SEDIMENTOLOGY OF THE CARDIUM FORMATION, WILLESDEN GREEN FIELD, ALBERTA

SEDIMENTOLOGY OF THE CARDIUM FORMATION (UPPER CRETACEOUS), WILLESDEN GREEN FIELD, ALBERTA

By

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ABSTRACT

Examination of 178 cores from the Cardium Formation in the Willesden Green Field area allows sub-division into facies: two which are predominantly mudstone, 3 muddy siltstone to silty sandstone bioturbated facies, 3 sandstone facies and 1 conglomeratic facies. Wave ripples and hummocky cross stratification are the dominant sedimentary structures preserved in the sandy facies suggesting deposition in a storm dominated environment. These facies occur within the coarsening-upward Raven River Sequence.

The Raven River Member comprises the upper sandy and conglomeratic portion of the Raven River Sequence and is correlative with though not continuous from Caroline, Garrington through Ferrier and Willesden Green into Pembina. The top surface of the Raven River Sequence within the study area, defined from study of 1083 well logs, shows positive relative topography ("highs") in areas of Cardium fields and negative relative topography ("lows") in off-field regions. Integrated core and well log study shows that the Raven River Sequence comprises 5 individual coarsening upward units - referred to as Raven River Units. Detailed correlations throughout the Willesden Green area reveal a northeastern shingling or offlapping of the Raven River Units. Cardium conglomerates are preferentially accumulated off the eastern and northeastern down-dipping unit flanks and hence postdate the deposition of all of the sandy facies

facies. Local scouring of the sandy facies by conglomerates occurred.

Mapping of facies distribution trends suggest north-west to southeast sediment dispersal. A northwest to south-east flowing storm-generated geostrophic current may be responsible for the off-shore transport of Cardium sands and pebbles to Willesden Green.

Fluxuations in sediment supply with or without minor sea-level fluxuations may be responsible for the offlapping geometry of the Cardium sandstones.

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CHAPTER 1: INTRODUCTION

1.1 THE PROBLEM

Shallow Marine Sedimentation - Cretaceous Seaway

This study was initiated to provide information on a single off-shore siliciclastic sandstone body deposited within the Cretaceous Interior Seaway of western North America. The occurrence of isolated sandstone bodies in the Cretaceous Interior Seaway remains problematic. Two major problems concerning these off-shore bodies are:

(1) Transportation of sand across the shoreface onto storm dominated shelves. Two possible mechanisms receiving a lot of attention currently (late 1984) are:

Storm-generated wind-forced currents - described as intermittent geostrophic flows resulting in the incremental transport of sediment offshore.

Turbidity currents - episodic density flows (density due to suspended sediment) generated at or near the shoreface by storm wave activity capable of transporting sediment offshore during a short duration catastrophic single event.

Both mechanisms are discussed in more detail along with of this study later (chapter 7).

(2) The second problem concerns the development of off-shore sandstone bodies. Swift and Rice (1984) have proposed a multi-faceted model which might account for the development of sandbodies in the Cretaceous Interior Seaway. They employ aspects of fluid dynamic theory and regional tectonics and their model may account not only for the sand body development but also for the specific site of development. Intermittent geostrophic storm flow is suggested to be the dominant sediment transporting mechanism. Episodic sediment supply to the Interior Seaway was suggested to have been controlled by thrusting of the foreland thrust belt - with renewed thrusting comes source area relief resulting in increased sedimentation and increased tectonic loading causing increased subsidence. They described the overall result to be an advance of the shoreline or a regional (tectonic) regression. As source-land relief is diminished through erosion both sedimentation and subsidence decrease, the latter decreases more slowly, eventually resulting in a retreat of the shoreline. With renewed tectonic activity this cycle is repeated. Deposition within each cycle occurs with decreasing water depths and increasing wave agitation causing fines to bypass and successively coarser material to be deposited. The result is a coarsening-upward sequence common to many of the sandbodies in the Cretaceous Interior Seaway. Swift and Rice (1984, p. 54) suggest that "under normal circumstances" deposits from geostrophic flow occur as graded beds of sandstone and mudstone, but when "appropriate conditions occur" these deposits may be localized by initially subtle topographic perturbations on the shelf. These regions of irregular topography may result from tectonic activity, possibly due to foreland thrusting (see Beaumont, 1981). Deceleration of the flow both across and down these "highs" results in deposition of coarser sediment (generally sand) over the high. This leads to enhancement of the "high" resulting in continual growth while sediment is available.

The important effects of eustatic sea-level changes during the Cretaceous (Vail et al., 1977, Kauffman, 1977, and Hancock and Kauffman, 1979) to sediment transport, deposition and erosion (Weimer, 1983) cannot be ignored and will be discussed further with the findings of this study in chapter 7.

Discussion

Many shallow marine sandstones deposited in the Jurassic and Cretaceous Interior Seaway have been interpreted as being emplaced and modified by storm related processes. These include the Cardium Formation (Krause, 1982 and 1983, Krause and Nelson, 1984, Swagor, 1975, and Walker 1983a, b, c, and in press); Duffy Mountain Member (Boyles and Scott, 1982); Fernie-Kootenay Transition (Hamblin and Walker, 1979); Frontier Formation (Winn et al.

Sandstone (Rice, 1984); several Oxfordian sandstones (Brenner and Davis, 1974); Shannon Sandstone (Spearing, 1976, and Tillman and Martinsen, 1984); Semilla Member (La Fon, 1981); Sussex Sandstone (Berg, 1975, Brenner, 1978, and Hobson *et al*. 1982); and the Viking Formation (Koldijk, 1976, and Reinson *et al*. 1983).

In studies of Cretaceous Seaway sandstones there are numerous interpretations of storm dominated transport mechanisms. As discussed above (1.1), two off-shore sand transporting mechanisms are currently receiving a lot of attention, namely geostrophic flow and turbidity currents. Rice (1984) interprets geostrophic flow as the dominant mechanism of off-shore sediment transport for the Mosby Sandstone. Turbidity currents are interpreted as the mechanism of off-shore sediment transport in the Fernie-Kootenay transition (Hamblin and Walker, 1979) and in some parts of the Cardium Formation (Walker, 1983a, b, c, 1984c and in press).

With many detailed descriptions of facies, facies sequence and distribution and internal stratigraphy within individual Cretaceous shelf sandstone bodies (some listed above), a general sedimentological model describing these bodies may emerge. It is the aim of this thesis to provide a well-documented sedimentological and stratigraphic study of an individual Cretaceous shelf sandstone body which will stand alongside studies of other Cretaceous shelf sandstone bodies.

1.2 GENERAL INTRODUCTION TO THE STUDY

This study is part of a long term project at McMaster University investigating storm-dominated, shallow marine siliciclastic sandstones, mostly in the Cretaceous Interior Seaway of Western North America. Previous workers have attributed sediment dispersal of Cretaceous Seaway sandstones to differing processes and have described sandbody geometry as isolated, discrete sand (or conglomerate) accumulations and as more sheet-like deposits. Specifically, the McMaster study is investigating the Upper Cretaceous (Turonian) Cardium Formation in the subsurface beneath the Plains and in outcrop in the Foothills of Alberta. This thesis details the sedimentology of a single Cardium oil field - Willesden Green - which represents a sandstone and conglomerate body deposited in the Cretaceous Seaway.

1.2.1 The Cardium Formation

The Cardium Formation is an example of a shallow marine sandstone (Stott, 1963; Jeletzky, 1970). Ample outcrop exposures of the formation are provided on numerous thrust slices in the Foothills of the Rocky Mountains in Alberta. With the discovery of significant accumulations of hydrocarbons in subsurface Cardium of the Alberta Plains in 1953 (at the Pembina Field, the largest conventional oil field in Canada, Nielson and Porter, 1984) the continuing search for production provides excellent subsurface control in the form of well logs and cores. As is the case with many off-shore shallow marine deposits there is disagreement among workers concerning the mechanism of off-shore transport of the Cardium sandstones and conglomerates and the method by which the bodies have developed (previous interpretations discussed in chapter 2, p. 23).

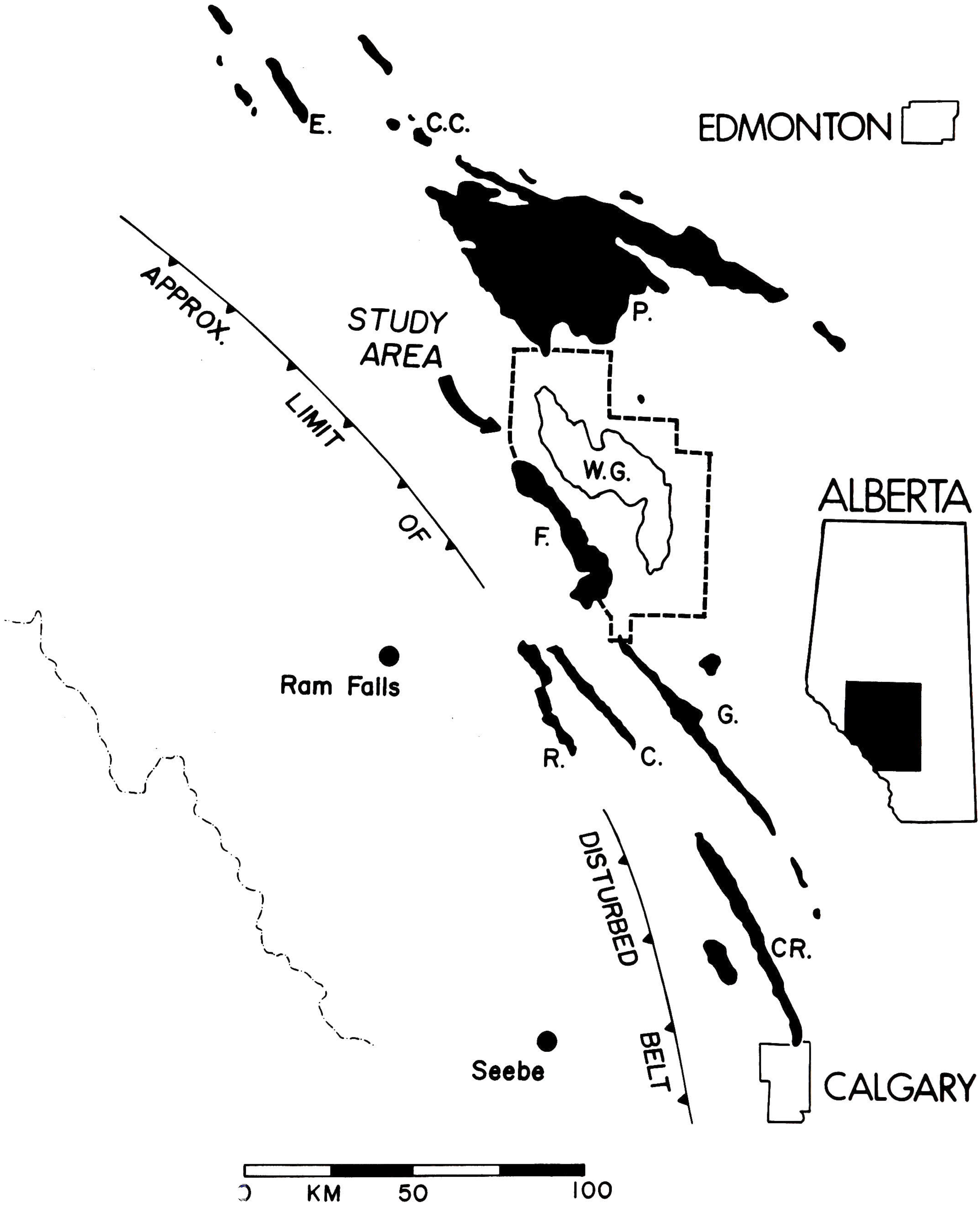
As mentioned, this thesis is a part of a long term sedimentological study undertaken by R. G. Walker and students at McMaster University. Previous and on-going studies of the Cardium Formation at McMaster include Ainsworth's (M.Sc. in prep.) investigation of Cardium outcrop from the Alberta - Montana border to Bow Valley, Alberta; Bergman's (Ph.D. in prog.) examination of the Cardium conglomerates in the Carrot Creek field; Costley's (unpublished B.Sc. thesis) study of the ichnology of the Cardium outcrop at Seebe, Alberta; Duke's (1980, 1981 and Ph.D., 1985) extensive study of the Cardium outcrop between the Athabaska River and Grande Cache, Alberta; Plint's (in prog.) examination of the Cardium Formation from the Kakwa field and surrounding areas; Walker's (1983a, b, c and in press) investigation of the Cardium Formation at the Ricinus, Caroline and Garrington fields; and Wright and Walker's (1981) detailed study of the Cardium outcrop at Seebe, Alberta. As will become apparent in this thesis, within this research group a number of sedimentological interpretations have been expressed about the Cardium Fm.

1.2.2 Willesden Green

Study of the Cardium Formation within Willesden Green, located in south-central Alberta (see Figure 1.1), serves as an important and necessary addition to the increasing wealth of information of ancient shallow marine sandbodies. This is especially true since there are no published sedimentological studies of the Cardium sediments at Willesden Green, yet recently published studies have examined Cardium sediments in surrounding fields (see Fig. 1.1). To the south, Ricinus, Caroline and Garrington by have been studied by Walker (1983a, b, c and in press); to the west Ferrier has been examined by Griffith et al. (1982); and to the north, Pembina has been studied by Krause (1982 and 1983) and Krause and Nelson (1984).

Willesden Green covers 50,827 hectares, and is the second largest of all Cardium fields after Pembina. It continues to produce significant quantities of oil (36,800 10^3 m^3). A sufficient number of wells are available within the field (more than 800 of which about 576 have been cored) to provide the control necessary for a detailed sedimentological study. Also, numerous wells, many of which are cored, are available along the margins of the Willesden Green, allowing investigation of this region.

Fig. 1.1. Location of the study area in south-central Alberta (within dashed lines). The inset to the right shows the location of the region in the figure. Positions of Calgary and Edmonton are included for reference and the approximate eastern limit of the disturbed belt of the Rocky Mountains is shown. The positions of two foothills Cardium exposures, Ram Falls and Seebe are shown. In black are approximate locations of producing Cardium Fields (E = Edson, CC = Carrot Creek, P = Pembina, F = Ferrier, WG = Willesden Green, R = Ricinus, C = Caroline, G = Garrington and CR = Crossfield; information from G.S.C. map 1559A). The study location included the Cardium Formation within the dashed lines.


E.
C.C.
EDMONTON
P.
STUDY AREA
APPROX. LIMIT OF
W.G.
F.
ALBERTA
Ram Falls
R.
C.
G.
DISTURBED BELT
CR.
Seebe
CALGARY
0 KM 50 100

1.3 Economic Justification

The sandstones and conglomerates within the Cardium Formation contain large quantities of oil and gas. The detailed sedimentological study of a producing Cardium field, especially a field as large as Willesden Green, could provide exploration models helpful in the search for as yet undiscovered Cardium Fields or aid in enhanced recovery schemes within producing fields. This may prove particularly applicable to the Cardium conglomerate, which is not a major hydrocarbon producer within the study area, but provides significant oil and gas production and is currently an active exploration target to the northwest.

1.4 THESIS FORMAT

Figure 1.2 shows the location of core examined and the location of well logs used in the study are shown in Fig. 1.3. Appendix 1 lists all cored wells examined and appendix 2 includes lithological logs of a number of these wells. Throughout the thesis whenever a well is mentioned whose lithological log is included in appendix 2 the appropriate page number is given in square brackets (i.e. [p._]).

Chapter 1 has presented an introduction to the problems of shallow marine sedimentation in the Cretaceous Seaway and to the nature and aims of this study. The first half of chapter 2 provides information with respect to the chrono-, bio-, and lithostratigraphy (outcrop and subsurface) and some previous sedimentological work about the Cardium Formation. The second half of chapter two is devoted to

Fig. 1.2. Map of Willesden Green and Ferrier showing the locations of wells from which cores from the Cardium Formation were examined. Solid circles indicate the location of cores for which lithological logs are included in appendix 1 (p. 185). Open circles show the location of core which were examined but whose lithological logs are not included in the appendix.

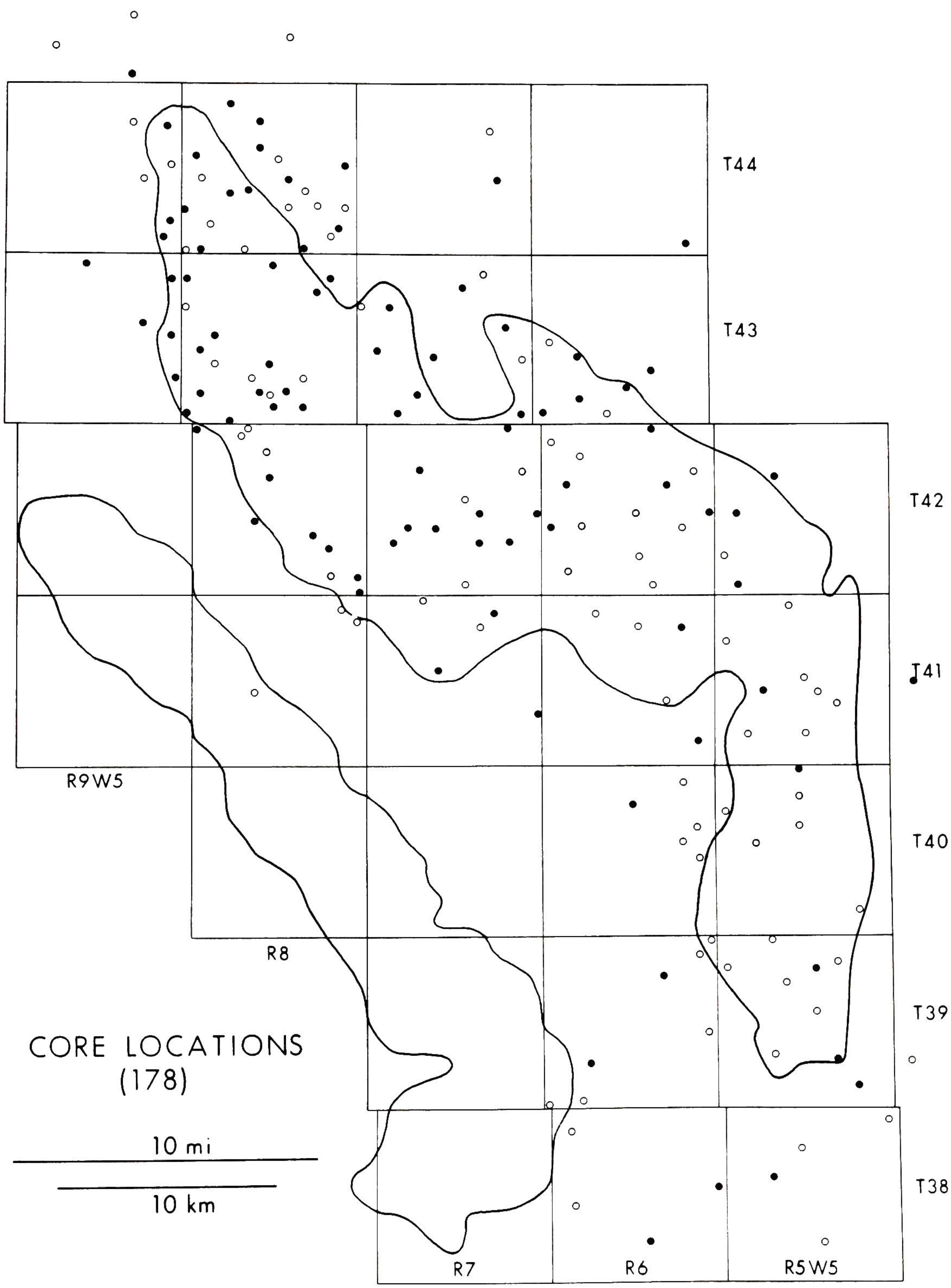
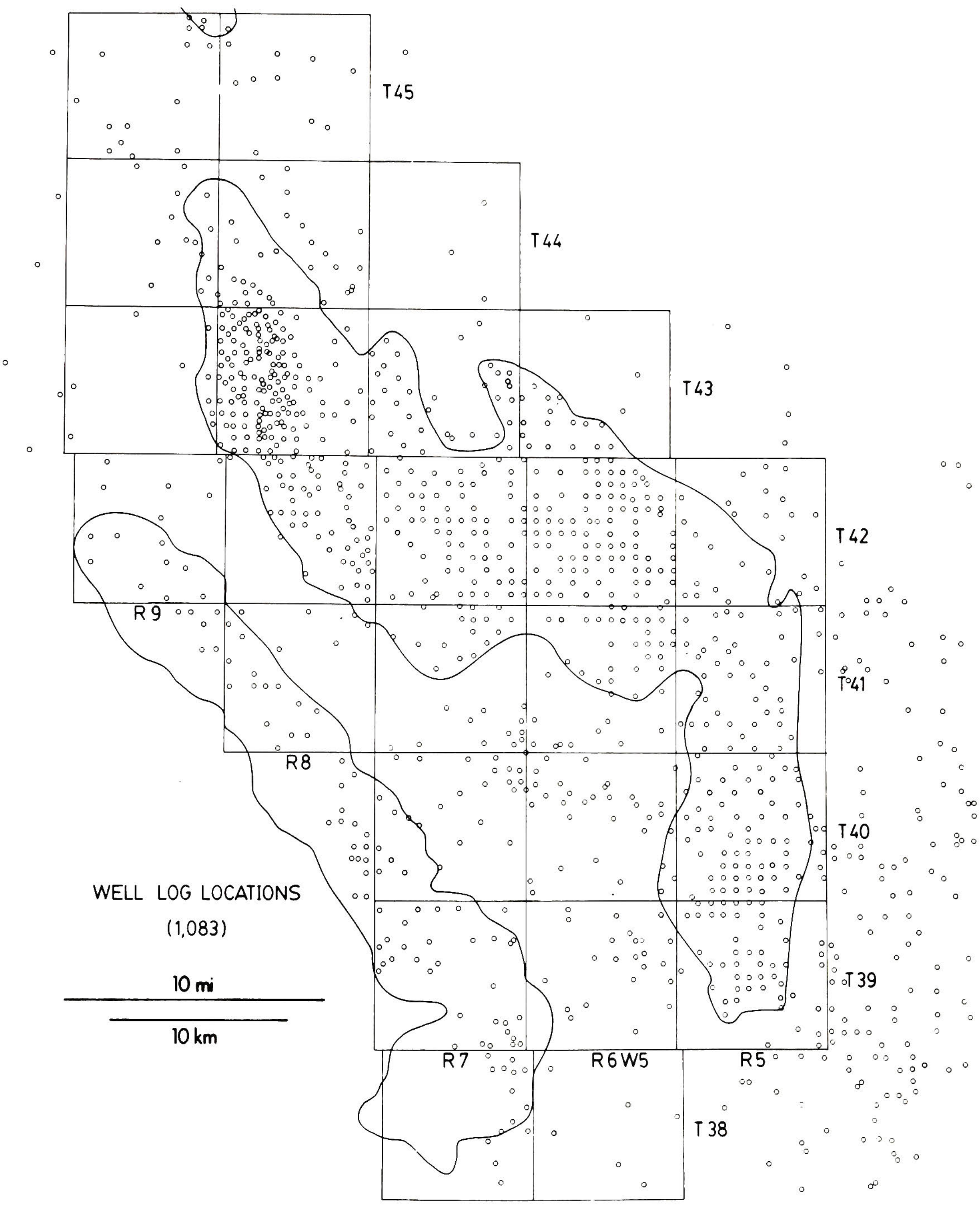

T44
T43
T42
T41
T40
T39
T38
R9W5
R8
R7
R6
R5W5
CORE LOCATIONS
(178)
10 mi
10 km

Fig. 1.3. Map of Willesden Green and Ferrier Cardium Fields showing the locations of wells from which resistivity logs where used in this study. The total number of wells from which logs were examined was 1,083.


T45
T44
T43
T42
T41
T40
T39
T38
R9
R8
R7
R6W5
R5
WELL LOG LOCATIONS
(1,083)
10 mi
10 km

a discussion of the history, stratigraphy and setting of Willesden Green. The litho-facies portion of this study is discussed and presented in chapter 3. Facies and facies sequences are described and interpreted. An introduction to the well log study of this thesis is given in chapter 4. All datums used in this study and those used in adjacent Cardium fields are discussed. The regional geometry of the top of the Raven River Sequence/Member (previously the Cardium A sandstone) is determined using an upper and lower log marker. The distribution of sandy and conglomeratic facies (defined in chapter 3) is shown in chapter 5. It is discussed with respect to the geometry found in chapter 4. Chapter 6 delineates and discusses the internal stratigraphy - specifically the more sandy facies and the conglomerates in Willesden Green. The inclusion and discussion of twelve cross sections provides the basis for further discussion in the latter half of the chapter. In chapter 7 findings of the study are discussed with respect to sand transport on storm dominated shelves and suggestions are made as to how the sand and conglomerates were transported to Willesden Green. The general nature of the Cardium sediments at Willesden Green is presented and suggestions are made as to what caused the sediment to accumulate where and in the manner it has. Chapter 8 provides a number of conclusions with respect to Cardium sediments in the Willesden Green area based on the findings of this study.

CHAPTER 2: SETTING AND STRATIGRAPHY

2.1 CARDIUM FORMATION

2.1.1 Chronostratigraphy And Biostratigraphy

The Cardium Formation is of Upper Turonian age (Stott, 1963). The Turonian extends from 88.5-91 Ma (Palmer, 1983). It is approximately coeval with the Frontier, Ferron and Gallup sandstones in the western United States.

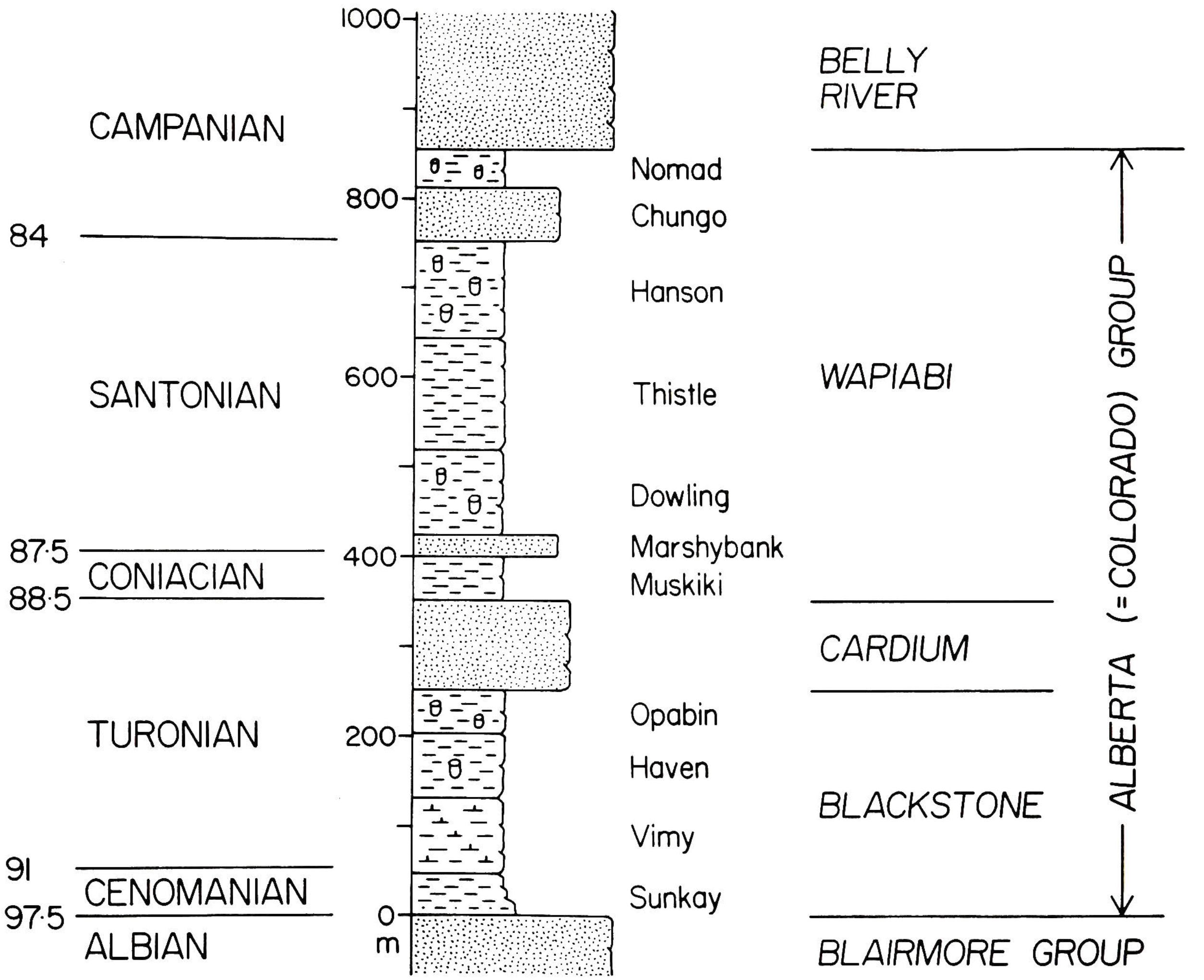
The Cardium Formation lies within the *Scaphites preventricosus* Cobban and *Inoceramus deformis* Meek molluscan zones of the Upper Turonian (Jeletzky, 1976, p. 651). The formation lies between the underlying *Pseudoclavulina* sp. foraminiferal Zone and the overlying *Trochammina* sp. Zone, as defined by Wall (1967 p. 18-23).

2.1.2 Setting

The Cardium Formation was deposited along the western margin of the Cretaceous Interior Seaway within the Alberta Foreland Basin of the Canadian Cordillera. It extends from south of the United States border to Dawson Creek, British Columbia.

The Cardium Formation is the main sandstone unit within the Alberta (Colorado) Group. The Alberta Group comprises three formations (in ascending order): the Blackstone, Cardium and Wapiabi. The Blackstone Formation (Cenomanian to Turonian) is about 400 m thick and consists predominantly of shales. The Cardium Formation contains about 100 m of interbedded sandstones and shales. It is overlain by the Wapiabi Formation (Coniacian to lower Campanian) which is about 600 m thick and consists mostly of shales. The Alberta Group, particularly the shales, may reflect a time of relative tectonic quiescence between two major clastic wedges; the Kootenay - Blairmore Assemblage (Upper Jurassic to Lower Cretaceous) and the Belly River - Paskapoo Assemblage (Upper Cretaceous) (Eisbacher et al., 1974, see Figure 2.1).

Fig. 2.1. Stratigraphy of Alberta (Colorado) Group in the Foothills of Alberta. Ages given at left are from Palmer, 1983 (from Walker, 1984c).


1000
800
600
400
200
0
m
CAMPANIAN
84
SANTONIAN
87·5
CONIACIAN
88·5
TURONIAN
91
CENOMANIAN
97·5
ALBIAN
Nomad
Chungo
Hanson
Thistle
Dowling
Marshybank
Muskiki
Opabin
Haven
Vimy
Sunkay
BELLY RIVER
WAPIABI
CARDIUM
BLACKSTONE
BLAIRMORE GROUP
ALBERTA (=COLORADO) GROUP

2.1.3 Stratigraphy

Outcrop

Stott (1963) reviewed the derivation of the nomenclature of the Cardium Formation and Cardium studies carried out prior to 1963. He divided the formation into six members: the Ram, Moosehound (nonmarine), Kiska, Cardinal, Leyland and Sturrock in ascending order. Subsequent work by R. G. Walker and W. L. Duke questioned the validity of these divisions. Inconsistencies between Cardium coarsening-upward cycles and Stott's member definitions were first noted by Walker in 1979 and were discussed briefly by Duke (1981). Walker (1983a, p. 15 and 16) clearly showed Stott's Cardium member boundaries to cross coarsening-upward depositional sequences. Duke (Ph.D., McMaster University, 1985) has defined a new member system for the Cardium in the Alberta Foothills. He based his member definitions on the thickening and coarsening-upward cycles within the Cardium. The new member names are (Duke, in prep.) the Seebe Member, Cutpick Member, Willmore Member, and Obstruction Member (in ascending order). The Baytree Member (the uppermost Cardium Member) was defined prior to Stott's (1963) work and is included in Duke's revised member scheme.

Subsurface

Member Definitions

In the subsurface, formal member definition has not, until recently, been emphasized. Between the top of the underlying Blackstone shales and the base of the Wapiabi Formation, two or more coarsening-upward sequences occur with a conglomerate frequently capping the upper sandstone sequence. The top of the Cardium Formation is recognized by the first appearance of a thin chert pebble bed (referred to as the Cardium zone, by for example Nielson, 1968) occurring below the First White Specks (a regionally recognizable well log marker - its position is shown in Fig. 4.1, p. 86) but above the main Cardium sandstones and conglomerates. It is identifiable in well cuttings or as a well log response and may its development may be related to a regionally erosive event. The Cardium zone is sometimes difficult to pick and, as shown by Griffith (1981, p. 5), has frequently been incorrectly positioned. The Cardium zone is infrequently cored in the Willesden Green area (cores from 13-31-42-8W5 [p.216] and 3-16-43-5W5 [p.216] include the Cardium zone).

In the literature, the sandy (or conglomeratic) portions of coarsening-upward sequences within the formation have been referred to as the "Cardium A sand" (which has included the "main", "upper", and "lower Cardium sand"), and a stratigraphically lower sand, the "Cardium B sand". [illegible]son (1984) reviewed numerous and somewhat [illegible]sions used by different authors to identify the multiple Cardium units at Pembina. The Cardium A and B sands were first formally defined as members by Walker (1983c). He named the A sand the Raven River Member and the B sand the Burnstick Member in the Caroline and Garrington fields. Krause and Nelson (1984) gave a different name to the A sand at Pembina. They called it the Pembina River Member and named its capping facies (from the top of the Pembina River Member to the Cardium zone) the Cardium Zone Member, the latter breaking several rules of nomenclature. Krause and Nelsons' stratigraphy has been revised in a regional attempt at a formal subsurface Cardium stratigraphy (Walker, et al., 1986).

The relation of the Cardium sediments at Willesden Green with the newly defined members at Caroline and Garrington (Walker, 1983c) and Pembina (Krause and Nelson, 1984) is discussed in the second half of this chapter, devoted to Willesden Green (stratigraphy section), below.

Inter - Field Correlations

Correlation between Cardium fields has not been emphasized, at least in published Cardium studies. Berven (1966) published several cross sections between Garrington and Crossfield, and Walker (1983b and c) published cross sections between the Ricinus, Caroline and Garrington Cardium fields. In addition to examining Willesden Green in some detail, this study investigates the region between Willesden Green and Ferrier and includes cross sections which traverse the region between Garrington (which has recently been studied by Walker, 1983b and c) and Willesden Green and also the region between Pembina (recently studied by Krause, 1982, 1983, and Krause and Nelson, 1984) and Willesden Green. This work is discussed in the second half of this chapter (2.2.2, p.28) and in the Regional Geometry chapter of this thesis (chapter 4, p.83).

<u>Subsurface to Outcrop Correlations</u>

Correlation of Cardium sequences has proven difficult, again because of the discontinuous nature of the Cardium sandstones and thrust faulting in the foothills. Differences in the absolute number of coarsening-upward sequences between outcrop and subsurface add to correlation problems. In outcrop there may be between 2 and 8 coarsening-upward sequences, while in the subsurface there are normally only 1 to 3 (major) coarsening-upward sequences. These difficulties notwithstanding, several workers have suggested the Cardium zone to be equivalent to the pebble bed above Stott's Sturrock Member (Berven, 1966; McMormack, 1972; and Swagor <u>et al</u>., 1972). The upper or A Cardium sand has been correlated with Stott's Ram member by Stott (1963), Berven (1966), McMormack, 1972 and Swagor <u>et al</u>. (1976).

2.1.4 Previous Work

In 1963, Stott presented a major study and review of the Alberta Group from foothills exposures between the U. S. border and Grand Cache. His field work was carried out during the years 1954 - 1957, soon after the discovery of the Pembina field in 1953; Nielsen and Porter (1984) review the discovery and significance of Pembina. Stott (1963) established five formal stratigraphic member divisions for the Cardium, discussed above, within the Cardium Stratigraphy section of this chapter.

The remainder of this discussion is mostly limited to Cardium studies from the mid seventies to present. Walker (1983a) reviewed many of the previous sedimentological interpretations of the Cardium Formation.

The importance of storm generated currents with respect to off-shore transport and deposition of Cardium sediments was first suggested by Michaelis and Dixon (1969). Swagor et al. (1976, p. 91) suggested the Carrot Creek Cardium field (specifically the Pool A conglomerate) to be a "shallow marine offshore terrace bar" with lateral accretion of the conglomerate on the terrace edge; the slope of the terrace edge was given as 40 ft/mile (7.6 m/km). Swagor et al. (1976) concurred with Michaelis and Dixon (1969) on the importance of storms in Cardium sediment transport and emplacement.

Griffith (1981) investigated the Cardium Formation at Ferrier. She examined the conglomerate diagenesis in detail and suggested off-shore sediment transport was due to both storm generated and "steady unidirectional currents". Localization of conglomerate deposition was suggested to be in part related to the break in slope of the terrace bar (c.f. Swagor et al., 1976).

In studies of the Cardium Pembina field, Krause (1982) suggested that the sediments were deposited episodically and that the upper sandstone had a ridge and swale topography. He found the conglomerates to be concentrated on the westward (landward) and southern sides of the sandstone ridges. Further studies by Krause (1983) suggested that the lower Pembina sandstone included multiple sandstones (an important suggestion closely comparable with findings of this thesis - chapter 6) and that the upper sandstone had a complicated, non layer-cake stratigraphy. He described the Cardium Formation at Pembina as a "tempestite". Krause and Nelson (1984) formally named two members from the Pembina Cardium, these are discussed in the Stratigraphy section of this chapter. They suggest that the sediments at Pembina may have been episodically transported off-shore by "downwelling coastal currents during storms" and by "large seasonal river floods"; they further suggest that these sediments were reworked and redistributed by later storm events. Krause and Nelson (1984) suggest additional sediments may have been supplied to Pembina during changes [illegible] nd reworked during periods with a stable sea-

Wright and Walker (1981) studied in detail the Cardium outcrop at Seebe Dam. They emphasized storm generated, density current transport of the sands and conglomerates and proposed that Cardium deposition at Seebe occurred below fair-weather wave-base but above storm wave-base. This was largely based on the common occurrence of hummocky cross stratification and lack of steeply dipping sets of cross strata. Pemberton and Frey (1983, 1984) discussed the ichnology of the Cardium sediments at Seebe.

Two studies from McMaster University re-examined the Cardium outcrop from the Alberta - Montana border to Grand Cache, Alberta. Duke (Ph.D, 1985) investigated 28 Cardium sections from the Athabasca River to the northern Alberta - B. C. border. Ainsworth (M.Sc., in preparation) examined Cardium outcrop between the Bow Valley and the U. S. border.

Examination of the Cardium Formation at Ricinus, Caroline and Garrington has led Walker (1983a, b, c and in press) to suggest that Beach (1955) was correct in his assertion that the Cardium Formation is a turbidity current deposit. Walker (1983a) reviewed much of previous Cardium sedimentological literature (as discussed) and, with evidence from his other Cardium work (1983b and c) presented the argument that part of the Cardium was emplaced by turbidity currents. He formally named two Cardium Members, as mentioned above (2.1.3). Walker (1983b) described the Cardium sandstones at Caroline and Garrington as "raggedly continuous", using ragged to indicate nonsystematic thickness changes of the sandstones. He described the distribution of the Raven River Member as a "ragged blanket" over the Caroline and Garrington region and further suggested (1983c) that the Raven River Sequence "might be correlative" and "raggedly continuous" from Caroline - Garrington [through Ferrier, Willesden Green and Pembina] into Carrot Creek. Walker's (1983c) use of the term "ragged" implied no systematic thickness changes in sediments of the Raven River Sequence throughout this entire region, although this is contrary to the findings of this study, those of Griffith (1981) and other Cardium workers. Walker (1983b) found the Raven River Member to be scoured into by a stratigraphically higher Cardium sandstone at Ricinus. He has called this sandstone the Ricinus Member (Walker, in press) and suggested the scour at Ricinus was cut and filled by the action of turbidity currents. A lower Cardium sandstone, the Burnstick Member is suggested by Walker (1983b, p.25) to be continuous between Ricinus and Caroline as a "ragged blanket" but not to be continuous to Garrington where it occurs as a discrete "long thin strip".

2.2 WILLESDEN GREEN

2.2.1 History

Willesden Green was discovered in 1954 by Amerada Hess,

discovery of Pembina. The discovery well is located at 6-6-43-6W5 [p.216]. The field owes its name to Postmaster George Wagner who named his community Willesden Green, after Willesden Green, London, England. The name, originally Wilesdune, dates back to 1185 and means "hill with a well" (Holmgren and Holmgren, 1976, p. 295).

Willesden Green is the second largest Cardium field, both in area (50,827 hectares to Pembina's 191,669) and initial oil in place (117,000 10^3 m^3 to Pembina's 1,180,000 10^3 m^3). Willesden Green has 36,800 10^3 m^3 of initially recoverable oil (data from G.S.C. Map 1559A).

2.2.2 Stratigraphy

Correlation Between Willesden Green And Other Cardium Fields

Figure 2.2 shows Cardium coarsening-upward sequences from Caroline and Garrington (Walker, 1983c), Willesden Green (this study) and Pembina (Krause and Nelson, 1984). At Caroline and Garrington, Walker (1983a) informally designated the interval between the top of the Burnstick Member and the top of the Raven River Member as the Raven River Sequence. The Raven River Sequence begins in massive mudstones (facies 1) and is overlain by laminated mudstones (facies 2). Walker (1983a, p. 229-230) formally defined the upper sandy and/or conglomeratic facies of the Raven River Sequence as the Raven River Member. The Raven River Member at Caroline and Garrington appears lithostratigraphically correlative with the Cardium sandstones and/or conglomerates

Fig. 2.2. A generalized diagram illustrating the stratigraphic relationship between Cardium sediments at Ricinus, Caroline and Garrington, Willesden Green and Pembina. Information from Ricinus, Caroline and Garrington is from Walker (1983b) and information from Pembina is from Krause and Nelson (1984). The figure is not to scale and the coarsening-up trend of the Cardium in all areas is indicated by the right-hand curvature of a solid line. Heavy dashed lines show bounds to the various Cardium Members, the light dashed lines show approximate bounds to the muddy facies (facies 1 and 2, see chapter 3). The long arrows show the Raven River Sequence in the Ricinus, Caroline, Garrington and Willesden Green areas. Shorter arrows in the Willesden Green area indicate the Raven River Units within the Raven River Sequence. The Raven River Member (formerly the A sandstone) is correlative between Ricinus, Caroline, Garrington and Willesden Green (also Ferrier) and Pembina where it is referred to as the Pembina River Member (see text for basis for this statement). The Raven River Member is overlain by laminated dark mudstones (facies 2, Walker, 1983c and chapter 3). Its lower boundary is approximated by a log response and facies change (facies 4 to 5). The base of the Raven River Sequence in the Ricinus, Caroline and Garrington regions occurs at the top of the Burnstick Member (formerly B sandstone), in the [illegible]n area its base is less well defined.

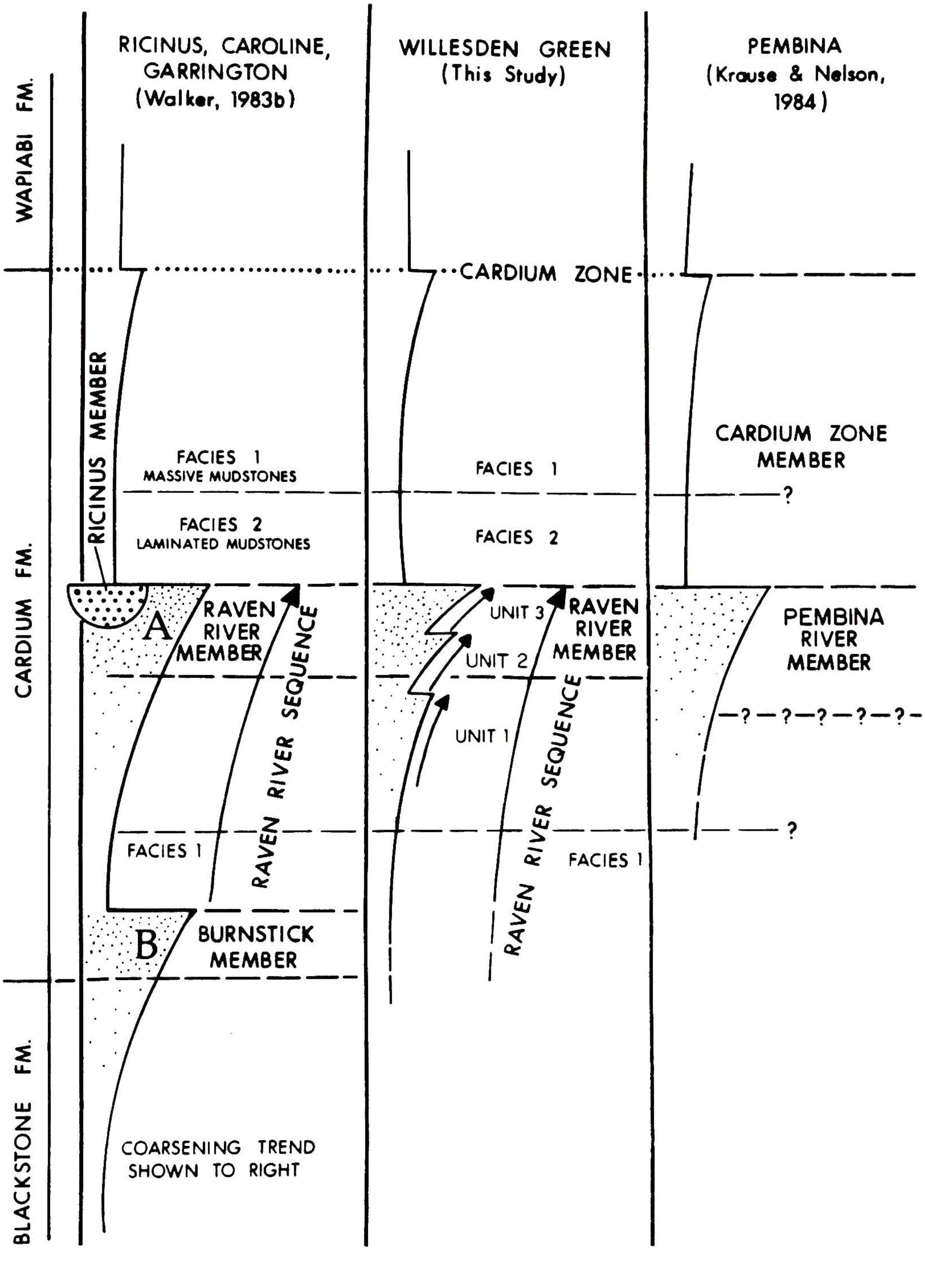
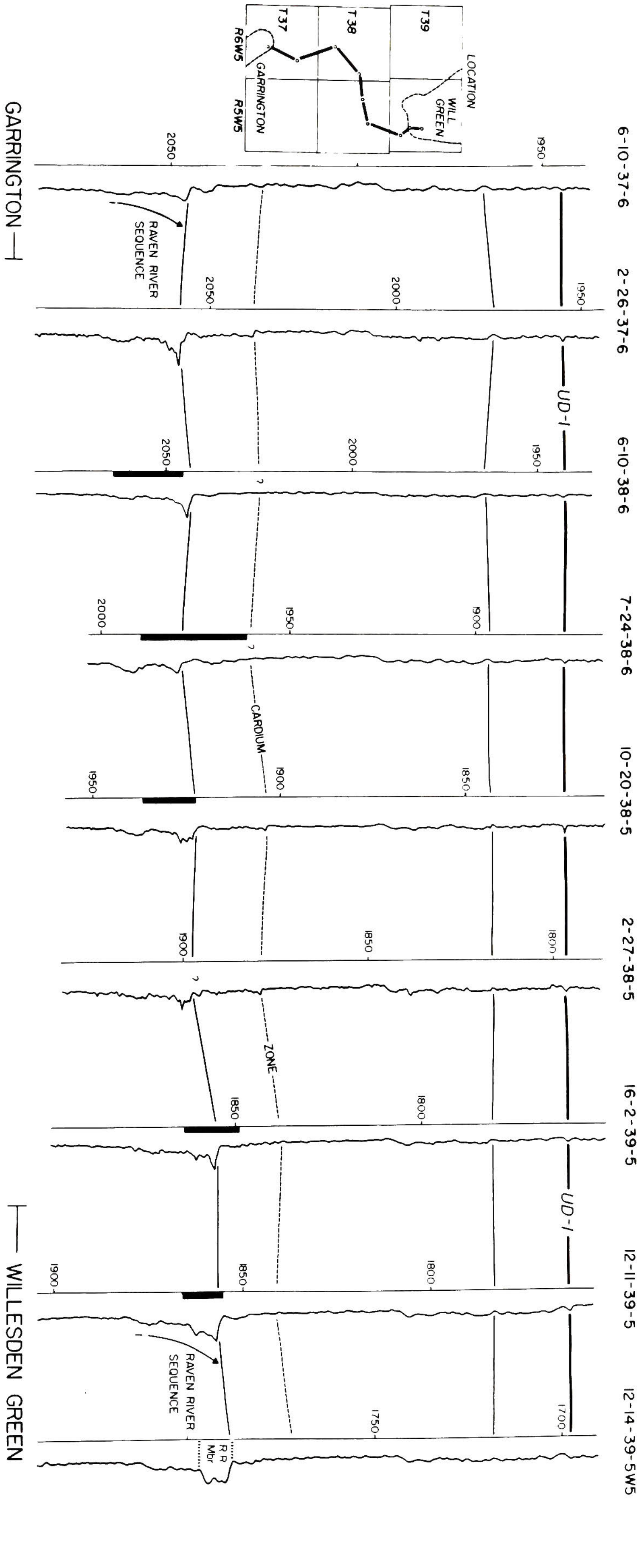

RICINUS, CAROLINE, GARRINGTON (Walker, 1983b)
WILLESDEN GREEN (This Study)
PEMBINA (Krause & Nelson, 1984)
WAPIABI FM.
CARDIUM FM.
BLACKSTONE FM.
CARDIUM ZONE
RICINUS MEMBER
FACIES 1
MASSIVE MUDSTONES
FACIES 2
LAMINATED MUDSTONES
FACIES 1
FACIES 2
CARDIUM ZONE MEMBER
A
RAVEN RIVER MEMBER
RAVEN RIVER SEQUENCE
UNIT 3
UNIT 2
UNIT 1
RAVEN RIVER MEMBER
RAVEN RIVER SEQUENCE
PEMBINA RIVER MEMBER
FACIES 1
FACIES 1
B
BURNSTICK MEMBER
COARSENING TREND SHOWN TO RIGHT

Fig. 2.3. Cross section from northern Garrington to southern Willesden Green, location shown on left margin of figure. Dark bars indicate intervals of examined core, all depths in metres. Datum is UD-1 (see chapter 4 for discussion of UD-1) and position of the Cardium zone is indicated by the dashed line. The lowest solid line correlates the top of the Raven River Sequence between Garrington (6-10-37-6W5) and Willesden Green (12-12-39-5W5 [p.199] and 12-14-39-5W5). The position of the Raven River Member is shown in 12-14-39-5W5, it appears to continue southward into 12-12-39-5 and 16-2-39-5 [p.199]. It may not be developed south of 16-2-39-5 where the top of the Raven River Sequence drops stratigraphically with respect to UD-1.

