section across township 72 at one well per township. B-B' North-south cross-section across range 12 at one well per township.

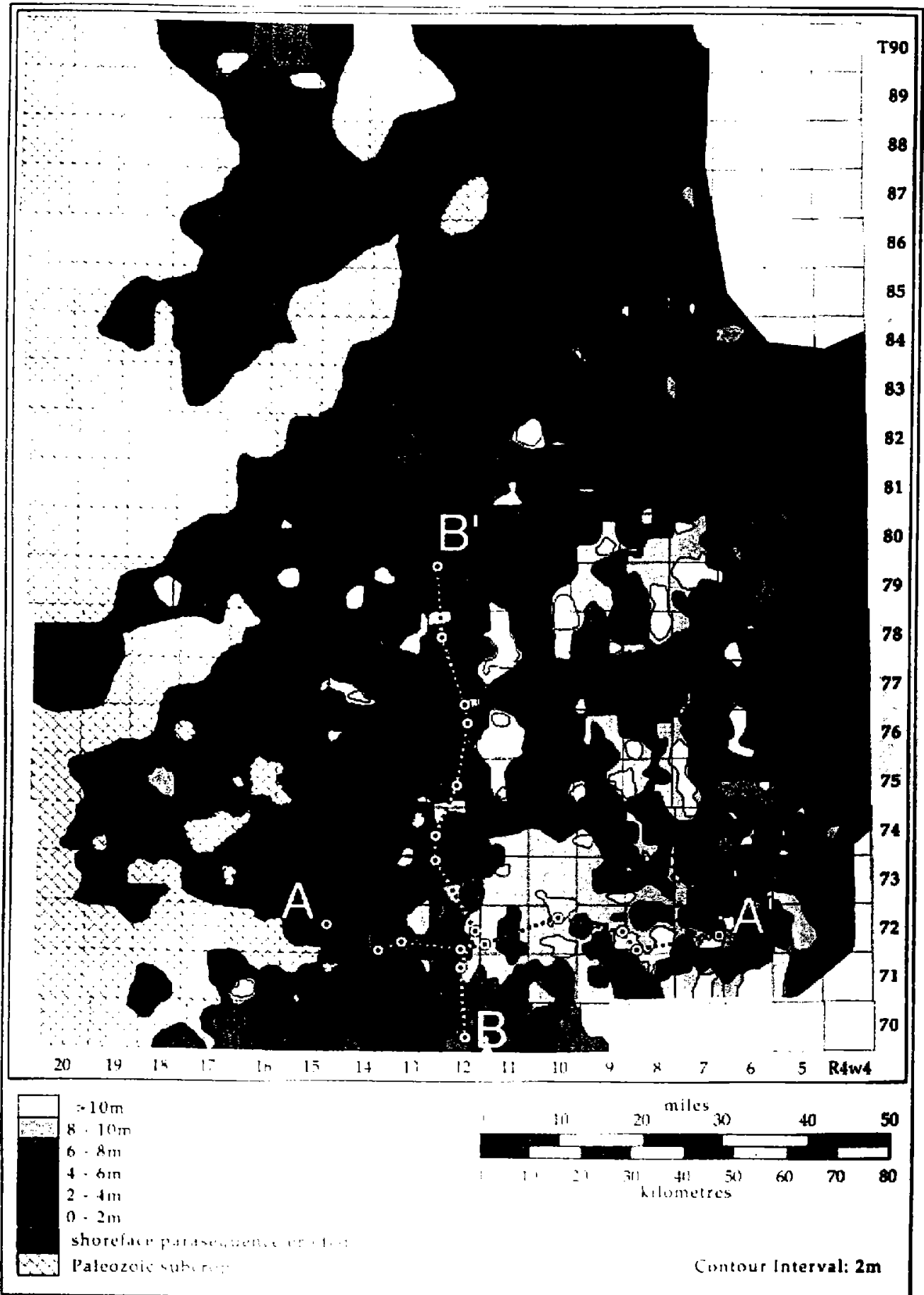


Fig. 11. Isopach of the Blue Bay aquifer on M. Murray Farm etc. A-A' and B-B' refer to the cross-sections in Figure 10.