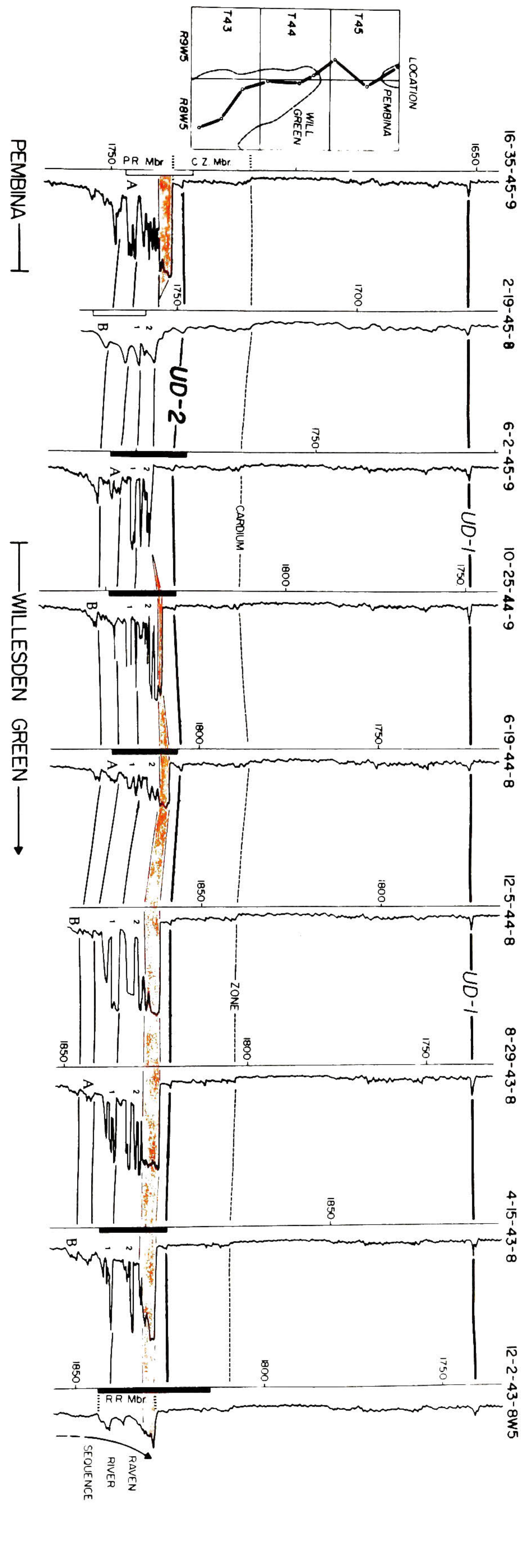


GARRINGTON
WILLESDEN GREEN
LOCATION
WILL GREEN
GARRINGTON
T37
T38
T39
R6W5
R5W5
6-10-37-6
2-26-37-6
6-10-38-6
7-24-38-6
10-20-38-5
2-27-38-5
16-2-39-5
12-11-39-5
12-14-39-5W5
UD-1
CARDIUM
ZONE
RAVEN RIVER SEQUENCE
R.R. Mbr

at Willesden Green and Ferrier and with the Pembina River Member at Pembina. Figure 2.3 - a cross section between northern Garrington and southern Willesden Green shows the Raven River Sequence (not Member) to be continuous between the two fields. The section shows the Raven River Member developed in well 12-14-39-5 to thin and drop stratigraphically southwards (into the Raven River Sequence) Willesden Green. Figure 2.4 - a cross section between northern Willesden Green and southern Pembina again shows the Raven River Sequence to be continuous between fields (Pembina River Member within Pembina). It also shows some of the Cardium sandstones at Pembina (those designated A and B on Fig. 2.4; see also sections 1, 2, and 3 in Fig. 6.1 where identical log responses A and B occur beneath the Raven River Member) to drop stratigraphically and show a less well developed log response towards Willesden Green; they occur below the Raven River Member at Willesden Green. Figures 6.1 through 6.4 show twelve cross sections between Willesden Green and Ferrier. The Raven River Member appears to be correlative though not continuous between Ferrier and Willesden Green. The Raven River Sequence is continuous through this region.

It is unfortunate two names (the Raven River and Pembina River) have been introduced to describe what are believed to be identical Cardium members. Since Walker's (1983c) Raven River Member has priority over Krause and Nelsons' (1984) [illegible] Member, the Raven River Member is extended

Fig. 2.4. Cross section from southern Pembina to northern Willesden Green, location shown on left margin of figure. Dark bars indicate intervals of examined core, light bars indicate intervals for which lithological data was available. Datum is UD-1, the position of the Cardium zone is indicated by dashed lines and the position of UD-2 is indicated by a solid line below the Cardium zone. Approximate bounds to the Raven River Member are indicated in 12-2-43-8W5 [p.223] and to the Pembina River and Cardium Zone Members in 16-35-45-9W5. Note the discontinuous nature of the conglomerate (colored orange) between Pembina (16-35-45-9W5) and Willesden Green (10-25-45-9W5 [p.241]). Raven River Units 1 and 2 occur in the section with lower log markers A and B, note the correlation of strong resistivity kicks representing relatively thick Cardium Pembina sandstones in 16-35-45-9W5 with log responses which drop stratigraphically and become less well developed into Willesden Green. It appears some of the Cardium Pembina sandstones may terminate below Willesden Green.


LOCATION
PEMBINA
WILL GREEN
T43
T44
T45
R9W5
R8W5
PEMBINA
WILLESDEN GREEN
16-35-45-9
2-19-45-8
6-2-45-9
10-25-44-9
6-19-44-8
12-5-44-8
8-29-43-8
4-15-43-8
12-2-43-8W5
P R Mbr
C Z Mbr
R R Mbr
UD-2
UD-1
CARDIUM
ZONE
RAVEN RIVER SEQUENCE

into the Willesden Green and Ferrier areas.

The members correlate in the sense that all occur at the same stratigraphic position within the Cardium Formation (see Figs. 2.3, 2.4, and 6.1 - 6.4). This position is defined as the upper sandy or conglomeratic portion (facies 5, 6, 7 or 8, see chapter 3 for facies descriptions) of the first major coarsening-upward sequence occurring below the Cardium zone (in Caroline, Garrington, Ferrier and Willesden Green this is the Raven River Sequence).

It must be stressed that use of the name Raven River Member at Willesden Green (and Ferrier) does not imply continuity between the various fields. Examination of cores from the off-field margins of Willesden Green shows the Raven River Member (my interpretation of Walker's (1983b) definition - rocks containing at least 50 % sandstone, or containing conglomerates) to sometimes be poorly developed or lacking. In these off-field wells, the sandiest facies has a very approximate range of 30 - 60 % fine sandstone within a predominantly muddy and silty facies (facies 4 and the lower range of facies 5). To further emphasize this point, the coarsest facies encountered at the top of the Raven River Sequence from a number of wells on the off-field margins of Willesden Green is discussed below.

To the South of Willesden Green (wells 10-28-38-3W5 [p.197] and 10-20-38-5W5 [p.197]) facies 5 is the sandiest facies in the Raven River sequence. A few chert pebbles scattered in mudstone overly facies 5 in 10-28-38-3W5 [p.197], and 6 cm of pebbly mudstone overlie facies 5 in 10-20-38-5W5 [p.197]. At 12-26-39-6W5 [p.201] and 10-8-39-6W5 [p.200] in-between Willesden Green and Ferrier, facies 3 is the sandiest facies in the Raven River Sequence. Conglomerates occur in both wells within laminated mudstones (facies 2) which overlie the Raven River sequence. In 16-12-41-7W5 [p.204], also in-between Ferrier and Willesden Green, facies 5 is overlain by a few centimetres of conglomerate which represents the Raven River Member. Northeast of Willesden Green, well 3-16-43-5W5 [p.216] shows facies 3 capping the upper sequence, with scattered pebbles in the overlying muddy facies. The cores described above, along with others examined, show the upper coarsening-upward sequence below the Cardium zone to have little in the way of sand development. In these areas, the Raven River Member is poorly developed to absent. Therefore, when referring to Cardium sediments in the the study area (which include both on-field and off-field wells) occurring near the top of Raven River Sequence, they are discussed as being contained within the Raven River Sequence. If sediments from within Willesden Green alone are being discussed, they are referred to as being contained within the Raven River Member.

Willesden Green Internal Stratigraphy

n in Figure 2.2, the upward-coarsening Raven in the Willesden Green area is composed of multiple coarsening-upward sequences. These multiple coarsening-upward sequences are henceforth referred to as **Raven River Units**. The Raven River Units which occur high in the Raven River Sequence (i.e. they contain sandy facies) are contained within the Raven River Member. The Units are discussed in terms of facies sequence in chapter 3 and their geometry, regional extent and relationship with the Cardium conglomerate are described in chapter 6.

2.2.3 Setting

Structural Setting

The sediments within the field are essentially structurally undisturbed and have a regional dip in the order of 60 ft/mile or 11.4 m/km (0.65 degrees). Average depth from surface to the reservoir, generally the uppermost sandstone within the Raven River Member, is 1897 m.

Jones (1980) has suggested the occurrence of a regional vertical fault trending along the northwestern margin (Twn. 43 and 44) of Willesden Green. A core from 7-32-44-8W5 [p.240] (1780 - 1796 m) shows fault repeated conglomerate; this is probably the result of localized, minor field margin faulting unrelated to Jones's (1980) suggested regional faults.

Paleogeographic Setting

It has been suggested that the Cardium fields south (Caroline and Garrington) and north (Pembina) of Willesden Green lay tens of kilometres off shore in a shallow epicontinental sea.

Walker (1983c, p. 226) suggests distances in the order of 140 to 200 km from any shoreline to the northwest of the Caroline and Garrington fields. Palinspastic reconstructions of foothills thrusts containing the westernmost Cardium outcrops (Seebe and Ram Falls, both fully marine) by Walker (1983c) give minimum distances of about 100 km to Caroline.

Krause and Nelson (1984, p. 500) suggest the sediments at Pembina were deposited approximately 100 km from shore, this distance based on positioning of Pembina on a paleogeographic map of North America during the Turonian (Williams and Stelck 1975, p. 11). In keeping with this work, I suggest that deposition of the coarse sediments at Willesden Green may have been initiated many tens of kilometres off-shore in a shallow epeiric sea. From study of the Cardium only at Willesden Green I lack sufficient information to suggest a precise depositional site with respect to paleoshoreline. However, due to the possibility of regional sea-level changes in the western Interior Seaway during Cardium deposition the possibility of a shoreline [illegible] suggested by Walker (1983c) or Krause and [illegible] annot be discounted. If the Cardium sediments at Willesden Green were deposited during a regional regression such as the R6 or Greenhorn regression suggested to occur from the mid to upper Turonian in the Cretaceous Interior Seaway by Kauffman (1977), a successively closer shoreline during the deposition of Cardium sandstones and conglomerates is probable.

CHAPTER 3: FACIES AND FACIES SEQUENCE

3.1 METHOD AND INTRODUCTION

The facies divisions discussed herein are based on information gained from examination of core at the Core Research Center, Calgary. Of approximately 576 cored wells within Willesden Green, 178 were examined (Fig. 1.2), roughly 30% of the total. The basis for facies divisions is discussed first, followed by the facies descriptions. Next, the general facies sequence at Willesden Green is discussed. Chapter 3 concludes with sedimentological interpretations of the facies and conclusions based on the sedimentology.

3.2 FACIES DIVISIONS

The term "facies" is used here in the sense of De Raaf *et al*. (1965, discussed in Walker, 1984a, p. 1) to subdivide a group of rocks on the basis of lithology, sedimentary structures and biological features (body and trace fossils). The Cardium sediments include clay through pebble sized terrigenous material. Biogenic activity ranges from absent, to a few burrows, to intense bioturbation.

Soon after beginning this study it became apparent that the rocks encountered at Willesden Green could be described s defined by Walker (1983c) from his study of

Cardium fields to the south of Willesden Green. The divisions used here are therefore, with a single addition, identical to those defined by Walker (1983c) from the Raven River Sequence at Caroline and Garrington. The additional facies is composed of nonbioturbated, interbedded fine sandstones and silty mudstones. This facies was later found to be somewhat similar to facies 3 of Krause (1983, p. 46).

3.3 FACIES DESCRIPTIONS

3.3.1 Introduction

A brief description of each of the facies is given below. Walker's (1983c) facies scheme and terminology will be used throughout, with the exception of facies 6. Figures 3.1 through 3.28 are core photographs illustrating various aspects of the facies described.

3.3.2 Facies 1: MASSIVE DARK MUDSTONE (Figures 3.1 and 3.2)

The massive mudstone facies envelops the Raven River sequence and its overlying laminated mudstones (facies 2) in Willesden Green. It occurs in the lower part of the Raven River sequence (Figure 3.1) and above facies 2 (Figure 3.2) at Willesden Green (Fig. 2.4). It is dark grey to black in color and lacks distinct silty to fine sand laminae.

Although distinct burrow forms are absent, a slabbed core will show a "stirred or mottled" appearance suggesting bioturbation (Walker, 1984, p. 216). Fragments of the bivalve Inoceramus sp. are common, and on bedding-planes, the trace fossil Gordia is common (George Pemberton, personal communication, 1983). Concretions of siderite commonly occur within the unit, as do occasional small clumps of pyrite.

3.3.3 Facies 2: LAMINATED DARK MUDSTONE (Figure 3.3)

This facies overlies the Raven River Member at Willesden Green, Ferrier, southern Pembina (Pembina River Member) and Caroline and Garrington (Walker 1983b; see Fig. 2.4). It is similar to facies 1 in that it is a dark mudstone, but is distinguished by the presence of thin (mm to 1 cm) silty to very fine sandstone laminations. These laminations are commonly sharp-based with diffuse tops. Grading within the laminations is suggested by upward color grading; dark corresponding with finer sediment and lighter colors with coarser sediment. Individual laminae are generally continuous although some show evidence of burrowing; the traces Gordia, and Planolities? are present. Siderite and pyrite concretions may occur.

Walker (1983c) reported the average thickness of this facies to be 6.45 m within the Caroline - Garrington region. Study at Willesden Green has shown the average thickness of be 6.29 m, with the thickest developments of facies 2 found in wells near the margin of Willesden Green. The data comes from 38 cores between Townships 36 and 44; in all cores facies 2 graded up into facies 1, and was underlain by facies 5, 7 or 8. The similarity in average thickness is remarkable over such a large area and will be discussed later.

3.3.4 Facies 3: DARK BIOTURBATED MUDDY SILTSTONE (Figure 3.4)

This facies gradationally overlies facies 1, with an increase in fine sand percentage from almost zero (facies 1) to a maximum of 20 percent fine sandstone in facies 3. Preservation of sandstone beds is extremely rare within this facies due to the high degree of bioturbation. With the relatively low percentage of sand, distinct and identifiable burrow forms are generally not discernible. Concretions of sideritized mudstones, and clusters or disseminated crystals of pyrite commonly occur within this facies.

3.3.5 Facies 4: PERVASIVELY BIOTURBATED MUDDY SANDSTONE (Figures 3.5 - 3.8)

Facies 4 gradationally overlies facies 3, and contains roughly 20 to 50 percent fine sandstone. Preservation of fine sandstone beds is more common than in the muddier facies below, although they still occur relatively rarely. Walker (1983c, p. 218) notes that much of the dispersed sand was probably originally deposited as discrete, sharp based beds. With the increased sand content (relative to previously described facies) many distinct burrow forms are identifiable in this unit. They include: *Zoophycos*, *Teichichnus*, *Skolithos*, *Planolities* and *Paleophycus*. Occasional siderite concretions occur within the unit.

Partial, or wholly preserved beds are generally thicker than 5 cm, but are rare.

3.3.6 Facies 5: BIOTURBATED SANDSTONE (Figures 3.9 -3.12)

The bioturbated sandstone facies contains between 50 and 90 percent fine sand. It overlies facies 4 very gradationally, and much experience and familiarity is necessary to estimate a contact. There are, however, several features which allow the bioturbated sandstone facies to be distinguished from the less sandy facies 3 and 4. These include an increased number of preserved burrows, including *Zoophycos*, *Rhizocorallium*, *Conichnus*, *Paleophycus* *Rosselia*, *Skolithos*, *Chondrites* and occasionally *Ophiomorpha*. Walker (1983c, p.218-219) notes that the bioturbated sandstone facies commonly shows an abundance of *Chondrites* whereas facies 3 and 4 generally lack this burrow form. The greater thickness and frequency of sandstone beds in the bioturbated sandstones also helps to distinguish the facies. As in facies 4, the best preserved sandstones are generally thicker than 5 cm and commonly show horizontal or low-angle inclined lamination. Bases of the beds are sharp [illegible] ioturbated. Ripple cross lamination, probably of wave origin frequently caps the sandstone beds.

Wave vs. Current Generated Cross Lamination

The majority of the ripple cross lamination show a shallowly dipping stoss side (Fig. 3.22), with foresets (where shown) dipping at a low angle (roughly 10 degrees or less). Some ripples show continuity of laminae over the ripple crests. Symmetrical profiles are shown in some ripples (Fig. 3.21). From these criteria, most ripples are interpreted as asymmetrical wave ripples with some symmetrical wave ripples. Current ripples would be expected to show more steeply dipping foresets, no continuity of laminae over ripple crests and no symmetrical ripple profiles. A thorough discussion of current and wave ripples is found in Reineck and Singh (1980, p. 22-55).

3.3.7 Facies 6: INTERBEDDED FINE SANDSTONES AND SILTY MUDSTONE (Figure 3.13)

This facies was not recognized by Walker (1983c) in the Caroline - Garrington area and is not equivalent to the facies he designated facies 6. My facies 6 most commonly occurs immediately above the bioturbated sandstones (facies 5) and below nonbioturbated sandstones (facies 7). Sand percentage of the unit, and bed thickness of discrete sandstone beds is the same as in facies 5. The similarity ends here because facies 6 lacks significant bioturbation. Burrows are rare and most sand beds show complete preservation. Sand beds are of the order of 3 to 8 cm thick and interbedded silty mudstones range from 2 to 5 cm thick. The sand beds are commonly sharp-based and internally may show horizontal stratification, low-angle inclined lamination (generally less than 10 degrees) or higher angle inclined stratification. The higher angle (greater than 10 to 15 degrees) inclined stratification occurs in sets no more than 10 to 15 cm thick. Ripple cross lamination frequently caps the individual sand beds (Figure 3.21). These ripples are interpreted as wave rather than current generated. Within facies 6 some scouring is evident (generally measurable in cm), with both mud and sand fill (Figure 3.19).

3.3.8 Facies 7: NONBIOTURBATED SANDSTONE (Figures 3.14 - 3.24)

This facies is composed of fine to very fine sandstones with very thin mudstone partings, it is the main reservoir facies within Willesden Green. Individual beds range in thickness from approximately 10 cm to several metres. The beds are commonly sharp-based. Internally they show horizontal lamination (Figure 3.14), or low-angle inclined lamination (less than 15 degrees) which shows subtle upward dip variations (Figures 3.15 to 3.18). The sandstones commonly show ripple cross laminated tops (Figures 2.20 and 2.23). Most of the cross lamination is suggested to be wave generated for the reasons discussed above. Thin (1 to 2 mm) mudstones and beds of mudstone clasts (some sideritized) separate sand units. This facies is commonly capped by thin sideritized mudstones and calcite cemented fine sandstones. Near or at the top of this facies Ophiomorpha burrows sometimes occur.

3.9 Facies 8: CONGLOMERATE (Figures 3.25 - 3.28)

The coarsest Cardium facies, a chert pebble conglomerate, occurs below facies 2 and caps facies 5, 6, or 7 (or a less sandy facies in off-field regions). Individual clasts range from coarse sand to pebbles of up to 7cm. The facies ranges from a few cm to more than 5 m in thickness.

Conglomerates may be subdivided into clast supported (Figs. 3.25 and 3.26) or matrix supported (pebbly mudstones, Fig. 3.27); and conglomerates also occur as thin bands in mudstone (Fig. 3.28).

CLAST SUPPORTED CONGLOMERATE

Clast supported conglomerates are most common in the regions of thick conglomerate accumulation (chapter 4) and consist of well rounded chert pebbles and occasionally sandstone or mudstone rip-up clasts (Fig. 3.25). The subfacies generally lacks stratification (graded bedding is extremely rare) or preferred fabric and the thickness of individual beds (where determination is possible) is of order the tens of cm.

MATRIX SUPPORTED CONGLOMERATE

In regions of Willesden Green having conglomerate accumulation of less than 1 m, matrix supported conglomerates frequently occur. Mudstone matrix ranges from less than 20 percent to greater than 80 percent and therefore the subfacies may be called a pebbly mudstone. Stratification or preferred fabric is lacking. Sideritization of the mudstone is common, often with calcite filled fractures; both appear to occur randomly. Griffith (1981, p. 63-83) gives a thorough discussion of Cardium conglomerate diagenesis in Ferrier.

THIN CONGLOMERATE BANDS

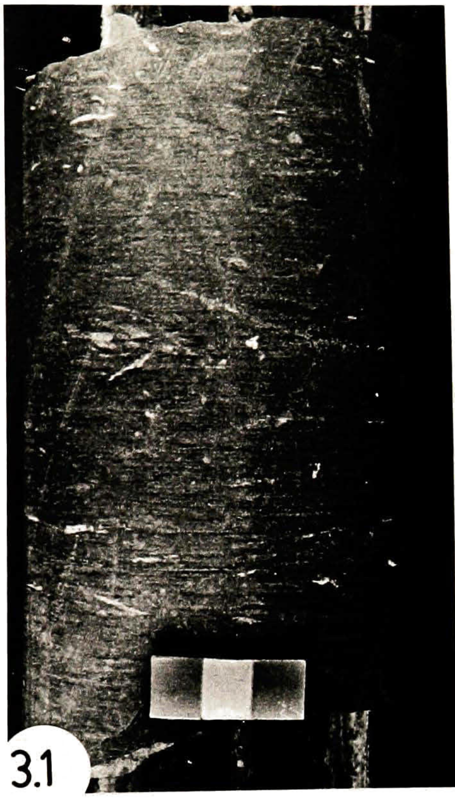
Thin discrete conglomerate bands occur within the laminated dark mudstones (facies 2), and range in thickness from a single pebble diameter to several centimetres. Infrequently, graded bedding is present though no stratification or preferred fabric occurs.

Fig. 3.1. Massive dark mudstone, facies 1. Note absence of any lamination and rare patchy occurrence of siltstone (lighter color). From below Raven River Member, 15-27-43-7W5 [p.222], 6024 ft (1836.1 m). Scale in cm.

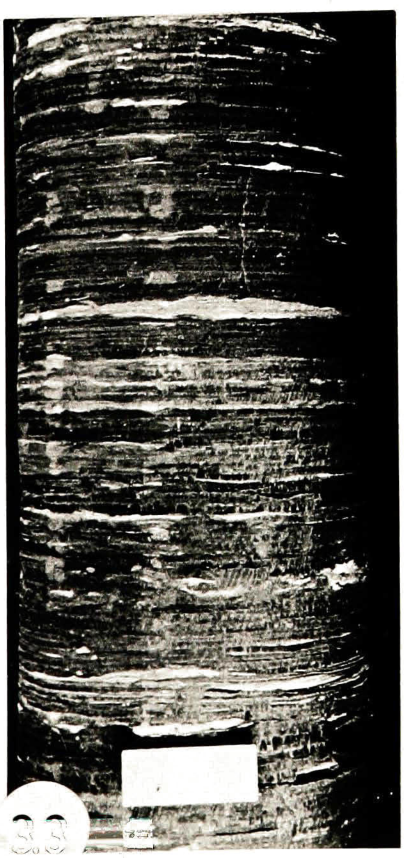
Fig. 3.2. Massive dark mudstone, facies 1. Note absence of any lamination and occurrence of siderite bleb at the top. From above facies 2 which overlies the Raven River Member, 6-6-43-6W5 [p.217], 1950.2 m. Scale in cm.

Fig. 3.3. Laminated dark mudstones, facies 2. Note sharply based silt and fine sandstone laminae (mm to 1 cm thick) within dark mudstones. The occurrence of discontinuous laminae suggest bioturbation. Compare with Figures 3.2 and 3.4, 13-11-43-6W5 [p.218], 5858 ft (1785.5 m). Scale in cm.

Fig. 3.4. Dark bioturbated muddy siltstones, facies 3. Note the churned, thoroughly mixed appearance with only few partially preserved silt- and fine sandstone laminae. Compare with Fig. 3.3, 6-18-42-6W5 [p.207], 6357 ft (1937.6 m). Scale in cm.


3.1


3.2


3.3

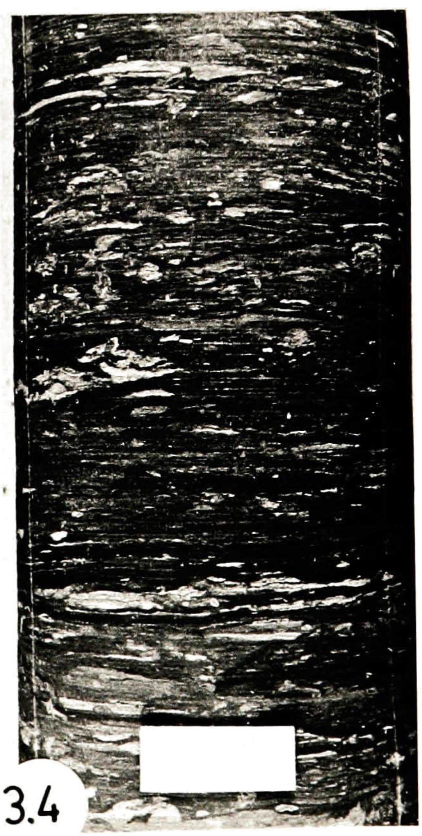

3.4

Fig. 3.5. Pervasively bioturbated muddy siltstone, facies 4. Note thin (2 cm) preserved sandstone bed at top. A Zoophycos burrow is evident in the upper and middle portions of the photo. Note disrupted sandstone laminations in lower portions of the photo. Compare with Figures 3.4 and 3.10, 2-9-43-8W5 [p.226], 6385 ft (1946.2 m).

Fig. 3.6. Pervasively bioturbated muddy siltstone, facies 4. Note thoroughly churned appearance with several remnants of fine sandstone laminae. Note Paleophycus burrow at extreme left, below break in core, 15-5-43-6W5 [p.217], 6859 ft (2090.6 m). Scale in cm.

Fig. 3.7. Pervasively bioturbated muddy siltstone, facies 4. Note large vertical burrow (Skolithos?) and churned appearance of most of core, 7-16-43-7W5 [p.221], 6216 ft (1894.6 m). Scale in cm.

Fig. 3.8. Pervasively bioturbated muddy siltstone, facies 4. Note Zoophycos burrow at top and churned appearance of core, 4-9-43-7W5 [p.220], 1941.8 m. Scale in cm.

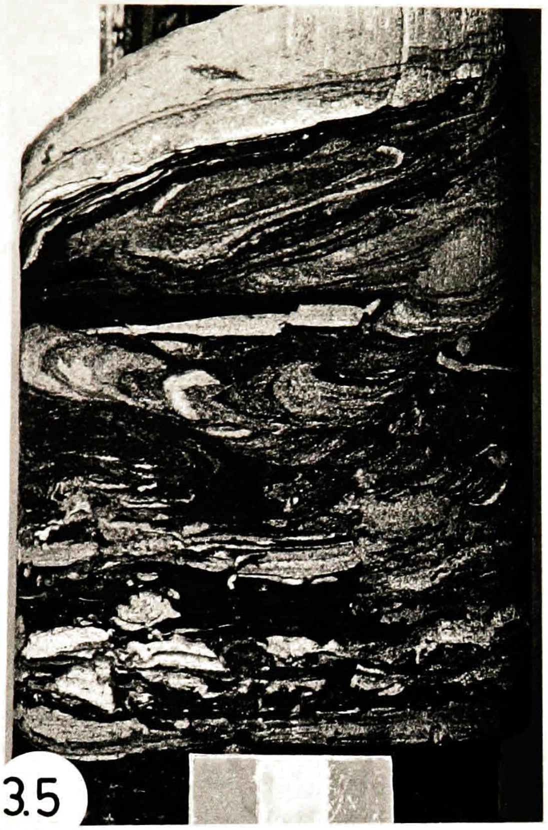


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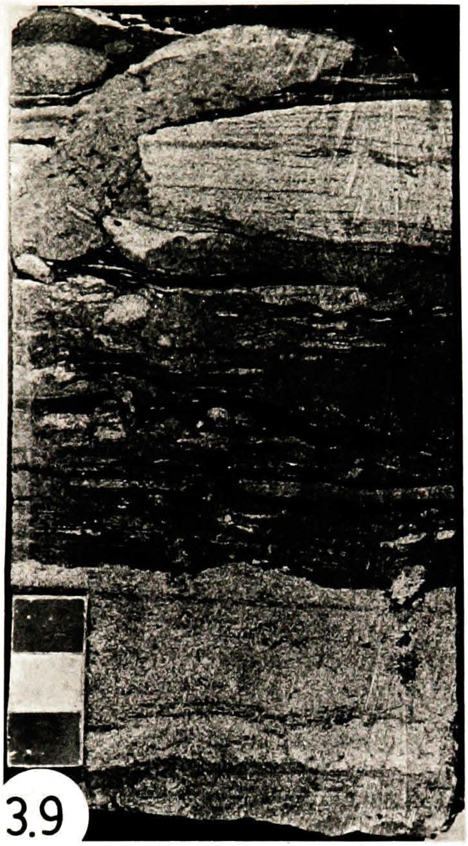
Fig. 3.9. Bioturbated sandstone, facies 5. Note sandstone beds separated by a bioturbated interval (with Paleophycus burrows). The top sandstone has been burrowed, 16-7-42-7W5 [p.209], 6331 ft (1929.7 m). Scale in cm.

Fig. 3.10. Bioturbated sandstone, facies 5. Note the thoroughly churned sandstones with no preservation of original laminae, 16-35-42-7W5 [p.212], 6334 ft (1930.6 m). Scale in cm.

Fig. 3.11. Bioturbated sandstone, facies 5. Note Chondrites surrounding remnants of sandstone beds. Nonbioturbated sandstone beds occur at the top and bottom, 6-18-42-6W5 [p.207], 6386 ft (1946.5 m). Scale in cm.

Fig. 3.12. Bioturbated sandstone, facies 5 and nonbioturbated sandstones, facies 7. Note 15 cm subhorizontally laminated sandstone bed surrounded by bioturbated sandstones. Both the base and top of the sandstone bed are bioturbated, 6-18-42-6W5 [p.207], 6390 ft (1947.7 m). Scale in cm.

Fig. 3.13. Interbedded sandstones and mudstones, facies 6. Note 5 cm lower sandstone and 3 cm upper sandstone separated by 3 cm of mudstone. Lower sandstone shows a symmetrical ripple profile, overlain by subhorizontal sandstone. Note sharp tops on both sandstone beds, 15-5-43-6W5 [p.217], 6000 ft (1828.8 m). Scale in cm.



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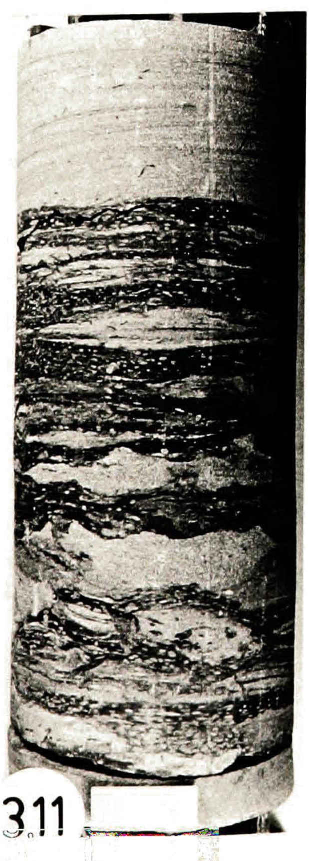

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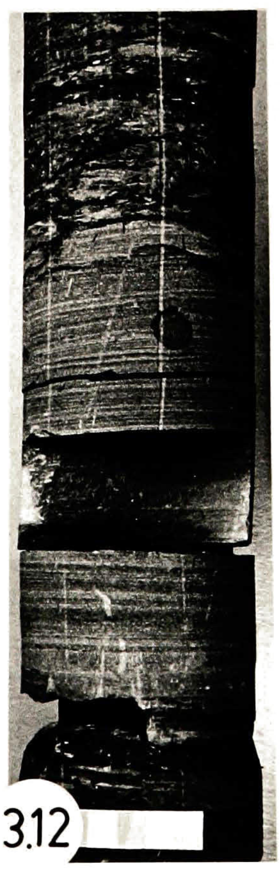

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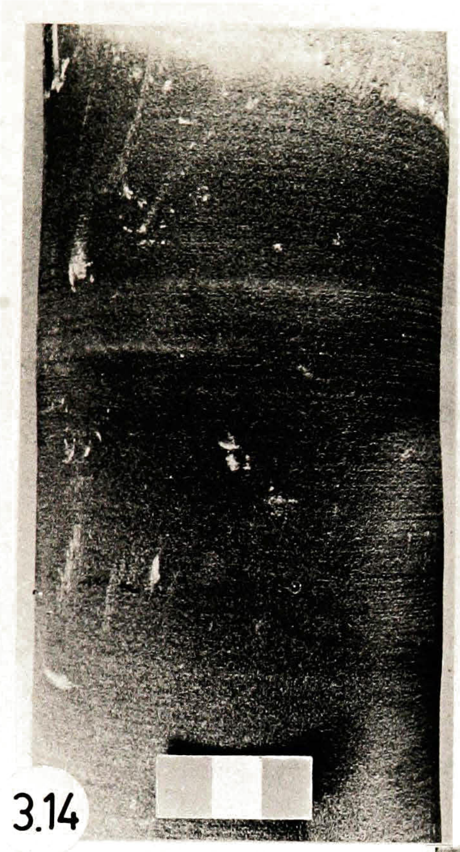
Fig. 3.14. Nonbioturbated Sandstones, facies 7. Note horizontal laminations, 16-31-42-7W5 [not logged in detail], 6431 ft (1960.2 m).

Fig. 3.15. Nonbioturbated Sandstones, facies 7. Slabbed core shows low-angle (less than 5 degrees) inclined lamination (emphasized with lower dashed lines), overlain by low-angle inclined lamination with the opposite dip direction. Thin, flattened mudclasts lie within the third and between the third and forth dashed lines, suggesting erosion of the substrate prior to deposition (c.f. Walker, 1983c, Fig.15, p. 222). This structure is interpreted as hummocky cross stratification, from 10-1-42-8W5 [p.213], 6360 ft (1938.5 m). Scale in cm.

Fig. 3.16. Nonbioturbated Sandstones, facies 7. Note low-angle lamination (less than 5 degrees) is truncated (at second dashed line) and overlain by laminae inclined (maximum of 13 degrees) in the opposite direction which grades up into horizontal laminae. As was Figure 3.15, this structure is interpreted as hummocky cross stratification, 4-14-42-8W5 [p.214], 6276 ft (1912.9 m). Scale in cm.

Fig. 3.17. Nonbioturbated Sandstones, facies 7. Note low-angle inclined laminations truncated and overlain by laminae dipping in the opposite direction. The laminae flatten upward into 5 cm of bioturbated sandstone capped with interlaminated sandstone and mudstone, 16-13-42-7W5 [p.210], 6566 ft (2001.3 m). Scale in cm.

Fig. 3.18. Nonbioturbated Sandstones, facies 7. Enlargement of divergently dipping laminae from Figure 3.17. Note upward flattening of upper laminae, 16-13-42-7W5 [p.210], 6566 ft (2001.3 m). Scale in cm.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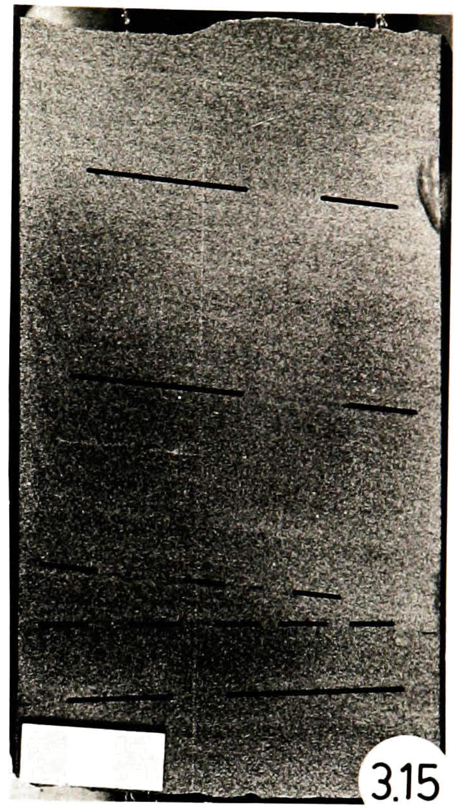
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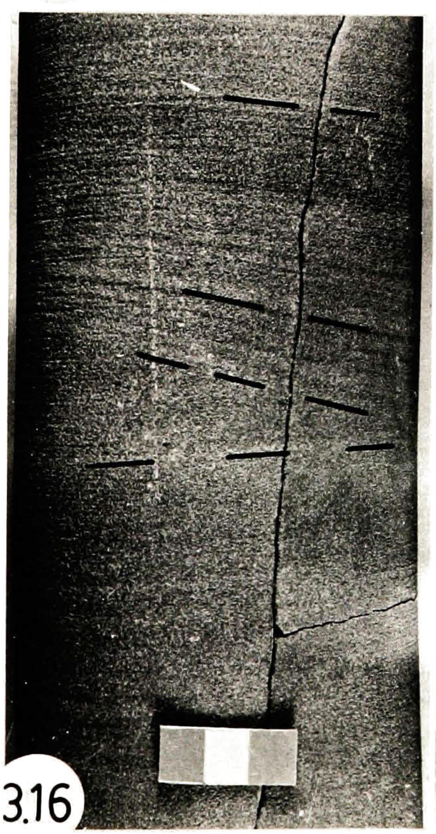
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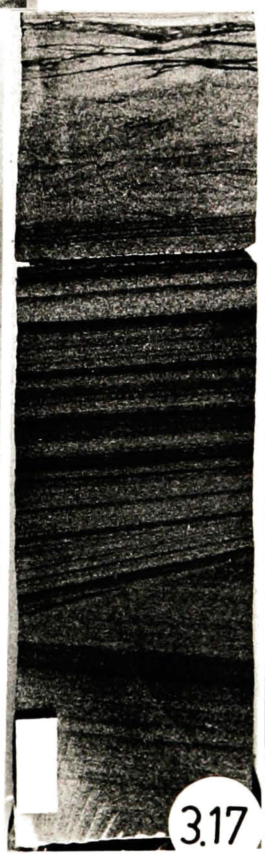
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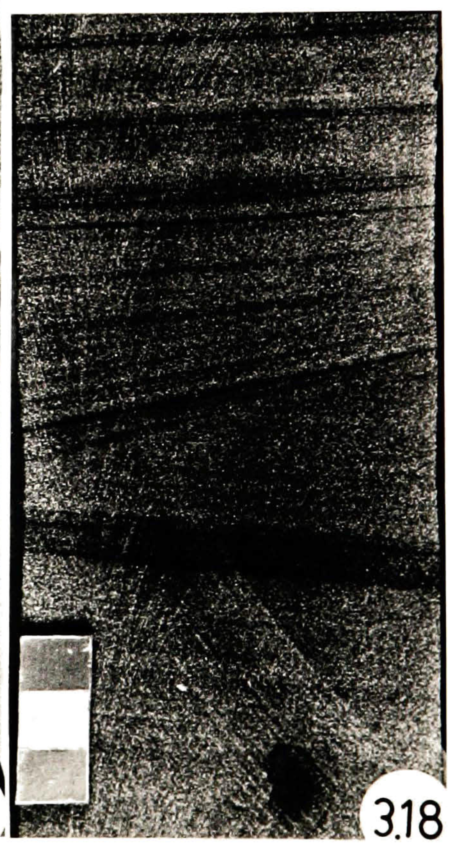
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Fig. 3.19. Nonbioturbated Sandstones, facies 7. Note horizontal to very low-angle inclined sandstone with row of sideritized mudstone pebbles. Structureless sandstone fills scoured upper surface, 16-19-42-6W5 [p.207], 6253 ft (1905.9 m). Scale in cm.

Fig. 3.20. Nonbioturbated Sandstones, facies 7. Note horizontally laminated sandstones truncated by a symmetrically undulating surface which is overlain by 6 cm of hummocky bedded sandstones? grading up into wave ripples. The upper surface of the sandstone is truncated and capped with dark mudstone, 15-5-43-6W5 [p.217], 6002 ft (1829.4 m). Scale in cm.

Fig. 3.21. Nonbioturbated Sandstones, facies 7. Top of sandstone bed shows an excellent example of symmetrical ripples, these are draped by dark mudstone, 6-16-42-7W5 [p.211], 6330 ft (1929.4 m). Scale in cm.

3.19

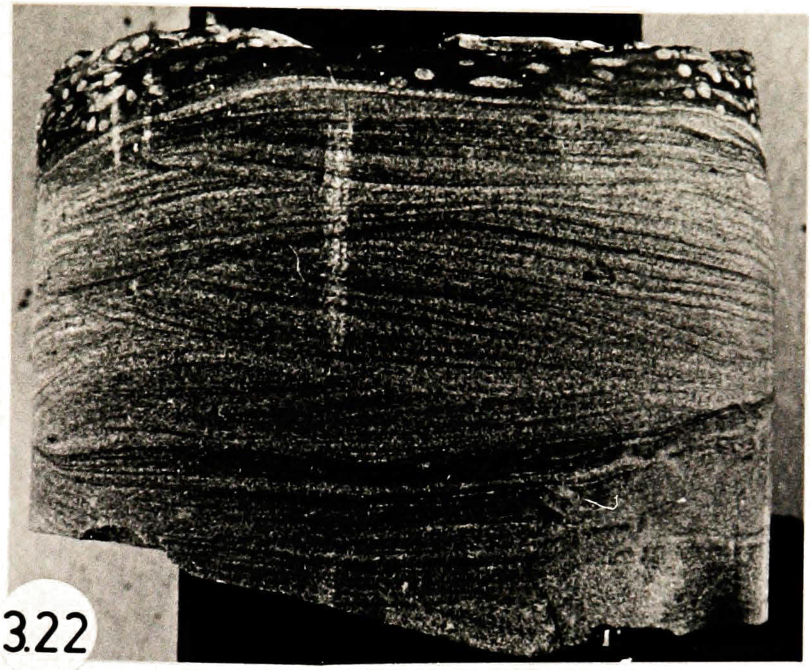
3.20

3.21

Fig. 3.22. Nonbioturbated Sandstones, facies 7. Note multiple sets of shallow dipping foresets capping a horizontally laminated sandstone bed and the smooth, symmetrical top set of the ripple in the center. They are interpreted as wave ripple cross lamination, 6-35-41-7W5 [p.205], 6553 ft (1997.4 m). Scale in cm.

Fig. 3.23. Nonbioturbated Sandstones, facies 7. Note low angle inclined lamination grading upward into 8 cm of low amplitude ripples. Some of the ripple foresets are draped with mudstone, the ripples are interpreted as current ripple cross lamination. Horizontal lamination overlies the ripples, they represent a different depositional event, 16-26-41-6W5 [p.203], 6116 ft (1864.2 m). Scale in cm.

Fig. 3.24. Nonbioturbated Sandstones, facies 7 and Laminated Dark Mudstones, facies 2. Note mudstone clasts near the top of the horizontally laminated sandstone. Laminated mudstones (note thin silt laminations in mudstones, c.f. Figure 3.3) overlie the sandstones, 13-31-42-8W5 [p.216], 6395 ft (1949.2 m). Scale in cm.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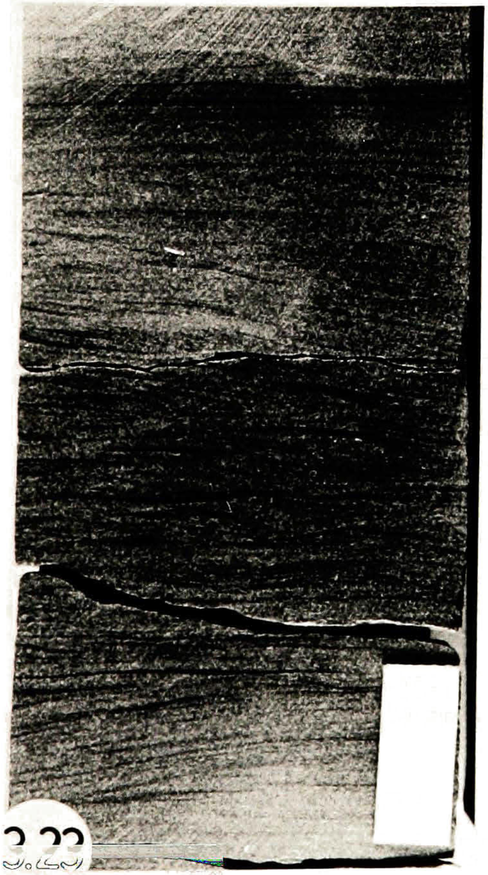
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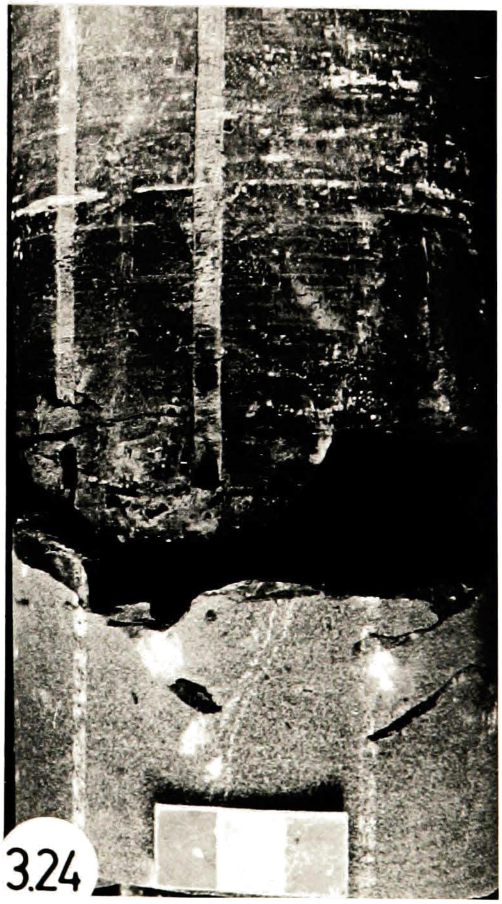
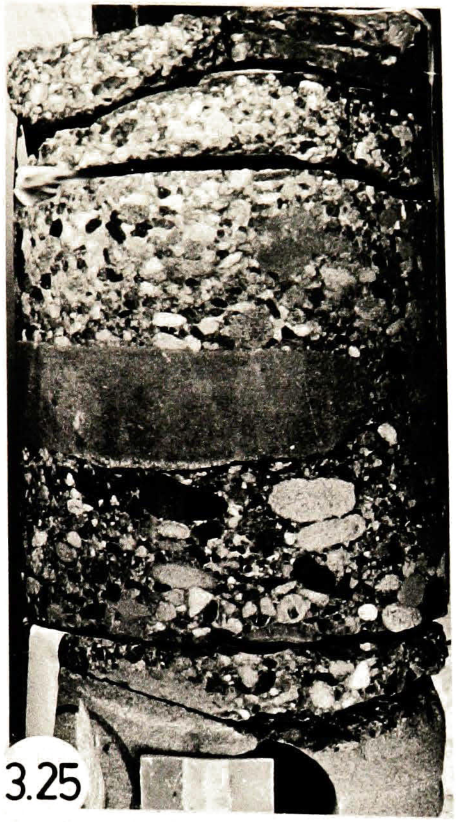

3.24

Fig. 3.25. Conglomerate, facies 8. This clast supported conglomerate may show grading (from 5 cm above base to top). Presence of the large (2.5 cm x more than 8 cm), angular sandstone block suggests erosive conglomerate emplacement, 10-23-43-9W5 [p.231], 6589 ft (2008.3 m). Scale in cm.

Fig. 3.26. Conglomerate, facies 8. Note the size variability of chert clasts (to greater than 40 mm) within this clast supported conglomerate. Lower pebbles show a hint of a preferred orientation but are randomly orientated elsewhere, 12-3-43-8W5 [p.224], 6335 ft (1930.9 m). Scale in cm.

Fig. 3.27. Conglomerate, facies 8. In this matrix supported, pebbly mudstone note the randomly oriented pebbles, many of which appear to be floating in the mudstone. Note the appearance of disrupted pebble bands, particularly in the center, 10-28-38-3W5 [p.197], 5451 ft (1616.5 m). Scale in Fig 3.25.

Fig. 3.28. Conglomerate, facies 8. Typical conglomerate banding within laminated mudstones (facies 2). Note the distinct bases and tops of the two lower pebble bands; the upper band appears, perhaps by burrowing organisms, 14-22-41-6W5 [not logged in detail], 6301.5 ft (1920.7 m). Scale in cm.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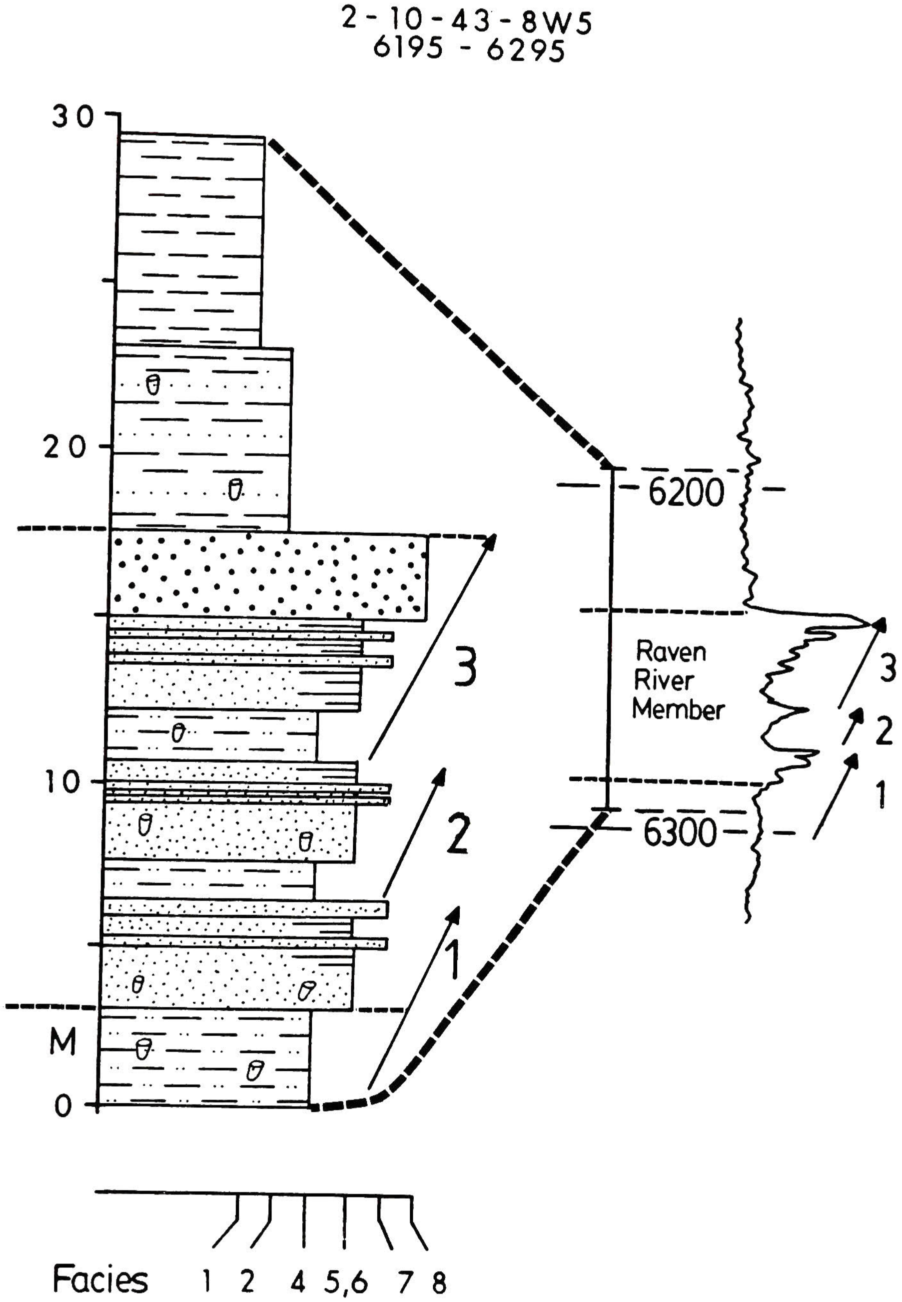
3.4 GENERAL FACIES SEQUENCE

3.4.1 Discussion

Facies sequences from three cores within the field (Figures 3.29, 3.30 and 3.31) serve as representative examples to describe the facies sequences. Diagrammatic core descriptions with a resistivity log are shown in each of the figures. The northernmost example, 2-10-43-8W5 [p.226] is shown in Figure 3.29, Figure 3.30 shows 15-5-43-6W5 [p.217] from northeastern Willesden Green and 10-11-42-8W5 [p.214] from the central region of the field is shown in Figure 3.31. In each case, well depths are in feet, core measurements in metres. The thick dashed lines join the described cored interval to the resistivity log. Stippled lines show the upper and lower bounds of the Raven River Member. The facies number is given in the lower portion of each figure and facies symbols within a generalized, composite core summarizing Cardium facies sequences at Willesden Green are shown in figure 3.32.