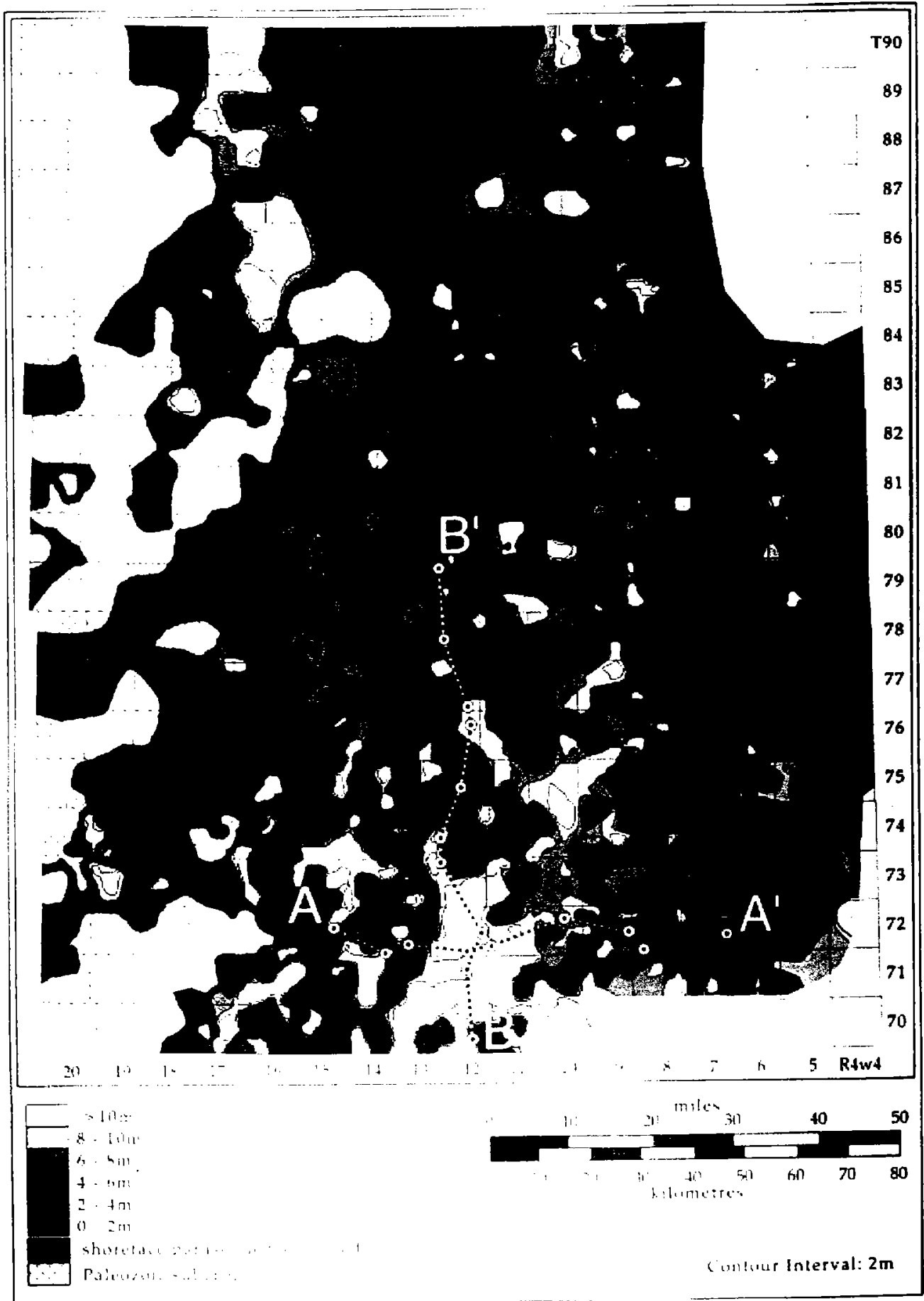


Fig. 12. Isopach of the Murrumbidgee Formation, Murrumbidgee system, A-A', B-B' and B'-B' are the cross-sections in Figure 10.

ing large areas and causing erosion and destruction of the highstand shoreface deposits by channels cutting down to base level. Subaerial exposure would have been accompanied by the development of paleosols, and rooted horizons.