The cored interval from 2-10-43-8W5 [p.226] (Figure 3.29) shows three coarsening-upward sequences, which culminate in Raven River Member Units 1, 2 and 3 in ascending order (these Units are discussed thoroughly in chapter 6). The coarsening-upward sequences all begin with pervasively bioturbated muddy sandstones (facies 4) and the lower two coarsening-upward sequences end with laminated fine sandstones and mudstones (facies 6) or relatively thin,

Fig. 3.29. Lithologic and resistivity logs from 2-10-43-8W5 [p.226]. Well depths are in feet and core measurements are in metres. Thick dashed lines join the described core interval with the corresponding interval on the resistivity log. See text for discussion of the facies sequence. The thin dashed lines indicate the upper and lower bounds to the Raven River Member. Note the occurrence of Raven River Units 1, 2 and 3 in this well. See 9-9-43-8W5 in section 3 of Fig. 6.1 for comparison of the facies sequence from this core with that of adjacent wells.


2-10-43-8W5
6195 - 6295
30
20
10
0
M
3
2
1
6200
6300
Raven
River
Member
Facies 1 2 4 5,6 7 8

nonbioturbated sandstones (facies 7). The top coarsening-upward sequence ends with 2.5 m of conglomerate (facies 8) and is overlain by laminated mudstones (facies 2), which grades up into massive mudstone (facies 1).

Well 15-5-43-6W5 [p.217], east of the previous example shows two coarsening-upward sequences, but in this case over an increased interval (30 m). The lowest sequence begins with massive dark mudstones (facies 1) and coarsens into bioturbated sandstones (facies 5, this represents Raven River unit 2). The top sequence begins with facies 3, coarsening-up through facies 4, 5, 6 and 7 (representing amalgamated Raven River Units 4 and 5) into conglomerates (facies 8). A thin interval of laminated mudstone caps the conglomerate in this core.

Figure 3.31 (10-11-42-8, [p.214]) shows a similar cored interval to that of 2-10-43-8W5. Here, the lower two coarsening-upward sequences begin with dark bioturbated muddy siltstones (facies 3) and the top coarsening-upward sequence begins with pervasively bioturbated muddy sand-stones (facies 4). All three coarsening-upward sequences end with bioturbated sandstones (facies 5) or nonbioturbated sandstones (facies 7). A thin conglomerate (1 cm) caps the top sequence. The coarsening-upward sequences in 10-11-42-8W5 (as in Fig. 3.29) culminate in Raven River Member Unit 1 (the sandiest portion of the lowest sequence, Unit 2 (sandiest portion of the middle sequence and Unit 3 portion of the top sequence.

Fig. 3.30. Lithologic description from 15-5-43-6W5 [p.217] and a resistivity log from 5-5-43-6W5 (since well log and core description were unavailable for both wells these adjacent wells were used). Well depths are in ft and core measurements are in metres. Thick dashed lines join the described core interval with the approximate corresponding interval on the resistivity log. The thin dashed lines indicate the upper and lower bounds to the Raven River Member. See text for discussion of the facies sequence. Raven River Units 2, 4 and 5 occur in this core, units 4 and 5 are amalgamated (see 5-5-43-6W5 in section 6 of Fig. 6.2 for comparison of this sequence with other wells).

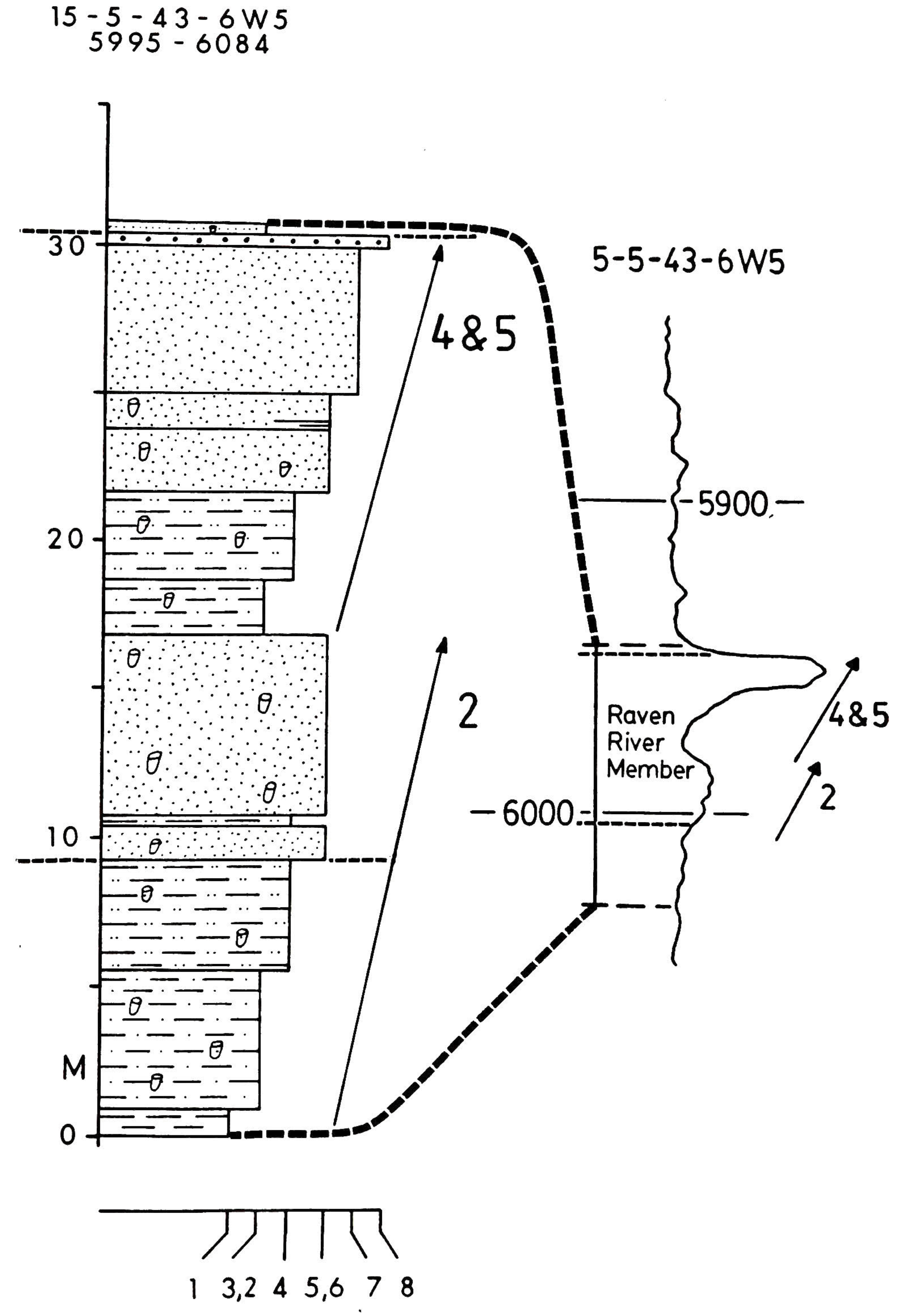
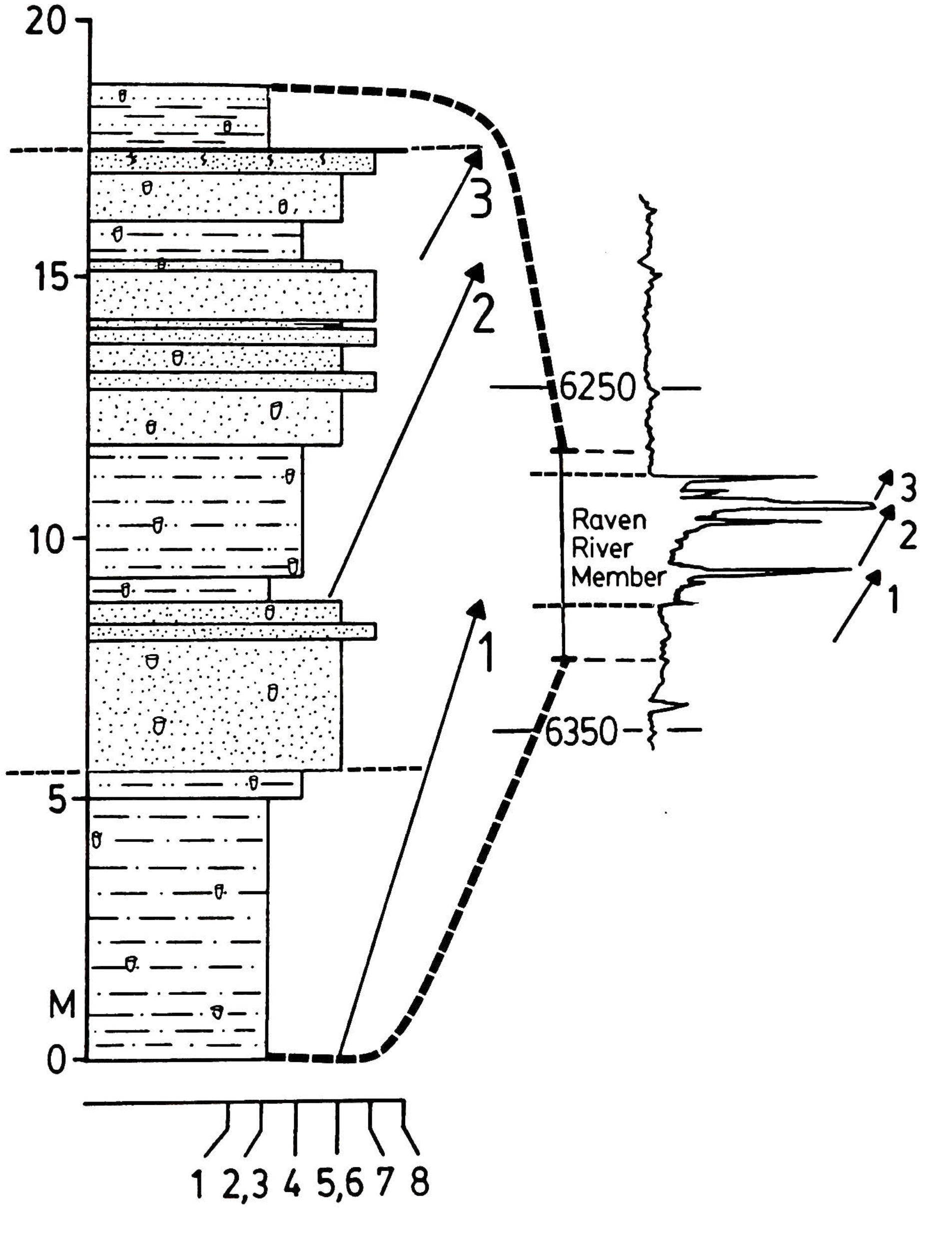

15 - 5 - 43 - 6W5
5995 - 6084
30
20
10
M
0
4&5
2
5-5-43-6W5
5900
6000
Raven
River
Member
4&5
2
1 3,2 4 5,6 7 8

Fig. 3.31. Lithologic and resistivity logs from 10-11-42-8W5 [p.214]. Well depths are in feet and core measurements are in metres. Thick dashed lines join the described core interval with the corresponding interval on the resistivity log. See text for discussion of the facies sequence. The thin dashed lines indicate the upper and lower bounds to the Raven River Member. Note the occurrence of Raven River Units 1, 2 and 3 this core. See 10-11-42-8W5 in section 6 of Fig. 6.2 for comparison of the facies sequence from this core with that of adjacent wells.

10-11-42-8W5
6269 - 6329

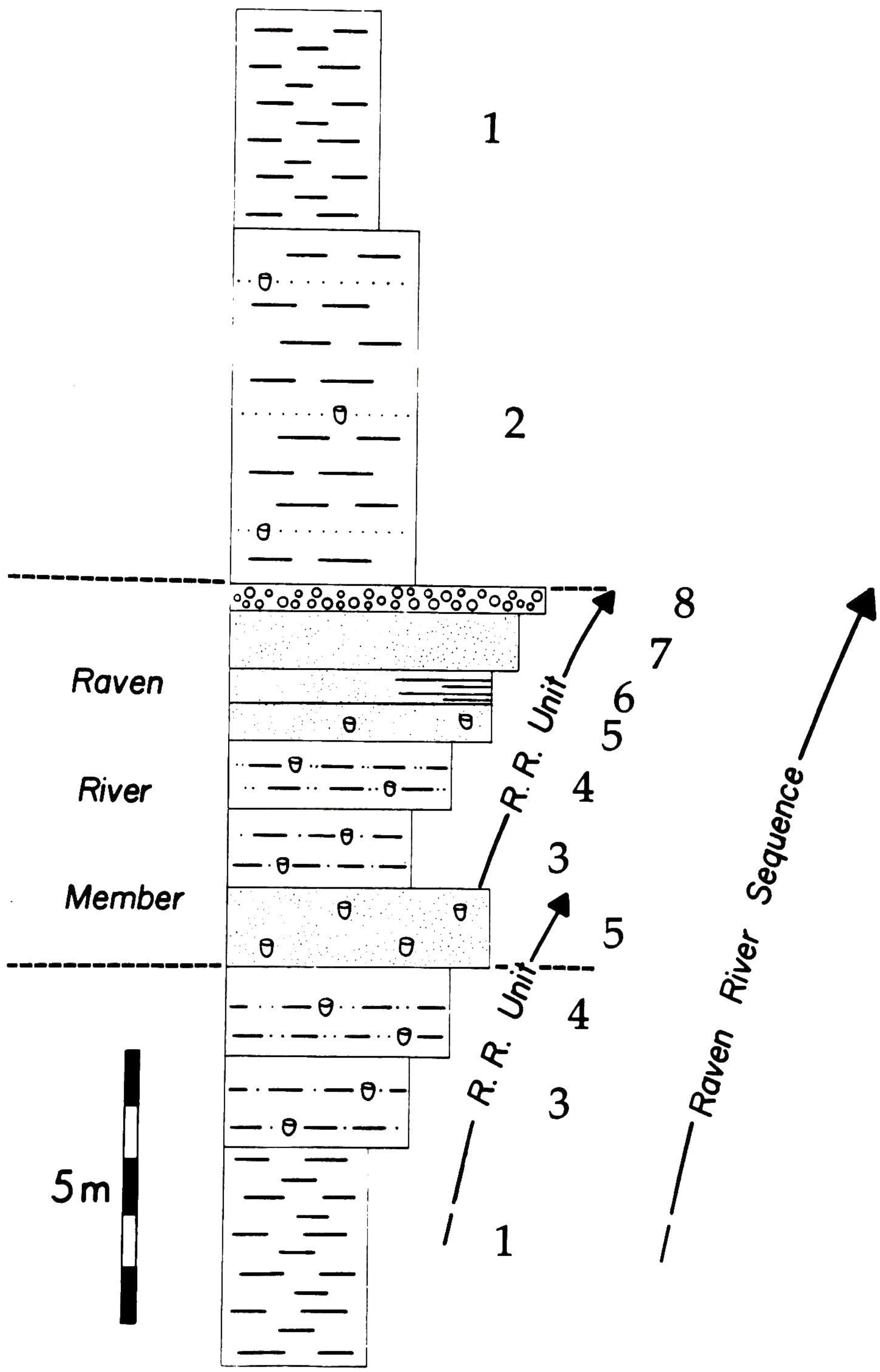


3.4.2 Facies Sequence Conclusions

Careful study of facies sequences in the examples of figures 3.29, 3.30 and 3.31 and in the other 176 cores examined in the Willesden Green area allow a number of generalizations about the field-wide nature of the facies sequences to be made.

1. The Cardium Formation at Willesden Green shows multiple individually coarsening-upward Units within the Raven River Sequence (see Fig. 3.32). Each Unit begins with coarser sediments than the one below, giving the complete, composite Raven River Sequence an overall coarsening-upward character. Massive mudstones (facies 1) begin the lowest Unit of the Raven River Member (though only the sandy upper portion of the lowest Unit occurs within the Raven River Member, i.e. Unit 1 in Fig. 3.29). Dark bioturbated muddy siltstones (facies 3) or pervasively bioturbated sandstones (facies 4) generally begin higher Units. Lower Units commonly end with bioturbated sandstones (facies 5), whereas upper Units commonly culminate in nonbioturbated sandstones (facies 7), the uppermost Unit may be capped by conglomerates (facies 8).

Fig. 3.32. Generalized, composite facies sequence of Cardium sediments from the Raven River Sequence and overlying facies in the Willesden Green Field. Facies thickness are approximations from the mid field region and, with the exception of facies 2 vary throughout the field (see discussion of the constant regional facies 2 thickness in the text). With the exception of facies 6, the numbers of the facies are identical to those used by Walker (1983c). The numbers correspond to the facies as follows: 1 - Massive Dark Mudstone, 2 - Laminated Dark Mudstone, 3 - Dark Bioturbated Muddy Siltstone, 4 - Pervasively Bioturbated Muddy Sandstone, 5 - Bioturbated Sandstone, 6 - Interbedded Fine Sandstone and Silty Mudstone, 7 - Nonbioturbated Sandstone, and 8 - Conglomerate. The Raven River Sequence and position of the Raven River Member and Raven River Units (R. R. Unit) are indicated. The same facies symbols are used in appendix 1.



1
2
8
7
Raven
6
5
River
4
3
Member
5
4
3
5m
1
R. R. Unit
R. R. Unit
Raven River Sequence

2. The laminated mudstone (facies 2) which overlies the Raven River sequence (within or adjacent to fields it overlies the Raven River Member) was found to have an average thickness of 6.29 m in wells between Townships 38 and 44. This value is remarkably similar to the average thickness for the same facies found by R. G. Walker in the Cardium Ricinus, Caroline and Garrington fields (personal communication, 1984). This similarity suggests blanketing by the laminated mudstone throughout the Willesden Green, Ricinus, Caroline and Garrington regions after cessation of deposition of coarser Cardium sediments. The greatest thickness of facies 2 was measured at 6-10-43-6 [p.218], (11.43 m) and 12-26-39-6 [p.201], (10.91 m), both off the margin of Willesden Green where the Raven River Member facies have thinned or are absent.

3. Massive mudstones (facies 1) underlie coarser facies grading up into the Raven River Member and overlie the laminated mudstones (facies 2).

3.5 SEDIMENTOLOGICAL INTERPRETATIONS

3.5.1 Introduction

Though the facies and facies sequence are interrelated they will be discussed individually. Facies are interpreted below, but interpretations of the facies sequence are deferred until information dealing with detailed sequence geometry at Willesden Green has been discussed.

3.5.2 Facies

The facies will be interpreted in four suites, each corresponding to a lithological grouping of the facies. The four subdivisions are: Mudstones (facies 1 and 2; predominantly mudstone facies); Bioturbated facies (facies 3 and 4, facies lacking nonbioturbated sandstone beds with up to 50% sandstone); Sandstone Facies (facies 5, 6 and 7, all facies in which nonbioturbated sandstone beds frequently occur); and Conglomerates (facies 8).

1. Mudstones (Facies 1 and 2)

Facies 1 and 2 were accumulated under relatively quiet conditions and may represent the deepest water deposits. Both were deposited below storm wave base. Facies 2 is suggested to have been deposited after a rapid regional deepening, based upon its blanketing of the Raven River Member from Willesden Green through Caroline and Garrington.

(see Fig. 2.4). Depth indicators (foraminifera) within and above the mudstone of the Raven River sequence at Caroline - Garrington give very approximate water depths of the order of 50 m (Walker, 1983c, p. 215-216).

2. Bioturbated Facies (only rarely preserved sandstone beds occur, Facies 3, 4 and 5 - excluding the nonbioturbated sandstone beds within facies 5)

These facies contain few nonbioturbated fine sandstone beds but show an increased percentage of coarse sediment relative to facies 1 and 2. In the rarely occurring nonbioturbated sandstone beds preserved sedimentary structures are similar those which occur in the sandstones facies and are interpreted below. As their name implies, these facies show an abundance of bioturbation. Pemberton and Frey (1983 and 1984) have studied ichonology of the Cardium Formation and a very abbreviated discussion of their findings and the sedimentological significance of the ichnofossil assemblage at Willesden Green will be discussed.

Pemberton and Frey (1983 and 1984) have suggested the ichnofossils preserved in the Cardium Formation at Seebe, Alberta are indicative of relatively shallow water environments. They correlated coarsening-upward sequences within the Cardium Formation at Seebe to individual ichnofossil suites. In general they found two dominant ichnofossil suites represented. The most abundant ichnofossil suite was the Cruziana ichnofacies. It includes the feeding structures Rizocorallium and Teichichnus preserved in the more argillaceous sediments representing offshore, "quiet-water" conditions. They follow Frey and Seilacher (1980) and suggest the Cruziana ichnofacies is characteristic of marine deposits below fair-weather wave-base, but within storm-wave base. The Skolithos ichnofacies was the second most abundant ichnofossil suite. It includes dwelling structures Skolithos and Ophiomorpha which are preserved in more arenaceous sediments. The Skolithos ichnofossils most commonly occur in sandy intervals, commonly found high in the coarsening-upward sequences and represent higher energy conditions than does the Cruziana ichnofacies.

As mentioned in the facies descriptions ichnogenera identified in the Cardium sediments at Willesden Green include: Zoophycos, Chondrites, Teichichnus, Planolities, Paleophycus, Rhizocorallium, Conichnus, Skolithos, Rosselia and Ophiomorpha. In general, Teichichnus, Chondrites, Zoophycos, Planolities, Paleophycus, Rosselia and Rhizocorallium occur in more argillaceous sediments (facies 4 and less sandy 5). It is suggested these ichnogenera represent dominantly the Cruziana ichnofacies, which is characteristic of below fair-weather but above storm-wave base deposition (Frey and Sielacher, 1980). Some of the ichnogenera (e.g. Zoophycos) may be representative of the "quieter-water" Zoophycos ichnofacies (below storm wave-base ?). Skolithos and Ophiomorpha commonly occur in the more argillaceous facies (sandy facies 5 and only infrequently in facies 6), they are characteristic of deposition under higher energy conditions.

The ichnofauna preserved in the Raven River Sequence at Willesden Green are characteristic of deposition within storm wave base but below fair-weather wave-base for most of the sequence, with deposition during higher energy conditions (perhaps nearing fair-weather wave-base) towards the top of the Raven River Member.

3. Sandstone Facies (Facies 5-unbioturbated sandstone beds, 6 and 7)

These facies all have nonbioturbated sandstone beds. Most of the sandstone beds within facies 5, 6 and 7 have sharp bases suggesting sudden sand emplacement. Mudstone rip-up clasts (some sideritized) are often found within sandstone beds and suggest erosive emplacement of the sand beds. Internally, the sandstone beds show horizontal or low-angle inclined stratification. The horizontal lamination probably represents upper plane bed and therefore indicates rapid as well as sudden emplacement. It may be formed under high unidirectional currents or oscillatory wave action and it is difficult to determine which. If unidirectional currents were dominant during deposition of the sands at Willesden Green, abundant current ripple cross lamination would be expected to accompany the horizontal [illegible] [illegible] However at Willesden Green current ripples occur infrequently. High angle cross stratification would not be expected since the sands are too fine grained (mean of roughly 2.5 phi) to allow the development of sand waves (see Harms et al. 1982, p. 212-216).

The occurrence of low-angle inclined stratification was first reported in subsurface Cardium by Michaelis and Dixon (1969). Based on the gently dipping, sometimes divergent character of the laminae and the ubiquitous occurrence of hummocky cross stratification in Cardium outcrop exposures, this structure is interpreted as hummocky cross stratification (HCS). HCS was first described within the Cardium Formation by Wright and Walker (1981). The development and preservation of this wave-generated bedform (Harms et al., 1975) suggests deposition below fair-weather wave-base, but above storm wave-base (Wright and Walker, 1981).

Most sandstone beds are capped with ripple cross lamination. The majority of the cross lamination appears to be wave rather than current generated.

The scarcity of current ripples coupled with the abundance of (suggested) wave ripple cross lamination strongly suggests that unidirectional flow was not the dominant current during deposition of the Cardium sands at Willesden Green. If unidirectional currents were responsible for the offshore transport of sand, subsequent wave reworking has obliterated almost all current-formed sedimentary structures.

4. Conglomerate

The lack of stratification, preferred fabric or significant development of texture makes interpretation of the conglomerates difficult. The presence of ripped-up sandstone and mudstone clasts suggests erosive emplacement of the conglomerates. Discussions concerning conglomerate emplacement mechanisms are deferred to chapter 7, when aspects of conglomerate distribution with respect to gross field geometry (chapter 5) and the detailed conglomerate and the sandstone facies relationships have been discussed.

3.5.3 Facies Conclusions

Based on examination of 178 cores and an investigation of a number of recurring facies and facies sequences a number of generalizations can be made.

1. The sandstones which occur low in the Raven River Sequence were suddenly and rapidly emplaced into a dominantly mudstone depositional environment.

2. The development and preservation of hummocky cross stratification along with the ichnology suggests deposition probably occurred below fair-weather wave-base but above storm wave-base.

3. The sands at Willesden Green are suggested to have been deposited and modified by oscillatory, wave dominated currents. If unidirectional currents are responsible for the offshore transport and emplacement of the sands any sedimentary structures characteristic of such currents have been modified by subsequent wave activity.

4. The conglomerates were erosively emplaced upon the Cardium sandstones.

CHAPTER 4: REGIONAL GEOMETRY

4.1 INTRODUCTION

Before a detailed investigation of the facies distribution and internal stratigraphy of Willesden Green can be meaningfully carried out it is necessary to understand fully the relationship of Willesden Green with its off-field margins, and with adjacent Cardium fields. This chapter attempts to do this by investigating the surface defined by the top of the Raven River Sequence (Raven River Member in on-field regions) within and between Ferrier and Willesden Green and into southern Pembina (Pembina River Member). Is this a flat, sheet-like surface (similar to the Caroline and Garrington area as described by Walker, (1983a) or does a discernible relative topography exist? The upper and lower markers used to investigate this surface will be discussed first, along with other markers used in this study, and those by other workers in studies of adjacent Cardium fields.

4.2 DATUMS

4.2.1 Datums used in this study

Introduction

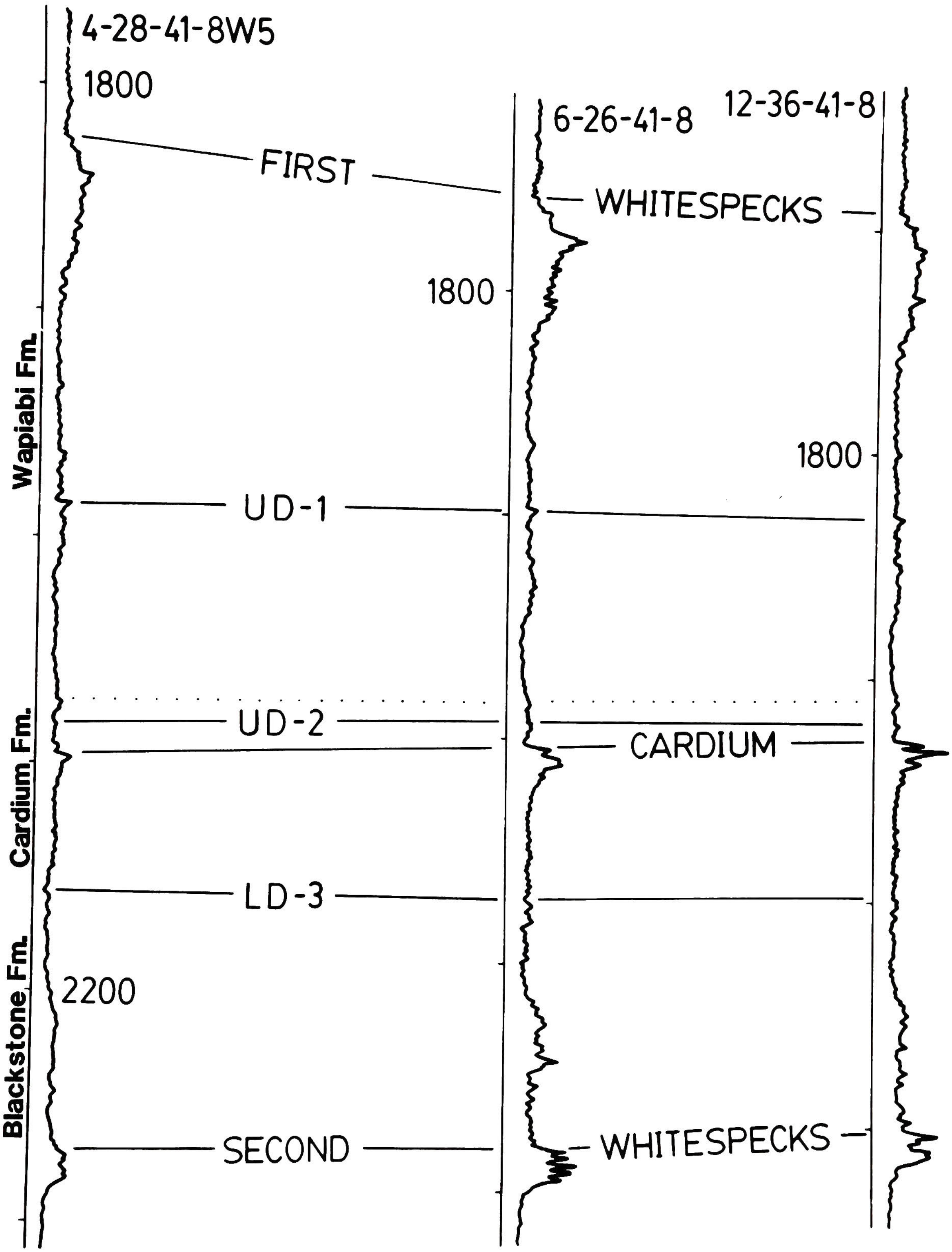
The datums employed in this study are all regionally extensive and easily identified from resistivity logs. Three datums are used in the study, upper datum-1 (UD-1), upper datum-2 (UD-2) and lower datum-3 (LD-3) (Figure 4.1).

Resistivity logs are used since they provide the largest data base for the field and allow the easiest and most accurate differentiation to be made between clean and muddy sand. The field is oil-wet rather than water-wet, and hence porous sand has a high resistivity relative to more shaley sediments; conglomerates generally show an even higher resistivity than the clean sandstones.

Upper Datum-1 (UD-1)

Figure 4.1 shows the well character and relative position of UD-1 with respect to the First White Speckled Shale and the top of the Cardium. The marker is a high resistivity kick which infrequently can be identified on gamma logs. It is identified from Townships 38 to 44 in Ranges 4 to 10 west of the 5th Meridian. Willesden Green,

Fig. 4.1. Reference section for positions of well log markers. Positions of upper datum-1 (UD-1), upper datum-2 (UD-2) and lower datum-3 (LD-3) are shown with positions of the Raven River Member - its top is shown by the solid line labeled Cardium; the Cardium Zone - its position shown by the stippled line. Positions of the First and Second White Speckled Shale - two regionally identifiable markers are shown. This section is from the western margins of Willesden Green and is representative of well log marker positions throughout the study area.


4-28-41-8W5
1800
6-26-41-8
12-36-41-8
FIRST
WHITESPECKS
1800
Wapiabi Fm.
1800
UD-1
UD-2
CARDIUM
Cardium Fm.
LD-3
Blackstone Fm.
2200
SECOND
WHITESPECKS

Ferrier and southern most Pembina occur within this region. Maximum separation of 382 ft (116.43 m) occurs between UD-1 and the top of the Cardium (referring to the top of Raven River Member) in well 10-31-41-8W5, between Willesden Green and Ferrier. The minimum separation between UD-1 and the top of the Cardium in Willesden Green is 278 ft (84.37 m) and occurs at 6-16-43-8W5 (Figure 4.3).

Upper Datum-2 (UD-2)

Figure 4.1 illustrates the log response and relative position of UD-2, a resistivity kick, occurring between the Cardium Zone and top Cardium. The marker is identified from Townships 38 to 44.

Lower Datum-3 (LD-3)

The log character and relative position of LD-3 is shown in Figure 4.1. The marker is a resistivity and gamma log response and is identifiable from Townships 38 to the southern regions of 43. The northern regions of Willesden Green have only rare penetrations through the Cardium into LD-3 resulting in a paucity of data in this region. A minimum separation of 194 ft (59.13 m) between the top Cardium and LD-3 occurs east of Willesden Green at 8-13-40-4W5 and 8-24-40-4-W5. Maximum separation between the top Cardium and LD-3 within Willesden Green is 247 ft (75.3 m) and occurs at 6-13-40-5W5 (Figure 4.5).

Datum Relationships

Upper datum 1 and lower datum 3 are not parallel, as is clearly shown in Figure 4.1. Their separation increases southwestward at roughly 5 ft/mile (0.96 m/km). Upper datum 2 is subparallel to upper datum 1 and its use gives the same thickening and thinning isopach trends with respect to the top of the Raven River Sequence.

4.2.2 Datums in other Cardium studies

Ferrier

Griffith (1982) used an upper (Marker A) and lower (Marker B) datum to establish Cardium geometry at Ferrier. Marker A is a negative resistivity kick which occurs approximately 20 m below my UD-1. Both are evident on Figure 4.1 and Griffith's Figure 15 (1982, p. 27). Also evident on Griffith's Figure 15 is my UD-2.

Griffith notes that lower Marker B, a negative resistivity kick representing the initial coarsening-upward sequence in the Cardium is difficult to identify field-wide. She accounts for this correlation problem by suggesting Cardium sand progradation which is shown by a weaker and topographically lower log response towards the southeast. Examination of well logs to the northwest of Ferrier shows this marker to represent the uppermost or top sandstone of the Raven River Sequence (this is shown in wells between northwestern Ferrier and 4-6-43-10W5).

Pembina

Krause and Nelson (1984) use primarily two upper resistivity markers, M1 and M2 (1984, Figure 5, p. 492-493). The uppermost marker, M2, occurs between my UD-1 and the First White Speckled Shale. M2 represents the Badheart Sandstone and occurs between my UD-1 and UD-2. Neither has been found regionally within Willesden Green.

Ricinus, Caroline and Garrington

Walker (1983b) used gamma responses in his study of three Cardium fields south of Willesden Green. He used a pair of markers, K and L as upper markers; these occur between my UD-1 and UD-2 and are identifiable in only the southern most regions of Willesden Green. Lower gamma responses M and N serve as lower markers, but these do not continue into Willesden Green.

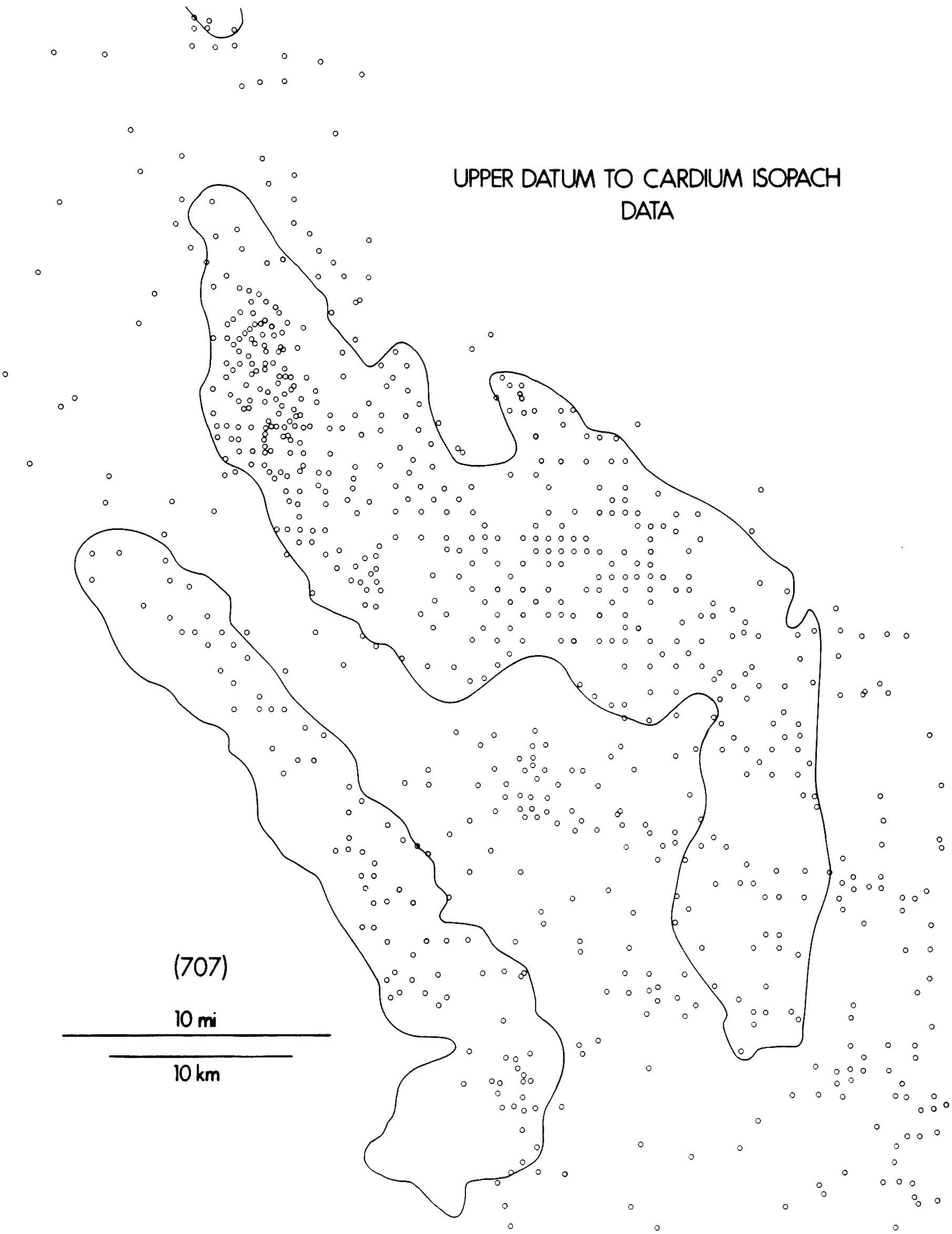
4.3 GROSS STRUCTURE: TOP RAVEN RIVER SEQUENCE

4.3.1 Method

It is useful to establish a framework or context within which the distribution of facies at Willesden Green may be discussed. Documentation of any topographic trends on the surface of the top of the Cardium provides such a framework. Topographic trends were delineated by isopaching the interval between the top of the Cardium (defined by the top of the Raven River Sequence or Member) and UD-1 and LD-3. Figures 4.2 and 4.4 show the control available for each isopach map. Seven hundred and seven wells penetrate UD-1 and hence provide excellent control within Willesden Green, westward into Ferrier and northward into Pembina. Marker LD-3 has been penetrated by fewer wells (283), largely in the southern and central regions of Willesden Green and its margins.

To show topographic trends on the top of the Cardium with relative values of relief on the surface, methods were employed which warrant explanation. The interval was isopached between the top of the Cardium and a surface parallel to UD-1 which contains the point of maximum separation between the top Cardium and UD-1 (see the discussion of UD-1 for this location) labeled MAX. ISOPACH in Figure 4.3. Similarly, for comparison of the top of the Cardium and LD-3, the interval between the top Cardium and a surface parallel to LD-3 containing the point of minimum

Fig. 4.2. Location of well logs (open circles) in the study area from which isopach data was collected to investigate the top of the Raven River Sequence with respect to upper datum-1 (UD-1). Data was collected from a total of 707 wells. The field outlines of Willesden Green, Ferrier and southernmost Pembina are shown by solid lines. Note extensive coverage within Willesden Green and Ferrier and in the off-field areas.


UPPER DATUM TO CARDIUM ISOPACH
DATA
(707)
10 mi
10 km

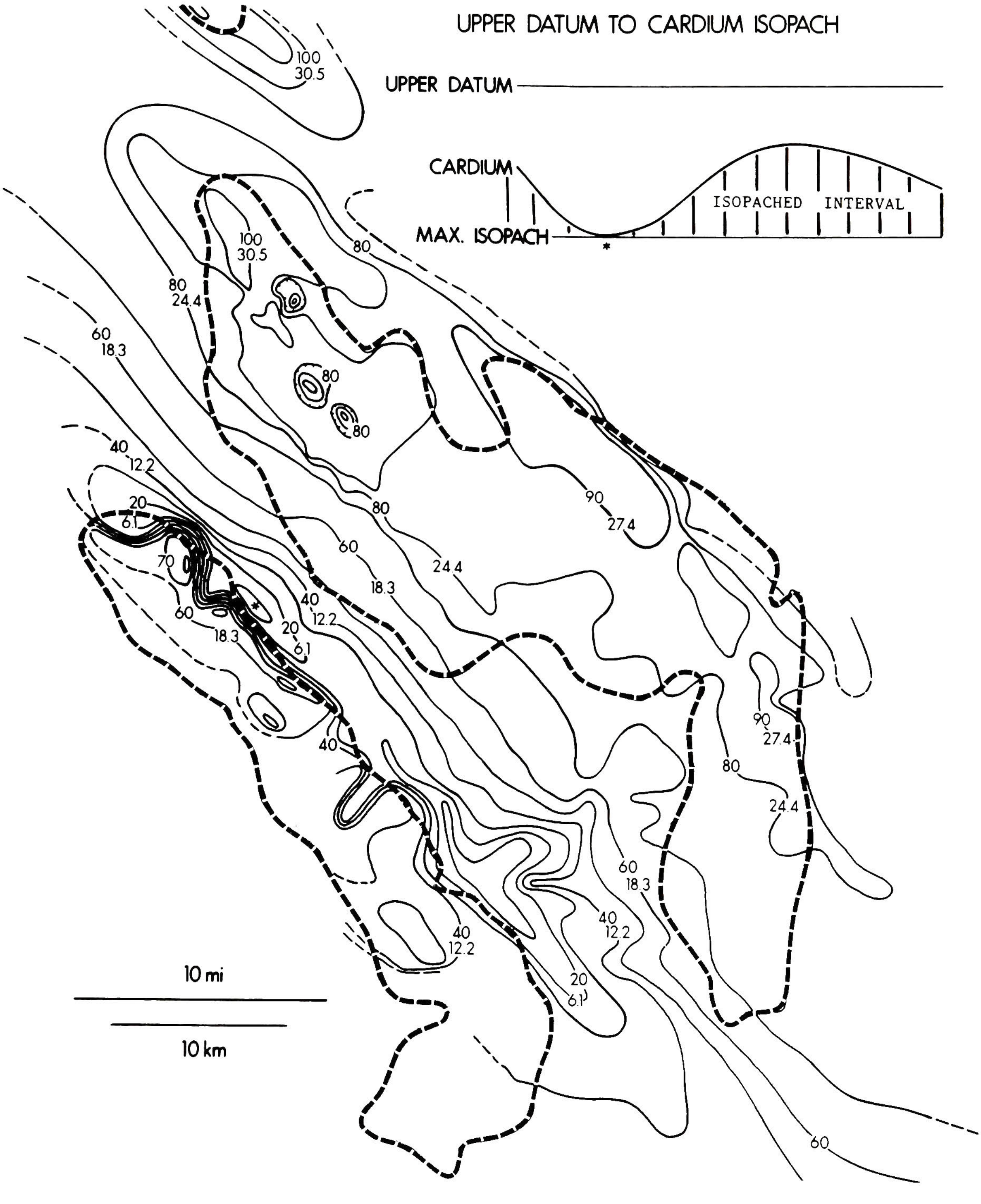
separation between the top Cardium and LD-3 (see the discussion of LD-3 for this location) labelled MIN. ISOPACH in Figure 4.5 was isopached.

4.3.2 Results

Top Raven River structure based on UD-1

Figure 4.3 shows a representation of the paleotopographic surface on the Raven River Sequence based on the method outlined above. Clearly shown are relative highs within Ferrier, Willesden Green and southern most Pembina, and relative lows between the fields. The relative topography is well developed between Willesden Green and Ferrier, where 104 ft (31.7 m) of relief occurs between Willesden Green (6-16-43-8W5) and the area between Willesden Green and Ferrier (10-31-41-8W5). This represents a slope of about 1.12 degrees from Willesden Green (6-16-43-8W5) towards the area between Willesden Green and Ferrier (10-31-41-8W5).

Fig. 4.3. Representation of the paleotopographic surface of the top of the Raven River Sequence in the Willesden Green area based on upper datum-1. The outlines of Willesden Green, Ferrier and southern most Pembina are highlighted with heavy dashed lines. Inset in the upper right corner indicates how the figure was constructed (see text for discussion). The contour interval is 10 ft (metric equivalents are indicated). It is evident that regions of positive relative relief (which correspond to thinner isopach intervals between UD-1 and the top of the Raven River Member) occur in on-field areas and areas of low relative relief (corresponding to thicker isopach intervals between UD-1 and the top of the Raven River Sequence) occur between fields. See text for further discussion.


UPPER DATUM TO CARDIUM ISOPACH
UPPER DATUM
CARDIUM
ISOPACHED INTERVAL
MAX. ISOPACH
100
30.5
80
24.4
60
18.3
40
12.2
20
6.1
70
90
27.4
10 mi
10 km

Top Raven River structure based on LD-3

A representation of the paleotopographic surface on the top of the Cardium based on LD-3 is shown in Figure 4.5. The topography is subdued with a maximum of 16 m relief between Willesden Green (6-13-40-5W5) and off-field of Willesden Green to the east (8-13-40-4W5). This represents a slope of about 0.79 degrees from Willesden Green (6-13-40-5W5) toward a position to the east of the field (8-13-40-4W5). The relationship of relative highs on-field to relative lows off-field coincides with that found using UD-1.

4.3.3 Discussion and Conclusions

The top of the Raven River Sequence can be shown to have essentially the same topography, whether an upper or lower datum is used. Absolute values differ between Figures 4.3 and 4.5 due to the regional westward divergence of the two markers: however the relative topography is the same. The very subtle nature of the topography is similar to that encountered by Seeling (1978, p. 40) in his study of the Shannon Sandstone in the Heldt Draw field, Wyoming. The top of the Raven River Sequence is not a sheet-like flat surface, but rather shows relative highs developed within Willesden Green, Ferrier and southern Pembina, with relative lows in regions off these fields.

Fig. 4.4. Location of well logs (open circles) in the study area from which isopach data was collected to investigate the top of the Raven River Member with respect to lower datum-3 (LD-3). Data was collected from a total of 283 wells. The field outlines of Willesden Green and Ferrier are shown by solid lines. Note coverage within central and southern Willesden Green and extensive coverage in the off-field regions west, east and south of the field. Data is lacking in the northern portion of Willesden Green since almost no wells were found that penetrated and logged through the Cardium and LD-3.

LOWER DATUM TO CARDIUM ISOPACH
DATA

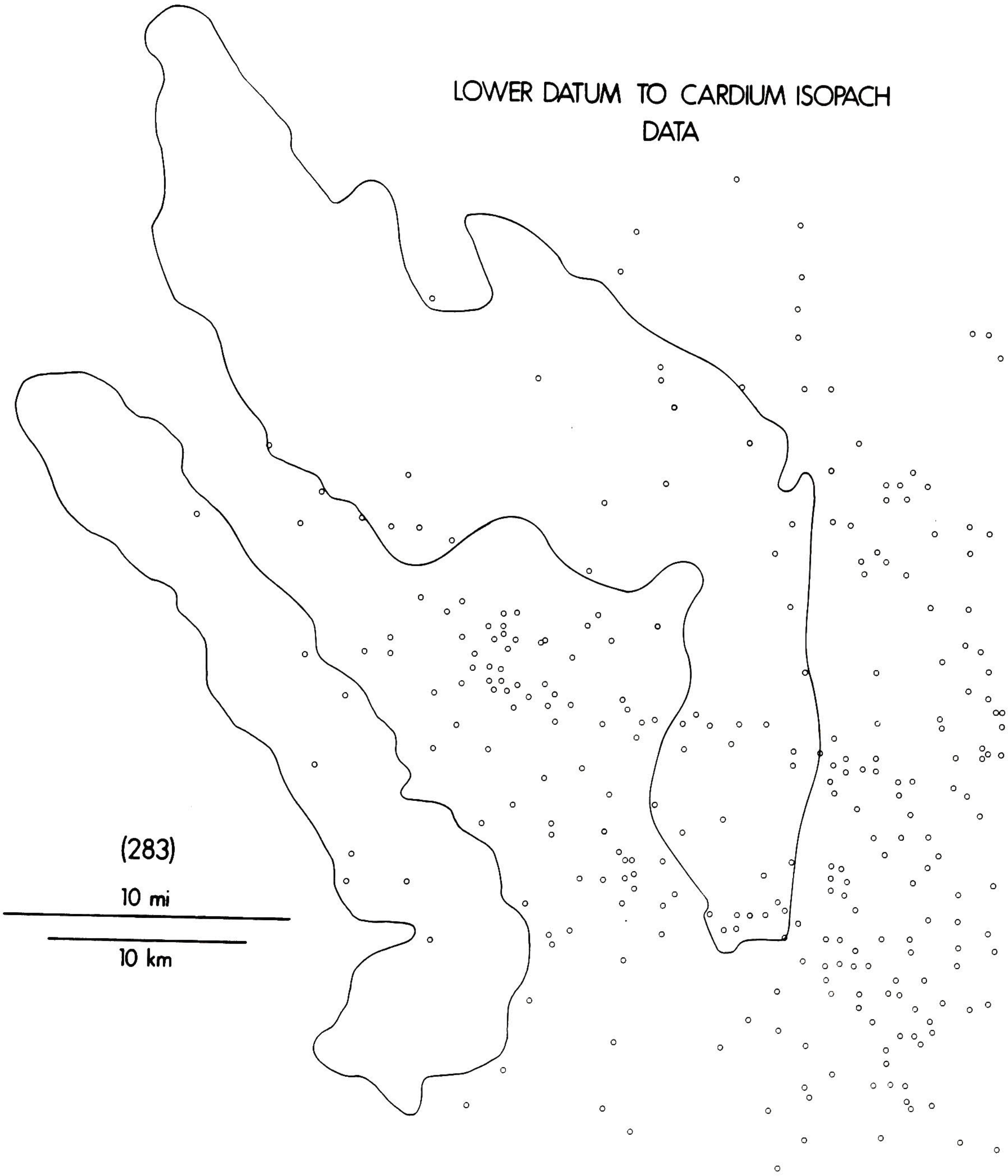
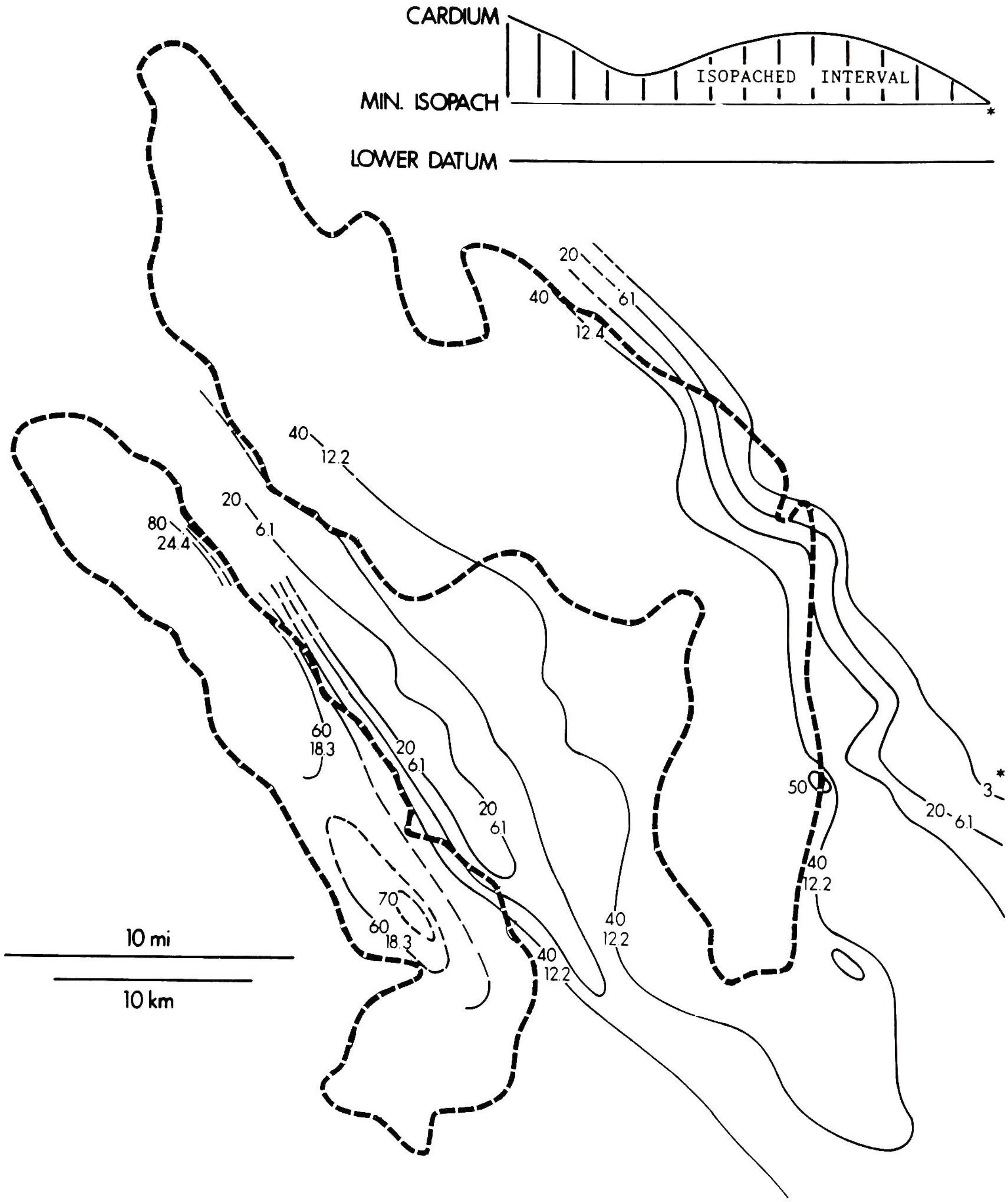


Fig. 4.5. Representation of the paleotopographic surface of the top of the Raven River Member in the Willesden Green area based on lower datum-3. The outlines of Willesden Green and Ferrier are highlighted with heavy dashed lines. Inset in the upper right corner indicates how the figure was constructed (see text for discussion). The contour interval is 10 ft (metric equivalents are indicated). It is evident that regions of positive relative relief (which correspond to thicker isopached intervals between LD-3 and the top of the Raven River Member) occur in on-field areas of Ferrier and Willesden Green. Areas of low relative relief (corresponding to thinner isopached intervals between LD-3 and the top of the Raven River Member) occur between Willesden Green and Ferrier and east of Willesden Green. See text for further discussion.

LOWER DATUM TO CARDIUM ISOPACH



CHAPTER 5: FACIES DISTRIBUTION

5.1 INTRODUCTION

In this chapter the distribution of the sandstone (facies 5, 6 and 7) and conglomeratic facies is presented. They are discussed with reference to the topographic trends delineated on the top of the Raven River Member in chapter 4.

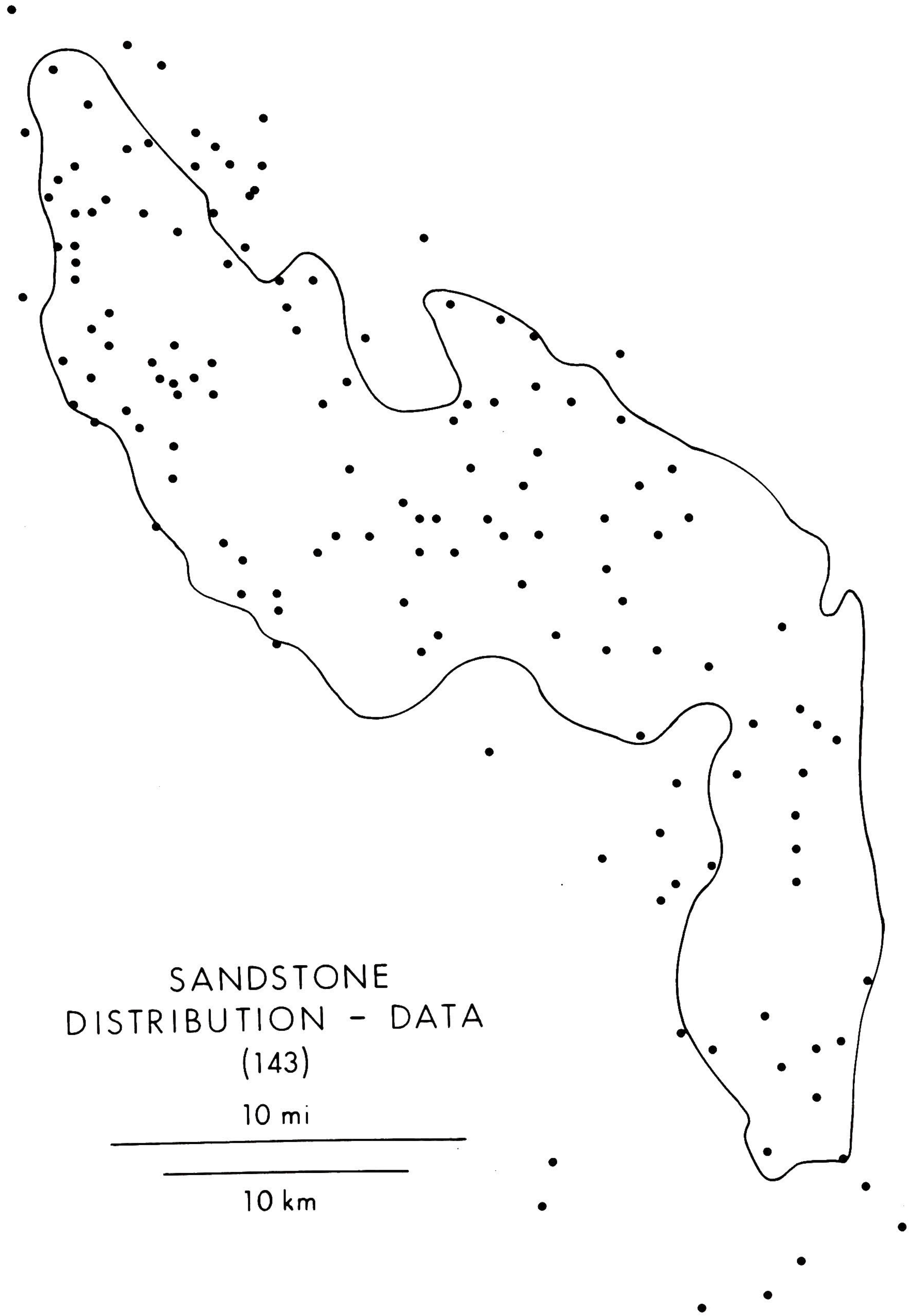
5.2 BIOTURBATED AND NONBIOTURBATED SANDSTONE DISTRIBUTION

5.2.1 Method

To give an indication of sandstone thickness variations at the top of the Raven River Member the upper sandy Units (facies 5, 6 and 7) were isopached. Different Raven River Units occur at the top of the Member, due to their off-lapping relationship, therefore different Units were isopached. This is illustrated in Figure 6.4, section 10, where the top of the Raven River sequence includes Unit 3 in the western regions, Units 3 and 4 in the central regions and Unit 4 in the extreme eastern regions of the field. The isopached interval in all cases was underlain by facies 3 or other less sandy facies and overlain by facies 8 or facies 2. Since all Raven River Units decrease in sandy facies as they shingle down (Unit relationships are described in

paching sandy facies thickness from upper

Fig. 5.1. Location map showing positions of cores from which the thickness of facies 5, 6, and 7 in Units from the upper portion of the Raven River Member were measured. Core locations are shown by solid circles. Sandy facies thickness was measured from a total of 143 cores from throughout Willesden Green (the field outline is indicated by the solid line).


SANDSTONE
DISTRIBUTION - DATA
(143)
10 mi
10 km

Units only includes most of the sandy facies within the field. Delineation of these thickness variations allows comparison with the top Raven River paleotopographic surface and with trends of conglomerate accumulation (both shown below). Figure 5.1 shows the location of the 143 core from which data was collected.

5.2.2 Results and Discussion

From Figure 5.2 it is evident thick accumulations of the sandy facies occur in roughly linear northwest to southeast trends in Willesden Green. The sandy facies are thickest in the northwestern region of the field. Sandy facies thin off-field, diminishing from greater than 12 m in northern Willesden Green to less than 3 m towards field margins, illustrating preferential accumulation of the sandy facies within the field.

Comparison of the information from Figure 5.2 with the paleotopographic surface on top of the uppermost sandstone of the Raven River Member is shown in Figure 5.3. This surface was generated by isopaching the interval between the maximum separation of UD-1 and the top of the uppermost Raven River Member sandstone, not the overlying conglomerate (as was done in Figure 4.3). Areas of thickly accumulated sandy facies coincide reasonably well with relative highs on the top of the Raven River Member. It seems reasonable to conclude that the "highs" are in fact real and occur due to preferential accumulation of the sandy facies.

Fig. 5.2. Distribution of the sandy facies (facies 5, 6 and 7) at the top of the Raven River Member from upper sandy Units (see text for discussion). Sandy facies thickness is shown with 3, 6, 9 and 12 m isopachs (highlighted in yellow). The outline of Willesden Green is indicated with heavy dashed lines. Note thinning of sandy facies off-field, maximum accumulation in northwestern Willesden Green with apparent northwest to southeast discontinuous trends of thick sandy facies.

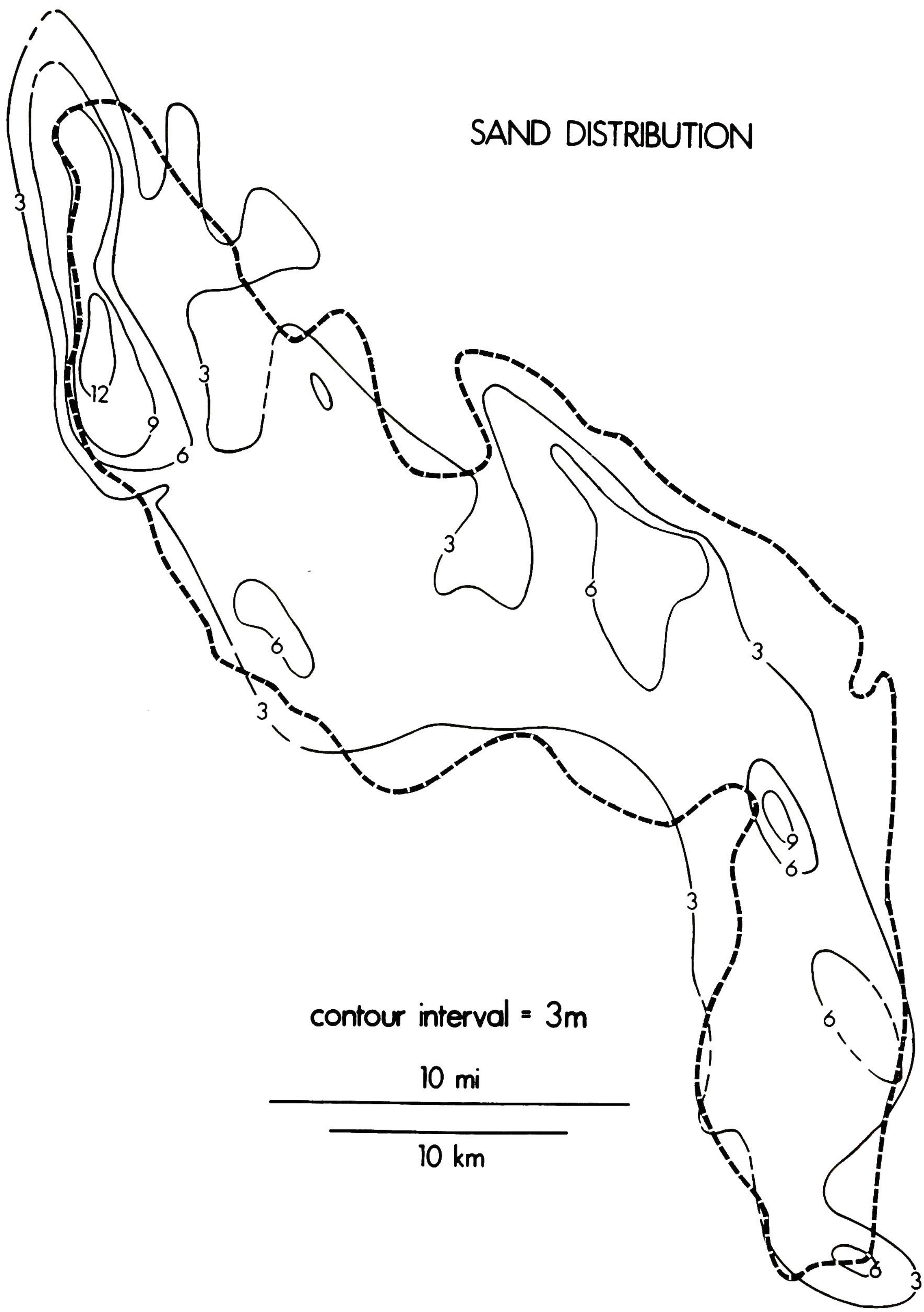
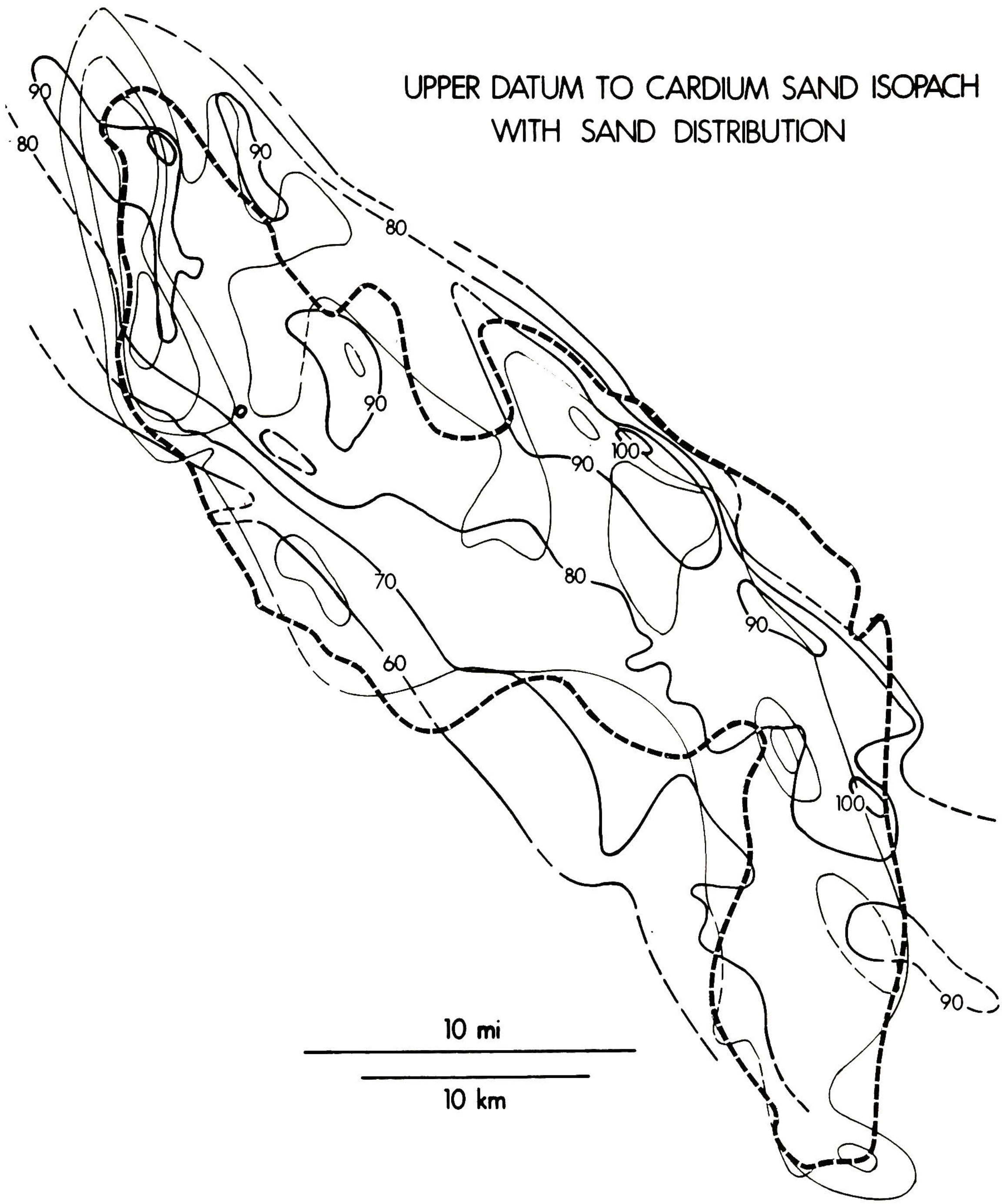

SAND DISTRIBUTION
3
12
9
6
3
3
6
6
3
3
9
6
3
6
contour interval = 3m
10 mi
10 km
6
3

Fig. 5.3. Map showing comparison of the sandy facies distribution (Fig. 5.2) and the paleotopographic surface on top of the uppermost Raven River Member Unit (see text for explanation). Sandy facies thickness is shown with a 3 metre contour interval (they are highlighted in yellow and unlabeled, but are identical to those in Fig. 5.2). Contours on the paleotopographic surface at the top of the top Raven River Member Unit are shown with solid lines (lines are dashed where data extended with uncertainty) with a 10 ft contour interval (metric equivalents shown in Fig. 4.3). The outline of Willesden Green is indicated with heavy dashed lines. Note coincidence of thick accumulations of sandy facies with relative "highs" on the paleotopographic surface. See text for discussion.


UPPER DATUM TO CARDIUM SAND ISOPACH
WITH SAND DISTRIBUTION
90
80
90
80
90
100
90
80
70
90
60
100
90
10 mi
10 km

5.3 CONGLOMERATE DISTRIBUTION

5.3.1 Method

Conglomerate thickness was measured in 160 cores (in all measured core the conglomerate was underlain by facies 5, 6 or 7 and overlain by facies 2) and collected from 381 wells for which Core Labs. core analysis data was available. Where my measurements and Core Labs. data were available for the same wells, the values were found to be close. For example, in 4-20-43-8W5 [p.228] my measured conglomerate thickness was 3.31 m, the Core Labs. value was 3.36 m; similarly for 4-31-43-8W5 [p.229] the values were 0.08 m and 0.09 m respectively. Combining the measured and Core Labs. data, 541 wells with conglomerate thickness were available; Figure 5.4 shows the location of this control.

5.3.2 Results and Discussion

Figure 5.5 shows the distribution of the conglomerate with a 1 m contour interval. The most abundant and thickest conglomerate accumulation (to greater than 5 m) occurs in the northwestern regions of the field. Northwest to southeast trends of thick conglomerate occur through much of the length of Willesden Green. In the southeastern regions of the field no conglomerate thickness of greater than 1 m are found. Here the conglomerate generally occurs thinly banded within laminated mudstones. A relatively thick (to

m), somewhat isolated pod of conglomerate

Fig. 5.4. Location of cores of from which conglomerate thickness was measured (indicated by solid circles) or collected from Core Labs. core analysis data (indicated by open circles). Note the extensive data coverage (541 wells). The field outline of Willesden Green is indicated by the solid line.

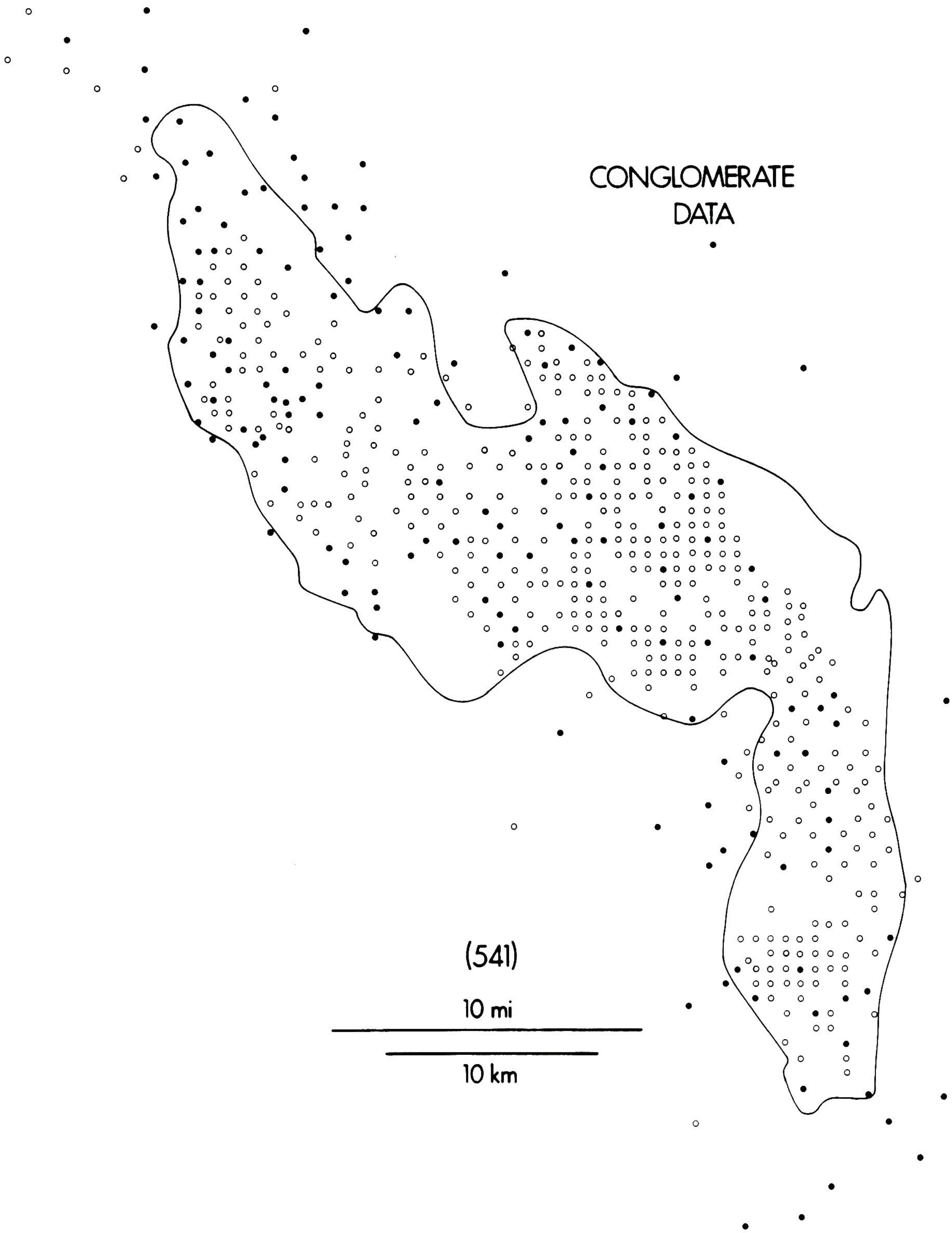
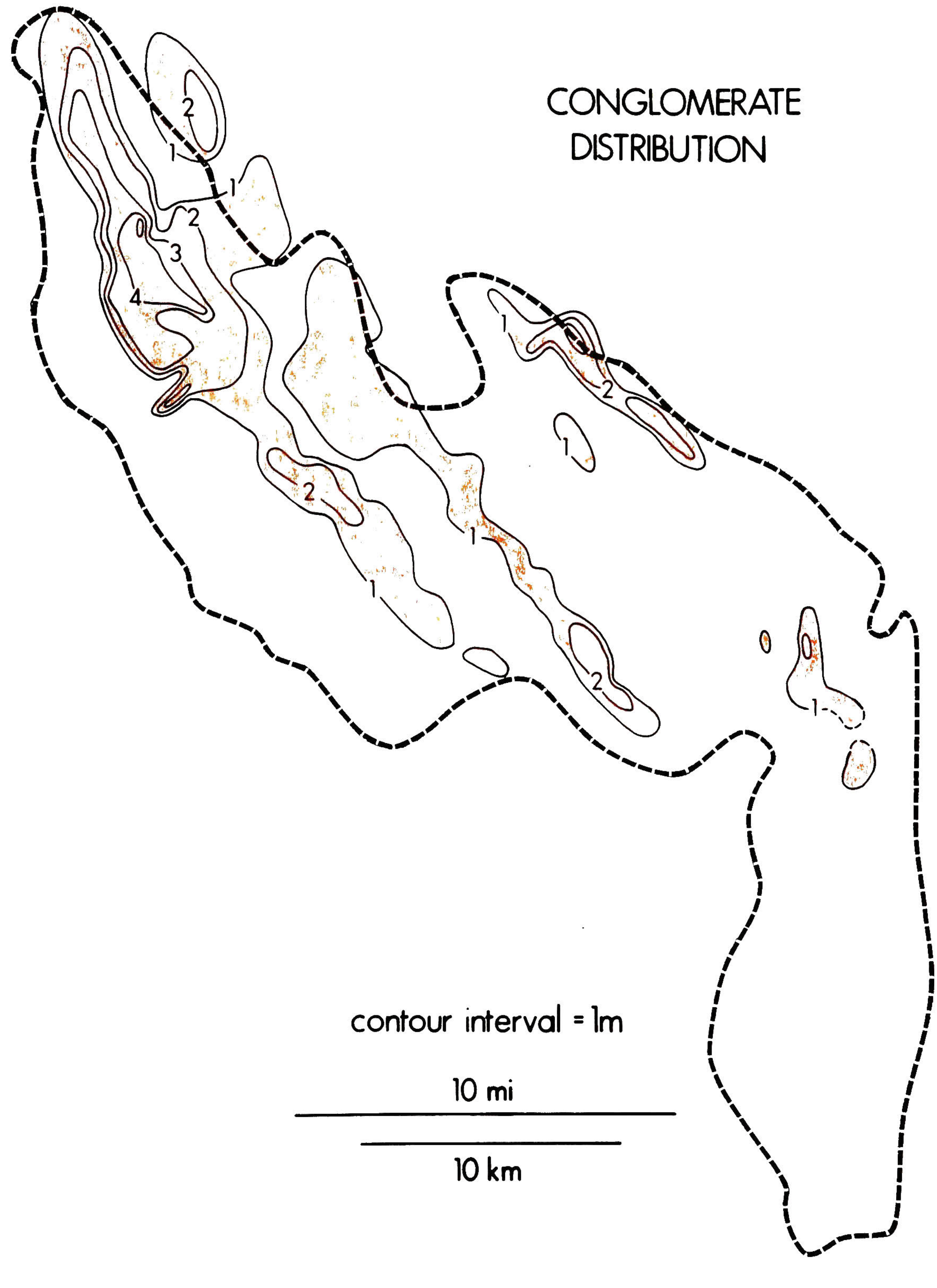
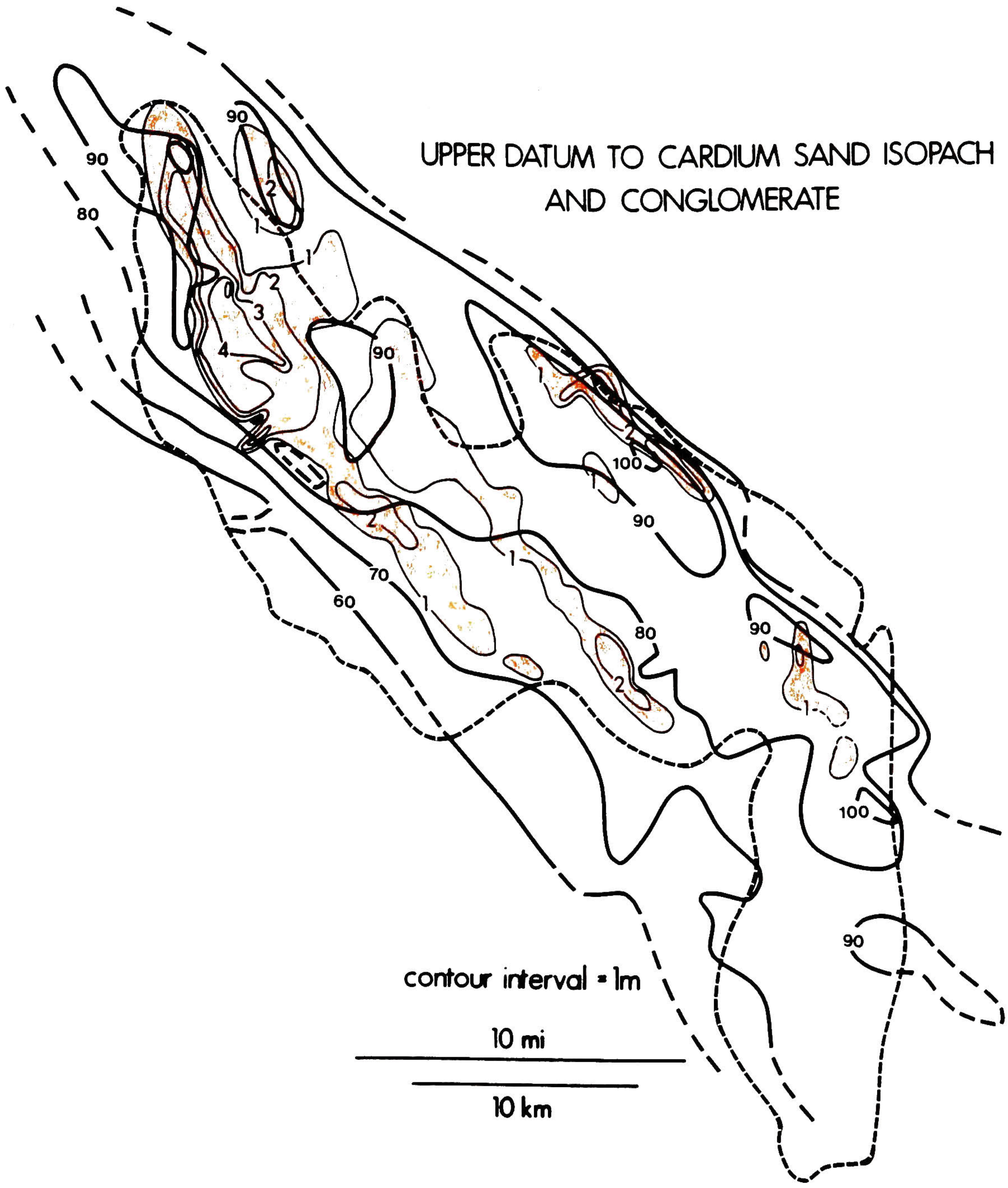

CONGLOMERATE
DATA
(541)
10 mi
10 km

Fig. 5.5. Isopach map of the Willesden Green Field - Cardium conglomerate. The contour interval is 1 m and all conglomerate accumulations of more than 1 m are colored orange. The outline of Willesden Green is indicated by the heavy dashed lines. Note occurrence of maximum thickness of conglomerate in northwestern Willesden Green and the northwest to southeast trends of thick conglomerate accumulation.


CONGLOMERATE DISTRIBUTION
contour interval = 1m
10 mi
10 km
1
2
3
4
0

occurs along the central-eastern margin of the field. Comparison of the conglomerate distribution with the paleotopographic surface on top of the Raven River sandstone is shown in Figure 5.6 (the conglomerate distribution is superimposed on the top of Raven River Member sandstone paleotopographic surface, generated in the same manner as for figure 5.3). The conglomerate sits just off the eastern side of relative "paleotopographic highs". This is particularly well shown in the extreme northern and in the eastern regions of Willesden Green. The relationship between conglomerate and sand distribution is discussed later in the chapter.

Fig. 5.6. Map showing comparison of conglomerate distribution (Fig. 5.5) and the paleotopographic surface on top of the uppermost Raven River Member sandstone (as generated for Fig. 5.3). Conglomerate thicknesses are shown as in Fig. 5.5 and the paleotopographic surface at the top of the Raven River Member sandstones is shown with solid lines (lines are dashed where data extended with uncertainty) with a 10 ft contour interval (metric equivalents are 60 ft - 18.3 m, 70 ft - 21.3 m, 80 ft - 24.4 m, 90 ft - 27.4 m, 100 ft - 30.5 m). The outline of Willesden Green is indicated with heavy dashed lines. Note occurrence of thick conglomerate accumulations on the eastern margin of relative paleotopographic "highs". See text for discussion.


UPPER DATUM TO CARDIUM SAND ISOPACH
AND CONGLOMERATE
90
80
90
2
1
1
2
0
3
4
90
1
2
100
1
90
2
1
70
60
1
80
90
2
1
100
90
contour interval = 1m
10 mi
10 km

5.4 CONGLOMERATE MAXIMUM CLAST AXIS DISTRIBUTION

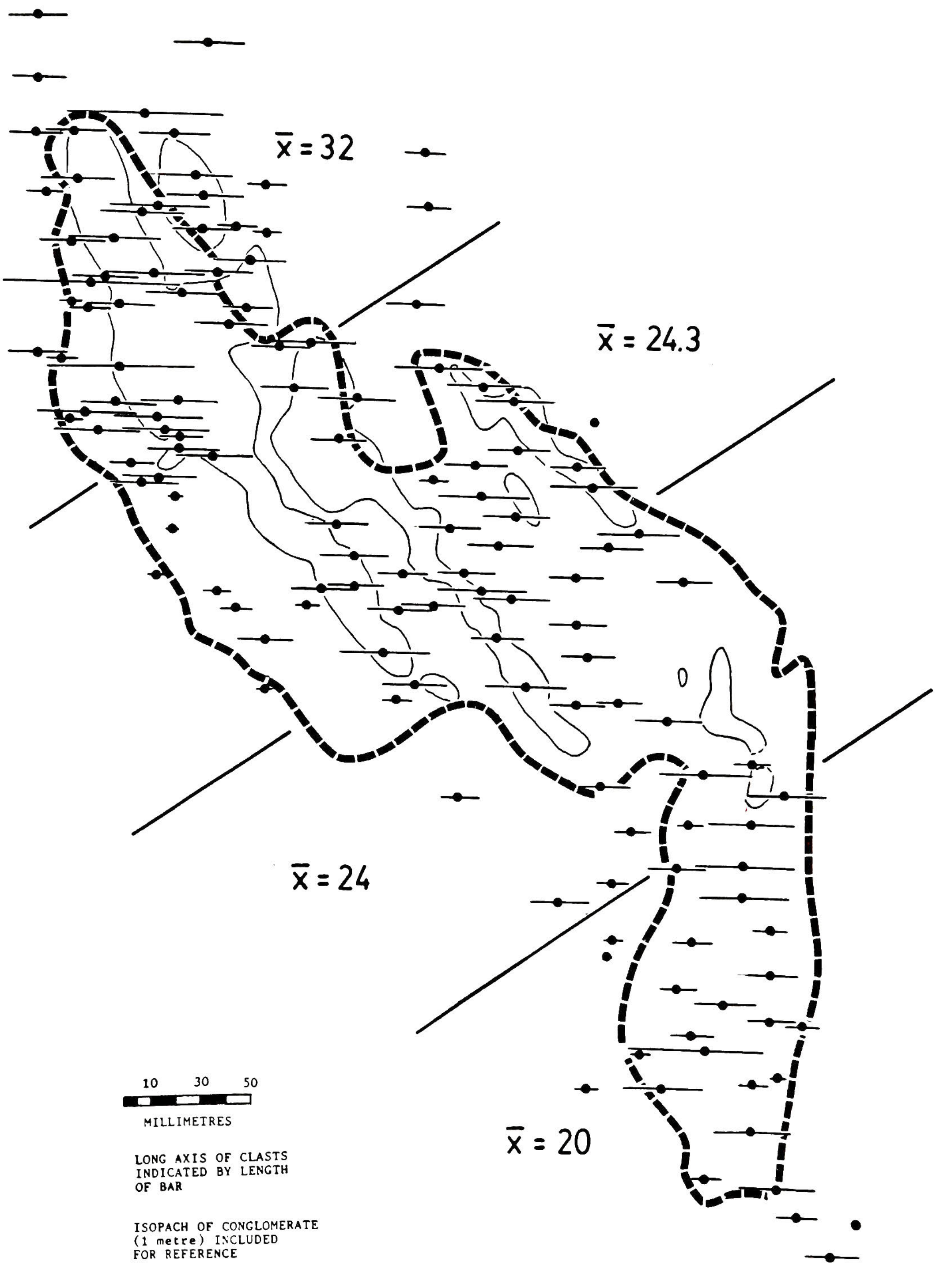
5.4.1 Method

Maximum chert pebble length was measured in most cores examined, these data are shown on Figure 5.7. The solid dots indicate sample locations with the pebble long axes indicated by the bar length. To determine clast axes trends down field, Willesden Green was divided in four regions by southwest to northeast running lines, mean clast axes length was calculated in each (using only on-field samples).

5.4.2 Results and Discussion

Mean clast axes length values are shown in Figure 5.7 in each of the quarters. From northwest to southeast the mean clast axes lengths are 32 mm (26), 24.3 mm (36), 24 mm (18) and 20 mm (18) (the number of samples within each quarter is given in parentheses). These values decrease southeastwards from a mean of 32 mm in the northwest to a mean of 20 mm in the southeast. The results compare favorably with findings of Griffith (1981, p. 16).

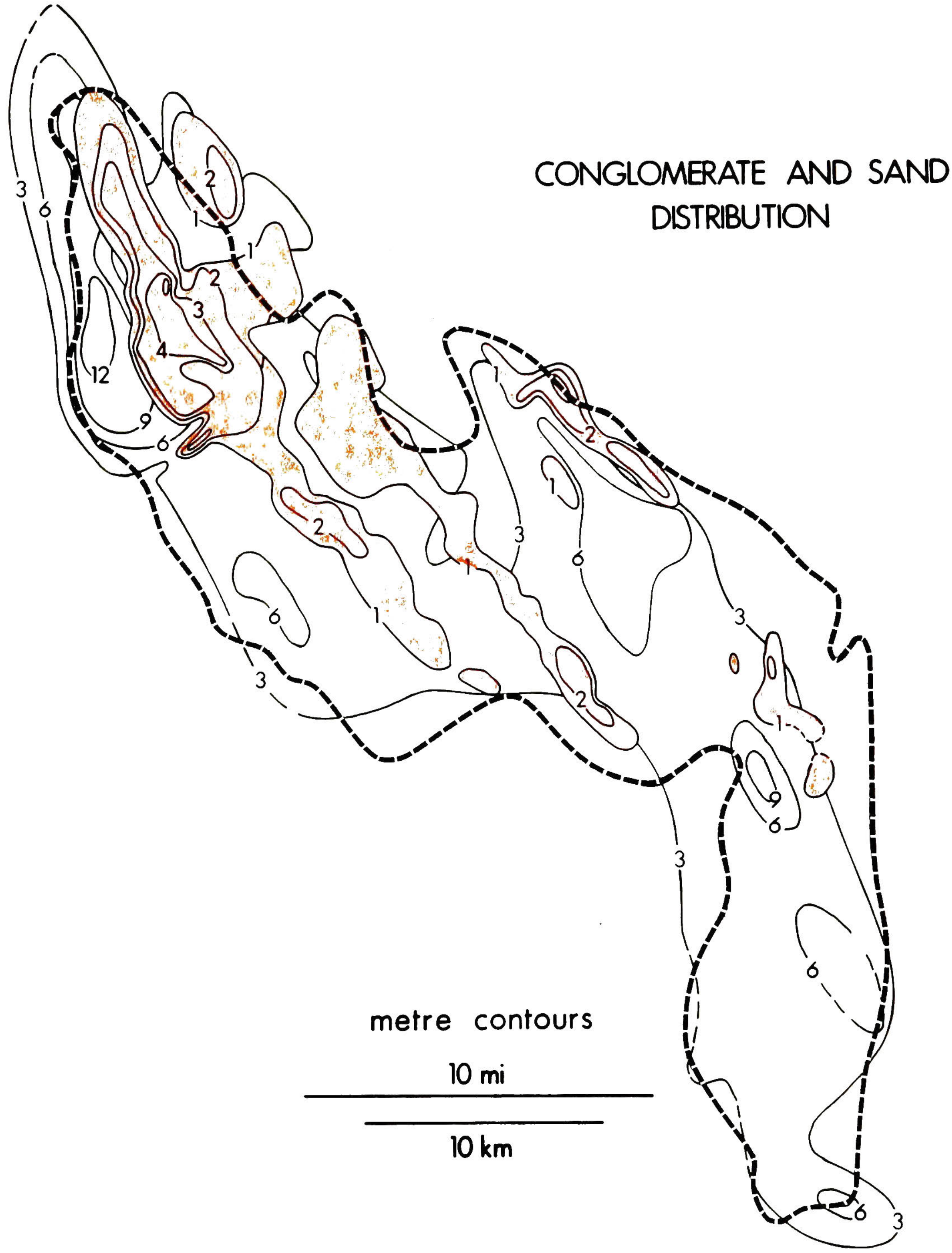
Fig. 5.7. Map showing the distribution of conglomerate clast long axes in the Willesden Green field. Black circles indicate sample core locations and length of bar (scale in lower left) indicates maximum clast axis from each location. The outline of Willesden Green is indicated by the heavy dashed lines and solid lines oriented southeast to northwest separate the field into quarters. Mean clast axes lengths are shown in each quarter.
See text for discussion.


$\bar{x} = 32$
$\bar{x} = 24.3$
$\bar{x} = 24$
$\bar{x} = 20$
10 30 50
MILLIMETRES
LONG AXIS OF CLASTS INDICATED BY LENGTH OF BAR
ISOPACH OF CONGLOMERATE (1 metre) INCLUDED FOR REFERENCE

5.5 CONGLOMERATE AND SAND DISTRIBUTION

The sandstone and conglomerate facies distributions are shown superimposed in Figure 5.8. Both show similar northwest to southeast trends with the thickest and most abundant accumulation in the northwest, decreasing southeastwards. It is evident that thick accumulations of conglomerate occur northeast of thick accumulations of the sandstone facies. This is particularly well shown in the northwestern Willesden Green and along the eastern margin of the field.

Fig. 5.8 Map showing a comparison of the sandy facies (Fig. 5.2) and conglomerate (Fig. 5.4) distribution. Sandy facies are shown with a 3 m contour interval (isopachs in yellow) and conglomerates are shown with a 1 m contour interval (conglomerate thicknesses of more than 1 m are colored orange). See text for discussion.


CONGLOMERATE AND SAND DISTRIBUTION
metre contours
10 mi
10 km

5.6 CONCLUSIONS

Based on the distribution of the sandy and conglomeratic facies and their relation to the regional structure on the top of the Raven River Member a number of conclusions can be made.

1. The Cardium sandstones at Willesden Green are preferentially accumulated within the field and do not continue in a "sheet-like" manner into off-field areas.

2. The development of topography on top of the Raven River Member based on isopaching intervals between the top of the Raven River Member and UD-1 and LD-3 (chapter 4) is substantiated by the preferential accumulation of the sandy facies within Willesden Green. This is particularly well illustrated by the coincidence of thick accumulations of sandy facies with relative "highs" on the paleotopographic surface at the top of the Raven River Member based on UD-1.

3. Dispersal of the sandy and conglomeratic facies was towards the southeast. Both facies show maximum accumulation and thicknesses declining southeastwards from the northern regions of Willesden Green and conglomerate clast long axes means decline towards the
These findings are similar to those of

Griffith (1981) in her study of the neighboring Cardium Ferrier field.

4. Conglomerate accumulation appears to be influenced by paleotopography developed at the top of the uppermost sandstone of the Raven River Member. Thick accumulations of conglomerate occur to the northeast of areas of thick sandstone accumulation. Detailed investigation of the geometry of the sandstones within Willesden Green are required before more can be concluded with respect to sandstone - conglomerate relationships.

CHAPTER 6 :

DETAILED FIELD GEOMETRY AND FACIES RELATIONSHIPS

6.1 INTRODUCTION

Gross field geometry and its relation to sandy and conglomeratic facies distribution has previously been shown. To gain a more thorough understanding of the internal field geometry and the sandy and conglomeratic facies distribution within Willesden Green, numerous cross sections traversing the field were constructed. A number of the sections are included in this chapter, and are discussed individually below. Examination of the cross sections suggests a number of general relationships between the Raven River Units (i.e. sandstones occur within Willesden Green; Units occurring off-field are less sandy) and conglomerate distribution. Discussion of these important aspects is deferred to sections 6.3 and 6.4. The Raven River Units are delineated and discussed in section 6.3 utilizing information from the cross sections and all available well logs (Fig. 1.3). The relationship between Raven River Member Units and the conglomerate distribution at Willesden Green are discussed in section 6.4.

6.2 CROSS SECTIONS

6.2.1 Introduction

Figures 6.1 to 6.4 show twelve southwest to northeast orientated cross sections. Sections with this orientation best illustrate the complex facies relations within Willesden Green. Each figure includes a location map and three cross sections to facilitate comparisons between cross sections. All sections are constructed with marker UD-2 drawn horizontally, and show the Raven River Member Units, numbered one through five. The first appearance or leading edge of Units three through five is noted above UD-2 on each section. The field-wide occurrence of the leading edge of Units two through five is shown on figure 6.5 and will be discussed later in this chapter. Conglomerates cap the Raven River Member in most sections and are colored orange. Examined core intervals are shown by shaded rectangles adjacent to its log and diagrammatic core descriptions for these cores are included in appendix 1. The intervals of cored wells with Core Lab. data (but not examined by me in this study) are shown by unshaded rectangles adjacent to its log. The position of the Cardium Zone is shown by a solid line above marker UD-2. In sections where two lines are shown, the lower generally represents the Cardium Zone. Correlations of this horizon are sometimes difficult, as is in section 3 (Fig. 6.1). In sections 1 through 3, two lower markers, A and B, are shown.

They represent initial coarsening-up sequences into the Cardium Formation and provide a close lower marker, helpful with correlations of the lowest Cardium Units. The reader may wish to refer back to the discussion of the significance of the A and B markers with respect to correlations between Willesden Green and Pembina in chapter 2, Fig. 2.4. Horizontal lines terminating with vertical bars which occur below the sections show the locations of field boundaries; these generally coincide with boundaries on the location map (boundaries on the location map are from G.S.C. map 1559A). The sections are discussed from southwest to northeast (left to right) on all figures. Information gained from these sections with respect to the Raven River Member Unit distribution, conglomerate distribution and their interrelationship is discussed in sections 6.3 and 6.4.

6.2.2 Section 1 (Figure 6.1)

Section 1, the most northerly section begins at 10-33-43-9 [p.232] west of Willesden Green where Units 1 and 2 show a "blocky" log response. Units 1 and 2 are shown in a similar fashion in 14-3-44-9. These Units separate at 2-12-44-9 [p.240] and continue to separate towards the northeast. The most southwesterly accumulation of conglomerate occurs at 12-7-44-8 [p.235], (3.08 m), and thins into 2-17-44-8 [p.237], (0.51 m). The conglomerates thicken again towards 6-16-44-8 [p.237], (1.04 m) and [illegible] 8], (1.87 m). The log response at 2-24-44-8 [p.239] is more subdued, which is characteristic of off-field wells to the east of Willesden Green. At 2-24-44-8 thin conglomerates (centimetres thick) cap the Raven River Member and are interbedded with laminated mudstones. The Willesden Green field boundary is shown to occur east of 6-16-44-8 on the location map but could probably be placed between 6-22-44-8 and 2-24-44-8 as shown in section 1. Lower markers A and B are identifiable through much of this section.

6.2.3 Section 2 (Figure 6.1)

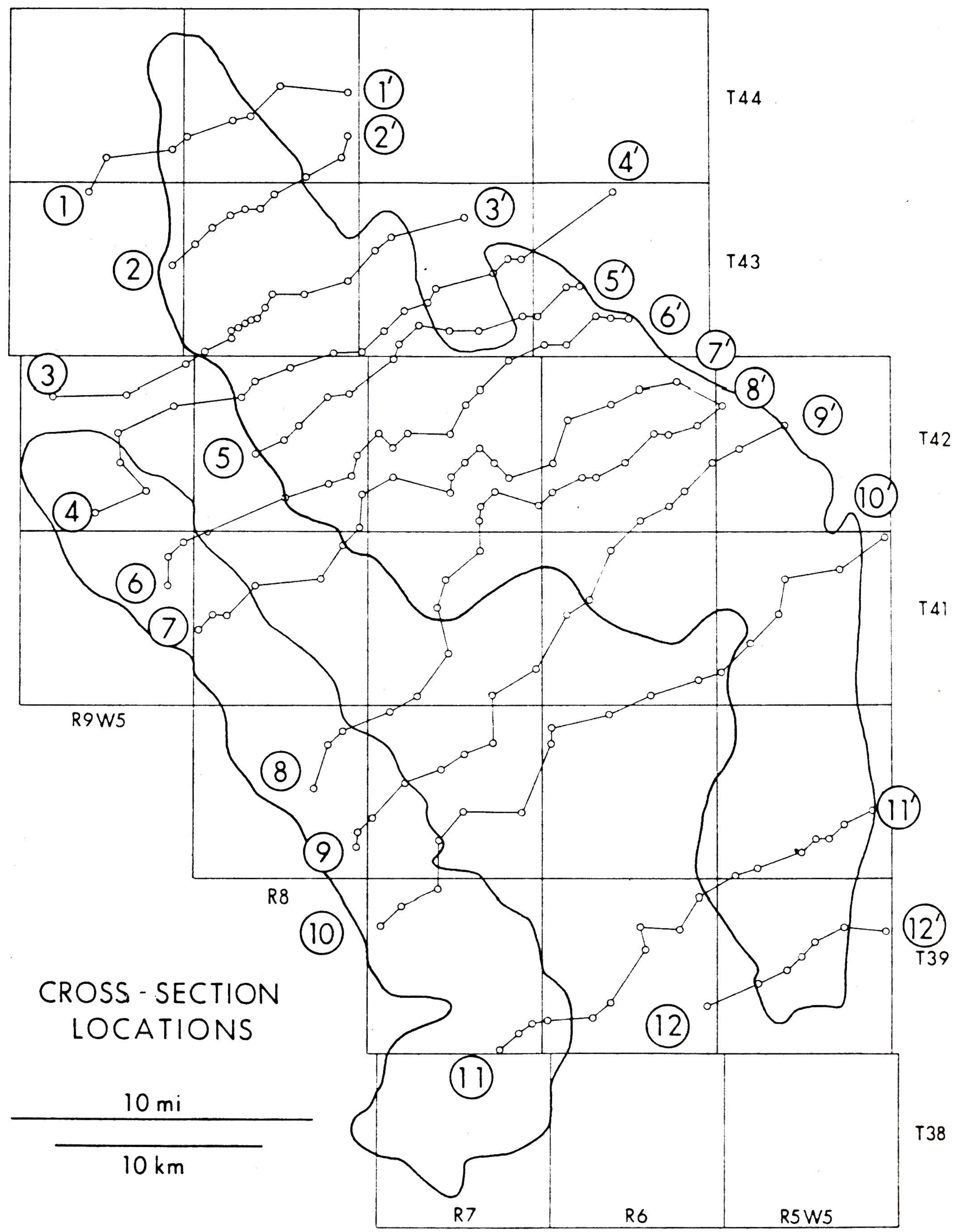
This section begins at 2-24-43-9 [p.231] where a "blocky" log response similar to that of the southeastern wells (10-33-42-9 and 14-3-44-9) of section 1 (Fig 6.1) occurs. The blocky response separates into 2 distinct Units (Units 1 and 2) in 14-19-43-8 and continues to separate towards the northeast through 8-30-43-8. The southwestern-most conglomerates occur at 15-29-43-8 (greater than 4 m). Thick accumulations of conglomerate continue through 4-33-43-8 (5.15 m) into 2-33-43-8, then thin slightly into 12-34-43-8 [p.229]. Conglomerate thickness has declined to 0.44 m by 10-12-44-8 [p.226]. The three northeastern wells (4-2-44-8 [p.234] through 10-12-44-8) show continuity of the conglomerates and Units 1 and 2. These wells occur off Willesden Green. Lower markers A and B are clearly identifiable through all of section 2.

6.2.4 <u>Section 3</u> (Figure 6.1)

Section 3 begins at 12-29-42-9, west of Willesden Green and north of Ferrier. Unit 1 is represented in 12-29-42-9 by a single "blocky" log response (as encountered in the southwestern wells of section 1 and 2). This log response separates at 10-27-42-9, but still represents only Unit 1 (c.f. Unit 1 response in 10-36-42-9). Unit 2 begins in 10-36-42-9. The log character of Units 1 and 2 continue in a similar fashion through 4-9-43-8, although the Units separate and Unit 2 thickens slightly. The leading edge of Unit 3 and thick accumulations of conglomerate (about 3 m) occurs at 6-9-43-8, where Unit 1 has dropped stratigraphically. All Units and the conglomerate occur in a similar fashion through 4-15-43-8 [p.227]. At 4-14-43-8 the conglomerates thin to 1.92 m and Unit 2 begins to drop stratigraphically with respect to Unit 3 and merge towards Unit 1. Only thin conglomerate caps the leading edge of Unit 4 at 10-13-43-8, where Unit 3 is poorly developed and Units 1 and 2 are amalgamated. A similar sequence continues into 10-19-43-7 although Unit 2 is not developed here or northeast of this well. Thicker conglomerates (1.03 m) cap 4-29-43-7 [p.223] and Unit 3 has dropped stratigraphically. Off-field well 15-27-43-7 [p.222] contains conglomerates capping the Raven River Member, but only Unit 3 is developed (an identical log response is shown in well 7-24-43-7, section 4, Fig. 6.2). Lower markers A and B are identifiable

the wells within Willesden Green section 3.

Fig. 6.1. Cross sections 1, 2 and 3 with location map on left. See text for discussion.