During subsequent sea-level rise the channel systems began to aggrade and fill first with fluvial sediments and then, as the channels became flooded, brackish estuaries evolved. In the subsurface, the preserved estuarine deposits appear to be sand- or mud-dominated, interbedded, point bar deposits. Destruction of the old shoreface parasequence subsequently slowed, then ended, and a marine flooding surface developed. The ensuing highstand sea level would then set the stage for the development of a new prograding shoreface. There is no evidence of a major phase of transgressive erosion at the base of any of the parasequences, not unexpected in a low energy, restricted basin. As a consequence, it is difficult to relate lowstand incision events to a particular stratigraphic horizon, and this has not been attempted in this study.

The three uppermost parasequences in the McMurray Formation are the best preserved. In general, the older the shoreface parasequence, the more poorly preserved it is. It appears that there is a bias toward the preservation of lowstand channelized deposits at the expense of the shoreface deposits with depth. There is a simple explanation for this. During early McMurray time the influence of the sub-Cretaceous unconformity was great and extensive exposed carbonate ridges separated the McMurray sub basin into long narrow valleys. Lowstand channels would have been more confined early in the depositional history of the McMurray Formation and it is likely that the channels would destroy all or most of any existing highstand shoreface by migrating from valley wall to valley wall. The lower McMurray is preserved only in the deepest valleys on the unconformity and it appears to be dominantly fluvial, given that no shoreface successions have yet been recognized. However, the lowstand fluvial deposits may have totally obliterated all trace of the shoreface in the deeper valley floors (Fig. 14).

Later, as the valleys in the basin became filled and the carbonate ridges covered, shoreface deposits would have had much wider aerial development, and thus more potential for preservation from destruction. Furthermore, the channels would still have tended to avoid migrating over the old buried ridges. Although the topography on the unconformity became more subdued as the McMurray Formation aggraded, the ridges would still have had a slight topographic expression, even in late McMurray time, due to differential compaction. Thus it can also be expected that the shoreface deposits exposed during lowstand sea level would be preferentially preserved from channel erosion over these topographic highs. Support for this suggestion is observed, in the distribution map of the Green parasequence (Fig. 12), where in several areas the shoreface appears to be preferentially preserved (see Figs. 9 and 10 between Twps. 72 to 77) over buried ridges (Fig. 3) on the sub-Cretaceous unconformity.

This observation may explain the standard belief that the overall vertical record of the McMurray Formation reflects a

transition from fluvial through estuarine to marine. In fact there does not appear to be any fully marine environments in the McMurray Formation of south Athabasca, and the perceived lower fluvial dominance giving way upward to estuarine dominance is largely preservational bias.

The three facies successions suggested by the Markov analysis fit the proposed depositional model. The coarsening and sandier upward succession is the preserved shoreface parasequence. It starts with a flooding surface on which is developed the lower shoreface. There is no facies that has a preferred transition to the lower shoreface, which is what is expected at a flooding surface, since a flooding surface abruptly blankets all environments.

The complex channel fill succession is the expression of the lowstand erosion of the shoreface sets and subsequent filling of incised valley systems. Its basal facies is a coarse pebbly channel fill to which no facies has a preferential transition. Again one would typically observe a "random" facies below an erosional channel. A channel fill succession is normally fluvial at the base, subsequently becoming brackish estuarine as sea level rises and the system aggrades.

The simple paleosol/marsh succession also has no facies with a preferred transition into it. This is what one would expect because the succession is an expression of subaerial exposure, and during sea-level lowering any facies at "random" may be exposed by channelized erosion.

The paleosol/marsh succession also has no preferred transition to any specific facies. Subaerial exposure surfaces may occur in channel valleys and be covered by fluvial pointbar deposits or a crevasse splay or estuarine deposits during sea-level rise or, in any setting, they may be abruptly covered by a flooding surface.

The top of the McMurray Formation in south Athabasca appears to be a significant erosional unconformity surface. This is evident from the log cross-sections (Fig. 10) where the upper "red" parasequence is commonly truncated, and its thickness varies greatly in comparison to the older parasequences. Remnants of a parasequence younger than the upper "red" interval may even be preserved in some wells (e.g. Fig. 10a, well 10-13-72-9W4). The nature of this unconformity is revealed by the presence in some areas of deep channel deposits, constituting a single genetic unit, that carve through the McMurray Formation, erasing the entire history of the parasequence development (Ranger and Pemberton, 1992). These channels appear to be related to the unconformity surface at the top of the McMurray Formation, and may incise all the way down to the sub-Cretaceous unconformity surface. The unconformity at the top of the McMurray is probably the result of a major sea-level lowering. The resulting deep channels make excellent reservoirs where they are sand-filled (Flach and Mossop, 1985; Ranger and Pemberton, 1992). It is significant that no paleosols, rooted horizons or other evidence of exposure have been recognized at the McMurray-Wabiskaw contact; therefore this surface probably corresponds to a transgressive surface of erosion, heralding the transgression of the Clearwater sea.