CROSS - SECTION LOCATIONS
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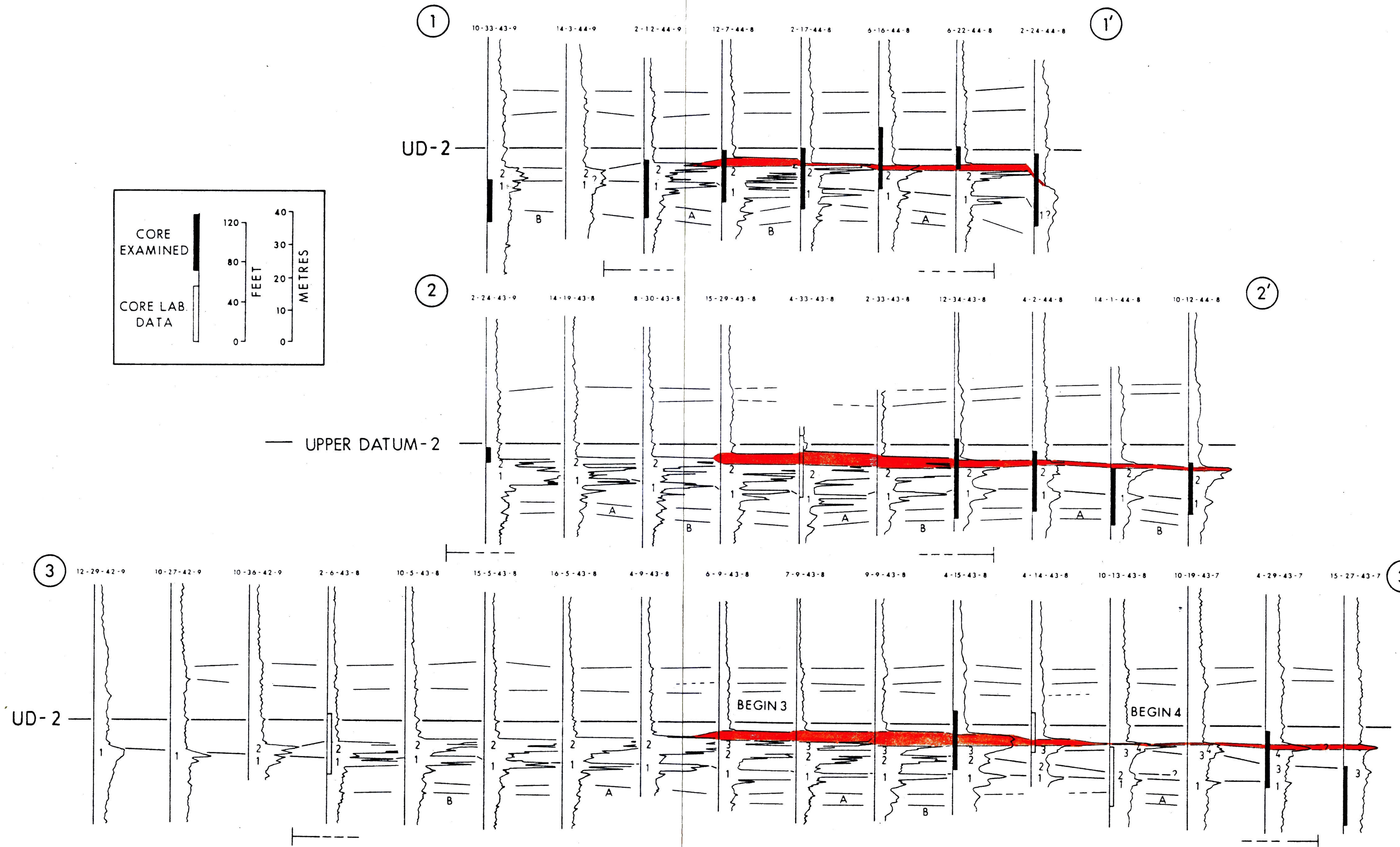
10 km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CORE LAB. DATA
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80
40
0
METRES
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20
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0
1
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2-12-44-9
12-7-44-8
2-17-44-8
6-16-44-8
6-22-44-8
2-24-44-8
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UD-2
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2-24-43-9
14-19-43-8
8-30-43-8
15-29-43-8
4-33-43-8
2-33-43-8
12-34-43-8
4-2-44-8
14-1-44-8
10-12-44-8
2′
UPPER DATUM-2
3
12-29-42-9
10-27-42-9
10-36-42-9
2-6-43-8
10-5-43-8
15-5-43-8
16-5-43-8
4-9-43-8
6-9-43-8
7-9-43-8
9-9-43-8
4-15-43-8
4-14-43-8
10-13-43-8
10-19-43-7
4-29-43-7
15-27-43-7
3′
UD-2
BEGIN 3
BEGIN 4

6.2.5 <u>Section 4</u> (Figure 6.2)

Section 4 begins in northern Ferrier at 10-4-42-9. Thick (greater than 12 m) conglomerates are encountered in 7-11-42-9 and 6-15-42-9. The position of UD-2 is unclear in the two of the Ferrier wells (7-11-42-7 and 6-15-42-9), therefore (unlabeled) local upper markers are used. Off-field to the east of Ferrier, well 6-22-42-9 contains Raven River Units 1 and 2. These Units might correlate with a log response immediately below the thick Ferrier conglomerates in 7-11-42-9 and 6-15-42-9, with the log response possibly continuing westward into 10-4-42-9. At 6-25-42-9 Units 1 and 2 lie stratigraphically higher than their position in 6-22-42-9. They separate in 10-29-42-8, and continue to separate through 4-33-42-8. The leading edge of Unit 3 occurs at 11-34-42-8 where both Units 1 and 2 have dropped stratigraphically. Thick accumulations of conglomerate (1.51 m) first occur at 4-1-43-8 where Unit 3 has dropped significantly from its position in 11-34-42-8. In 4-1-43-8 Units 1 and 2 drop with respect to the top of the Raven River Member. Conglomerates become thinner (0.69 m) into 4-6-43-7 where the leading edge of Unit 4 occurs. Note the similarity of western conglomerate occurrence (specifically with respect to Units 3 and 4) in section 6, wells 6-19-42-7 to 8-21-42-7, Fig. 6.2; section 8, wells 7-28-41-7 to 6-11-42-7, Fig. 6.3, and section 9, wells 1-19-41-6 to 6-5-43-6, Fig. 6.3. Also at 4-6-43-7 in section 4, Unit 3 continues to drop and Units 1 and 2 begin to merge.

Northeastward into 16-6-43-7, the upper portion of the Raven River sequence continues from 4-6-43-7, Unit 3 drops and Units 1 and 2 have merged (the Unit 2 log response is diminished). Unit 2 does not continue into 10-8-43-7, although Unit 1 does continue. The upper sequence continues, although Unit 3 has dropped and is not well developed. The following two wells (14-9-43-7 and 7-16-43-7 [p.221]) occur off the field (see location map), but conglomerates continue to cap the Raven River sequence although only Unit 1 in 14-9-43-7 is well developed. Moving back on-field, the following three wells show stronger log responses due to better development of the Units. Unit 5 begins at 15-14-43-7 with no overlying conglomerate. The Unit 4 response remains poor but Unit 3 is well developed (c.f. 7-12-43-7 in section 5, Fig. 6.2). No conglomerate is developed at 5-24-43-7 [p.222] and Unit 4 is indistinguishable within the lower Unit 5 response; Unit 3 continues from the previous well. Unit 5 is replaced by thick conglomerates (approximately 1.5 m) at 7-24-43-7 on the eastern margin of the field, while Unit 3 continues (c.f. 7-17-43-6 in section 5, Fig. 6.2). Well 10-33-43-6 shows a typical northeastern off-field Willesden Green log response where the Raven River Member is poorly developed to absent (c.f. 13-11-43-6 and 6-10-43-6, in sections 5 and 6 respectively, Fig. 6.2).

6.2.6 <u>Section 5</u> (Figure 6.2)

Section 5 begins within Willesden Green at 12-16-42-8 [p.205] where Units 1 and 2 are developed. The two Units separate through 4-22-42-8 into 10-22-42-8 where the first appearance of Unit 3 occurs. In 10-26-42-8, Unit three thickens and is capped by thin conglomerates (0.18 m); Units 1 and 2 drop with respect to Unit 3. A thicker conglomerate (2.54 m) is developed at 14-25-42-8 where the leading edge of Unit 4 occurs. In 14-25-42-8 Units 1 through 3 drop stratigraphically. This is the northeastern most extent of Unit 1. At 16-31-42-7 Unit 3 is not well developed and Unit 4 (with only a thin conglomerate) caps the Raven River Member. Unit 2 continues to drop with respect to the upper Units. Units 2, 3 and 4 and the conglomerate continue in a similar sequence through 6-5-43-7 [p.220] and 4-9-43-7 [p.210], where the Unit 3 log response is tenuous. In 13-3-43-7 Unit 3 is well developed and has dropped stratigraphically. Unit 4 is poorly developed and is capped by 1.05 m of conglomerate. Unit 5 begins at 13-2-43-7 where no conglomerate has accumulated and the Unit 2 log response is poorly developed. Conglomerate is again lacking at 7-12-43-7, where Units 4 and 5 are undifferentiateable. Thin conglomerates (0.18 m) cap Unit 5 at 5-7-43-7, thickening to 1.92 m at 5-17-43-6 where Unit 5 thickens and Unit 4 drops stratigraphically. Well 7-17-43-6 [p.219]

glomerates (3.25 m) replacing Units 4 and 5,

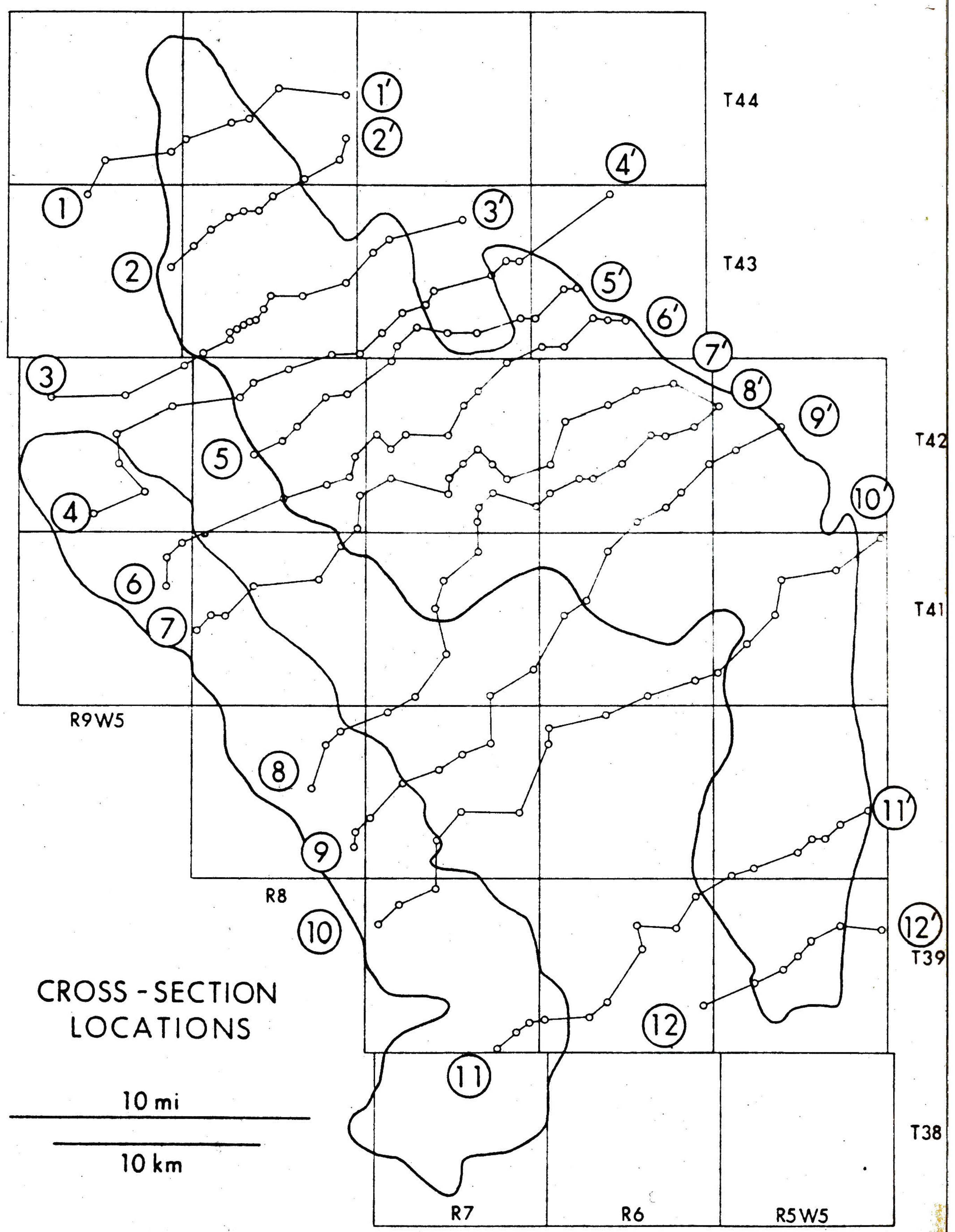
tinuing from previous wells. Well 13-11-43-6 [p.218] is a typical off-field well situated to the east of Willesden Green. In this well thin conglomerate bands cap a subdued Unit 3 log response.

6.2.7 Section 6 (Figure 6.2)

Section 6 begins in Ferrier at 2-25-41-9. To the east in 4-36-41-9 thick conglomerates occur on the eastern margin of Ferrier. A single log response in 10-31-41-8 is interpreted to represent Unit 1 (c.f. 16-31-40-7 in section 8, Fig. 6.3), and it appears to correlate with the lower log response (immediately below thick conglomerates) in 4-36-41-9. Northeastward, 4-10-42-8 is the first well within Willesden Green. It shows Units 1 and 2 to be well developed (c.f. 12-16-42-8 in section 5, Fig. 6.2 and 6-26-41-8 in section 7, Fig. 6.3). At 10-11-42-8 Units 1 and 2 separate and drop stratigraphically and the leading edge of Unit 3 appears (c.f. 10-22-42-8 in section 5, Fig. 6.2). Unit 3 thickens and Units 1 and 2 continue to drop through 14-22-42-7 into 10-13-42-8. Conglomerates (1.00 m) cap Unit 3 at 6-19-42-7 where Units 1 and 2 drop significantly with respect to their position in 10-13-42-8. This sequence continues into 16-18-42-7 where 0.31 m of conglomerate occurs. Unit 3 drops markedly at 6-20-42-7 where thick conglomerates (2.66 m) are developed. Well 8-21-42-7 shows the leading edge of Unit 4 capped by thin conglomerates. Units 1, 2, and 3 continue from preceding wells into 8-21-42-7. This sequence continues into

6-27-42-76. At 16-27-42-7 the conglomerates have thickened (1.58 m), replacing most of Unit 4. Unit 3 has dropped stratigraphically and Units 1 and 2 continue from the previous well. Unit 5 begins at 16-35-42-7 [p.212] where no conglomerate is developed; Unit 3 has dropped significantly, merging with Unit 2 (c.f. 13-2-43-7 in section 5, Fig. 6.2 and 6-18-42-6 in section 7, Fig. 6.3). Consequently, Unit 2 is difficult to distinguish, and Unit 1 is not developed. At 6-6-43-6 Units 4 and 5 continue and Unit 3 is poorly developed. Relatively thin conglomerates begin at 5-5-43-6 where Units 5, 4 and 2 are developed. At 5-9-43-6 thick conglomerates (approximately 3 m) on the eastern margin of Willesden Green occur and replace most of Unit 5. Unit 4 is not developed and Unit 2 continues. Well 7-9-43-6 shows approximately 2.5 m of conglomerate replacing Unit 5. Only Unit 2 continues from the previous well (c.f. 2-35-42-6 in section 7, Fig. 6.3). The northeasternmost well 6-10-43-6 [p.218], shows a typical subdued off-field log response and a topographically lower Raven River Member top, characteristic of wells to the east of Willesden Green.

Fig. 6.2. Cross sections 4, 5 and 6 with location map at left. See text for discussion.



T44
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CROSS-SECTION LOCATIONS
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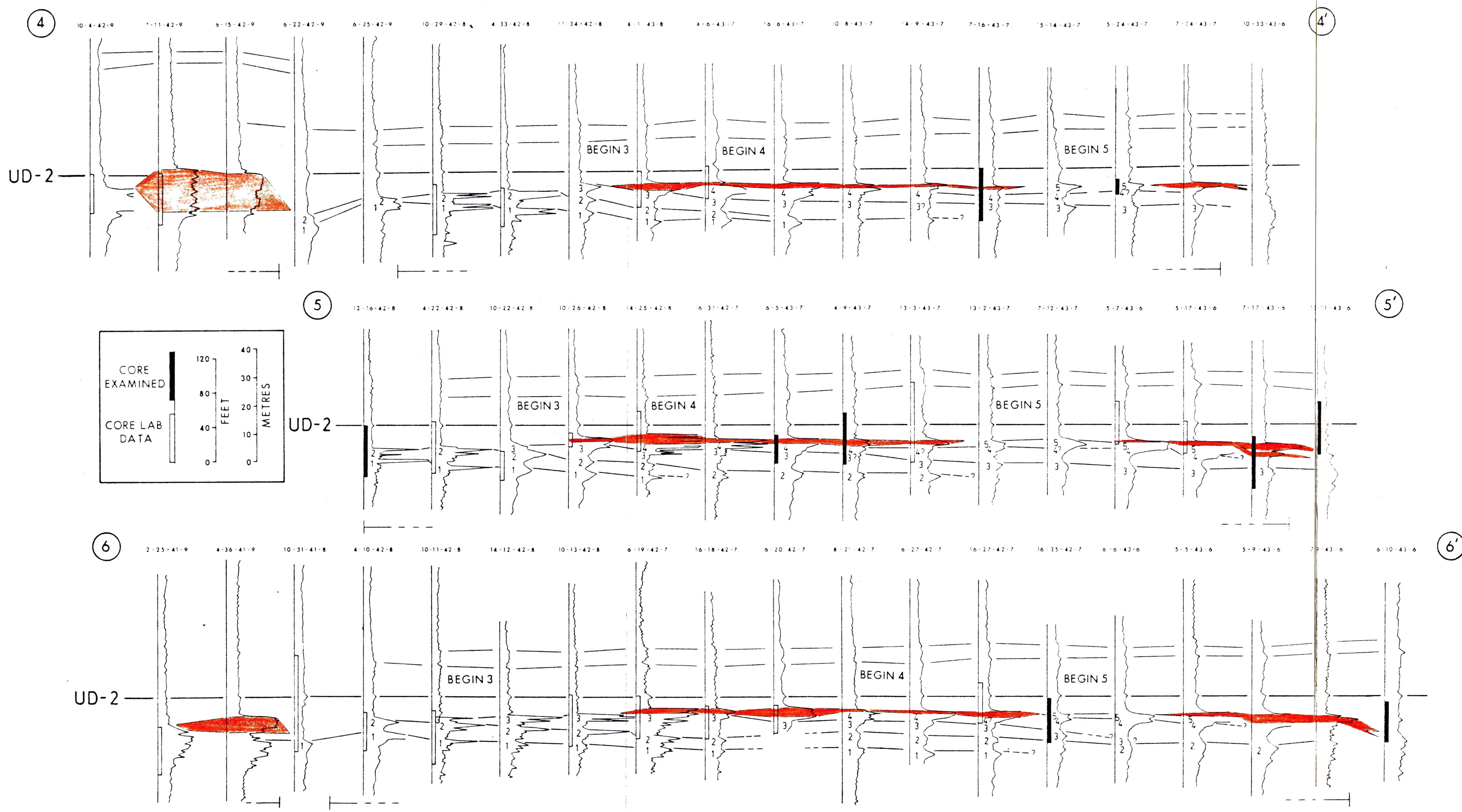


UD-2
BEGIN 3
BEGIN 4
BEGIN 5
CORE EXAMINED
CORE LAB DATA
FEET
METRES

6.2.8 Section 7 (Figure 6.3)

The first three wells of section 7 (12-18-41-8, 2-19-41-8 and 4-20-41-8) are in Ferrier. A thick conglomerate (5.09 m in 4-20-41-8) caps the two eastern wells in Ferrier. Well 4-28-41-8 shows a typical single Raven River Unit response between Ferrier and Willesden Green, and it is interpreted to represent Unit 1 (c.f. well 16-31-40-7 in section 8, Fig. 6.3 and well 10-31-41-8 in section 6, Fig. 6.2). Possible correlation between Unit 1 in 4-28-41-8 and a log response in the Ferrier wells is unclear. The leading edge of Unit 2 begins at 6-26-41-8, located between Ferrier and Willesden Green (c.f. well 10-11-42-8 in section 6, Fig. 6.2). The first well within Willesden Green is 12-36-41-8 where the leading edge of Unit 3 occurs and Unit 1 drops significantly. A similar sequence continues through 2-1-42-8 [p.213] and 8-12-42-8 into 16-5-42-7 where the log response of Unit 2 is subdued. Thick conglomerate (based on data from surrounding wells, some not shown in the section) caps wells 8-9-42-7 and 16-9-42-7. The subdued response of Unit 2 continues to 16-9-42-7, but it shows better development in 6-15-42-7. Here, Unit 4 begins and the conglomerate thins (0.34 m). Section 7 shows the thickest conglomerates in the western regions of the field. They occur between wells where Unit 3 drops and Unit 4 begins (this relationship is also shown in [illegible], for example section 9 (Fig. 6.3), wells [illegible] 6-3-42-6). Units 1, 2 and 3 all drop stratigraphically in 16-15-42-7 [p.211]. In 6-14-42-7 no conglomerate is developed (based on wells additional to those shown in section 7), and Unit 3 drops. No conglomerate occurs in 16-11-42-7 [p.210] and Unit 3 continues to drop. Conglomerates cap Unit 4 at 6-18-42-6, where Unit 3 is interpreted to have merged with Unit 2 (c.f. 16-35-42-7, section 6, Fig. 6.2). In 16-19-42-6 a similar overall sequence to 6-18-42-6 is shown, although the Unit 3 response is diminished. Thicker conglomerate caps 6-28-42-6 where Unit 5 is interpreted to begin and Unit 3 does not occur. Thick conglomerate continues into 14-27-42-6; under the conglomerate, Unit 5 is thick but Unit 4 is not present. A very thick conglomerate (approximately 3.5 m) caps 2-35-42-6 on the eastern margin of the field, replacing Unit 5 (conglomerate occurrence based on logs not show in section 7). Units 1 and 2 continue from 14-27-42-6. The final well, 5-30-42-5 (also in section 8) shows a typical subdued off-field log response and a topographically lower top to the Raven River Member. This log response is characteristic of wells to the east of Willesden Green.

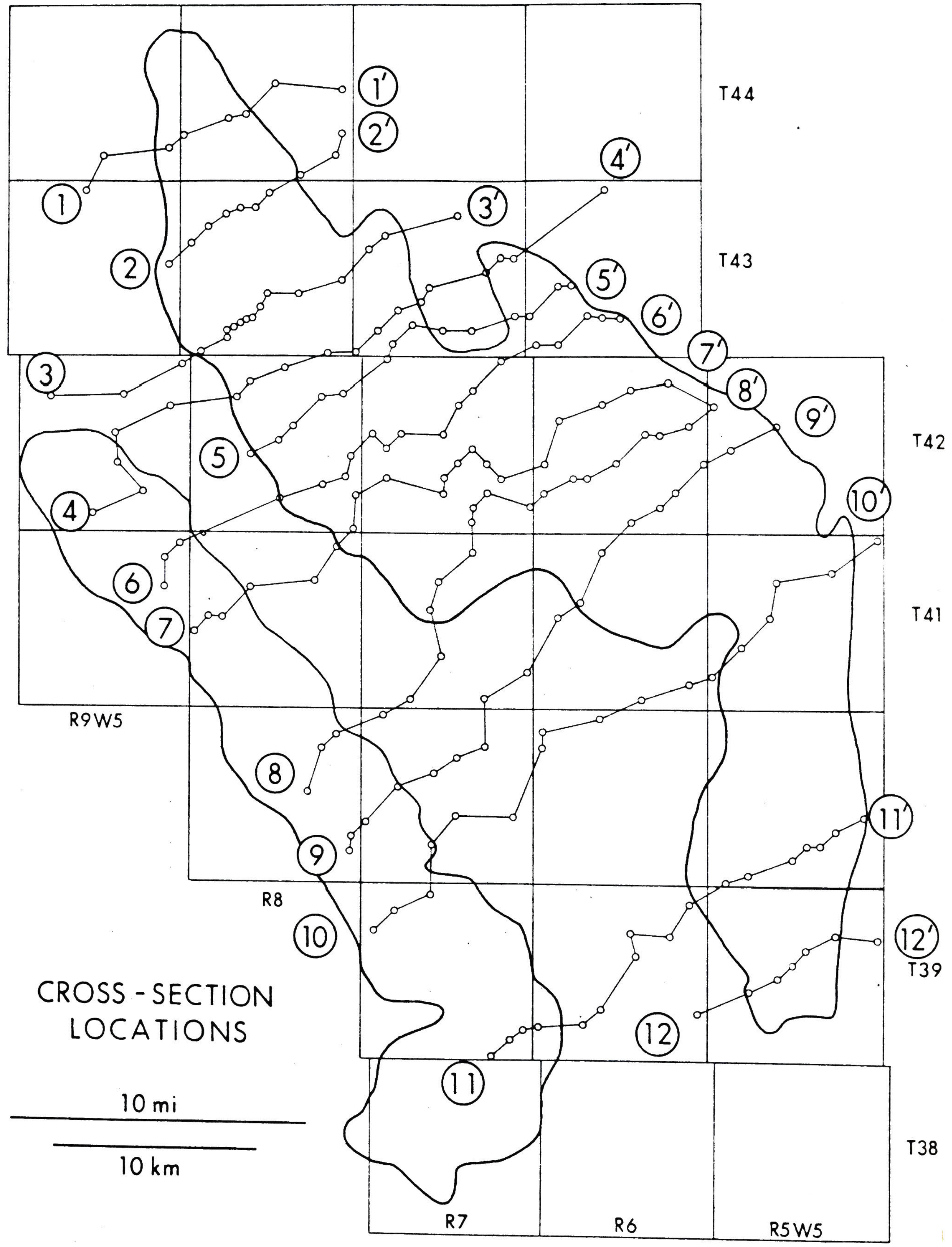
6.2.9 Section 8 (Figure 6.3)

The first three wells in section 8 (4-23-40-8, 10-26-40-8 and 4-36-40-8) are from Ferrier, and show conglomerates capping 2 thick log responses interpreted as sandstones. The upper sandstone terminates abruptly before 16-31-40-7, but the lower sandstone appears to correlate with the single log response shown in two wells east of Ferrier, 16-31-40-7 and 7-5-41-7. This single log response is interpreted to represent Unit 1 (c.f. well 4-28-41-8 in section 7, Fig. 6.3) and therefore Unit 1 appears to be continuous between Ferrier and Willesden Green. At 16-9-41-7 the leading edge of Unit 2 occurs (c.f. well 6-26-41-8 in section 7 and 6-27-40-7 in section 9, both in Fig. 6.3). The first well within Willesden Green, 6-21-41-7 [p.204], shows the leading edge of Unit 3; the log response is similar to that encountered at 12-36-41-8 in section 7 (Fig. 6.3) and 11-26-40-7 in section 9 (Fig. 6.3). Units 2 and 3 have separated, and although the Unit 2 log response is not well developed, it is discernible. Thin conglomerates cap 8-34-41-7, where Units 1 and 2 have dropped markedly with respect to Unit 3. The overall sequence in the next two wells, 8-3-42-7 and 16-3-42-7 is similar to 8-34-41-7 but thicker accumulations of conglomerate occur in both wells as Unit 3 drops stratigraphically. The leading edge of Unit 4 occurs at 6-11-42-7 where conglomerates thin. A similar sequence is shown at 16-1-42-7. Thick conglomerates (about 2 m) cap 6-7-42-6 replacing Unit 4 (c.f. 16-27-42-7 in section 6, Fig. 6.2). Wells 14-8-42-8 through 8-22-42-6 show a similar sequence to 6-7-42-6 but with progressively less conglomerate and more of Unit 4. At 6-23-42-6 Unit 5 begins, Units 3 and 4 drop stratigraphically, and Units 1 [illegible] in a similar fashion to that of 16-3-42-7. [illegible] (Units 3, 4 and 5 in this section) are difficult to pick in 11-24-42-6, where a conglomerate caps the sequence and Units 1 and 2 continue. Well 5-30-42-5 (the same well ending section 7) shows a typical off-field well to the east of Willesden Green with a subdued log response and a topographically lower top of the Raven River Sequence.

6.2.10 Section 9 (Figure 6.3)

This section begins in Ferrier with 4 wells (2-12-40-8 through 6-20-40-7), all of which are capped with conglomerate. Wells 2-12-40-8 through 4-18-40-7 show two log responses below the conglomerates, which are interpreted as sandstones. Thickened conglomerates in 6-20-40-7, off the eastern margin of Ferrier, appear to replace all but the lower sandstones. The following 6 wells are all between Ferrier and Willesden Green and show the initiation of Units 2 and 3. The first, 15-21-40-7 may show both Units 1 and 2 although Unit 2 is more distinctly shown in the next well, 6-27-40-7. Units 1 (and 2 ?) appear to correlate with the lower sandstone at Ferrier (shown in 6-20-40-7). The leading edge of Unit 3 is interpreted to occur at 11-26-40-7 with Unit 2 immediately below (c.f. 6-21-41-7, in section 8, Fig. 6.3). Unit 2 is not well shown between 11-26-40-7 and 8-12-41-7 (c.f. wells 7-28-41-7 to 8-3-42-7 in section 8, Fig. 6.3 and 16-5-42-7 to 16-9-42-7, section 7, Fig. 6.3) but it is easily identified at 1-19-41-6. From the position of Unit 2 in 1-19-41-6, from other sections (some referred to above) and from well logs, Unit 2 is interpreted to occur in the positions shown in wells 11-26-40-7 through 8-12-41-7. Well 1-19-41-6 clearly shows Units 1, 2 and 3. The first Willesden Green field well, 10-20-41-6, has about 0.80 m of conglomerate capping Unit 3 which has dropped stratigraphically, and Units 1 and 2 have dropped from their position in 1-19-41-6. The thickest conglomerate in section 9 occurs at 6-33-41-6 (about 4.4 m) where Unit 3 has dropped markedly from the previous well. The leading edge of Unit 4 occurs at 6-3-42-6, where no conglomerate is developed. The occurrence of thick conglomerates between wells where Unit 3 drops and Unit 4 begins is shown in other sections, for example in section 4 (Fig. 6.2), wells 11-34-42-8 to 4-6-43-7). At 14-2-42-6 Unit 3 continues to drop and Unit 4 is capped by approximately 1 m of conglomerate . Units 1 and 2 continue in a similar fashion to the end of the section. The leading edge of Unit 5 occurs at 8-11-42-6, where no conglomerates are accumulated, and where Units 3 and 4 drop stratigraphically. At 8-13-42-6, 0.13 m of conglomerate caps Unit 5, Unit 4 is absent, and Unit 3 has dropped stratigraphically. Unit 3 does not continue into 16-18-42-5 [p.206], where about a meter of conglomerate caps a dropped Unit 5. Well 11-21-42-5 shows a typical eastern off-field well with a subdued log response and a topographically lower top of the Raven River Sequence.

Fig. 6.3. Cross sections 7, 8 and 9 with location map on left. See text for discussion.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CROSS - SECTION LOCATIONS
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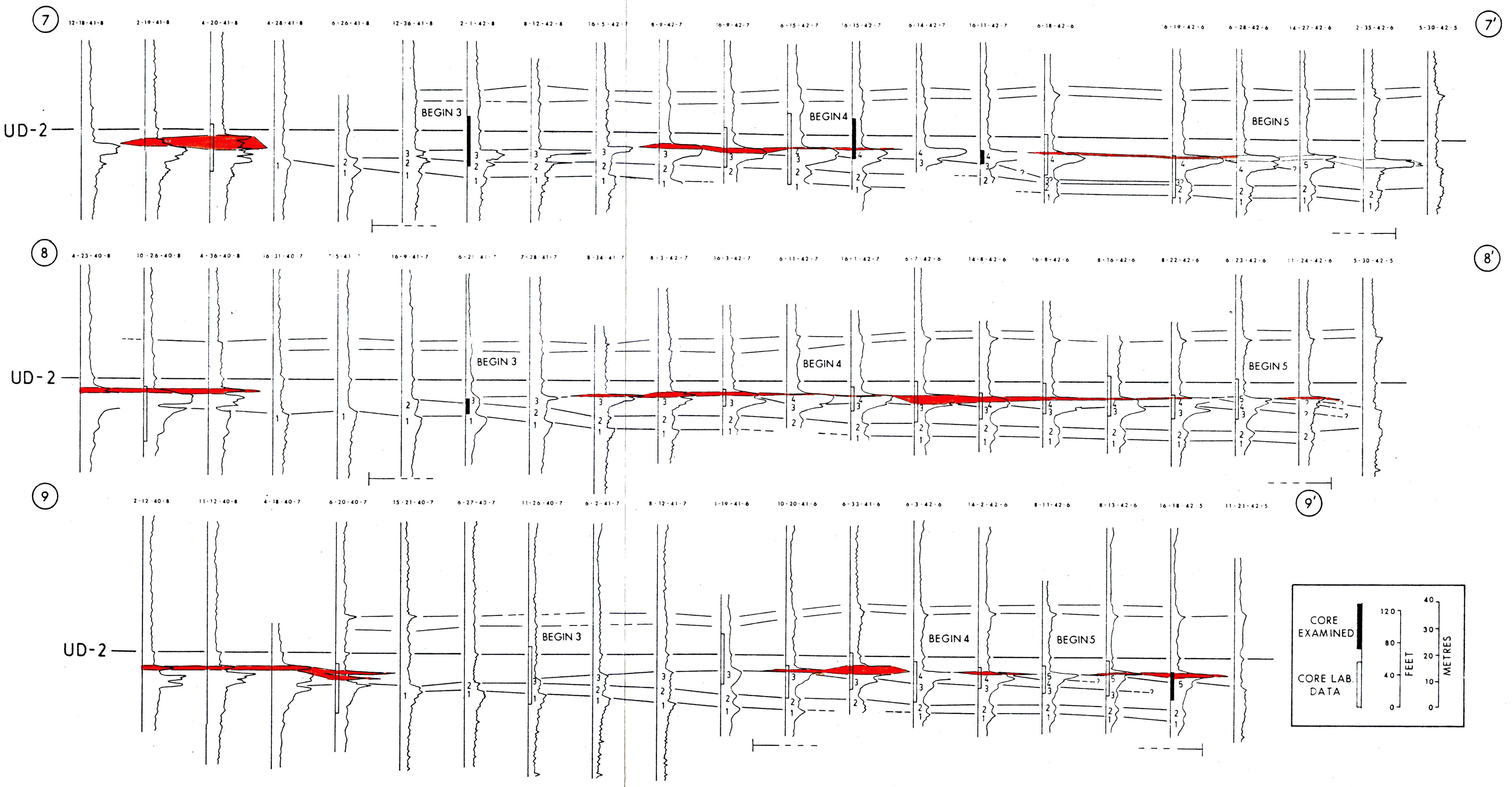
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UD-2
BEGIN 3
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CORE EXAMINED
CORE LAB. DATA
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40
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6.2.11 Section 10 (Figure 6.4)

Section 10 best shows the shingling nature of the Raven River Member Units at Willesden Green. The section begins in Ferrier with a thick (inferred) sandstone log response at 6-30-39-7. To the northwest, this log response thins into 4-32-39-7, 11-33-39-7 and 6-9-40-7 and is capped by conglomerates in 4-32-39-7 and 11-33-39-7 on the eastern margin of Ferrier. At 6-15-40-7, in-between Ferrier and Willesden Green, the single log response is interpreted to represent Unit 1 (c.f. 15-21-40-7 in section 9, Fig. 6.3 and 16-31-40-7 in section 8, Fig. 6.3). This log response may correlate with a lower log response (see section 10) at Ferrier (as shown between 6-9-40-7 and 6-15-40-7). The leading edge of Unit 2 occurs at 6-13-40-7 (c.f. 6-27-40-7 in section 9, Fig. 6.3 and 16-9-41-7 in section 8, Fig. 6.3), and Unit 1 has dropped stratigraphically with respect to its position in 6-15-40-7. Unit 3 begins at 2-30-40-6, where the Unit 2 log response is subdued (see discussion above concerning Unit 2 in 6-2-41-7 and 8-12-41-7 in section 9, Fig. 6.3), and Unit 1 continues to drop stratigraphically. In 11-29-40-6 a similar sequence occurs. Unit 2 is better developed and drops in 11-33-40-6, the remainder of the sequence continues as in 11-29-40-6. The leading edge of Unit 4 occurs at 7-3-41-6 where Unit 3 drops stratigraphically and Unit 2 merges with Unit 1. A similar sequence occurs through 14-1-41-6 [p.203], 4-7-41-5 to 4-17-41-5 (a local resistivity "kick" occurs between Units 2 and 3 in these wells). In 4-21-41-5 Unit 4 continues, though Unit 3 is not developed, and Units 1 and 2 are less well shown than in wells to the southwest. Conglomerates on the eastern field margin of Willesden Green cap Unit 4 at 6-28-41-5 and replace Unit 4 at 12-26-41-8 (based on wells additional to those in section 10). A relatively subdued log response typical of wells to the east of Willesden Green occurs at 16-36-41-5.

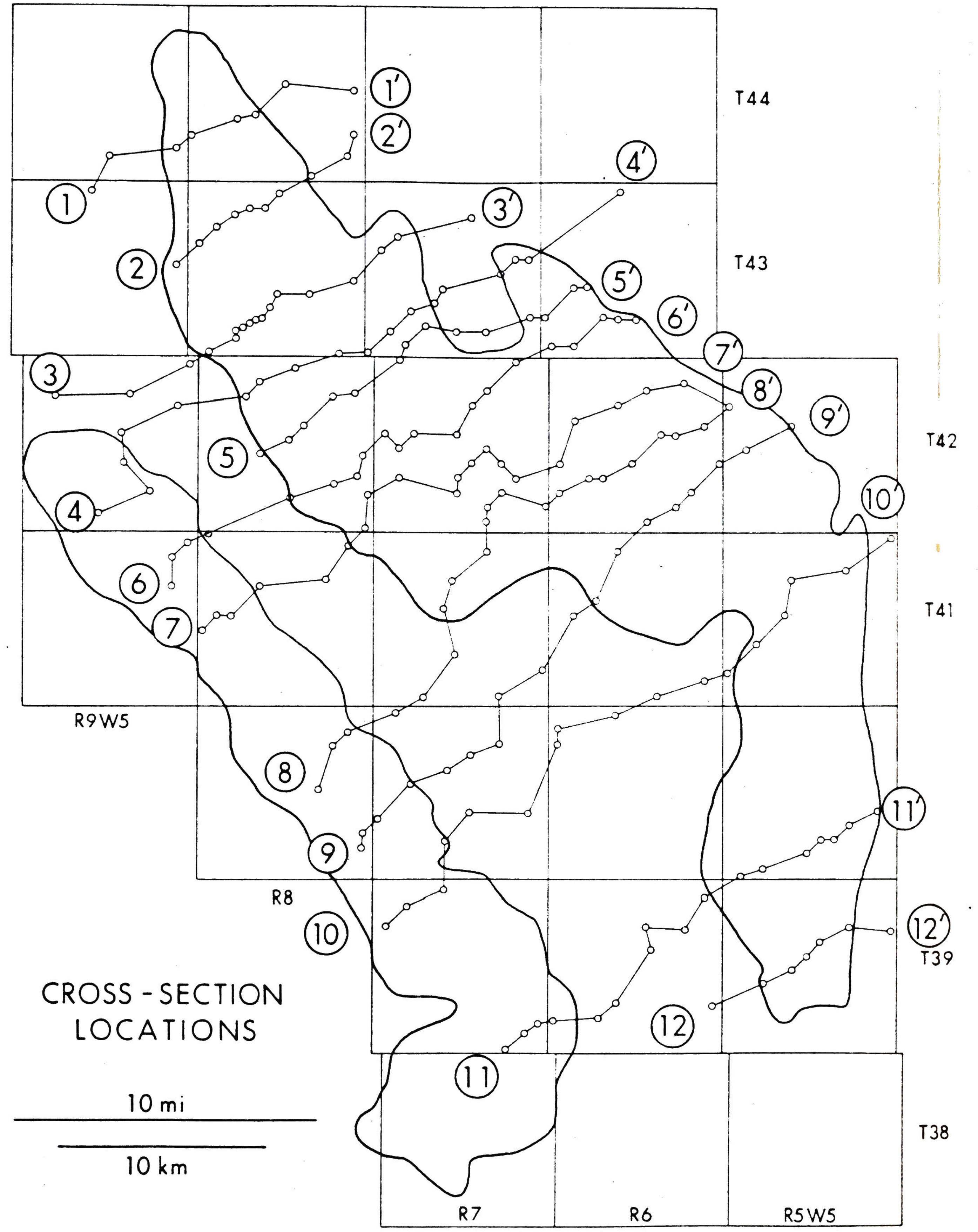
6.2.12 Section 11 (Figure 6.4)

Section 11 is the most southerly section traversing both Ferrier and Willesden Green. Wells 2-2-39-7 through 4-7-39-6 are all Ferrier wells. They show a conglomerate capping an upper and lower log response interpreted as sandstones. The lower log response continues in wells in-between Ferrier and Willesden Green (e.g. 7-8-39-6 and 10-21-39-6) and into Willesden Green (e.g. 2-6-40-5; c.f. 6-9-40-7 through 4-17-41-5 in section 10, Fig. 6.4). Unit 2 is interpreted to begin east of Ferrier at 7-8-39-6, but it does not continue into Ferrier. At 7-8-39-6 conglomerates on the eastern margin of Ferrier occur stratigraphically above Unit 2, and pinch out northeastward. Units 1 and 2 occur at 10-9-39-6, but are separated by an increased interval as compared to 7-8-39-6. Well 10-21-39-6 shows a similar sequence to 10-9-39-6, though Unit 1 drops [illegible]ly and the separation between Units 1 and 2 increases slightly. The leading edge of Unit three occurs at 6-27-39-6 and Units 1 and 2 drop stratigraphically. At 6-36-39-6 Unit 2 begins to merge with Unit 1 and Unit 3 is better developed than in southwestern wells. In the first Willesden Green well, 2-6-40-5, the leading edge of Unit 4 occurs, Units 1, 2, and 3 have dropped stratigraphically and Unit 2 has merged with Unit 1. At 6-5-40-5 Unit 4 thickens, Units 1 and 3 drop and Unit 2 is poorly developed or absent. A similar sequence continues into 16-4-40-5, where Unit 2 is absent. The leading edge of Unit 5 occurs at 6-10-40-5 and all other Units drop stratigraphically. A similar sequence continues into 8-10-40-5. Units 4 and 5 continue into 14-11-40-5, but lower Units are difficult to identify. Well 6-13-40-5 occurs on the eastern field margin of Willesden Green and shows a subdued log response.

6.2.13 Section 12 (Fig. 6.4)

Section 12 is the most southerly section traversing Willesden Green. No conglomerate of significance occurs. Units 1, 2 and 3 are identified in 10-12-39-6. At 6-17-39-5, the first Willesden Green well, the leading edge of Unit 4 occurs; Units 2 and 3 have dropped stratigraphically. Unit 3 is poorly developed and Unit 2 has merged with Unit 1 (c.f. 2-6-40-5 in section 11, Fig. 6.4 or 14-1-41-6, in section 10, Fig. 6.4). The leading edge of Unit 5 occurs in 14-16-39-5, where Units 3 and 4 have dropped stratigraphically, Unit 3 remains poorly developed and Unit 2 is absent. At 14-22-39-5 a similar, though subdued sequence continues. Only Units 4 and 5 are well developed in 6-26-39-5 on the eastern margin of Willesden Green. The easternmost well in section 12, 8-25-39-5, shows Unit 5 with no other identifiable Units.

Fig. 6.4. Cross sections 10, 11 and 12 with location map on left. See text for discussion.


CROSS - SECTION LOCATIONS
10 mi
10 km
T44
T43
T42
T41
T39
T38
R9W5
R8
R7
R6
R5W5


UD - 2
BEGIN 3
BEGIN 4
BEGIN 5
CORE EXAMINED
CORE LAB DATA
FEET
METRES

6.3 DELINEATION OF INDIVIDUAL RAVEN RIVER UNITS

6.3.1 Introduction and Method

The occurrence of coarsening-upward Units within the Raven River Sequence was briefly discussed in chapters 2 and 3. Relationships between individual Units in Raven River Sequence was shown in sections 1 - 12 (Figures 6.1 - 6.4) and will be discussed herein with the trends of the first appearance or leading edge of Units 2, 3, 4 and 5 (Fig. 6.5). These trends were mapped by utilizing all available resistivity logs in the study area (Fig. 1.3) along with my core control (Fig. 1.2).

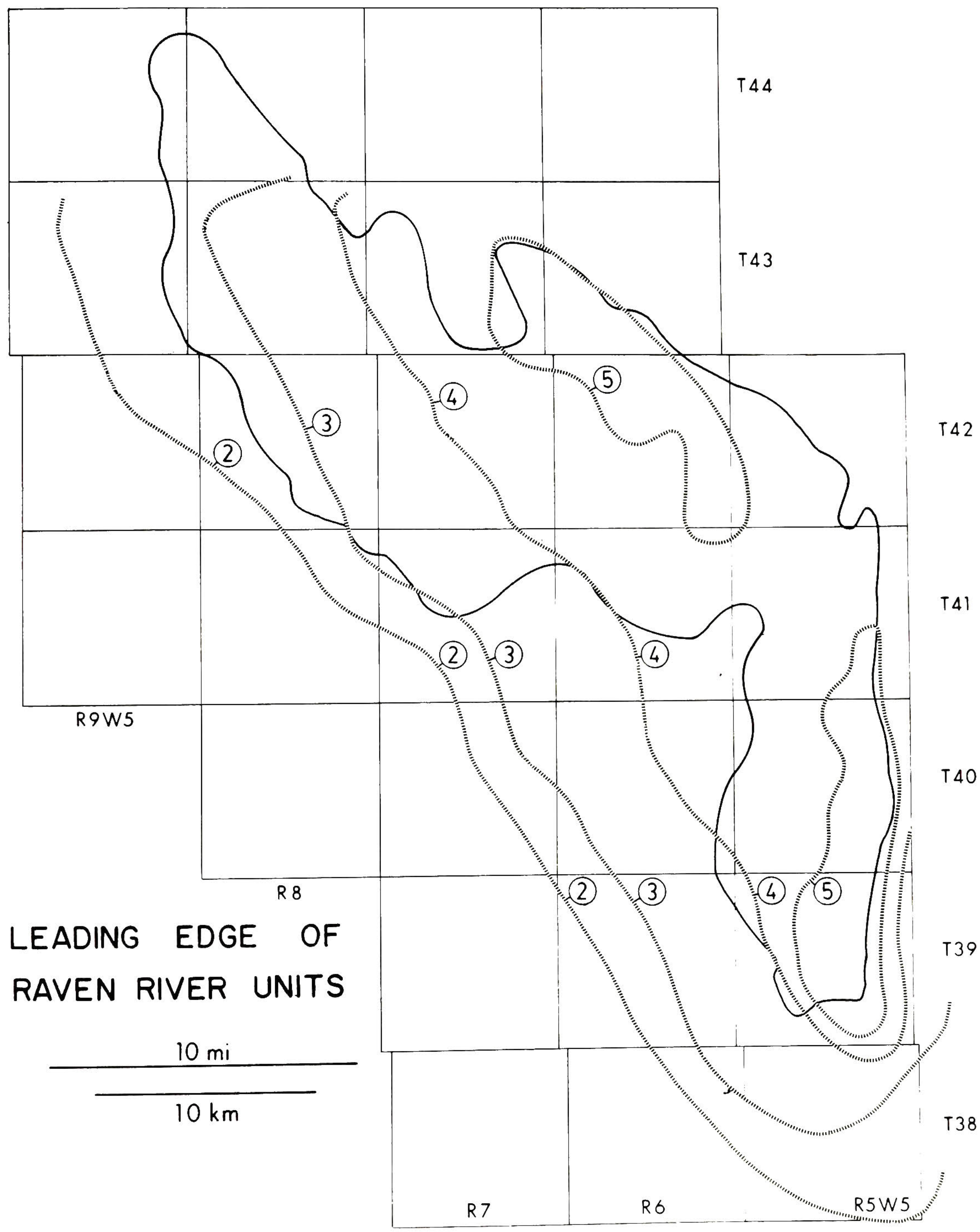
6.3.2 Results and Conclusions

From examination of Figures 6.1 through 6.5 a number of conclusions concerning the distribution of the coarsening-upward Units within the Raven River Sequence in the Willesden Green area can be made.

(1) In the Willesden Green area the Raven River Sequence of the Cardium Formation is composed of five Units.

(2) Unit 1 appears to be continuous between Willesden Green and Ferrier. This is particularly well shown in sections 6 (Fig. 6.2), 8 and 9 (Fig 6.3), 10 and 11 (Fig. 6.4).

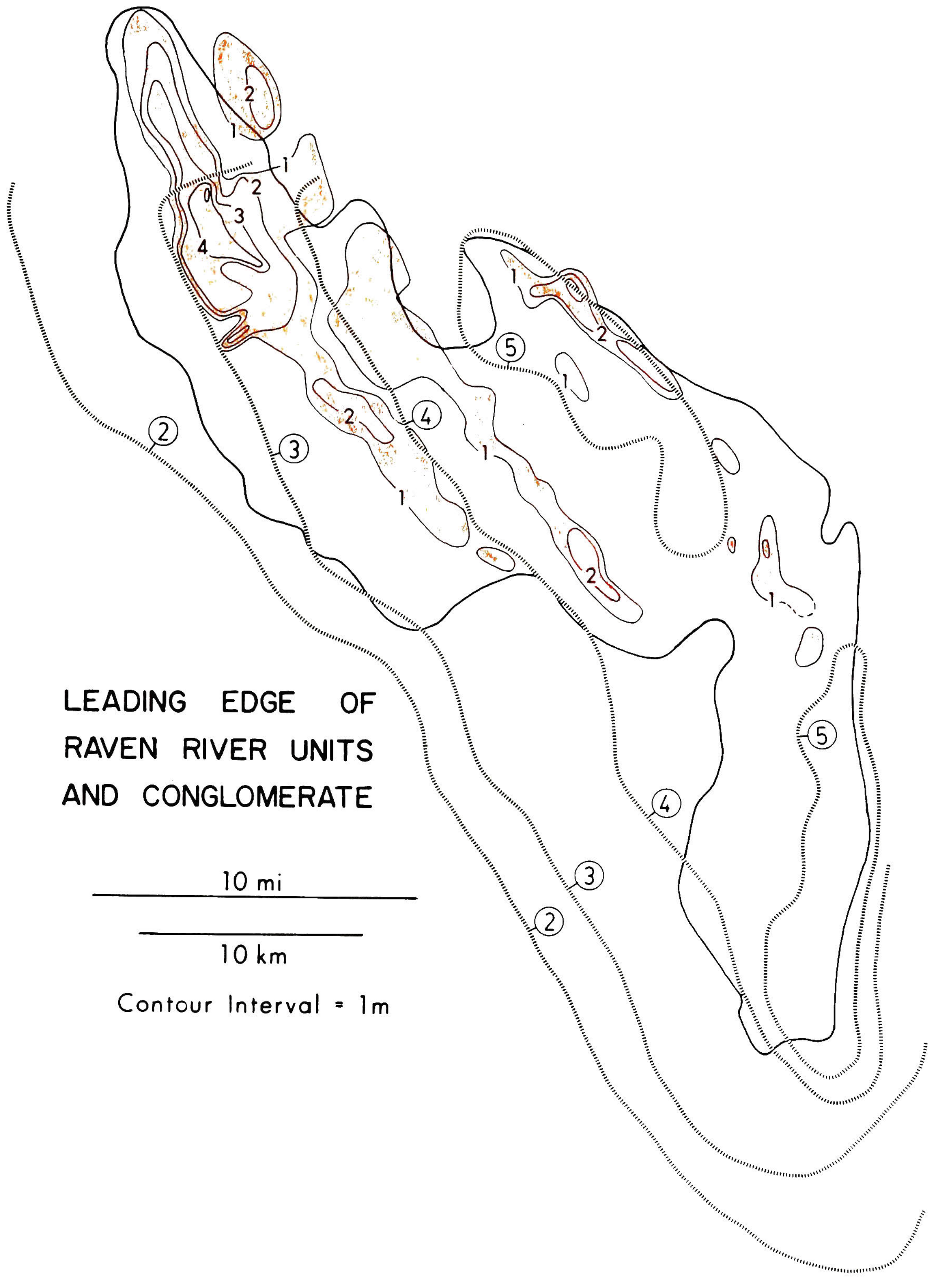
Fig. 6.5 Map showing the leading edge or first appearance of the Raven River Units. The leading edges of Units 2, 3, 4 and 5 (numbered on diagram) are shown by the stippled lines (highlighted in yellow). The Willesden Green Field boundary is indicated by the heavy solid line. Township and ranges are included for reference. See text for discussion.