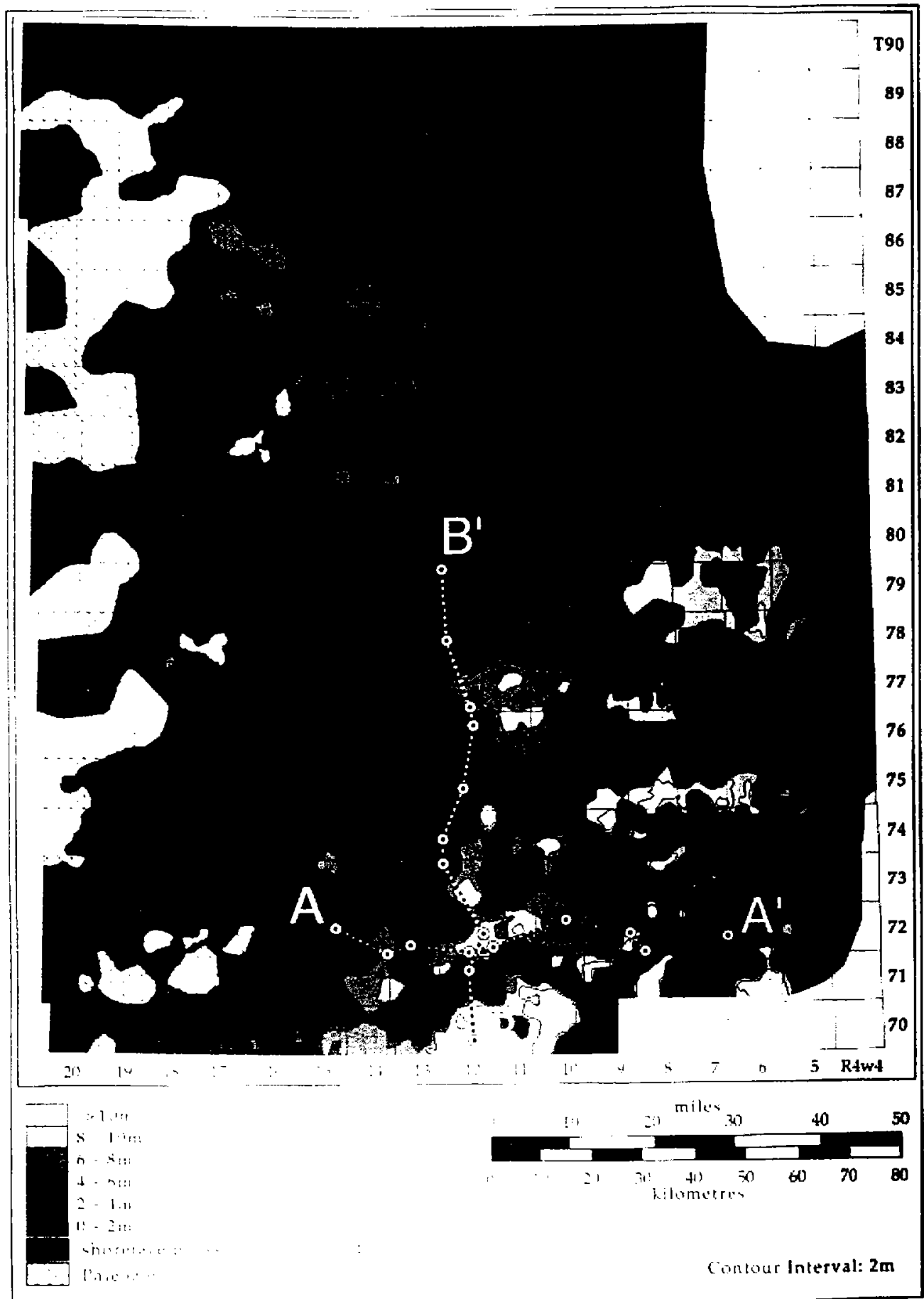


Fig. 13. Isopach of the Red Parasequence of the McMurray Formation. A-A and B-B refer to the cross-sections in Figure 10. Note that progressively less of the Paleozoic terrane is covered by the McMurray Formation from the Blue (Fig. 11) to the Green (Fig. 12) to the Red parasequences.

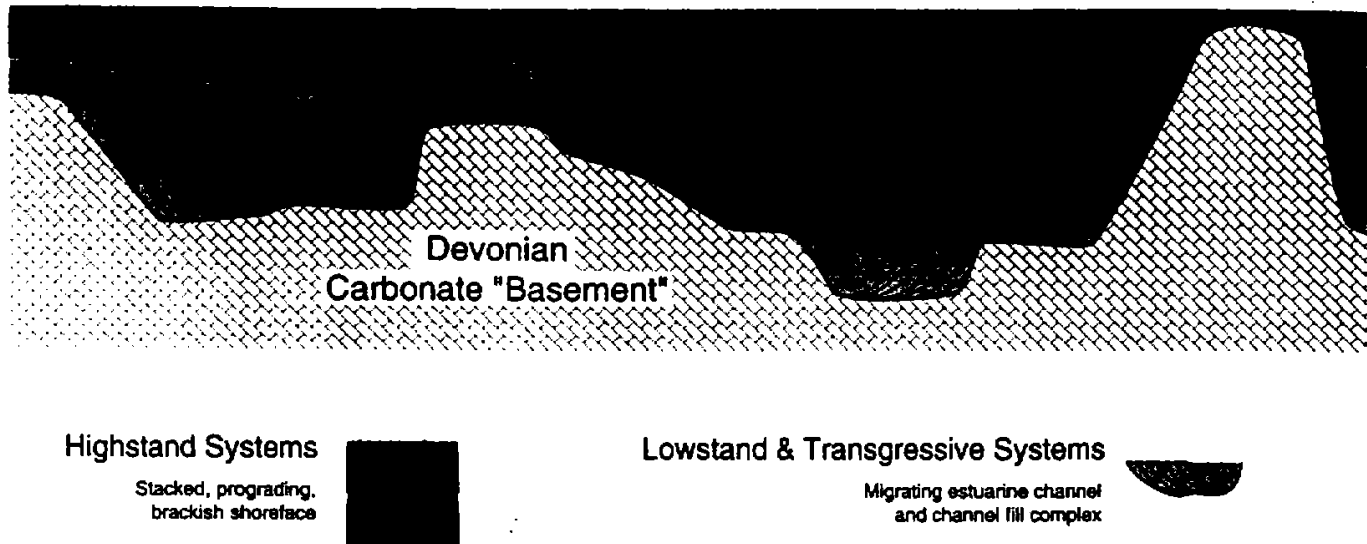


Fig. 14. Model for the preservational bias of shoreface parasequences with depth. Older shoreface parasequences are more poorly preserved. During early McMurray time the basin topography was dominated by extensive exposed carbonate ridges separating long narrow valleys. Lowstand channels would have been confined to these valleys. It is likely that the channels would destroy all or most of any pre-existing highstand shoreface by migrating entirely across the narrow valleys. During later McMurray time, the confining valleys were filled in, and the migrating channel systems were not as likely to have destroyed as much of the highstand shoreface deposits.