T44
T43
T42
T41
T40
T39
T38
R9W5
R8
R7
R6
R5W5
2
3
4
5
LEADING EDGE OF
RAVEN RIVER UNITS
10 mi
10 km

(3) Units 2 through 5 offlap or shingle towards the northeast. Their extent is restricted to the Willesden Green area. I know of only one published account of a similar relationship in Cardium sandstones (though it does not follow the orientation at Willesden Green); that of McKenzie and Russum (1976). They showed a generalized section (their Figure 2) with Cardium sandstones at Pembina shingling? off each other towards the south.

(4) The leading edges of Units 2, 3 and 4 in Raven River Sequence parallel each other, trending roughly northwest to southeast. This trend also parallels the general northwest to southeast regional trend of Cardium fields.

(5) Unit 5 has two distinct occurrences. The northern occurrence trends northwest to southeast, but the southern occurrence trends roughly north - south.



LEADING EDGE OF
RAVEN RIVER UNITS
AND CONGLOMERATE

10 mi

10 km

Contour Interval = 1m

6.4.2 Results and Discussion

From Figures 6.1 through 6.4 and 6.6 a number of points concerning conglomerate accumulation are evident:

(1) Conglomerate thicker than 1 metre overlies Unit 2 in the northern regions of Willesden Green (Twn. 44) and elsewhere overlies Unit 3, 4 or 5. Therefore the conglomerate must have been emplaced at Willesden Green after emplacement of all of the Raven River Member sandstone Units.

(2) Conglomerate has accumulated to the east of the topographically highest position on top of the Raven River Member sandstone (here represented by Unit 2) in sections 1 (wells 2-12-44-9 [p.240] and 12-7-44-8 [p.235]) and 2 (wells 8-30-43-8 and 15-29-43-8). This compares favorably with Swagor's (1975) and Griffith's (1981) findings of conglomerate accumulations on the eastern side of a "break in slope".

(3) The most westerly northwest-to-southeast trend of thickly accumulated conglomerates seems to parallel the western margin of the leading edge of Unit 4. This is well shown in sections 4 (wells 11-34-42-8 to 4-6-43-7, Fig. 6.2), 6 (wells 6-19-42-7 to 8-21-42-7, Fig. 6.2), 8 (wells 7-28-41-7 to 6-11-42-7, Fig. 6.3) and 9 (wells 1-19-41-6 to 6-3-42-6, Fig. 6.3). The thick conglomerates seem to

accumulate in regions where Unit 3 has dropped stratigraphically, and Unit 4 is not developed.

(4) The northwestern to southeastern trend of thick conglomerate in the central region of Willesden Green lies within Unit 4. Sections 5 (well 4-9-43-7 [p.220]), 6 (well 16-27-42-7) and 8 (well 6-7-42-6) all show the conglomerates replacing what might have been a previously continuous Unit 4.

(5) Thick conglomerate accumulation in the northeastern region of Willesden Green occurs on or just off the eastern margin of Unit 5. This is particularly well shown in section 5 (Fig. 6.2), wells 5-17-43-6 to 7-17-43-6 [p.219]. As was the case with conglomerate accumulation in sections 1 and 2, conglomerate accumulation in the northeastern portion of section 5 compares favorably with findings of Swagor (1975) and Griffith (1981) and other Cardium workers.

(6) The area separating the southern and northern occurrences of Unit 5 (Twn. 41 Rge. 6) has the thickest southerly conglomerate accumulation in Willesden Green. The Unit 5 sandstones might have been removed and replaced by the conglomerates.

6.4.3 Conclusions

(1) Cardium conglomerates overlie all of the Raven River Units.

(2) Areas of thickest conglomerate accumulation are east and northeast of relative highs both within and off the eastern margin of Willesden Green.

(3) Some scouring of the Cardium sandstones by the conglomerates is probable within Willesden Green.

CHAPTER 7: DISCUSSION

7.1 INTRODUCTION

Chapter 7 begins with a discussion of two currently popular mechanisms for transporting sand offshore into the Cretaceous Interior Seaway, namely geostrophic flow and turbidity currents (mentioned in chapter 1.1). Findings presented in chapters 2 through 6 are compared with each of these sand transporting mechanisms and one of the mechanisms is suggested as having been the more likely mechanism of sand transport to Willesden Green. Important aspects of the configuration of the Cardium sandstone and conglomerate at Willseden Green (chapters 5 and 6) are restated leading to a discussion of the possibility of a pre-Cardium topography (depositional or structural) at Willesden Green. Examples of other Cretaceous seaway deposits showing an offlapping geometry are discussed and a depositional framework for the Cardium sediments at Willesden Green is suggested.

7.2 SAND TRANSPORT PROCESSES ON STORM DOMINATED SHELVES - IMPLICATIONS TO SEDIMENT TRANSPORT TO WILLESDEN GREEN

7.2.1 Information from the modern environment - Geostrophic Flows

Our knowledge of sand transport on shelves comes mostly from study of modern continental shelves. The Atlantic continental shelf of North America is one of the most thoroughly studied and understood modern shelves (for example see Beardsly *et al.*, 1976 and Mayer *et al.*, 1979). The Atlantic continental shelf is storm dominated (Vincent *et al.*, 1981), as are about 80% of the world's continental shelves (Swift, 1984). The dominant sediment transport mechanism on most of the central portion of the Atlantic continental shelf is geostrophic storm flow (Boicourt and Hacker, 1981 in Swift and Rice, 1984, p. 46). As mentioned previously, geostrophic storm flow is currently receiving a much attention as a mechanism by which sand may have been transported out across the shoreface in the Cretaceous Interior Seaway. Can sand transport processes observed on the Atlantic continental shelf be applied to the Cretaceous epeiric seaway ? The sandbodies on the Atlantic Continental Shelf originated as shoreface attached sand-bodies. During subsequent transgression these sandbodies were detached (Swift, 1976). However, the sandbodies of the Cretaceous epeiric seaway are generally larger, enveloped in mudstones and may have developed during regional regression of the sea, tens to hundreds of km off-shore (Swift and Rice, 1984). These differences notwithstanding Swift and Niedoroda (1984) suggest that "the textures, primary structures, and facies patterns of epicontinental sea and continental shelf deposits are fundamentally similar despite the differing dimensions and boundaries, because the processes which create them are similar".

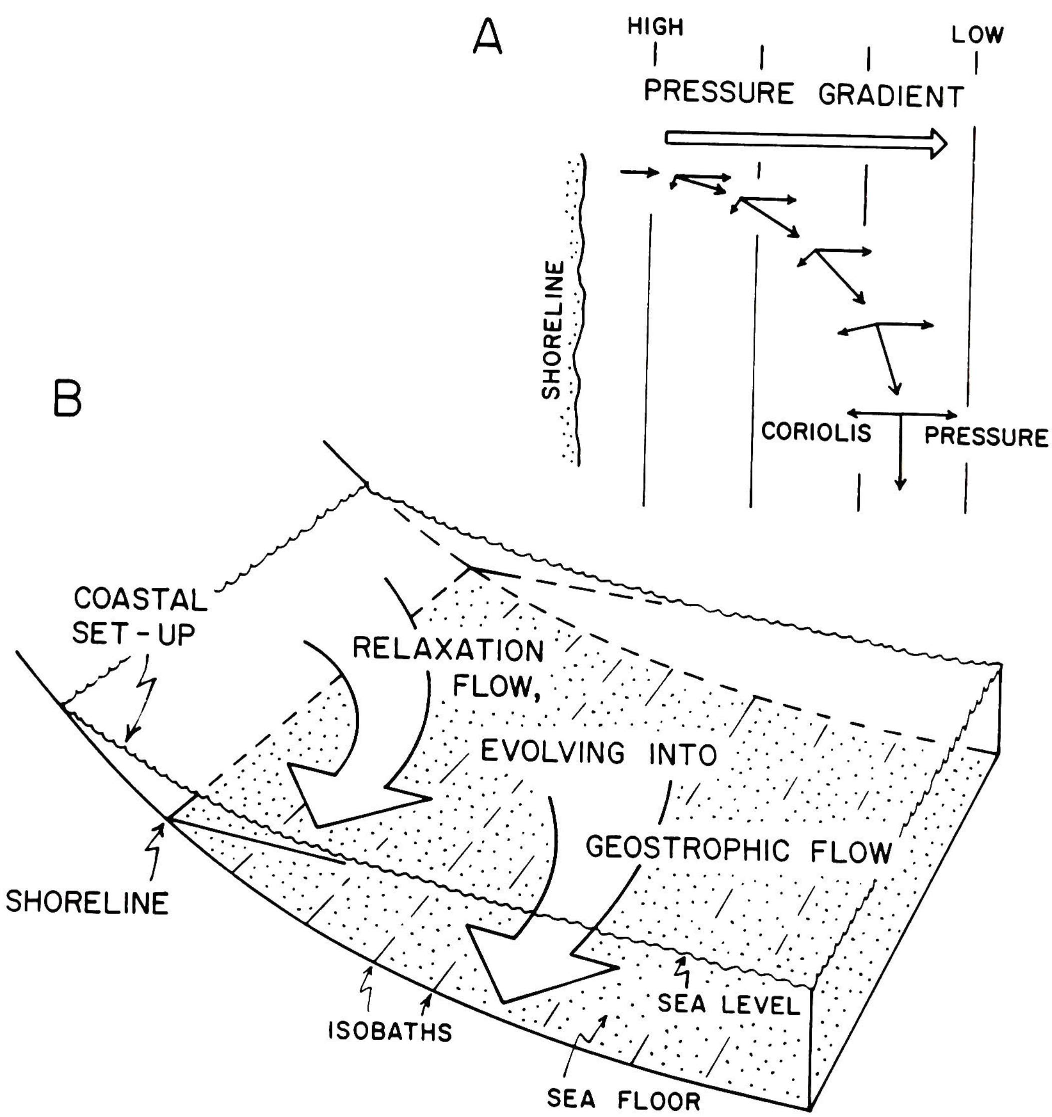
Geostrophic Flow

As discussed previously (chapter 1.2), storm-generated, wind-forced geostrophic flow is a popular topic of research. Swift (1984) gives a thorough discussion of modern shelf currents including geostrophic flow and Walker (1984a) provides a succinct summary of many of these processes.

Figure 7.1 (from Walker, 1984a, p. 142) shows a north-south, east facing coast (such as the western coast of the Cretaceous epeiric seaway) where storm winds have acted to force water on-shore (coastal set-up), creating a seaward pressure gradient. The seaward flow is acted upon by Coriolis force which causes a deflection to the right (in the northern hemisphere), thus a geostrophic flow parallel to isobaths is generated (Swift, 1984). Swift (1984) suggests that both the initial and final discharge associated with a relaxation flow (i.e. seaward directed storm surge ebb) is "trivial" in comparison to the discharge of geostrophic flow.

Niedoroda (1984) note that storms are

Fig. 7.1 Storm winds from the north or northeast result in storm surge or coastal set-up along a north-south, east facing coast which creates a seaward directed pressure gradient. The storm-surge ebb or relaxation flow is deflected to the right (in the northern hemisphere) by Coriolis force (see A) resulting in a geostrophic current flowing parallel to isobaths or shoreline (B). The figure is not to scale. From Walker (1984, p. 142).


A
HIGH
LOW
PRESSURE GRADIENT
SHORELINE
CORIOLIS
PRESSURE
B
COASTAL SET - UP
RELAXATION FLOW,
EVOLVING INTO
GEOSTROPHIC FLOW
SHORELINE
ISOBATHS
SEA LEVEL
SEA FLOOR

particularly efficient sediment transporters due not only to the geostrophic flow they generate, but also to the surface waves generated and their high-frequency wave orbital currents. The wave orbital current component is very important in sediment entrainment and transport (Swift and Niedoroda, 1984).

7.2.2 Some Ancient Studies - Turbidity Currents

As previously discussed, Walker (1983a, b, c and in press) has suggested that storm-generated turbidity currents are responsible for the offshore transport and emplacement of some of the sediments deposited within the Western Interior Seaway - specifically those of the Cardium Formation within the Ricinus, Caroline and Garrington fields (these fields occur immediately south of the study area). He has based his conclusions on several features, including (1) preserved sedimentary structures observed in core, namely sharp based sandstone beds and mud clasts interpreted to represent deposition by sudden and erosive flow, i.e. turbidity currents. (2) The occurrence of associated sedimentary structures, namely massive to parallel laminated to ripple-cross laminated sandstones interpreted to represent Bouma (1962) A-B-C sequences. (3) The sequential occurrence of certain facies in thick stratigraphic sections - namely (in ascending order, with the interpreted site of deposition following in parentheses) classical turbidites (deposition below storm wave-base); hummocky cross stratified sandstones interbedded with bioturbated mudstones (deposited above storm wave base, but below fair-weather wave-base); swaley cross stratified sandstones (possibly representing deposition in the storm dominated upper shoreface); and shoreline deposits. This general sequence was recognized and first published on by Hamblin and Walker (1979) for the Jurassic Fernie - Kootenay transition and was modified later by Walker (1984). The importance of this sequence with respect to the present Cardium discussion is that it associates hummocky cross stratification (interpreted by Walker (1983c) to have developed in sands which were deposited by turbidity currents and later reworked by the action of storm waves) with turbidites. Hummocky cross stratification is ubiquitous in outcrop exposures of Cardium sandstones (W. L. Duke personal communication, 1984) and occurs in Cardium sandstones in the subsurface (Walker, 1983c and this thesis, chapter 3) as well as in other Cretaceous Interior Seaway sandbodies (e.g. Boyles and Scott, 1982, p. 500). Another basis (4) for Walker's turbidity current interpretation is his determination that the sandy Cardium facies (particularly the Raven River Member) throughout the Caroline and Garrington areas occur as a sheet with holes or are "raggedly continuous" (Walker, 1983b, see discussion in chapter 2, p.23). He suggests (Walker, 1984c and in press) that these sediments have been scoured into and removed at

ld, where a later sandstone (the Ricinus

Member) has been deposited; this field is suggested to represent a turbidity current-cut and filled channel.

Walker (1984a, p. 153) has suggested substrate liquification by cyclic storm wave loading as a possible mechanism by which turbidity currents could be initiated within the Cretaceous Interior Seaway. He suggests that storm activity causing coastal set-up and wave loading of the shoreface could result in sediment liquifaction. The liquified sediment could flow and accelerate basinward forming a turbidity current. Walker (1984a, p. 153) has also suggested several deposits which might result from such a flow. As discussed above, sediment transported and deposited below storm wave base would be deposited as turbidites with Bouma (1962) sequences. Above storm wave base, storm waves could rework these deposits into hummocky cross stratified sandstones. Turbidity current deposits above fair-weather wave base would be within reach of fair-weather processes and be reworked.

7.2.3 Sediment Transport To Willesden Green

Within the study area, as has been discussed earlier, detailed investigations (chapter 4) have revealed that positive topography is developed on-field and negative topography occurs off-field. Sandstone facies have been shown (chapter 5.2) to be preferentially accumulated within the Willesden Green field and not to continue in a "sheet-like" manner unlike what Walker (1983b, p.19) described in Cardium fields to the south of the study area. From an examination of the gross field geometry (unsheet-like, unchannelized) and facies distribution (preferential accumulation, preserved as highs) sediment transport by turbidity currents seems unlikely.

Some sedimentary structures and features preserved in sandstone beds (i.e. sharp bases and mud clasts) suggest sudden and erosive emplacement. Emplacement by one of several processes - including geostrophic currents and turbidity currents, could be responsible for the development of sharp based beds and ripped-up mud clasts (chapter 3). The most frequently preserved sedimentary structures in the sandstones are wave-ripple cross-lamination and hummocky cross stratification (chapter 3). Their ubiquitous presence suggests deposition in a wave dominated environment (i.e. storm dominated), but does not suggest specific processes of emplacement. The absence of Bouma A divisions or B-C sequences, such as those described at Ricinus by Walker (1983b and in press), does not support sediment emplacement by turbidity currents at Willesden Green. Storm-generated geostrophic flow could account for the transportation of these sediments.

Detailed studies of the stratigraphy of the Raven River Units within Willesden Green area have revealed a shingling or offlapping relationship towards the northeast (chapter 6). Sediment transport by geostrophic flow to Willesden

nfluence of a number of other important

factors (discussed later in this chapter) may have been responsible for the geometrical configuration of the Cardium sandstones at Willesden Green.

Cardium conglomerates within Willesden Green have been shown to accumulate most frequently on the east and northeastern margins of positive sandstone "highs" within depositional sandstone lows (developed as the Raven River Units shingle towards the northeast). In some areas the conglomerate appears to have scoured into sandstones (chapter 6.3). The absence of sedimentary structures or fabric (other than chaotic) in the conglomerates contributes to the problematic nature of these deposits. No evidence of any turbidity current "feeder channel network" was found northwest of Willesden Green - up the suspected dispersal direction (chapter 5).

As will be discussed later in this chapter, sea-level changes - particularly drops in sea-level, probably played an important role in sediment transport and in the development of many Cretaceous Interior Seaway sandbodies (e.g. Kauffman, 1977, and many others) including the Willesden Green field. Conglomerate transport to Willesden Green may have occurred at a time of maximum regression in the Upper Turonian (Kauffman's (1977) R6 or Greenhorn regression). During such a time the study area would have been situated relatively close to the paleoshoreline (tens of km maximum). Over these relatively short distances conglomerates could have been intermittently transported, possibly as bedload during storm-generated geostrophic flow.

Based on the findings of this thesis, some briefly outlined above, sand and conglomerate transport and emplacement by turbidity currents in the study area appears unlikely. The necessity for turbidity current transport for Cardium sediments in other regions may be questioned, e.g. Wright and Walkers' (1981, p. 806) discussion of the necessity for off-shore transport of the Cardium conglomerates at Carrot Creek in suspension (by turbidity currents) rather than as bedload. Their conclusions do not account for the possibility of incremental off-shore movement of sediment by multiple storms (R.G. Walker, personal communication, 1984) or for the possibility of sea-level changes during Cardium deposition. They argued (p. 806) that conglomerate transport as bedload would require an "unreasonably long period of time for one powerful storm to persist", not allowing at the time for the possibility of many successive flows.

An intermittent northwest to southeast current capable of transporting the Cardium sediments by intermittent suspension and bedload in conjunction with significant wave (i.e. storm) activity appears as a likely means of sediment transport. Storm-wind generated geostrophic flow, as described by Swift and Rice (1984) and Swift (1984) appears as a likely process which could be responsible for the off-shore transport of the Cardium sand and conglomerates

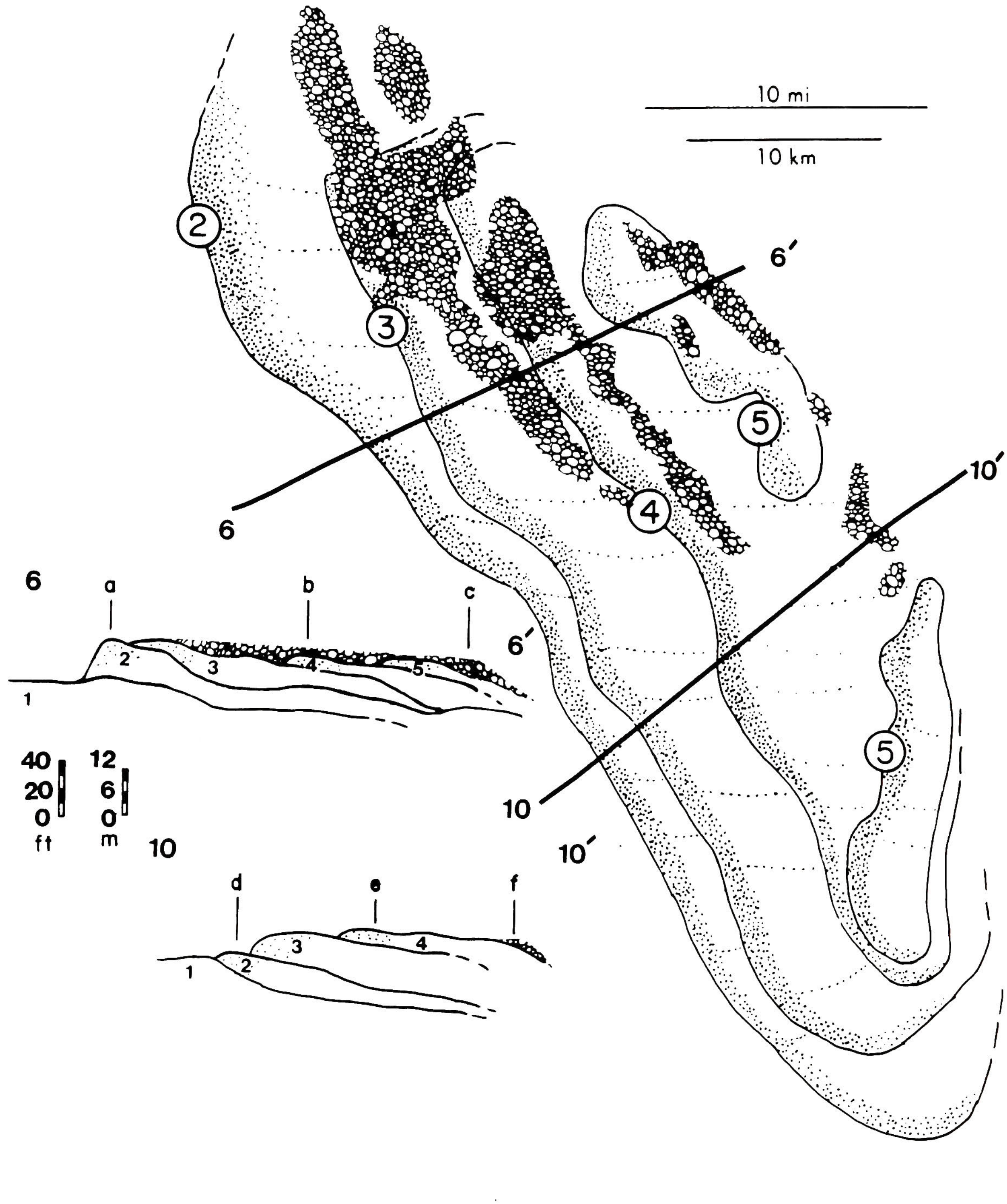
area.

7.3 GEOMETRY AND DEVELOPMENT OF THE WILLESDEN GREEN CARDIUM FIELD

7.3.1 Geometry of the Willesden Green Field - important considerations.

As has been shown (chapter 6), Raven River Units in the Willesden Green area occur as sandy bodies shingled toward the northeast. Cardium conglomerates appear to have thickest accumulations on the northeastern (down-dipping) flanks of the Units in depositional lows. Figure 7.2 shows a representation of the Raven River or Cardium A sediments in the Willesden Green area (data from Fig. 6.6). The shingled nature of the Units is emphasized by cross sections 6 (from Fig. 6.2) and 10 (from Fig. 6.4). Unit 1, the lowest coarsening-upward sequence within the Raven River appears to be continuous from Ferrier into Willesden Green. Within Willesden Green Unit 1 drops stratigraphically and terminates. The topography emphasized by the stratigraphic lowering of Raven River Unit 1 may have had a dominant factor in controlling the accumulation of the Raven River Units and later deposited conglomerates. Similar interpretations have been offered by Swift and Rice (1984), discussed in chapter 1, and others, who have suggested that shelf topographic irregularities may influence the preferential accumulation of sediments. Unfortunately, it was not possible to investigate the nature of any previous topography implied by the shingling of Unit 1 since a

Fig. 7.2. Representation of the Cardium sandstone and conglomerate deposition in the Willesden Green area. Sediment dispersal is from the northwest. Circled numbers 2 through five show the leading edges of Raven River Units 2 through 5 (this information is from Fig. 6.6). Sections 6 and 10 are included in the lower left-hand corner to emphasize the shingled nature of the Units; data for section 6 is from Fig. 6.2 and section 10 is from section 6.4, the vertical scale is shown. The Raven River Units are labeled in each cross section. Positions of three reference wells are included in each section - section 6, a (4-10-42-8W5), b (8-21-42-7W5), c (5-9-43-6W5); section 10, d (6-13-40-7W5), e (14-1-41-6W5), f (16-36-41-6W5).


10 mi
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5
6′
40
20
0
ft
12
6
0
m
10
10′
d
e
f
1
2
3
4

suitable log marker directly below Unit 1 was not found.

7.3.3 Pre-existing Topography

It is suggested the topography shown by Unit 1 pre-dated and initiated the deposition of the Cardium sands and conglomerates at Willesden Green. A pre-existing topography has been suggested for other Cardium fields such as Carrot Creek (Swagor, 1976) and Ferrier (Griffith, 1981). Both describe pre-existing topography as a "break-in-slope" or "terrace edge" - concepts introduced with respect to shelf sandstone bodies by Campbell (1971 and 1973) in a study of the Upper Cretaceous Gallup Sandstone of northwestern New Mexico. Geometry of the Gallup Sandstones are discussed below (section 7.3.3). He described the "terrace edge" (p. 407, 1971) as a "seaward steepening or break in slope of the seafloor (a terrace edge)"... and that "the changed slope is probably less than 1 degree steeper than the nearly horizontal landward extending sea bottom." This is apparently referring to a depositionally developed topography. Such a topography would have formed as a result of thickness variations arising from different rates of sedimentation. This was demonstrated by Asquith (1970 and 1974) in offlapping Cretaceous rocks of Wyoming. Asquith's studies along with other examples of Cretaceous shingled units deposited due to marine depositional topography are discussed below.

tive to a depositionally developed topography is structural topographic development. Weimer (1983) discussed how recurrent movement of basement fault blocks influenced Cretaceous siliciclastic depositional patterns. However, no evidence of such control has been shown to occur in the Cardium sediments in the study area. By contrast, basin flexure might be important. Beaumont (1980) suggested that basinal flexures developed as a result of foreland thrusting - such flexures could account for pre-Cardium topography in the study area.

Assuming a pre-Cardium topography did exist, it is difficult to ascertain its origin as either depositional or structural. As Weimer (1983, p.364) notes, "thick and thin sediment accumulations associated with depositional topography can be confused with thickness patterns related to structural topography, and a careful analysis of depositional environment, processes and subtle breaks is needed to determine what controlled thickness variation." Regional investigations of offlapping in the Raven River Sequence (and Member) along with detailed investigations of pre-Cardium surfaces are required to fully understand the nature and significance of any pre-Cardium topography.

7.3.3 Offlapping Geometry - other examples in the Cretaceous Seaway

Asquith (1970 and 1974) demonstrated an offlapping depositional pattern in the Cretaceous Pierre Shale of Wyoming using closely spaced electric logs and bentonite markers. He showed a number of eastward prograding shale through sandstone pulses. Electric logs through individual pulses show a coarsening-upward sequence. Maximum slopes on inclined surfaces of these pulses range up to half a degree, which is similar to the dips of inclined surfaces of the Units at Willesden Green. However, all of the progradational bodies Asquith (1970 and 1974) shows are several hundreds of feet thick and represent eastward progradation of the shelf edge into the Cretaceous seaway. These progradational bodies are much thicker that the Raven River Units in the study area.

Weimer (1983) suggests a model for sea-level highstand deposition in the Cretaceous seaway which is based in part on Asquith's (1970) findings. In his model, offlapping depositional surfaces develop in the lower shoreface (or deltafront-prodelta) and at the shelf-slope interface (Weimer, 1983, p.386). He suggests later sea-level drops may erode and transport seaward the thickly accumulated sediments.

Brenner (1978) in a study of the Cretaceous Sussex Sandstone of Wyoming suggested the shelf edge prograded eastward as a series of sediment sheets or lenses (Brenner, 1978, figure 19, p.199) upon which northwest to southeast regional currents created the Sussex sandbodies.

The examples discussed above of offlapping sedimentation in the Cretaceous seaway all occur on a much and horizontal scale than Units developed at

Willesden Green.

Campbell's (1971 and 1973) study of offshore bars of the Gallup Sandstone in New Mexico showed the bars to be composed of offlapping, seaward imbricated, parallel bedded sandstones.

Evans (1970) documented an excellent example of depositional offlapping in the Lower Cretaceous Viking Formation in the Dodsland-Hoosier area of southwestern Saskatchewan. He used bentonites and other resistivity log markers to delineate five southward offlapping "members". Individual "members" coarsen-upward from mudstone to sandstones. Locally accumulated basal chert pebble conglomerates occur, in contrast to the chert pebble conglomerate which caps the Raven River sequence in the study area. Evans (1970, p.488) suggests southward migrating tidal deposits during a sea-level still-stand to account for the configuration of these bodies. No evidence of tidal influence on Cardium deposition was found in the study area. Scale of the Viking "members" is similar to the Raven River Units in Willesden Green, but differences in facies and facies sequence are evident.

Except for their scale, the offlapping deposits described by Campbell (1970 and 1973) and Evans (1970) do not resemble the offlapping Units in the study area.

7.4 DEVELOPMENT OF THE WILLESDEN GREEN CARDIUM FIELD

The Cardium sediments at Willesden Green were deposited in a marine environment as shingled sandy Units probably below fair-weather wave-base, but above storm wave-base (chapter 3). As discussed above, Unit 1 appears to be continuous as the lowest coarsening-upward sequence within the Raven River Sequence from Ferrier to Willesden Green where it drops stratigraphically and terminates. It is proposed that a the deposition of the Raven River Units at Willesden Green occurred as a result of pre-existing shelf topography (depositionally or structurally developed) in a manner somewhat similar to that described by Swift and Rice (1984, discussed in chapter 1) and Swift (1984). The pre-existing shelf topography is of undetermined nature and origin.

The development of individual Raven River Units was likely controlled by sediment (i.e. siliciclastic sand) supply. Interuptions in siliciclastic sand supply could be caused by delta switching at the Cardium Raven River source area and/or minor fluxuations in sea-level. Interuption of sand supply would result in the deposition of muddy facies throughout the study area, blanketing the previously deposited sandy Units. Renewed sand supply to the study area would result in offlapping deposition of a progressively sandier sequence - a coarsening-upward sequence into the next Raven River Unit. This cycle would have been repeated until all Units were deposited.

The geometry of the Raven River Units at Willesden Green resembles a prograding siliciclastic shoreline sequence (e.g. Clifton, 1981; Heward, 1981), but no evidence for shoreline attachment or of a proximal shoreline (such as rooted beds or in-situ coals) was found in the study area. If any such non-marine deposits were deposited in the study area their absence might be attributed to erosion during later transgression.

Emplacement of the Cardium conglomerates may have occurred during maximum regression, perhaps during a rapid sea-level drop, as suggested for Cardium conglomerates at the Kakwa field by A. G. Plint (personal communication, 1985), prior to the Niobrara transgression (Kauffman, 1977 and Hancock and Kauffman, 1979) at the end of the Turonian. Conglomerate source areas would presumably have been relatively close to Willesden Green, possibly a few tens of kilometres away. During subsequent transgression which ended coarse sediment deposition, some reworking of the conglomerates would be expected, but it is suggested that conglomerate depositional patterns (chapters 4 and 5) at Willesden Green were established prior to transgression.

Regional study of the Raven River Sequence and Member (Cardium A), particularly investigations to determine the regional extent and trends of the southwest to northeast offlapping sandstones will help in further understanding of the Cardium Formation and of other Cretaceous Interior

Seaway siliciclastic shelf sandbodies.

CHAPTER 8: CONCLUSIONS

This thesis examined in detail Cardium facies, facies distribution and geometry in the Willesden Green field and surrounding areas using core and well logs. The conclusions are as follows:

1. The Raven River Sequence is continuous from the Caroline, Garrington, Ferrier, Willesden Green, and Pembina fields. The Raven River Member is lithostratigraphically corellative throughout these fields and northward into Pembina. Five individual sandy coarsening-upward Units comprise the Raven River Sequence (and Member) within the study area.

2. Isopaching the interval between the top of the Raven River Sequence (and Member) within the study area and upper and lower log markers shows regions within the Ferrier and Willesden Green fields to have a positive relative topography ("highs") and areas off the margins of these Cardium fields to have a negative relative topography ("lows"). The topography trends in a northwest to southeast orientation. Between Willesden Green and the region in-between Willesden Green and Ferrier a maximum of greater than 30 m of relief occurs. The slope of this surface of relief is about 1.12 degrees.

3. Cardium sandstones and conglomerates occur preferentially deposited within Cardium Fields in the study area, and do not continue in a sheet-like manner between fields. Areas of maximum sandstone and conglomerate accumulation correspond with regions of maximum relative positive topography.

4. Cardium sandstones in the study area occur as southwest to northeast offlapping sandbodies, referred to as Raven River Units. Unit 1, the lowest Raven River Unit appears to be continuous between Willesden Green and Ferrier. It drops stratigraphically towards the northeast and terminates below Willesden Green. Units 2, 3, 4 and 5 are developed in a northeastwards offlapping or shingling manner northeast of Unit 1. The leading edges of Units 2 through 5 parallel each other in a northwest to southeast orientation.

5. Detailed mapping of the Cardium conglomerate distribution in Willesden Green shows it to unconformably overlie the Raven River Units and show maximum accumulation on the eastern and northeastern margins of sandstone "highs" within sandstone depositional lows. Local scouring of the sandstone by conglomerates occurred.

6. Sedimentary structures and ichnofossils preserved within Cardium sandstones at Willesden Green suggest deposition occured below fair-weather wave-base but above storm wave-base.

7. The common occurence of wave ripples and hummocky cross stratification in Cardium sandstones at Willesden Green suggests storm (wave) dominated processes to have been responsible for the emplacement and subsequent modification of the Cardium sandstones and conglomerates at Willesden Green.

8. The occurence of southeastern thinning sandstones and conglomerates and a southeastern decline in maximum conglomerate chert pebble size, along with information from adjacent Cardium fields, suggests the dispersal direction of the Cardium sediment in the study area was from the north-west to southeast.

9. Storm-generated geostrophic flow may have been responsible for the offshore transport of the Cardium sands and conglomerates to Willesden Green.

10. Pre-Cardium shelf topographic irregularities (depositional or structural) may have influenced Cardium sandstone deposition and be responsible, in part, for the preferential accumulation of sandstones and conglomerates at Willesden Green.

11. Interruptions of sediment supply and/or minor sea-level fluxuations may account for the southwest to northeast offlapping of Cardium sandstones in the study area.

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APPENDIX 1: WELL LOCATIONS OF EXAMINED CARDIUM CORE

The locations of all of the Cardium Formation core examined in this study are listed on the following page. All locations are included in Figure 1.2 on page 12. Diagrammatic core descriptions of the cores whose locations are underlined are provided in appendix 2.

TWN. 38

10-28-38-3W5
06-10-38-5W5
10-20-38-5W5
06-28-38-5W5
10-36-38-5W5
06-10-38-6W5
09-18-38-6W5
07-24-38-6W5
02-31-38-6W5

TWN. 39

10-07-39-5W5
16-02-39-5W5
16-08-39-5W5
12-12-39-5W5
06-22-39-5W5
14-27-39-5W5
06-28-39-5W5
14-30-39-5W5
16-32-39-5W5
04-35-39-5W5
06-05-39-6W5
04-06-39-6W5
10-08-39-6W5
10-13-39-6W5
12-26-39-6W5
06-36-39-6W5
16-36-39-6W5

TWN. 40

16-02-40-5W5
06-20-40-5W5
16-21-40-5W5
16-28-40-5W5
06-30-40-5W5
16-33-40-5W5
15-13-40-6W5
08-23-40-6W5
14-24-40-6W5
12-27-40-6W5
08-35-40-6W5

TWN. 41

[illegible]
04-14-41-5W5
10-15-41-5W5
10-17-41-5W5
04-22-41-5W5
06-30-41-5W5
10-33-41-5W5
14-01-41-6W5
06-14-41-6W5
16-26-41-6W5
14-27-41-6W5
08-32-41-6W5
16-12-41-7W5
06-21-41-7W5
16-27-41-7W5
16-32-41-7W5
06-35-41-7W5
12-16-41-8W5
02-36-41-8W5

TWN. 42

08-06-42-5W5
06-07-42-5W5
16-18-42-5W5
04-28-42-5W5
08-03-42-6W5
16-06-42-6W5
06-10-42-6W5
16-13-42-6W5
08-14-42-6W5
14-15-42-6W5
06-17-42-6W5
06-18-42-6W5
16-19-42-6W5
14-23-42-6W5
06-25-42-6W5
14-29-42-6W5
06-31-42-6W5
16-34-42-6W5
06-03-42-7W5
16-07-42-7W5
16-10-42-7W5
16-11-42-7W5
16-13-42-7W5
16-15-42-7W5
06-16-42-7W5
06-17-42-7W5
06-22-42-7W5
06-25-42-7W5
08-29-42-7W5
16-35-42-7W5
02-01-42-8W5
10-01-42-8W5
10-02-42-8W5
10-11-42-8W5
04-14-42-8W5
12-16-42-8W5
02-28-42-8W5
13-31-42-8W5
10-32-42-8W5
16-32-42-8W5
02-33-42-8W5

TWN. 43

03-16-43-5W5
07-04-43-6W5
15-05-43-6W5
06-06-43-6W5
06-10-43-6W5
13-11-43-6W5
07-17-43-6W5
15-18-43-6W5
07-01-43-7W5
06-05-43-7W5
04-09-43-7W5
07-13-43-7W5
07-16-43-7W5
10-18-43-7W5
05-24-43-7W5
15-27-43-7W5
04-29-43-7W5
04-30-43-7W5
06-35-43-7W5
12-02-43-8W5
12-03-43-8W5
02-05-43-8W5
05-06-43-8W5
02-07-43-8W5
02-09-43-8W5
11-09-43-8W5
02-10-43-8W5
04-10-43-8W5
12-11-43-8W5
04-15-43-8W5
04-17-43-8W5
10-18-43-8W5
04-20-43-8W5
10-26-43-8W5
04-30-43-8W5
04-31-43-8W5
12-34-43-8W5
04-36-43-8W5
09-12-43-9W5
10-23-43-9W5
02-24-43-9W5
10-33-43-9W5
02-36-43-9W5

TWN. 44

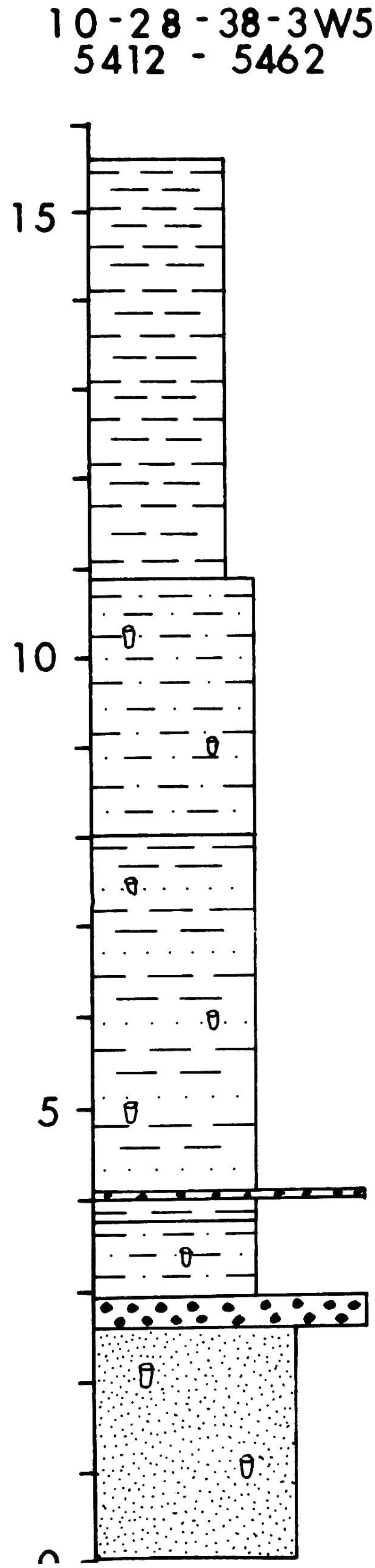
06-01-44-6W5
09-14-44-7W5
07-26-44-7W5
12-01-44-8W5
14-01-44-8W5
04-02-44-8W5
04-04-44-8W5
02-06-44-8W5
04-06-44-8W5
01-07-44-8W5
12-07-44-8W5
10-10-44-8W5
10-11-44-8W5
10-12-44-8W5
04-14-44-8W5
10-15-44-8W5
06-16-44-8W5
02-17-44-8W5
10-18-44-8W5
06-19-44-8W5
10-21-44-8W5
06-22-44-8W5
02-24-44-8W5
10-28-44-8W5
07-32-44-8W5
11-01-44-9W5
02-12-44-9W5
10-14-44-9W5
02-24-44-9W5
10-25-44-9W5
11-26-44-9W5

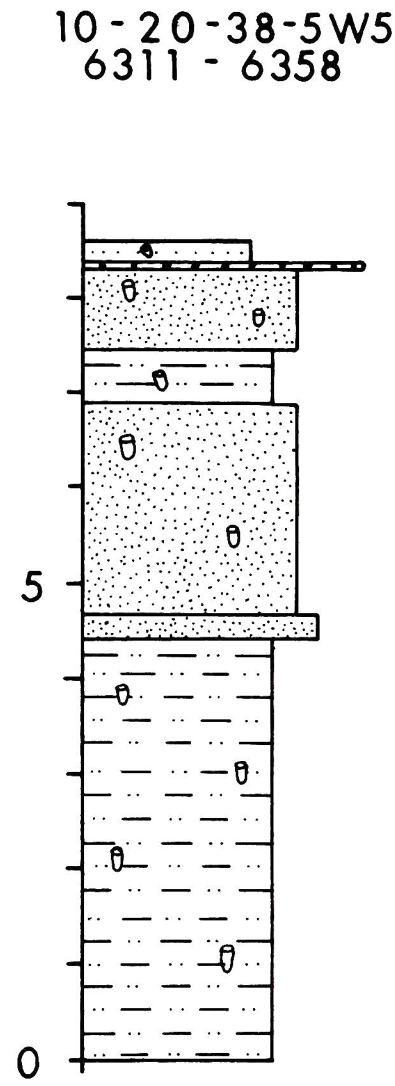
TWN. 45

10-10-45-8W5
06-02-45-9W5
07-08-45-9W5
06-14-45-9W5

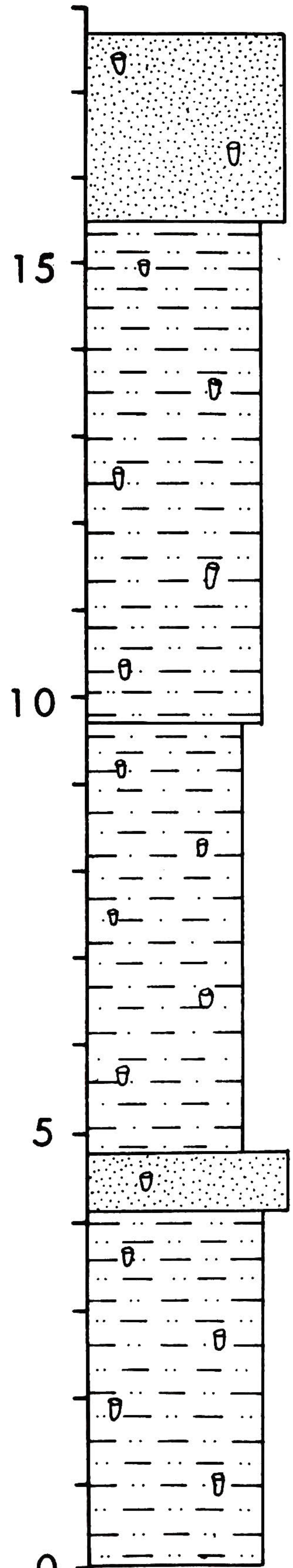
APPENDIX 2: DIAGRAMMATIC CORE DESCRIPTIONS

Diagrammatic core descriptions of 94 of the 178 core examined in this study are included herein. The cores included are shown as solid circles in Figure 1.2 on page 12. Facies symbols are identical to those used in Figure 3.32 on page 74 (the conglomerates are shown by heavy stipple rather than open circles).