Other major deep channels that cut through the McMurray Formation, up to 40 metres deep, are well known in north Athabasca in the shallow, surface mineable and outcrop areas. The best known of these channels crop out at the Steepbank River (Mossop, 1980; Flach and Mossop, 1985). These well-studied examples are also interpreted to result from a major episode of sea-level lowering (Mossop, 1980). This north Athabasca deep channeling event may be older than the subsurface channels in the south, however, because in the north, the channels are apparently overlain by a widespread marine unit identified as "upper" McMurray (Mossop, 1980). Therefore the northern channels appear not to be related to the erosion surface that characterizes the top of the McMurray Formation in the south. The precise stratigraphic relationship of the McMurray Formation in north Athabasca to that in the south Athabasca study area is, as yet, unknown, because a regional stratigraphy has so far been elusive for the north Athabasca area; and this may remain so, given that the correlatable parasequence stratigraphy discovered for the southern study area may be difficult to apply farther north. It can be observed on the distribution map of the "blue" parasequence, for example, (Fig. 11) that preservation of the shoreface, the key to the stratigraphic correlations, is significantly poorer in the north than in the south.

The top of the McMurray Formation is deeply eroded in the Kirby - Ipiatic area (Twps. 73-74, Rges. 7, 8 and 9W4). Major sand-filled channels in this area constitute important bitumen reservoirs (Dekker *et al.*, 1987). These channels are younger than the McMurray Formation, apparently Wabiskaw in age, and must also represent a major sea-level lowering. As yet, it is unknown how these incision events are related to regional Wabiskaw stratigraphy.

The only other comprehensive facies study of the McMurray Formation in the south Athabasca study area is that

of Nelson and Glaister (1978). This is a significant study because it is a detailed facies examination and interpretation, albeit in a relatively small area of about nine townships and using information from only 28 wells. Nelson and Glaister recognize three fundamental time-stratigraphic units separated by persistent shale markers, and they were the first to recognize the thin, coarsening-upwards successions as the development of prograding shoreface complexes. They assign these environments to deltaic development and, where channelized deposits dominated (in the northeast of their study area), they assign these to a fluvial-dominated, nearshore, distributary system of the proximal delta. Where the ichnofossil assemblages have been examined, it is evident now that there is a definite brackish overprint on the sediments in Nelson and Glaister's study area, which is indicative of estuarine, rather than deltaic conditions.

Furthermore, all of the three parasequence studied in detail in the present regional study are contained within Nelson and Glaister's "upper" unit, and their stratigraphy was much coarser than can now be discerned with modern data and methods. Their mapped distributary systems (Nelson and Glaister, 1978: their figures 12 to 15, p. 197) are thus actually amalgamated units. The interpretation of their study area based on the present study is that these systems are not dominantly deltaic in nature. The shoreface systems are remnant shoreface parasequences prograding not from the northeast, but from the south. We conclude that the channelized systems are not deltaic distributaries, but are part of a northwards or north-northeastwards draining system of lowstand tributaries cutting into these exposed highstand shoreface systems tracts. The channel fills may be fluvial or estuarine depending on their stage of development.