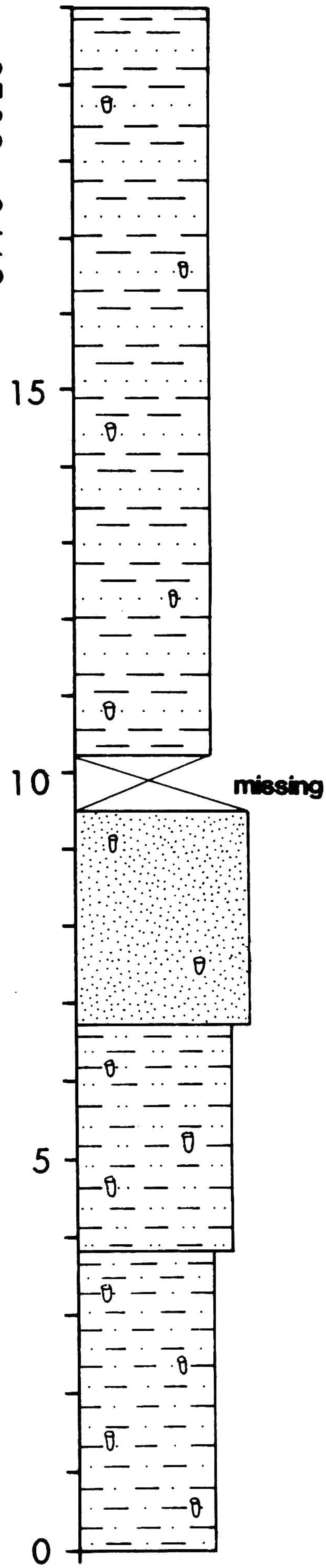

10-28-38-3W5
5412 - 5462
15
10
5
0


10-20-38-5W5
6311 - 6358
5
0

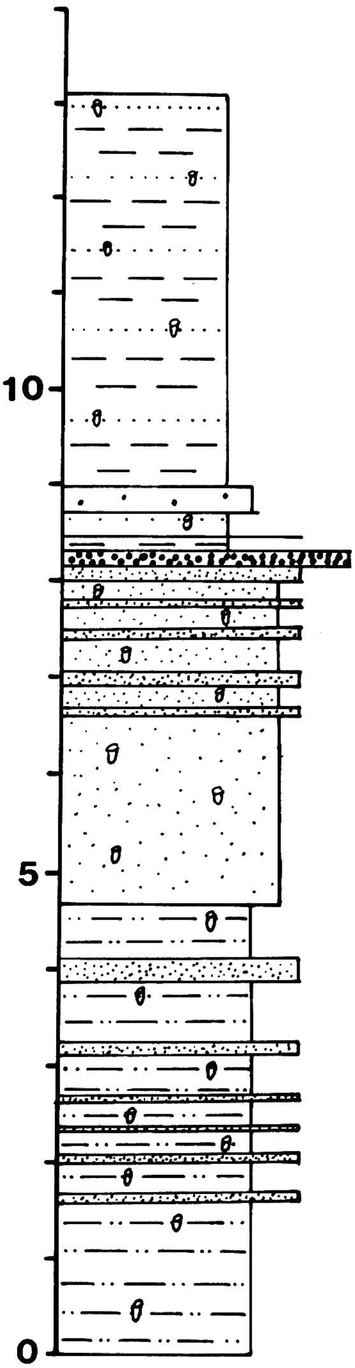
6-10-38-6W5
6714-6774



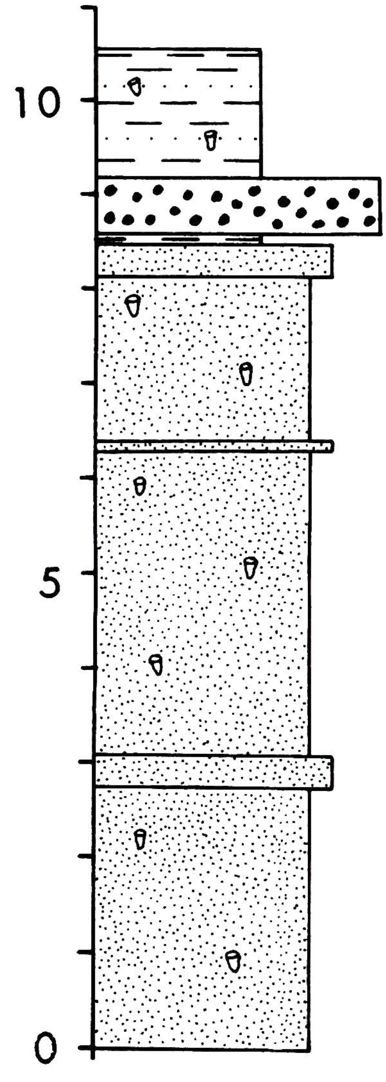
7-24-38-6W5
5970-6026

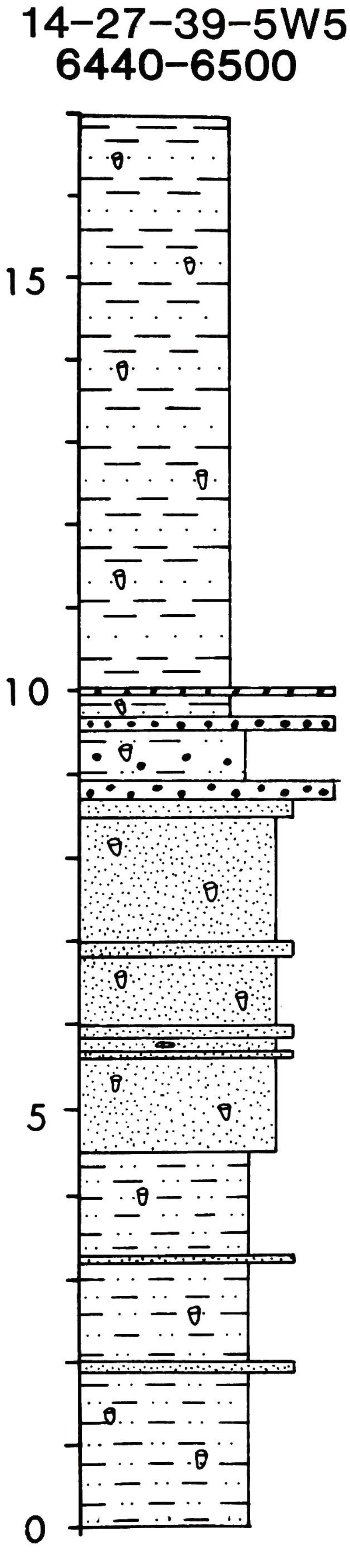


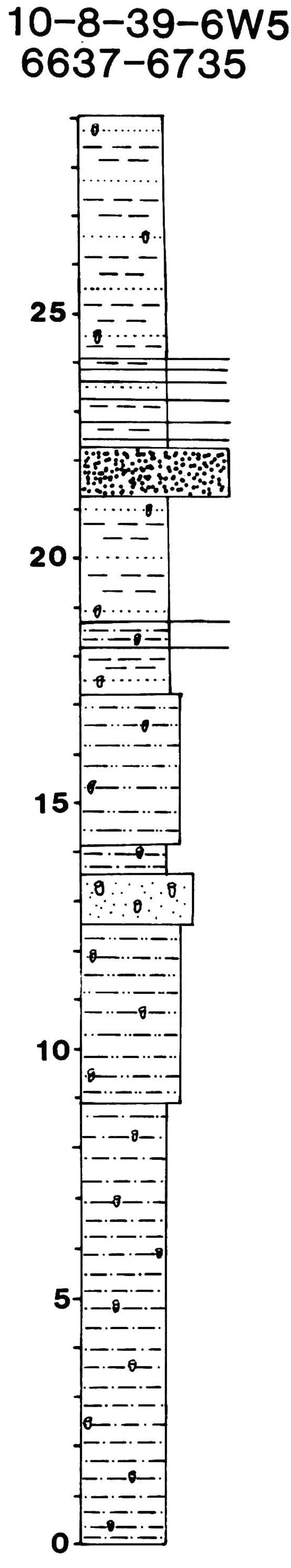
16-2-39-5W5
1849-1863.5m

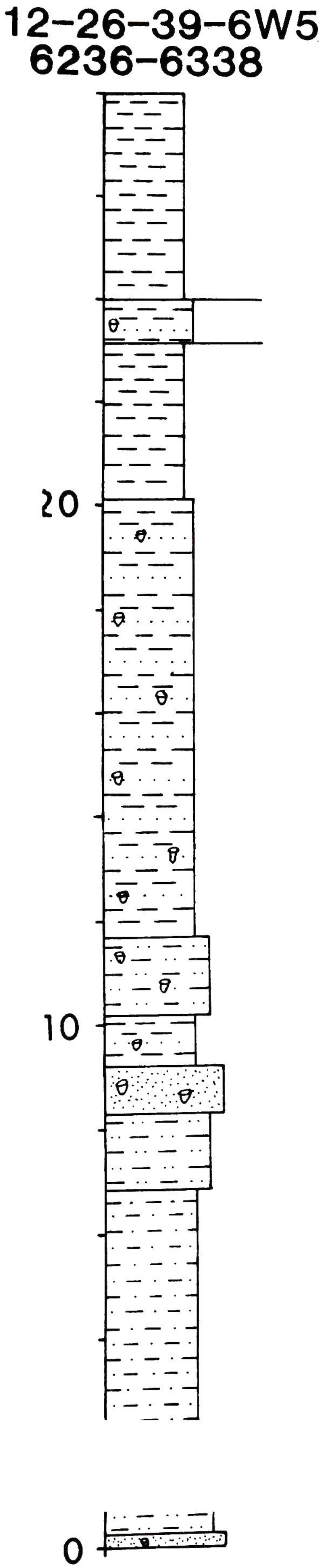


12-11-39-5W5
6089-6123




14-27-39-5W5
6440-6500
15
10
5
0


10-8-39-6W5
6637-6735
25
20
15
10
5
0


12-26-39-6W5
6236-6338
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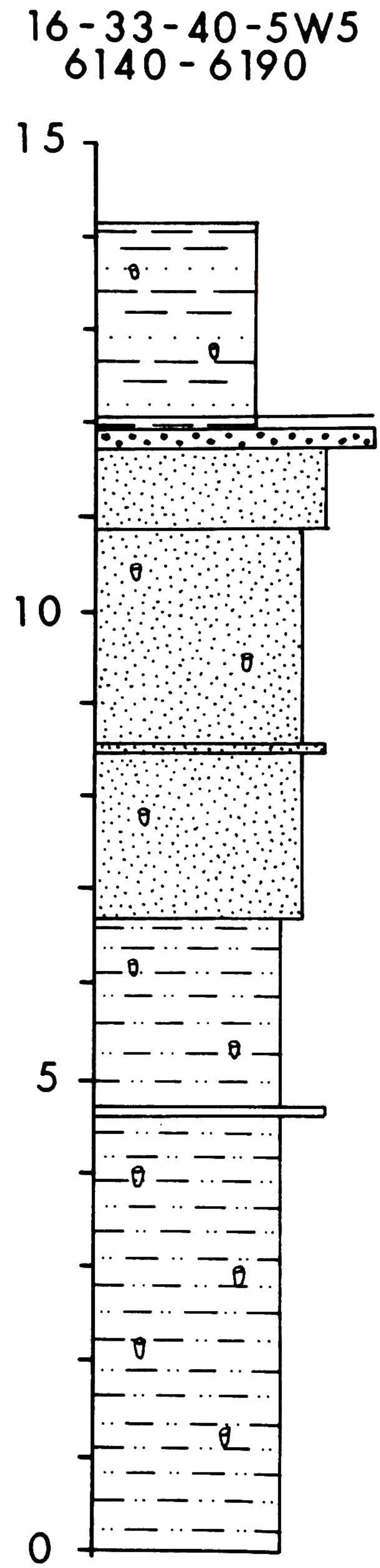
16-33-40-5W5
6140-6190
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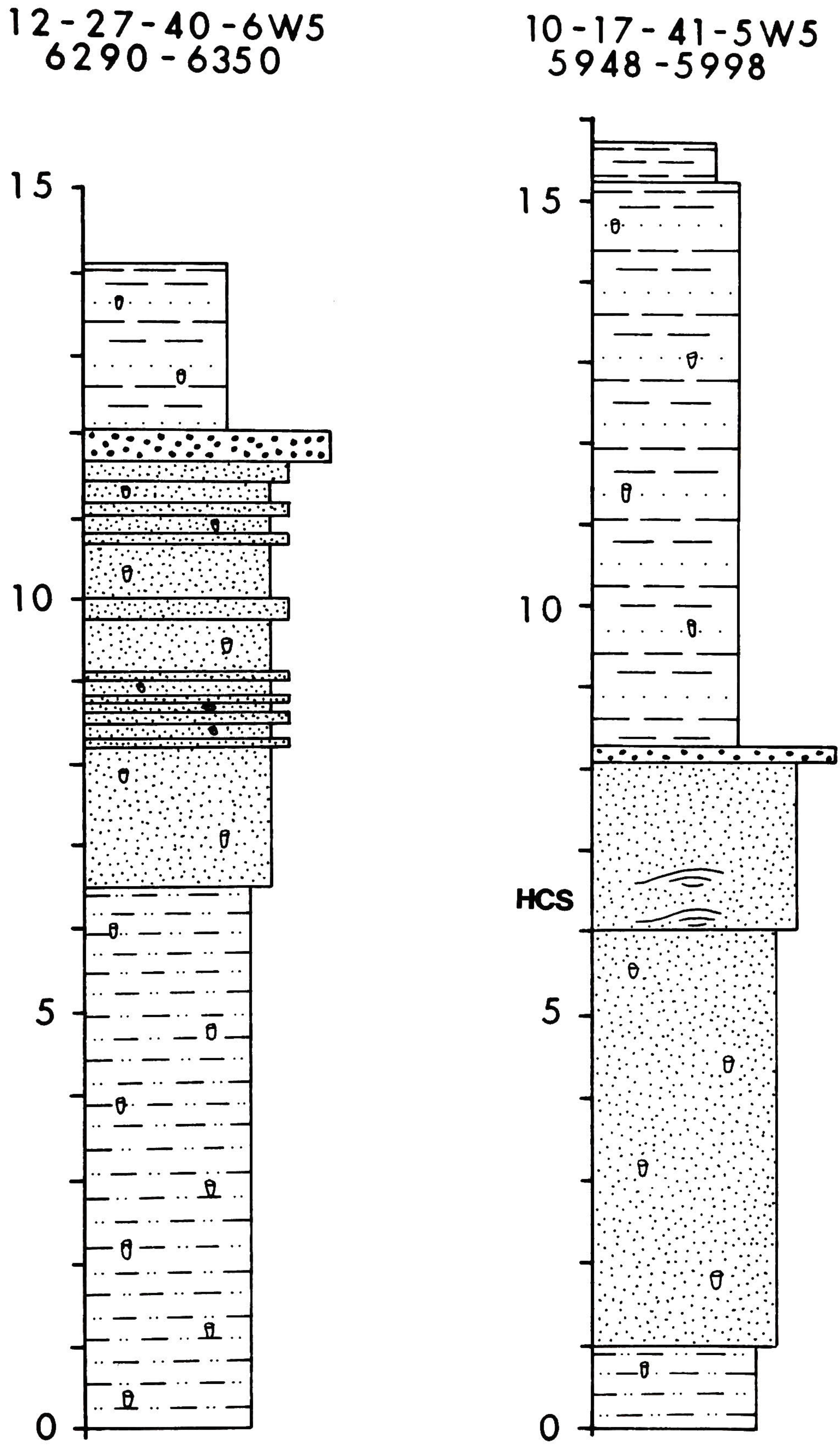
12-27-40-6W5
6290-6350
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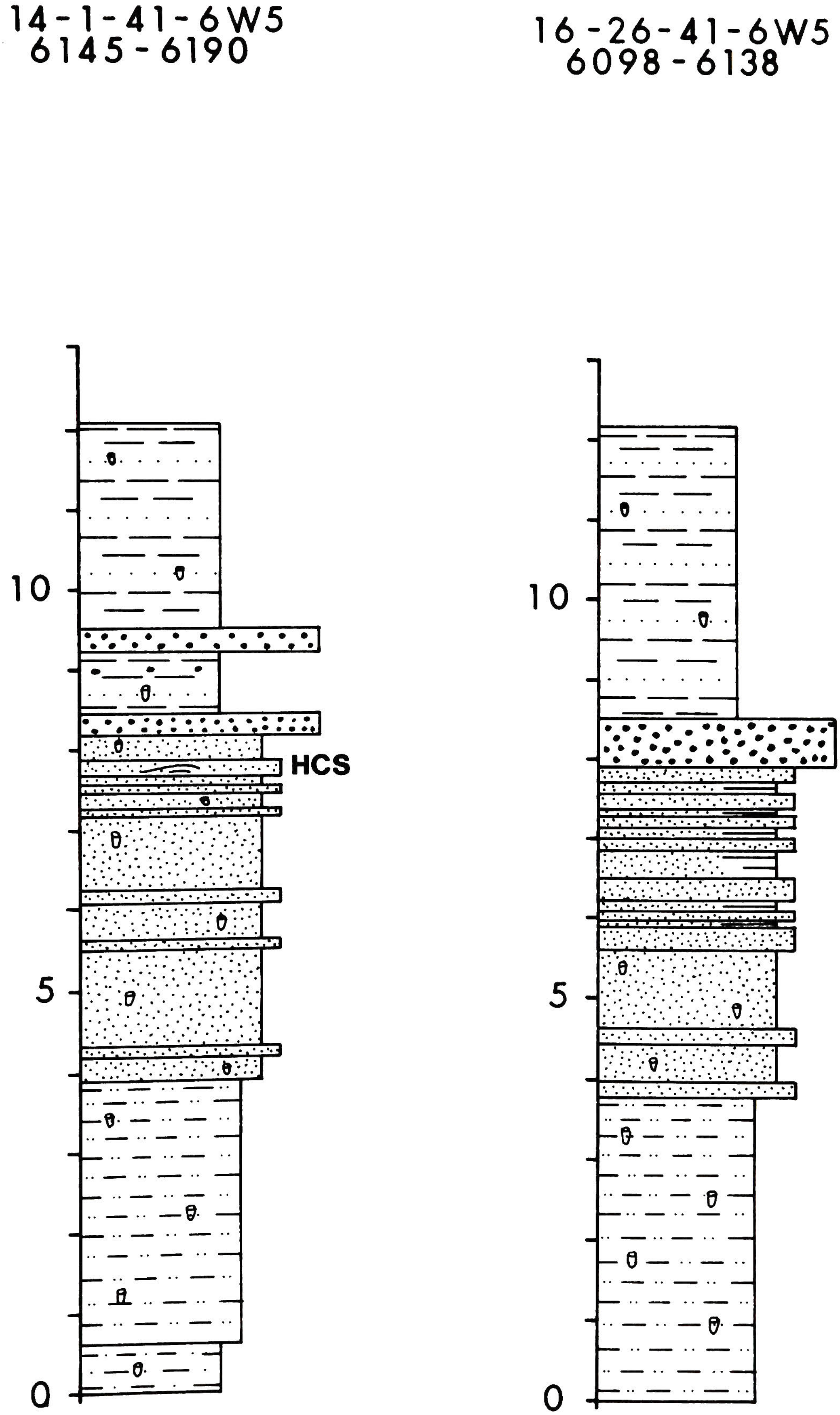
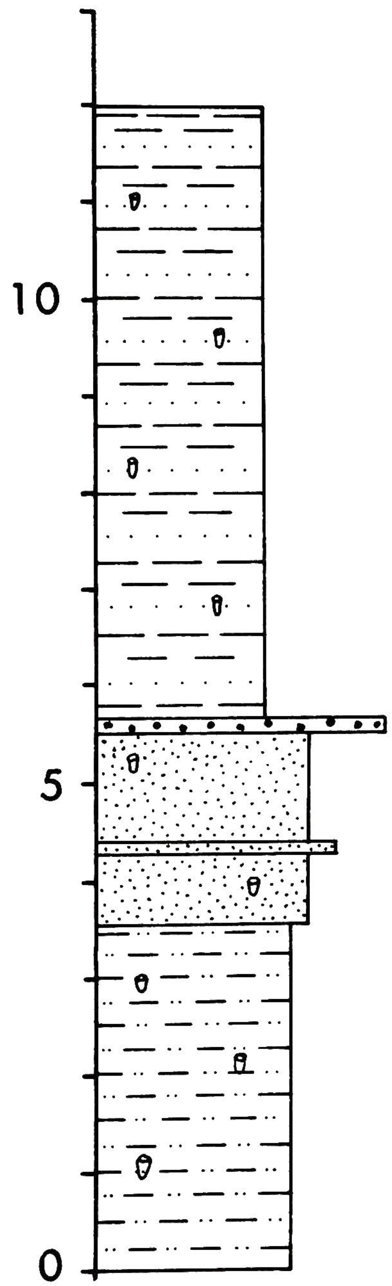
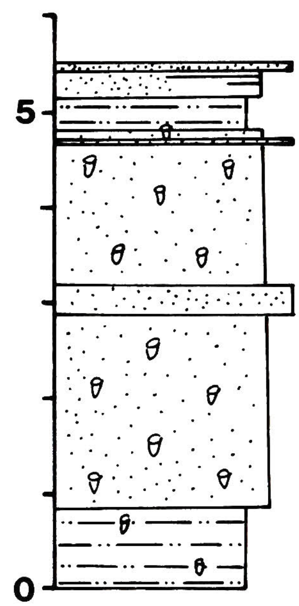
10-17-41-5W5
5948-5998
15
10
HCS
5
0


14-1-41-6W5
6145-6190
16-26-41-6W5
6098-6138
HCS
10
5
0
10
5
0

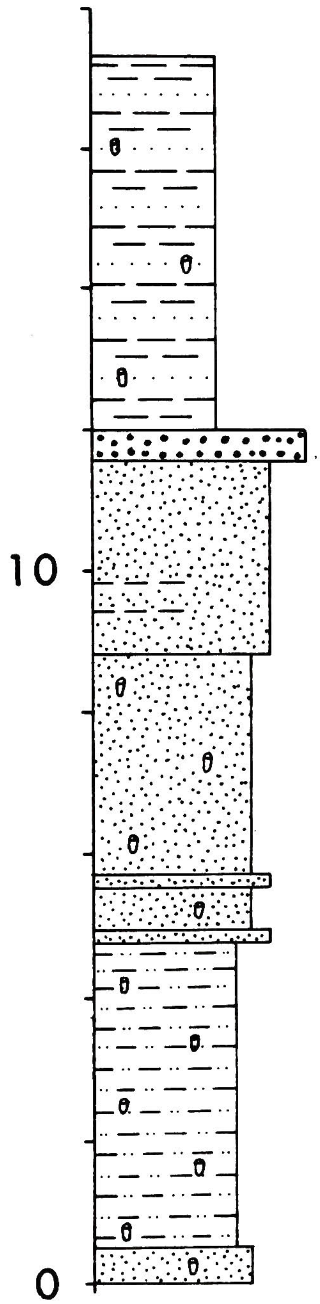
16-12-41-7W5
6637-6687



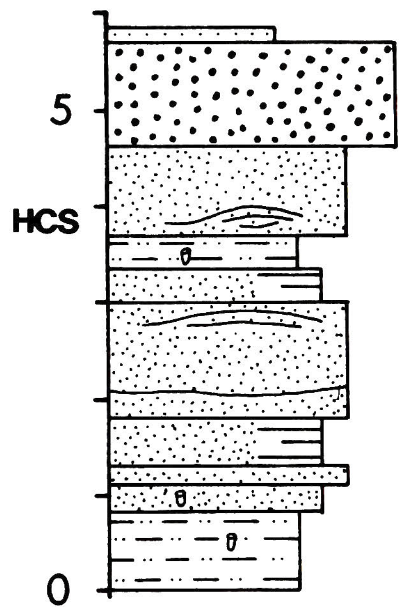
6-21-41-7W5
6506-6556

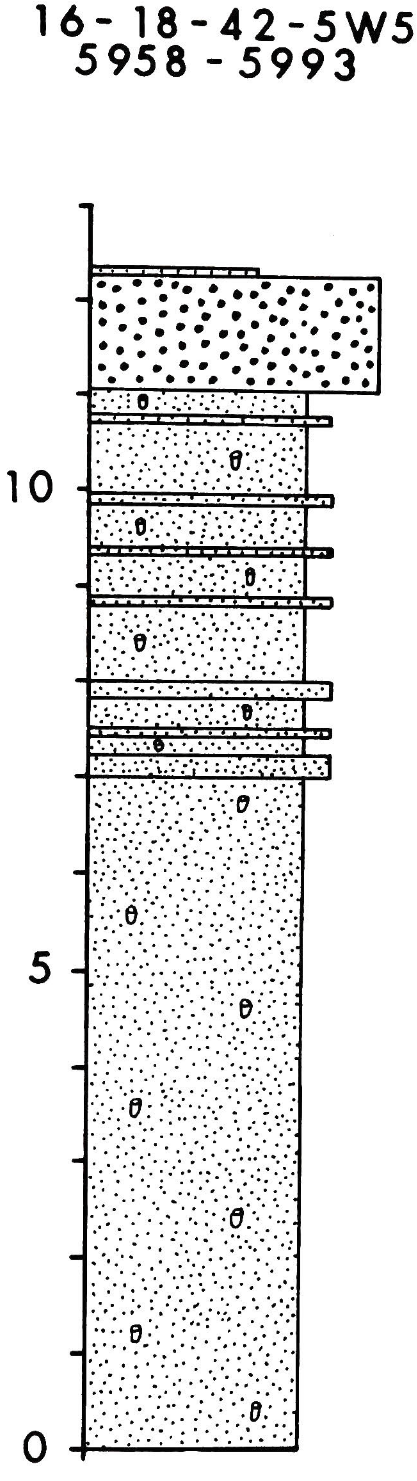


6-35-41-7W5
6540-6500



8-6-42-5W5
5966-6016




16-18-42-5W5
5958-5993
10
5
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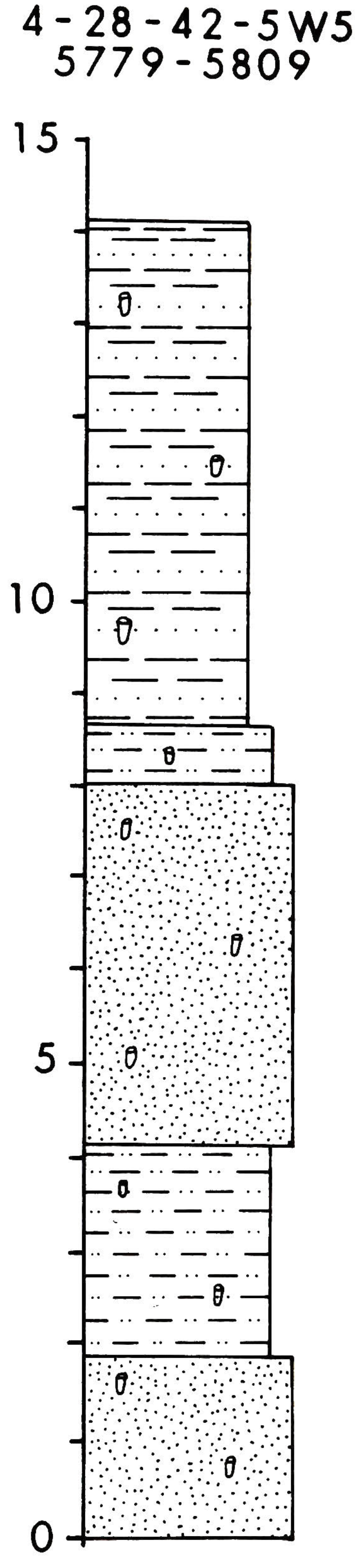
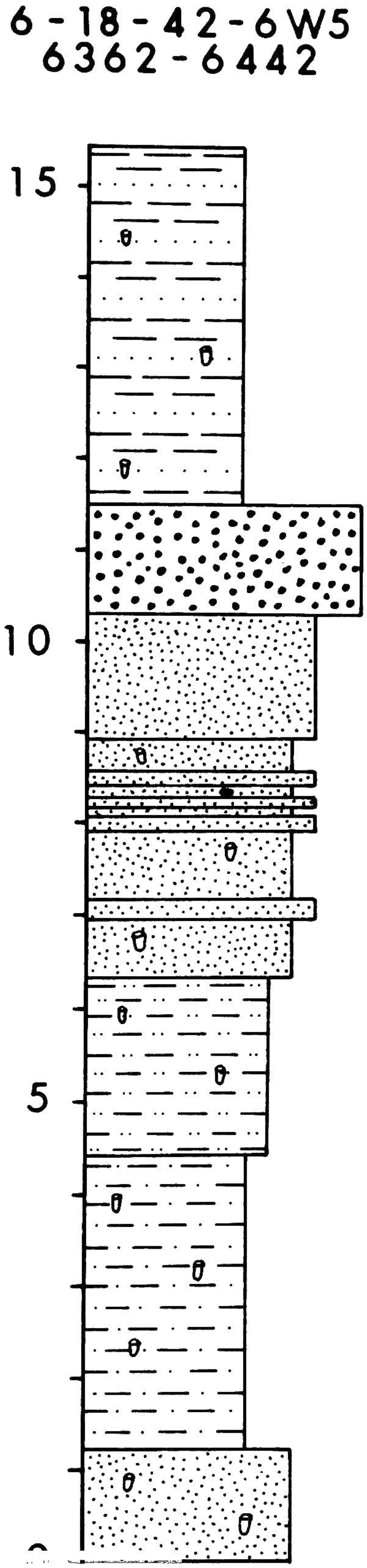
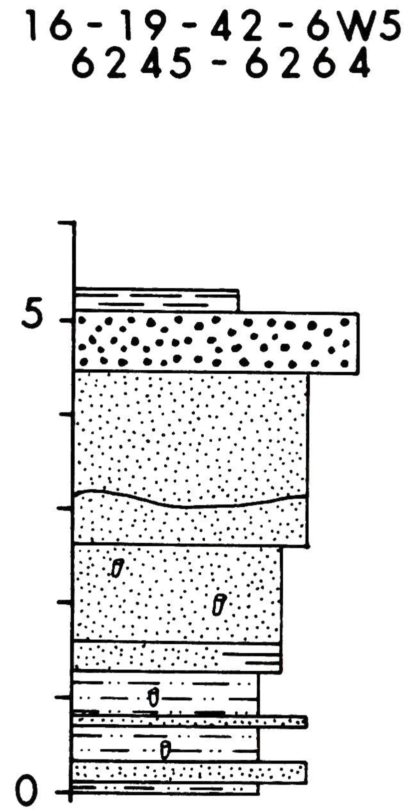

4-28-42-5W5
5779-5809
15
10
5
0


6-18-42-6W5
6362-6442
15
10
5
0


16-19-42-6W5
6245-6264
5
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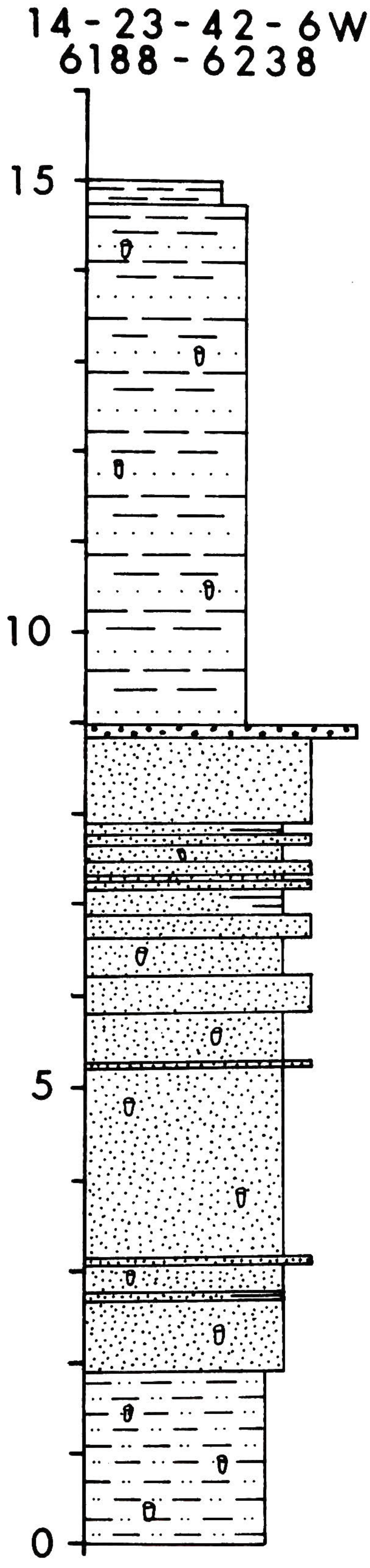
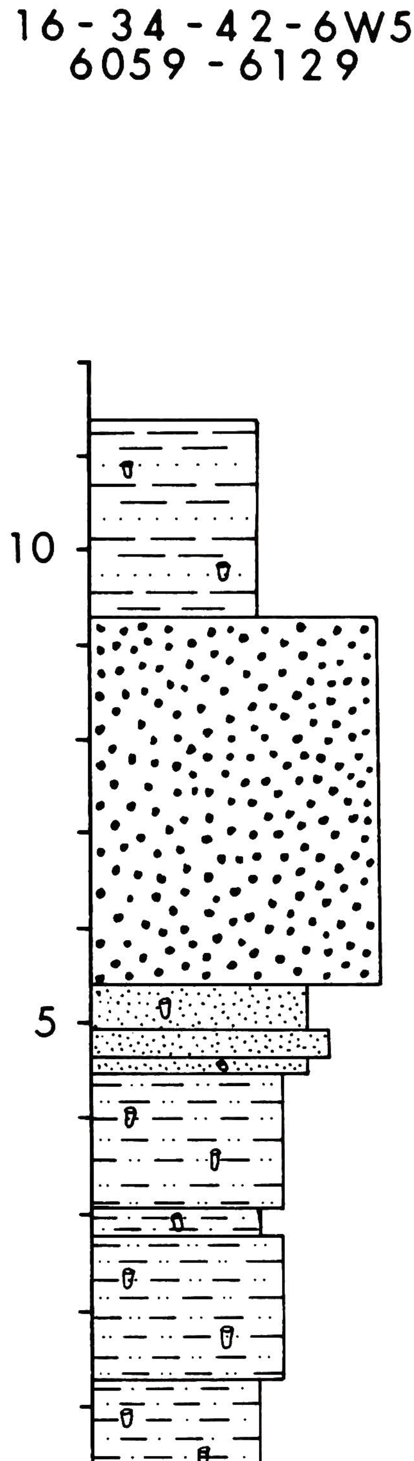
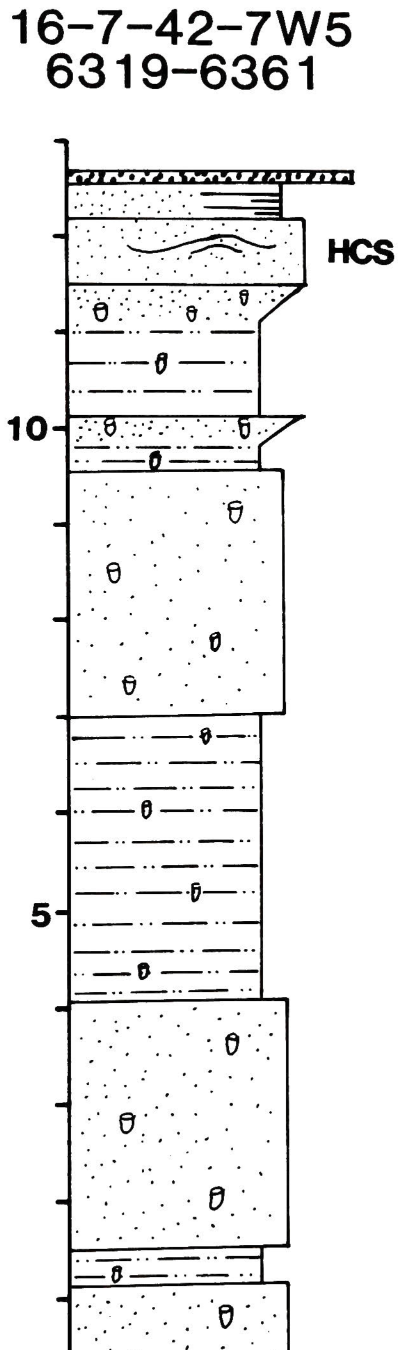
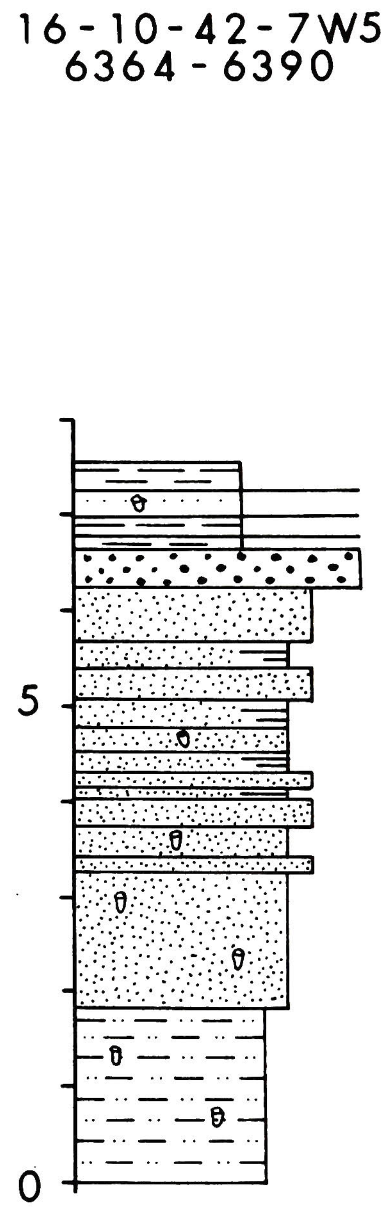

14-23-42-6W5
6188-6238
15
10
5
0


16-34-42-6W5
6059-6129
10
5
0


16-7-42-7W5
6319-6361
HCS
10
5
0


16-10-42-7W5
6364-6390
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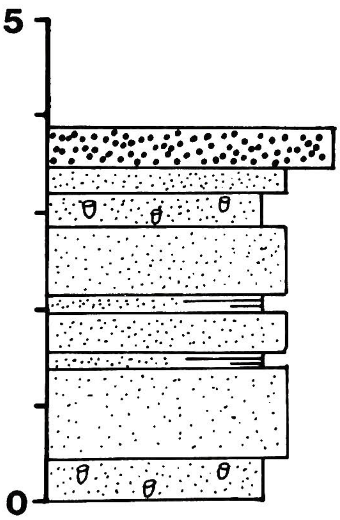
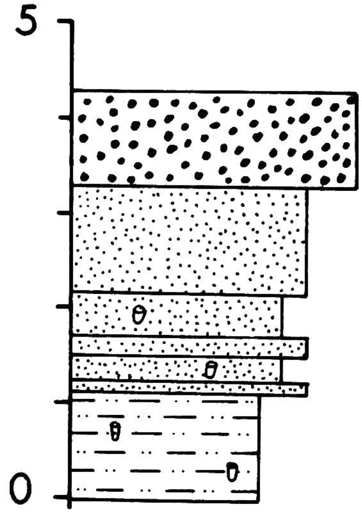
0

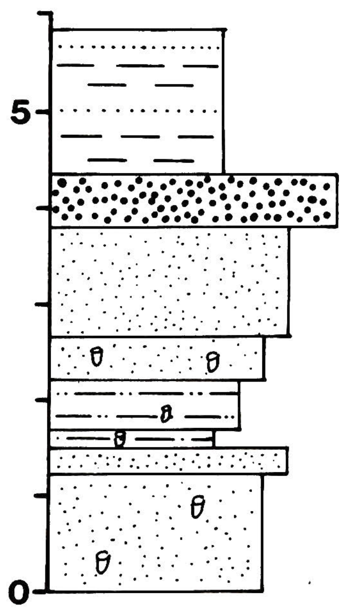
16-11-41-7W5
6458-6472



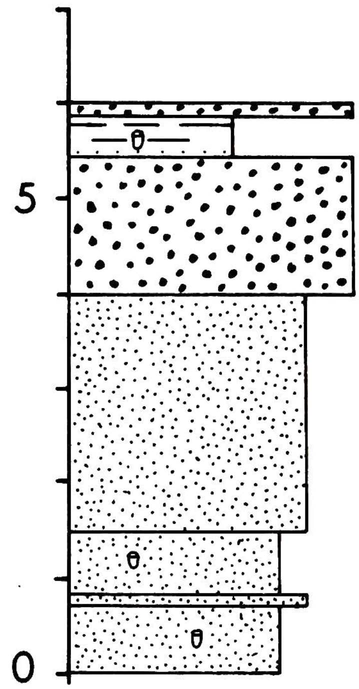
16-13-42-7W5
6415 - 6440

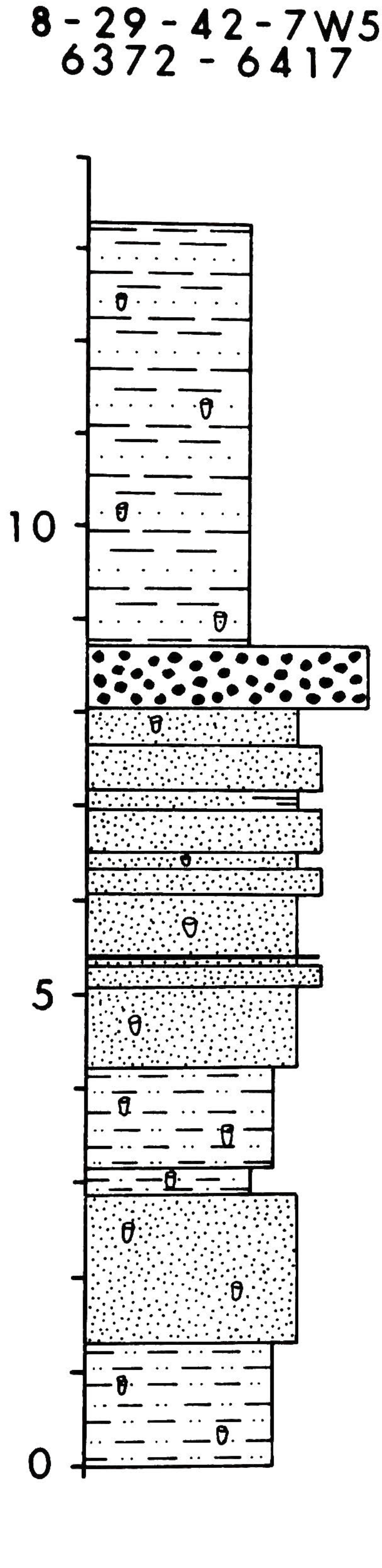


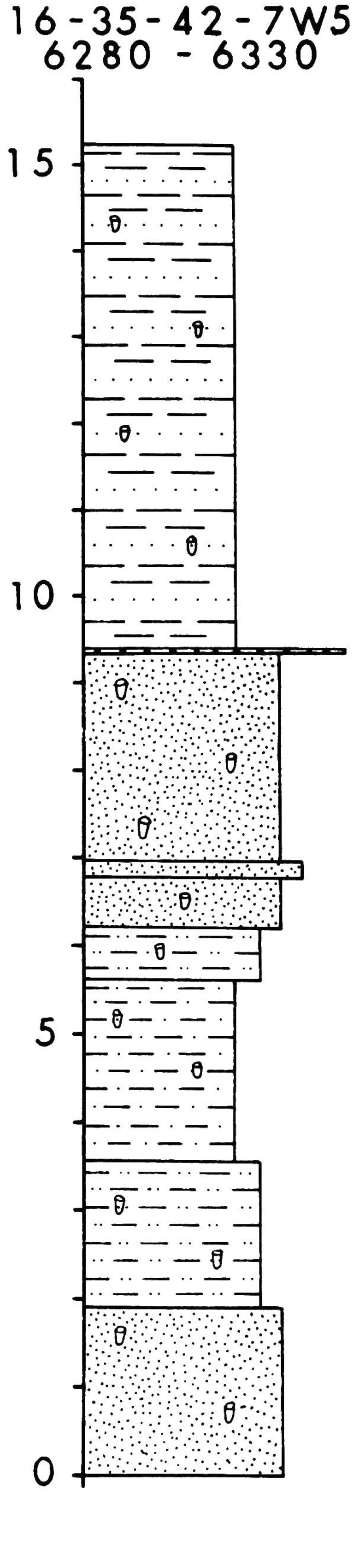
16-15-42-7W5
6342-6363

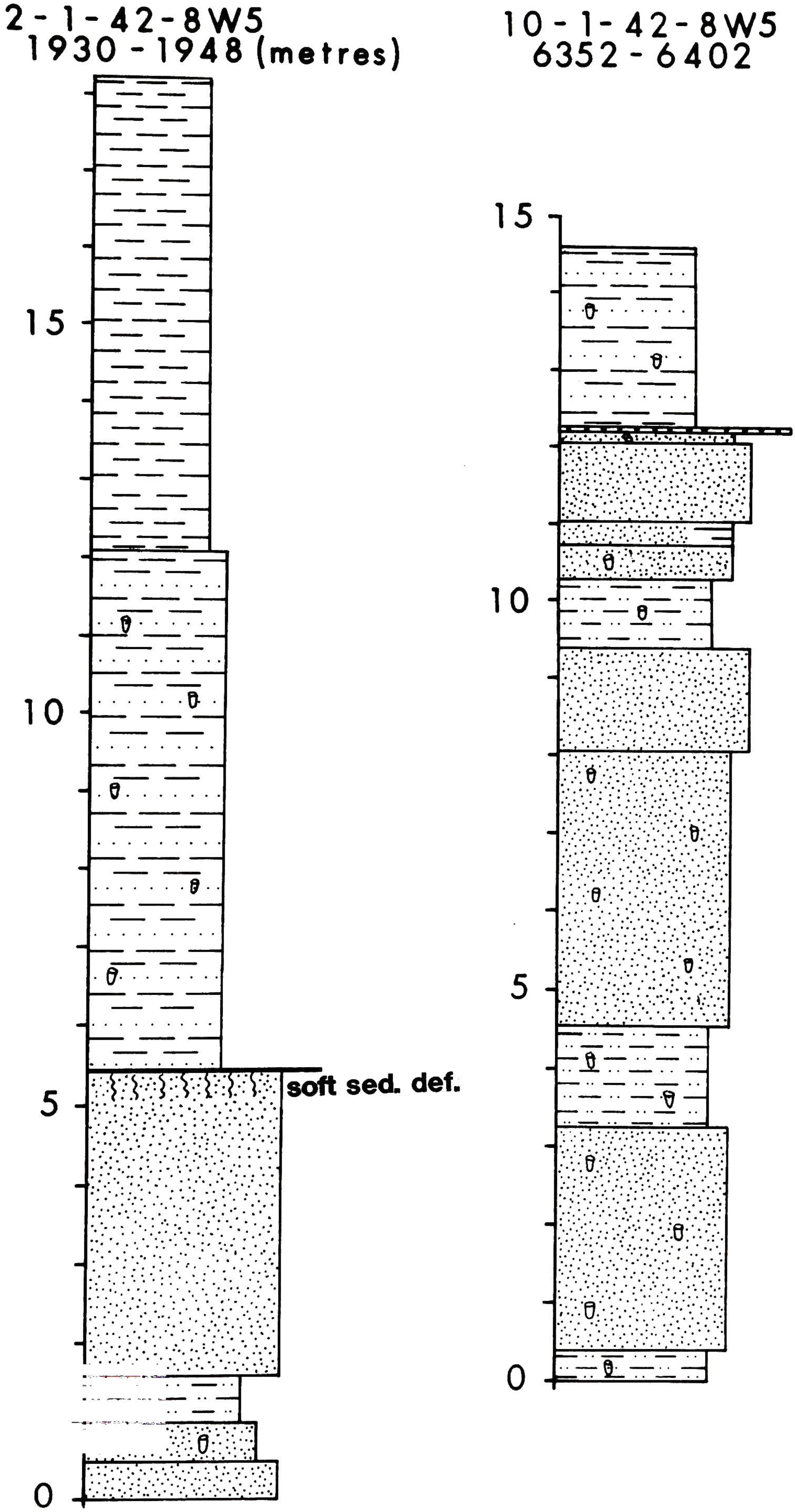


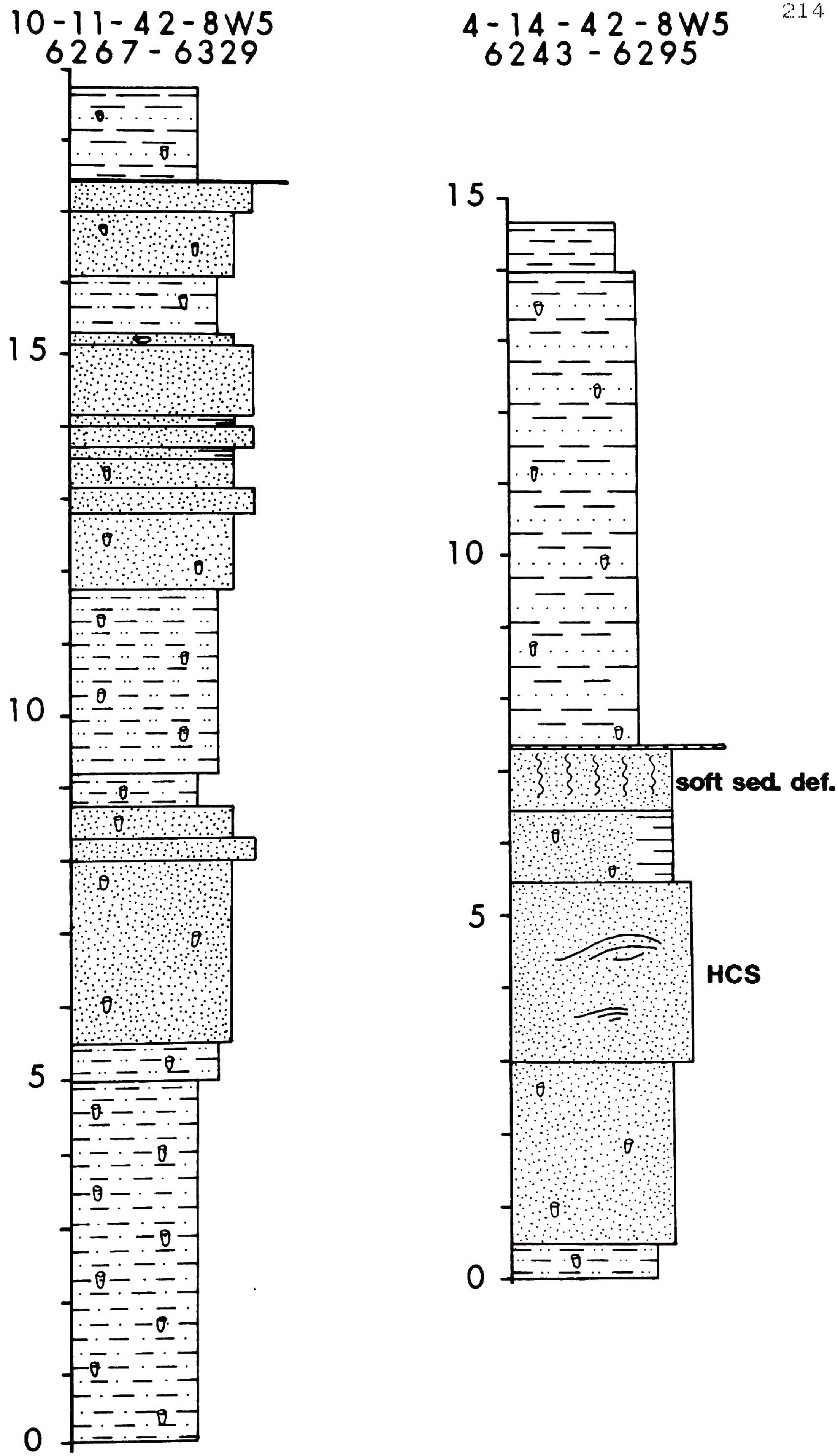
6-16-42-7W5
6336-6356



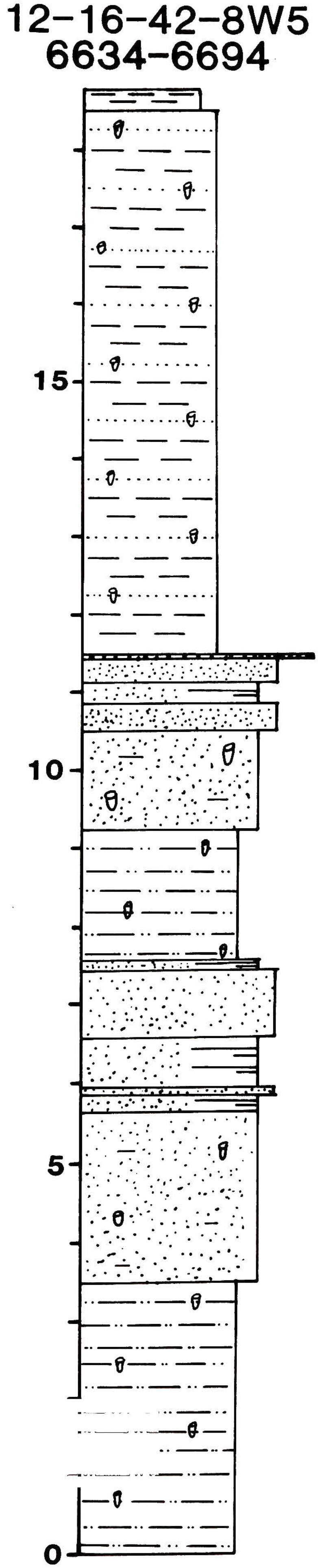

8-29-42-7W5
6372 - 6417
10
5
0

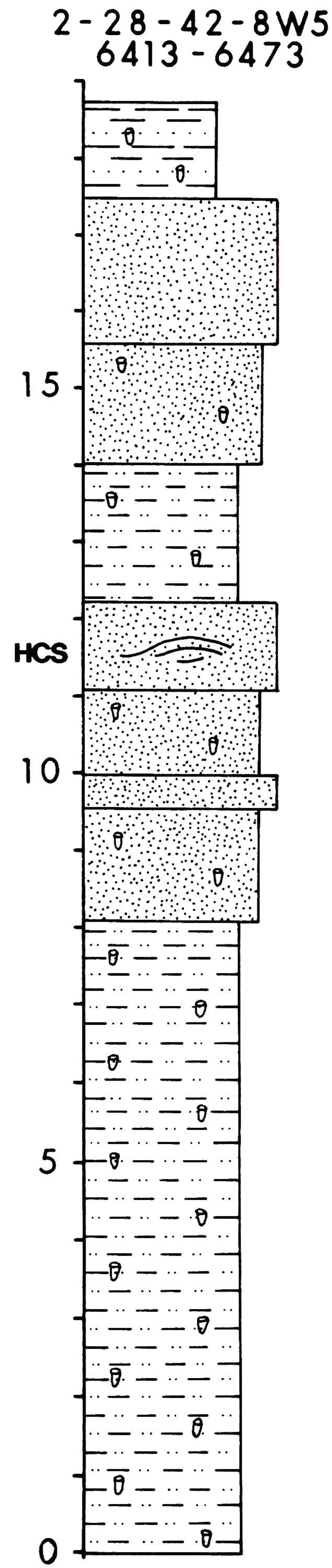

16-35-42-7W5
6280 - 6330
15
10
5
0

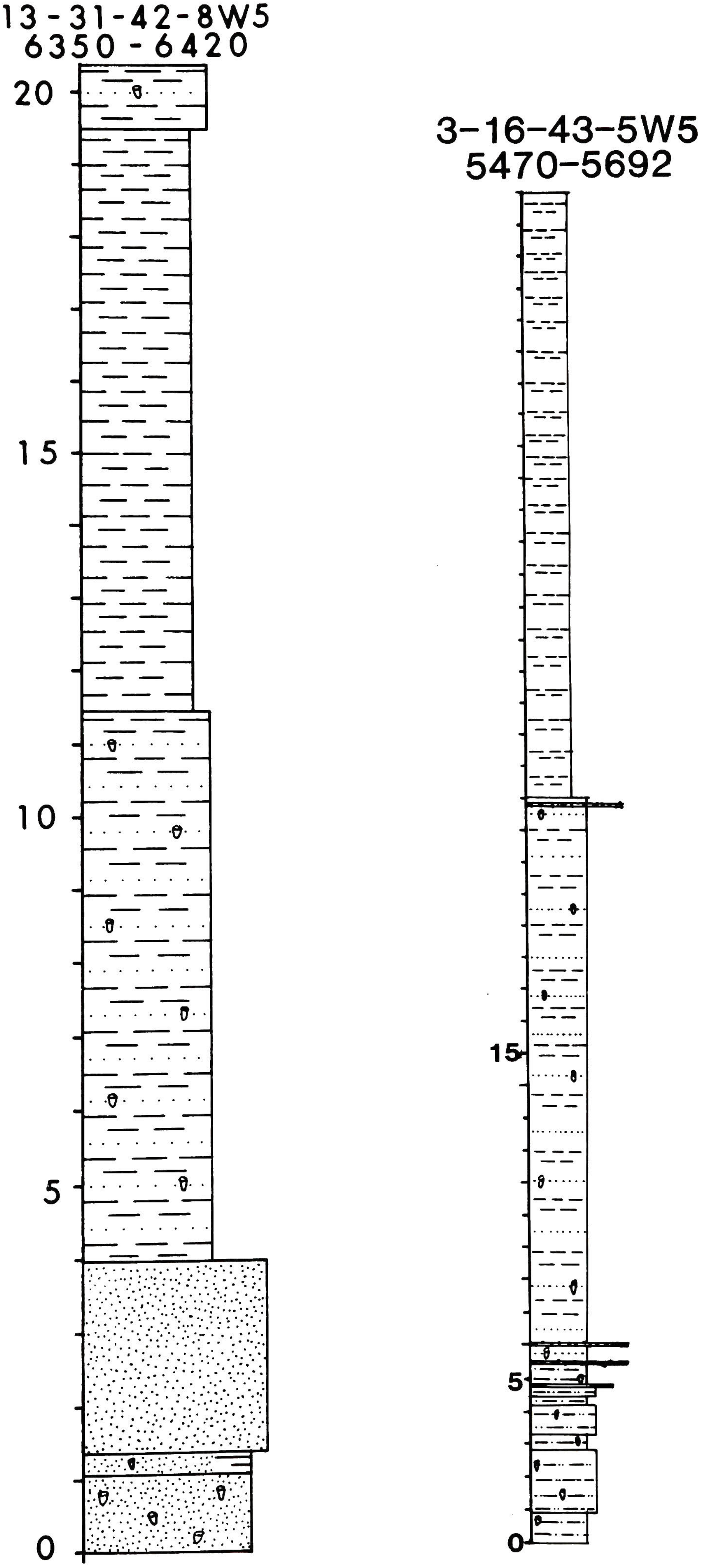

2-1-42-8W5
1930-1948 (metres)
15
10
5
0
soft sed. def.
10-1-42-8W5
6352-6402
15
10
5
0



10-11-42-8W5
6267-6329
15
10
5
0
4-14-42-8W5
6243-6295
15
10
5
0
soft sed. def.
HCS