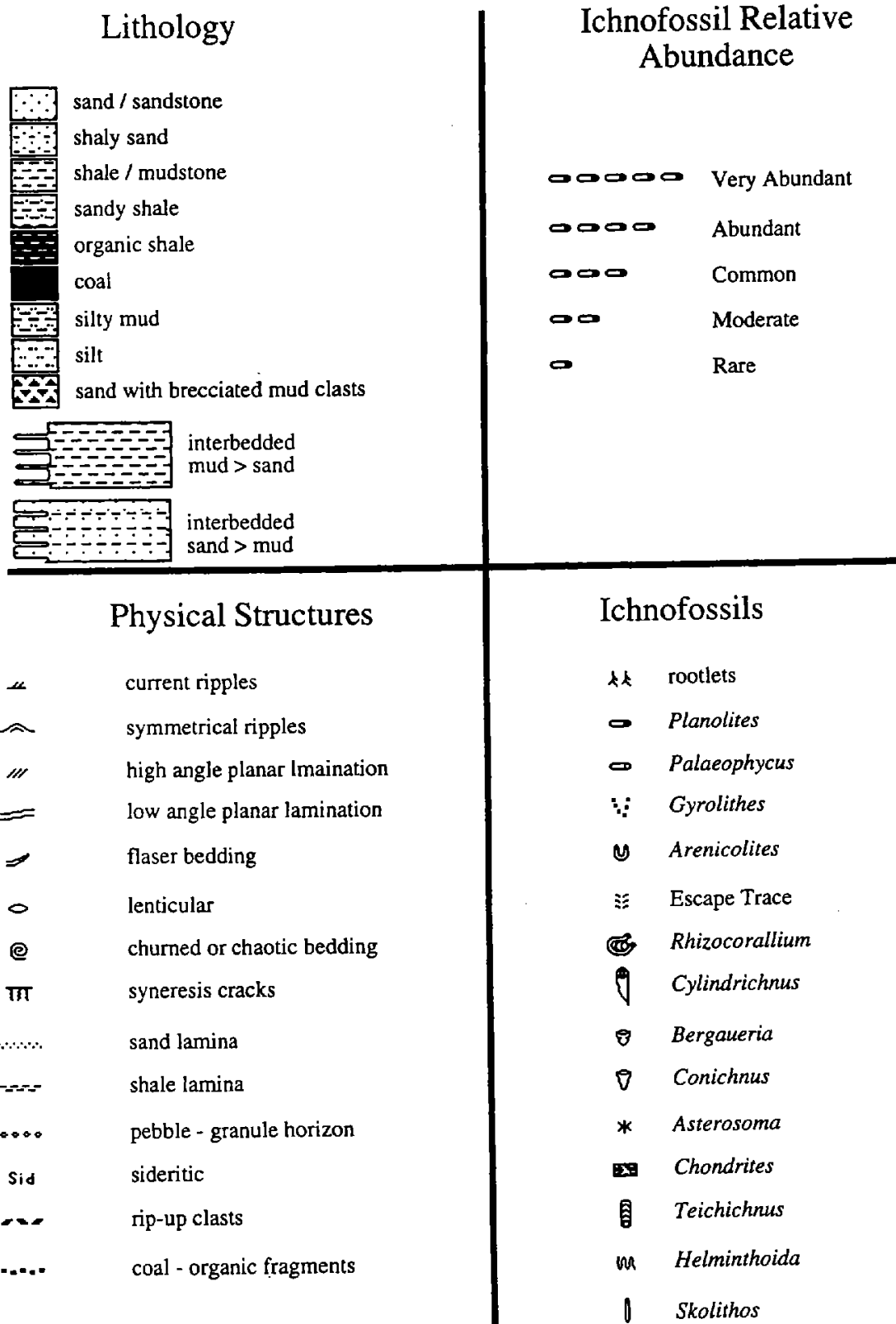


Fig. 15. Legend for the core log facies.

Despite the refined subdivision of the upper part of the McMurray Formation offered in this study, more detailed work may allow for further subdivision of the parasequences. In some wells, each of the units herein referred to as parasequences appear to consist of two or more, stacked, coarsening-upwards units. For example, note the Blue parasequence in wells 10-5-72-8W4 and 7-27-72-10W4 (Fig. 10a) or the Green parasequence in general (Fig. 10). Indeed, we speculate that each of the Red, Green and Blue units should ultimately be classified as parasequence sets, consisting of several stacked, prograding, shoreface successions. And it is for this reason, as well as the fact that a regional subdivision of the lower part of the McMurray has proven more difficult, that we believe it is still premature to suggest a formal stratigraphic nomenclature for the members of the McMurray Formation.

ECONOMIC IMPLICATIONS

The recognition of widespread, correlatable parasequences in this study has some economic significance for the recovery of bitumen. Beyond approximately fifty metres of burial, open pit mining of bitumen is currently not economically feasible. Thus, practically all of south Athabasca is in the area where *in situ* recovery techniques will be required. At the present time the most effective of these techniques involves steam-heating the reservoir from an injection well and recovery from a nearby production well. Such techniques therefore require reservoir continuity between the injection and the production wells. From an engineering standpoint, this criteria is of primary importance when selecting a production site. The preferred reservoirs are naturally those containing thick, sand-filled channels, although even these may contain both lateral and vertical permeability barriers (Ranger and Pemberton, 1992). Furthermore, these sites are not common and, as they constitute sinuous, migrating channels, they can be laterally unpredictable. On the other hand, the sandy shoreface parasequences are laterally and vertically continuous and correlatable, and therefore may provide an alternate target for an *in situ* recovery scheme. It has been shown in this study that given a detailed stratigraphic model, it is possible to differentiate the channel systems from the highstand shoreface sands.

One negative aspect of targeting the shoreface parasequence sands is that they are relatively thin, generally 8 to 12 metres in thickness. In addition, the shoreface sands become increasingly shaly downward, and they are therefore an increasingly poorer reservoir toward the bottom of each parasequence. It should be noted, however, that in the Wabasca area on the western edge of the Athabasca Deposit, Wabiskaw sands of thickness and geometry similar to the McMurray shoreface parasequences (Ranger, *et al.*, 1988; Ranger, 1994) have been explored and tested for many years as potential sites for commercial bitumen recovery projects. In recent years horizontal drilling has been utilized with some success in recovering low viscosity heavy oil on primary production from the Wabiskaw sands. Recovery schemes utilizing horizontal drilling such as Steam-Assisted Gravity Drive may be well-suited to the thin but laterally continuous shoreface sands in south Athabasca.

CONCLUSIONS

The McMurray Formation can be stratigraphically subdivided into correlatable genetic units, 8 to 12 metres in thickness, which are persistent over wide areas and are separated by marine flooding surfaces. These units consist of coarsening-upwards shoreface parasequences or parasequence sets representing highstand systems tracts, and have a distinct gamma-ray log signature. But lowstand systems tracts are generally dominant, especially in the north, and constitute complex fills of channels that incised the shoreface parasequence sets.

Facies from the shoreface show a distinct brackish water overprint expressed mainly in the ichnofossil assemblages. The channel complexes are primarily filled with estuarine point bar deposits that may be shale dominant or sand dominant. However the basal fill in the deeper channels is commonly fluvial in nature. The dominantly brackish nature of the basin is probably a result of a constriction at its northern mouth, formed by the convergence of the Grosmont High and the highlands of the Canadian Shield, which prevented dispersion of fresh water into the Boreal Sea.

The commonly held belief that the McMurray Formation becomes increasingly more marine upwards is probably oversimplified. There appears to be a preservational bias towards channelized systems in the lower part of the McMurray Formation, and shoreface systems towards the top.

The economic potential of south Athabasca may be enhanced by applying the new stratigraphic framework. Mappable, predictable reservoir geometry may produce new targets for *in situ* recovery schemes, even though each genetic unit is relatively thin.

ACKNOWLEDGEMENTS

The Alberta Oil Sands Technology and Research Authority (AOSTRA) has been instrumental in funding this research. Funding was provided to S. G. Pemberton under AOSTRA agreements 474, 615 and 876. Research support was also provided by an AOSTRA Research Fellowship and an Izaak Walton Killam Memorial Scholarship to M. J. Ranger. Special thanks are extended to Don McPhee for discussions on McMurray stratigraphy.

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