12-16-42-8W5
6634-6694
15
10
5
0


2-28-42-8W5
6413-6473
15
HCS
10
5
0


13-31-42-8W5
6350-6420
20
15
10
5
0
3-16-43-5W5
5470-5692
15
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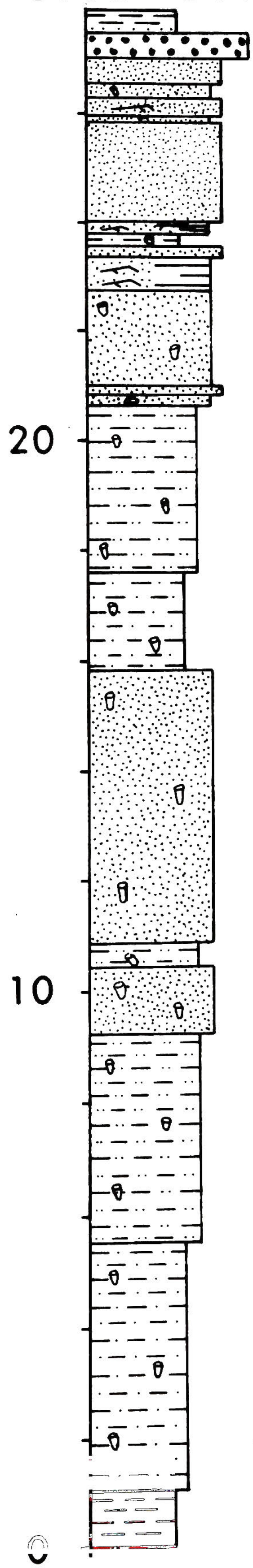
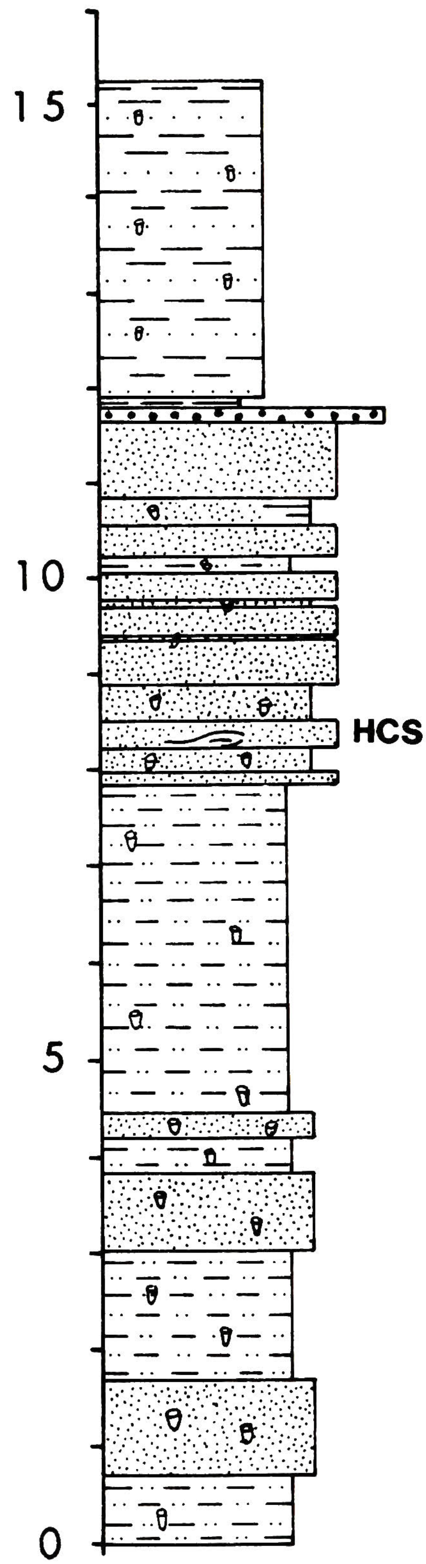
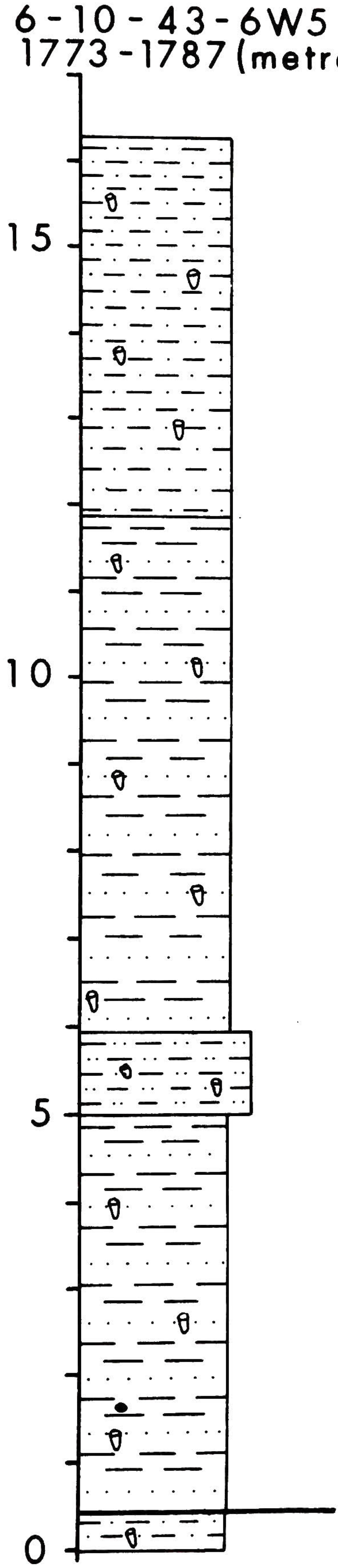
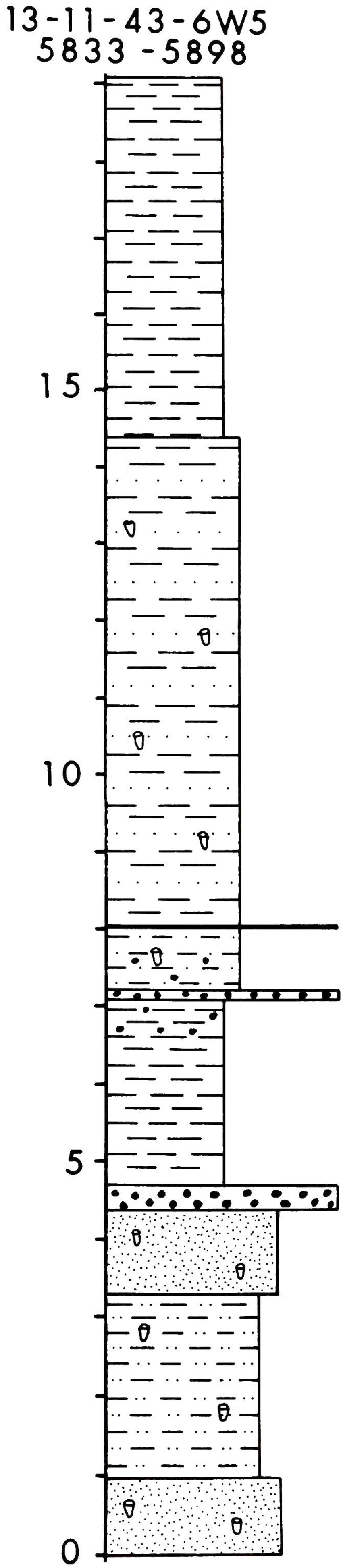
15-5-43-6W5
5995-6084

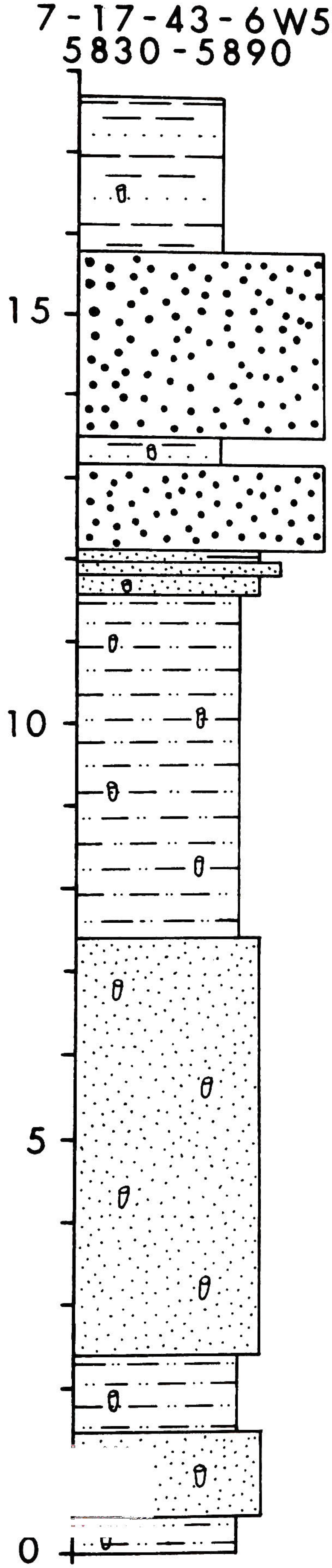


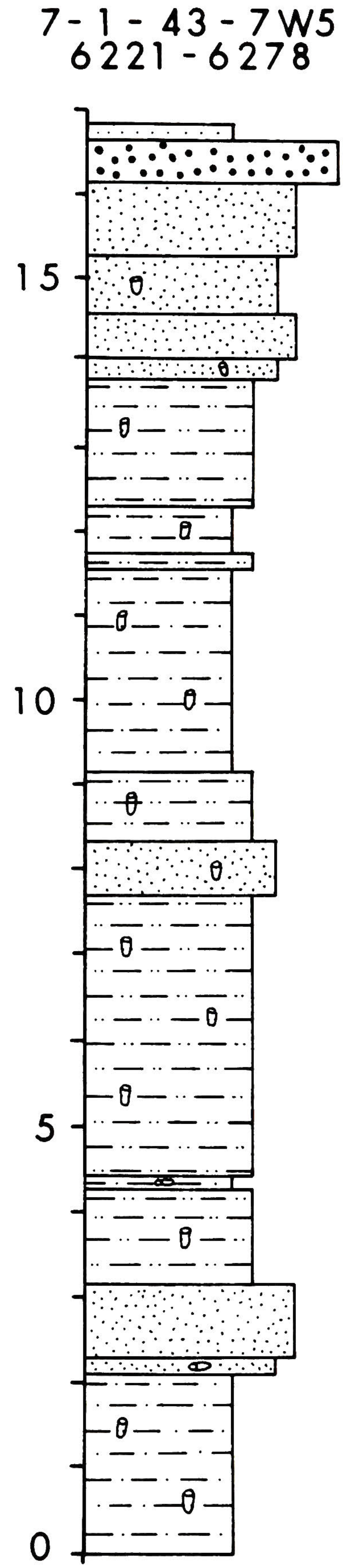
6-6-43-6W5
6045-6100




6-10-43-6W5
1773-1787 (metres)
15
10
5
0


13-11-43-6W5
5833-5898
15
10
5
0


7-17-43-6W5
5830-5890
15
10
5
0


7-1-43-7W5
6221-6278
15
10
5
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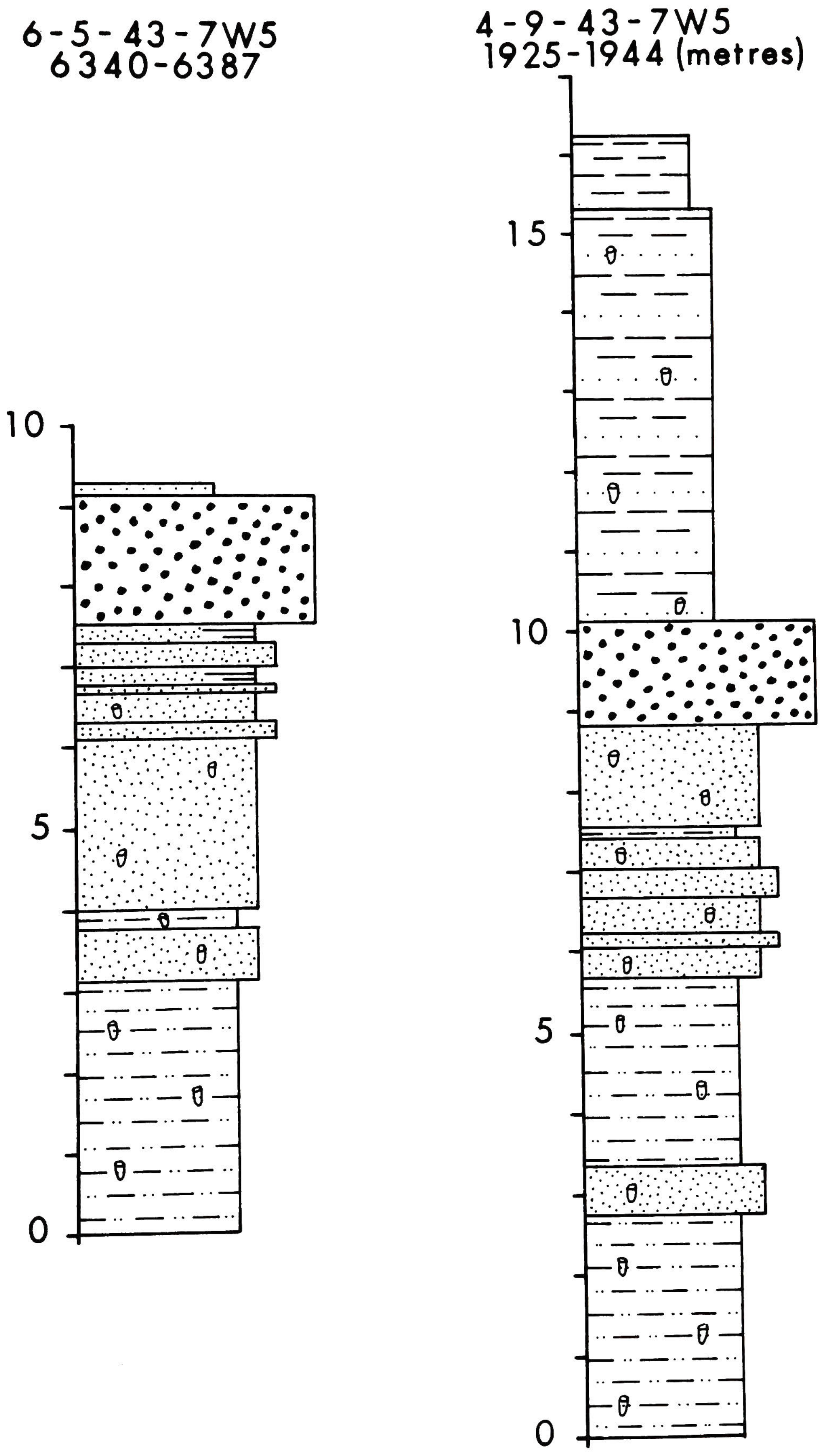
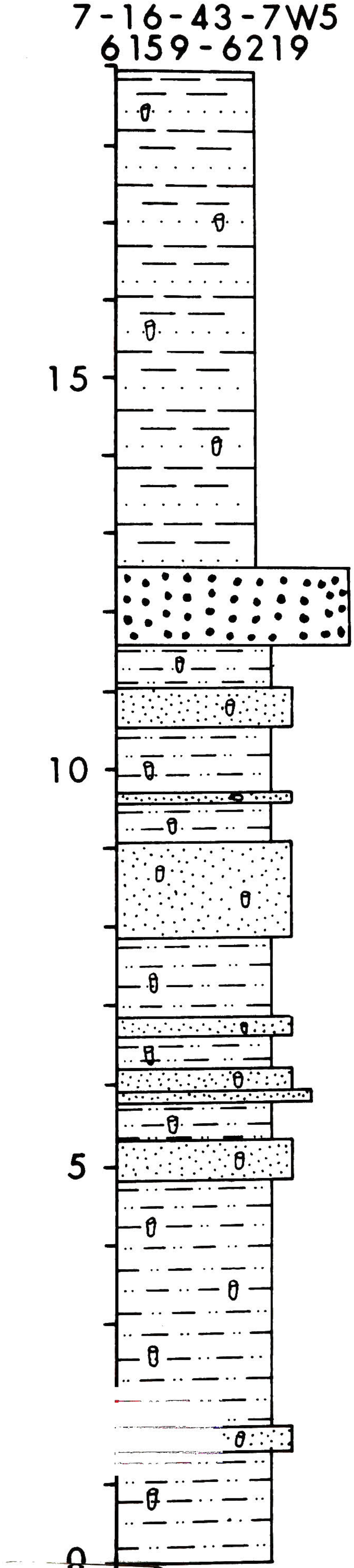
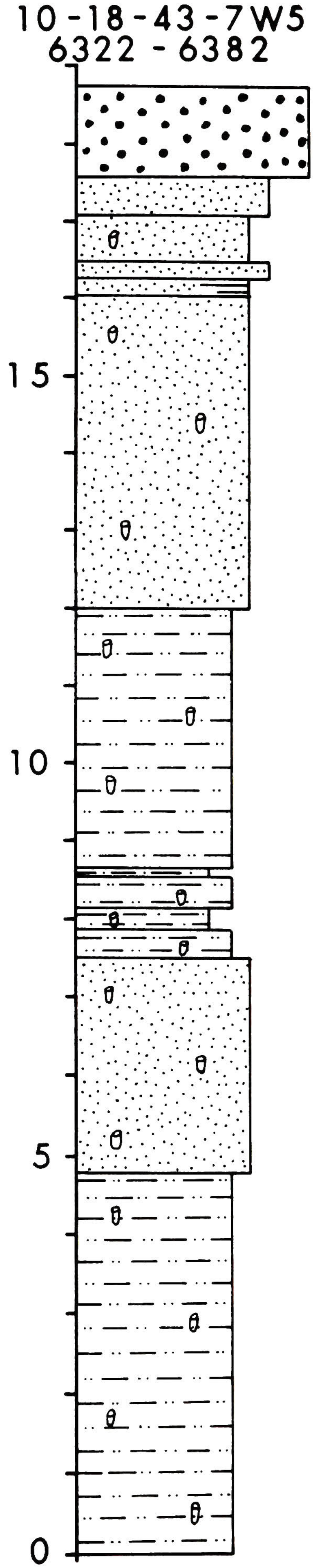
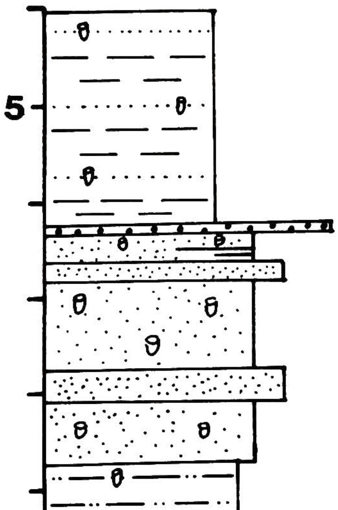

6-5-43-7W5
6340-6387
10
5
0
4-9-43-7W5
1925-1944 (metres)
15
10
5
0

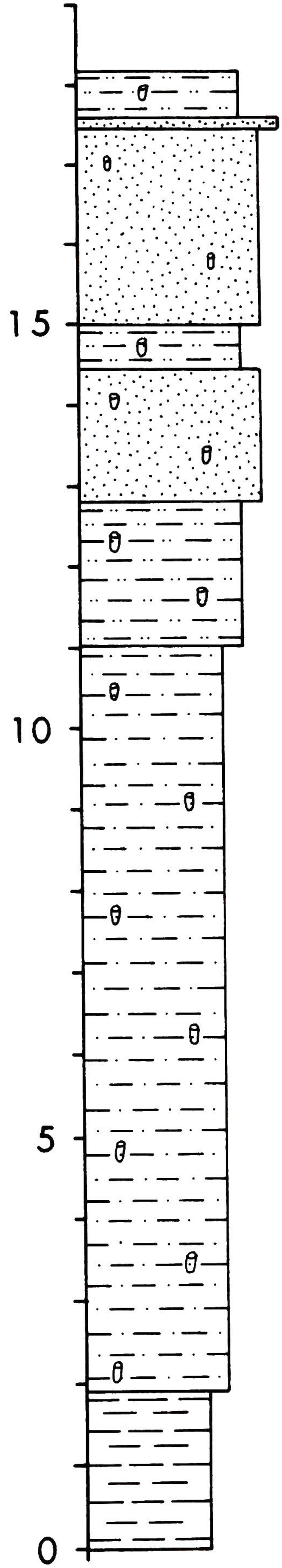

7-16-43-7W5
6159-6219
15
10
5
0

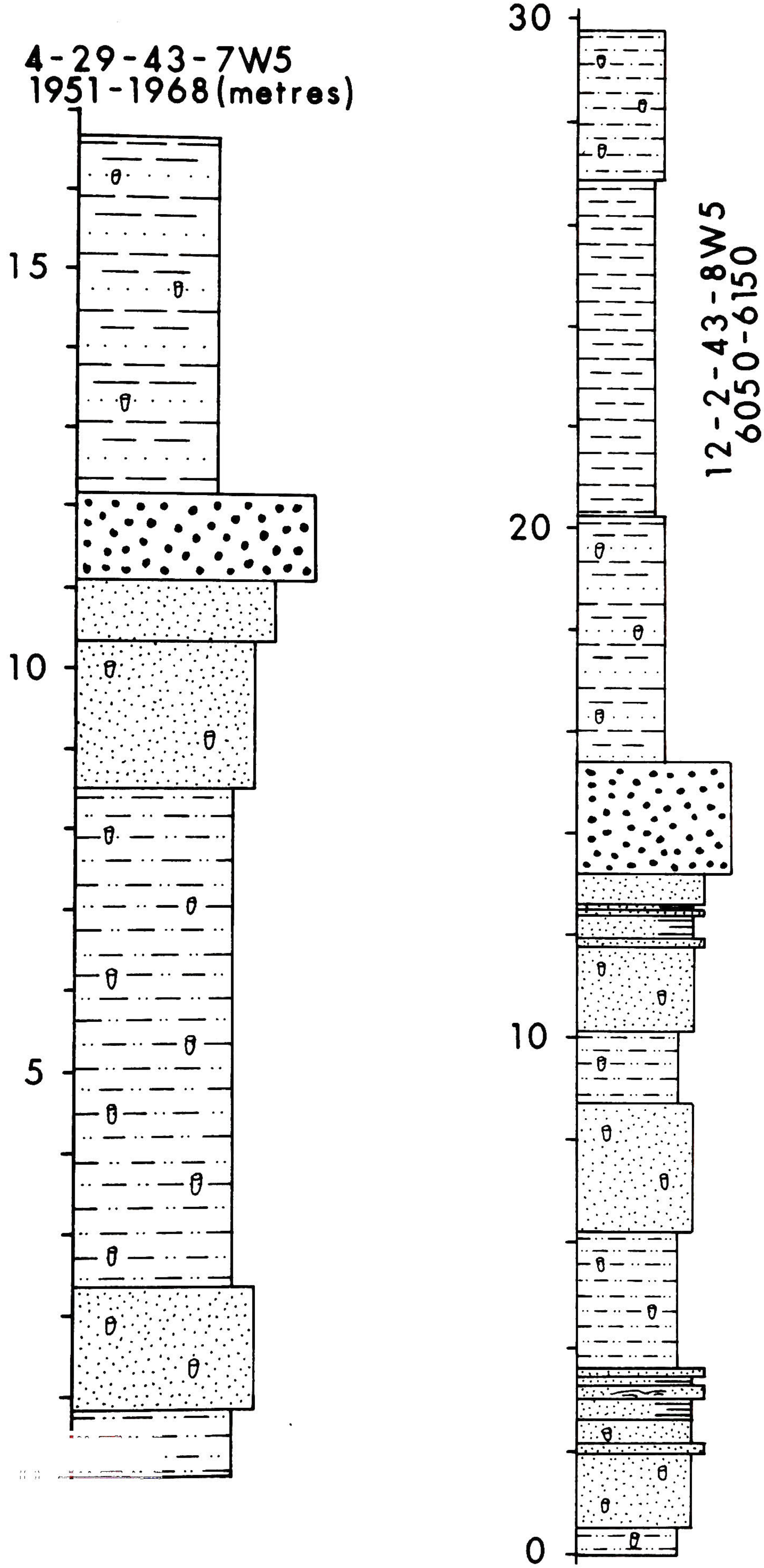

10-18-43-7W5
6322-6382
15
10
5
0

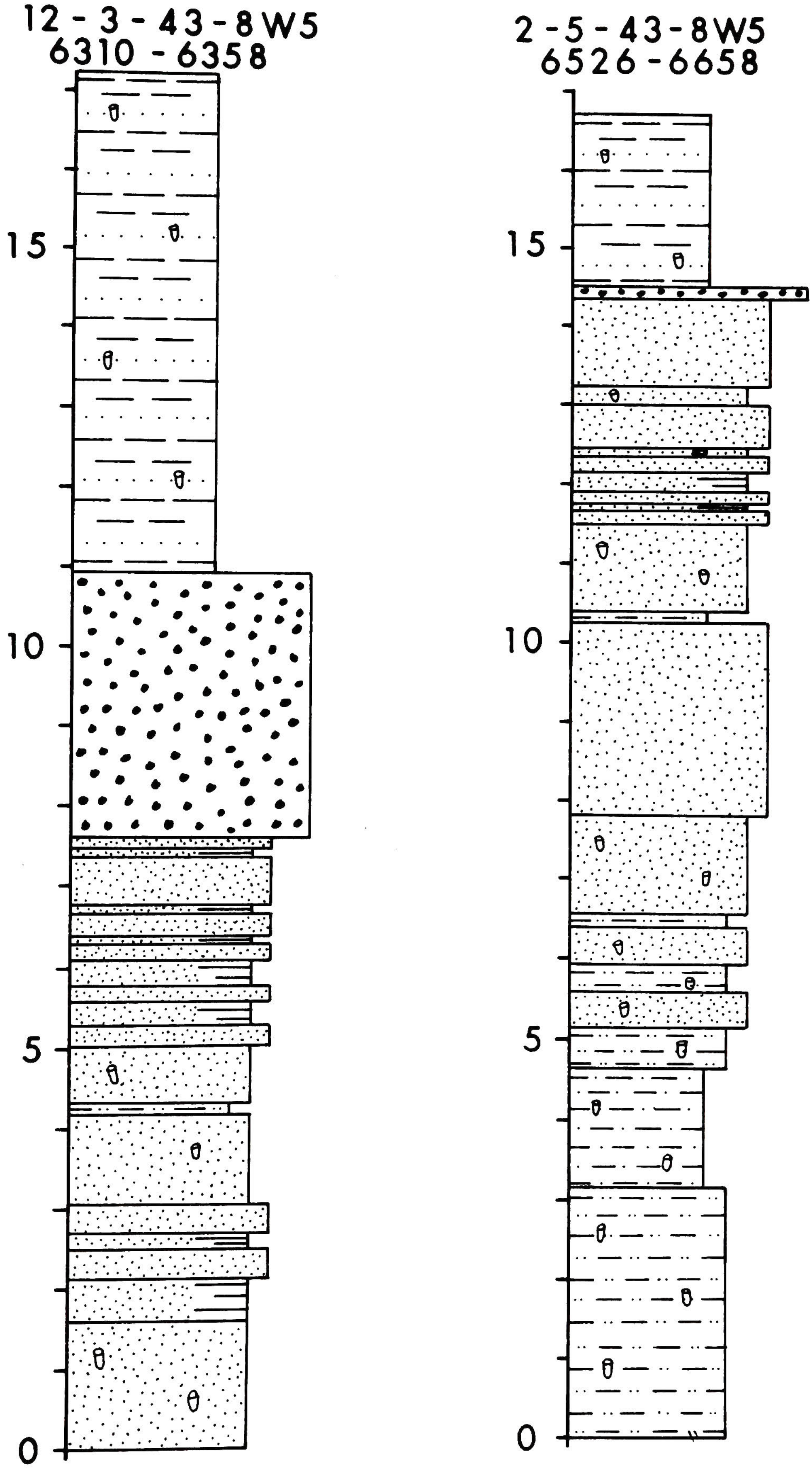
5-24-43-7W5
1809-1814.5m

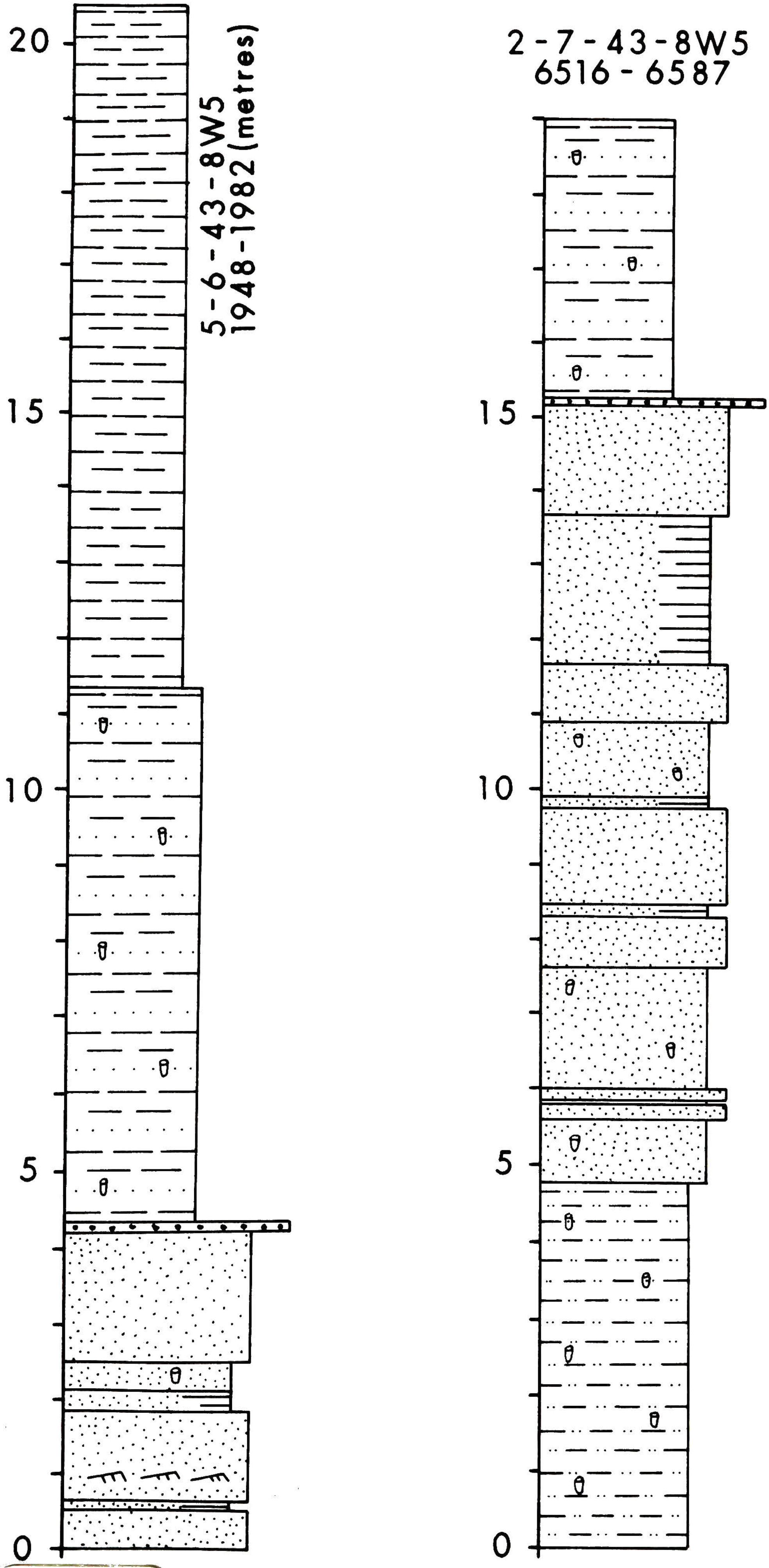


15-27-43-7W5
5960-6020



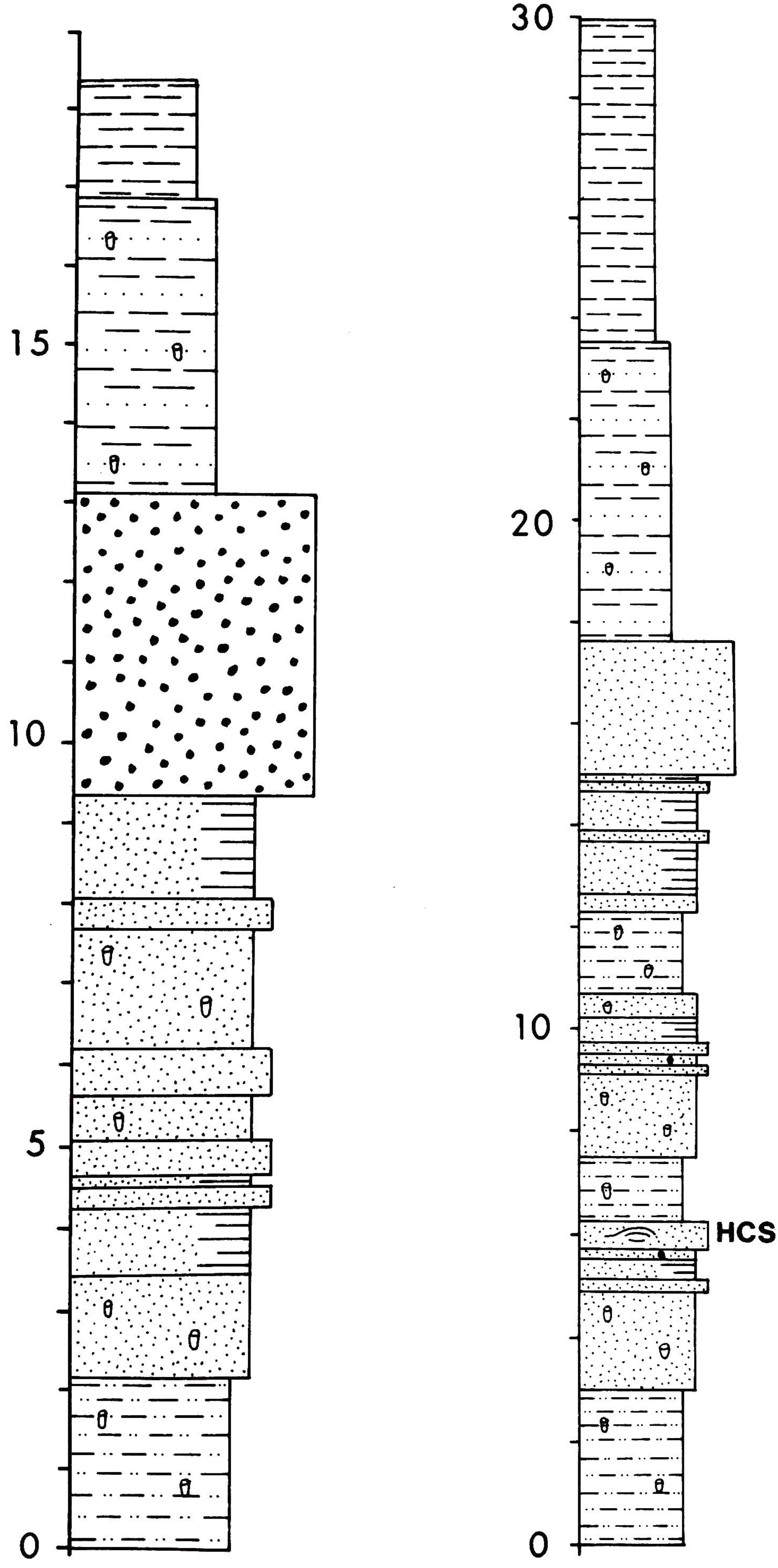

4-29-43-7W5
1951-1968 (metres)
15
10
5
30
20
10
0
12-2-43-8W5
6050-6150

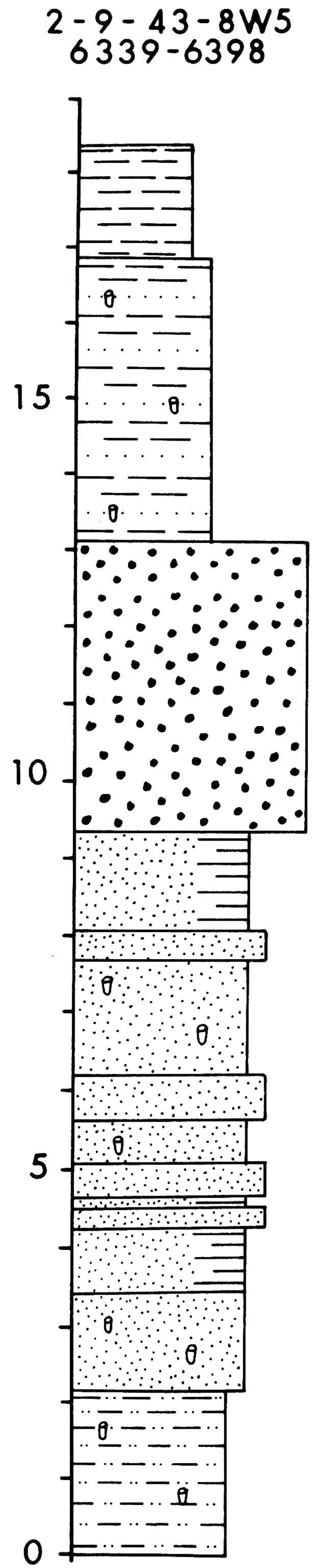

12 - 3 - 43 - 8 W5
6310 - 6358
2 - 5 - 43 - 8 W5
6526 - 6658
15
10
5
0
15
10
5
0

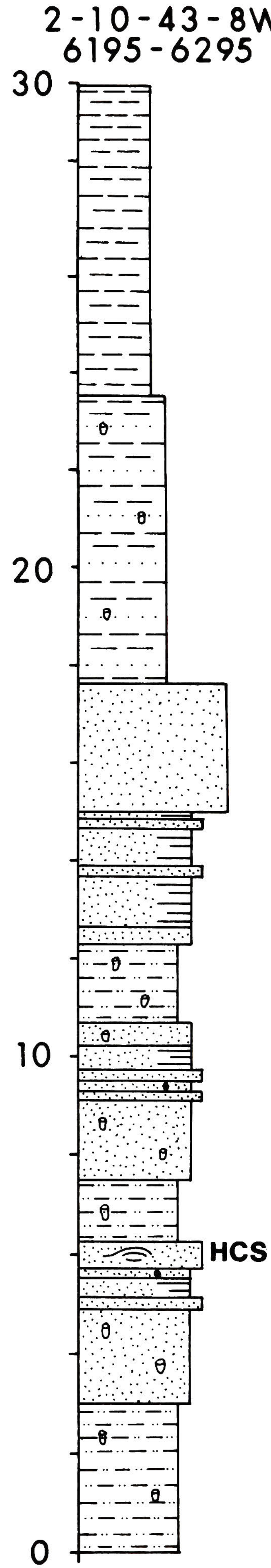

5-6-43-8W5
1948-1982 (metres)
2-7-43-8W5
6516-6587
20
15
10
5
0
15
10
5
0

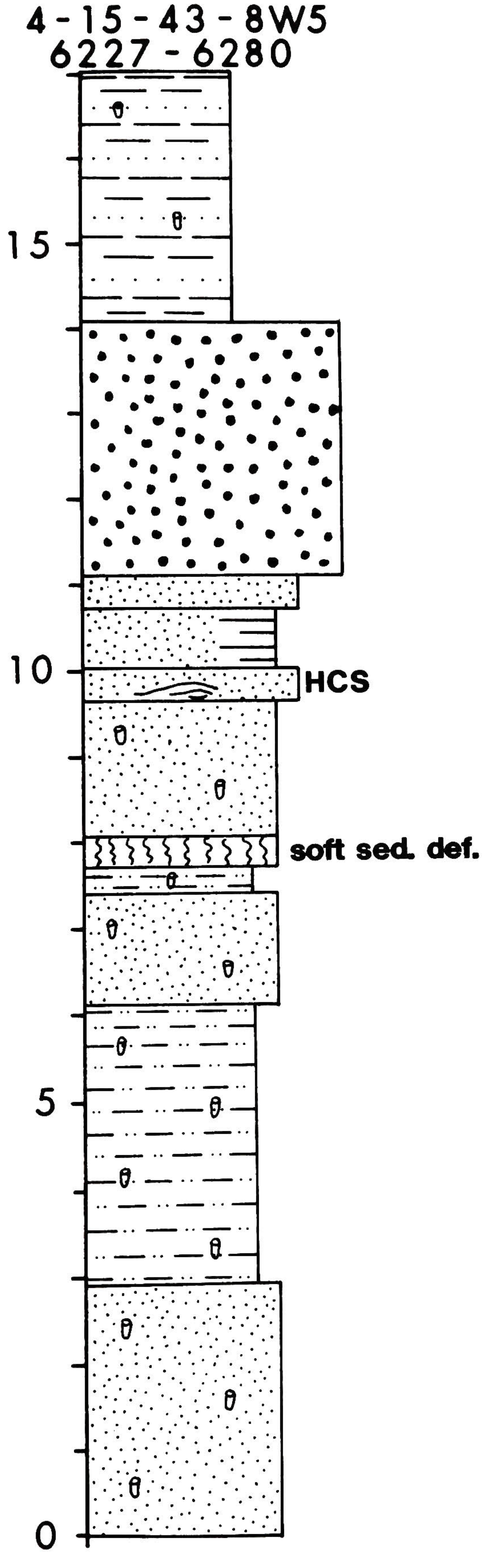
2-9-43-8W5
6339-6398

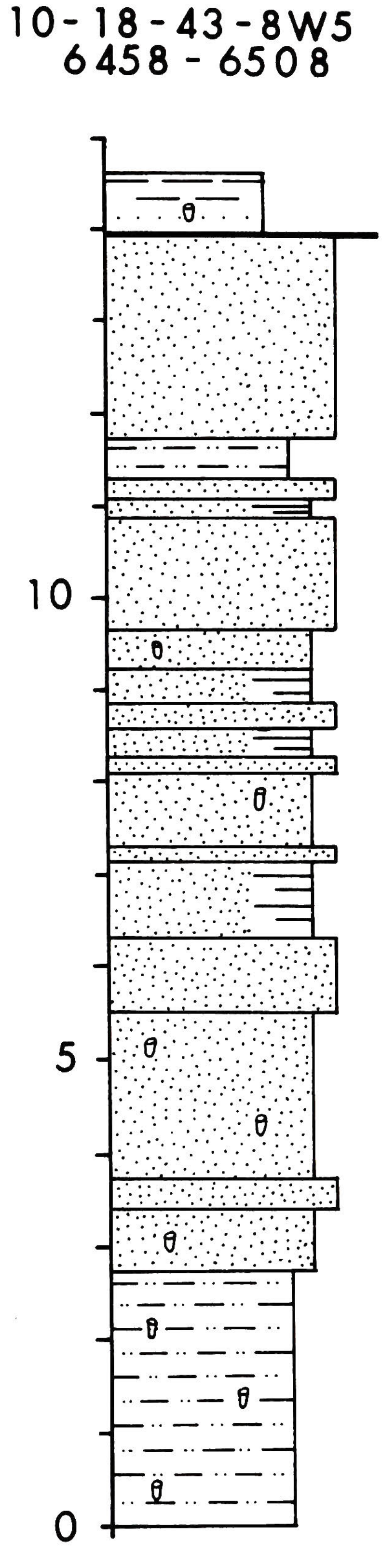
2-10-43-8W5
6195-6295

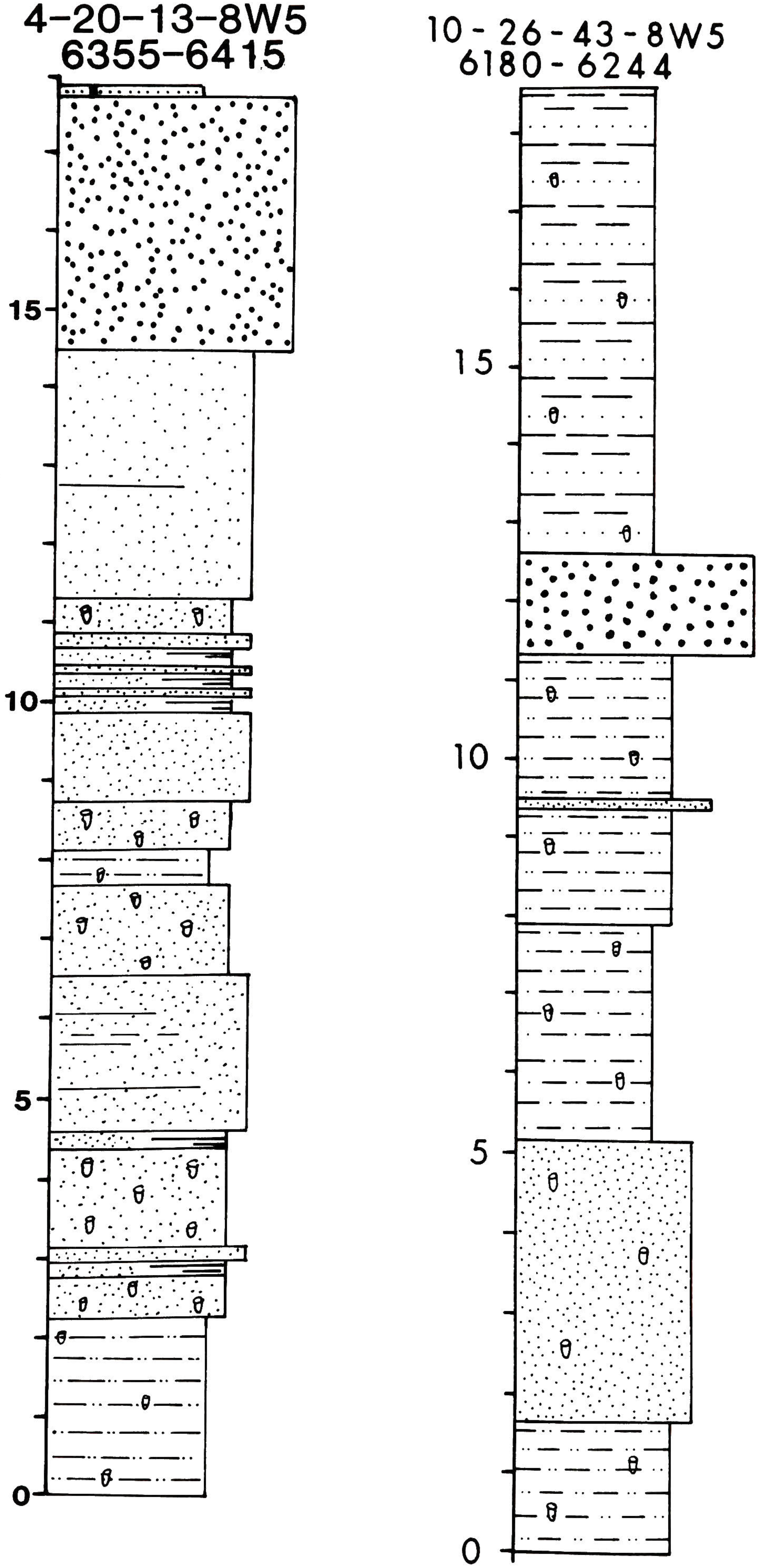



2-9-43-8W5
6339-6398
0
5
10
15


2-10-43-8W5
6195-6295
0
10
20
30
HCS


4-15-43-8W5
6227-6280
15
10
5
0
HCS
soft sed. def.


10-18-43-8W5
6458-6508
10
5
0


4-20-13-8W5
6355-6415
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10-26-43-8W5
6180-6244
15
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5
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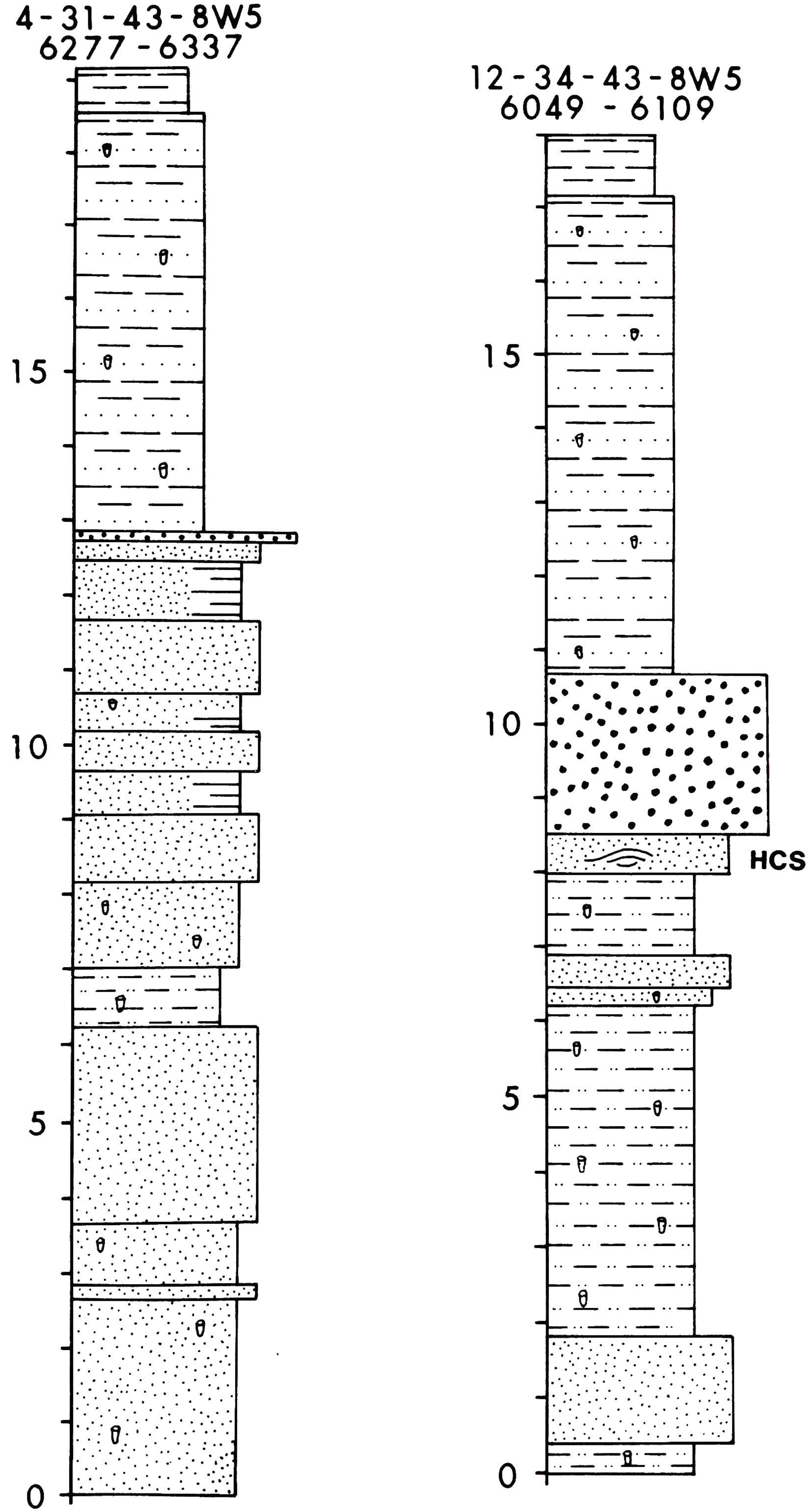
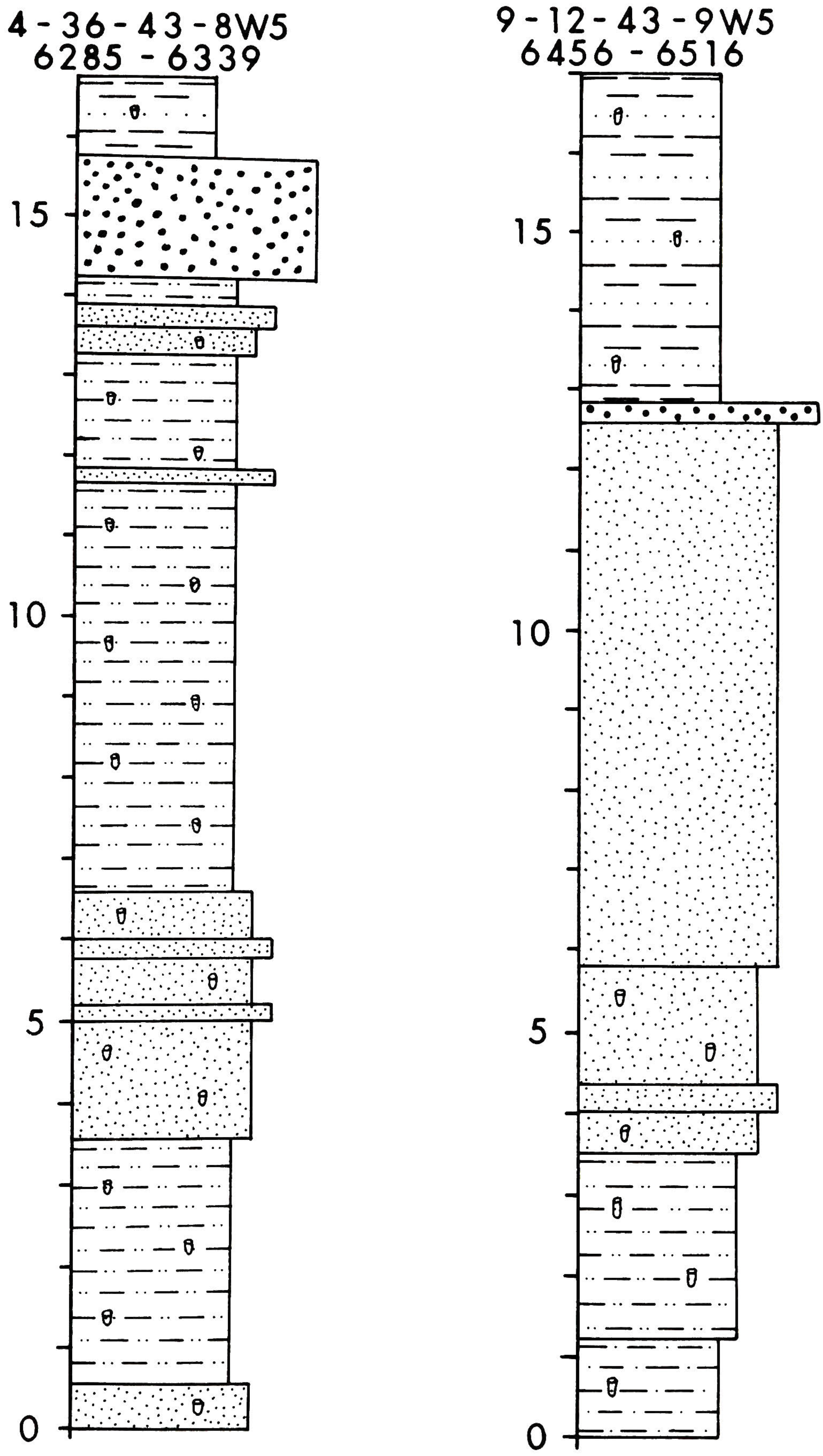

4-31-43-8W5
6277-6337
12-34-43-8W5
6049-6109
15
10
5
0
HCS


4-36-43-8W5
6285 - 6339
9-12-43-9W5
6456 - 6516
15
10
5
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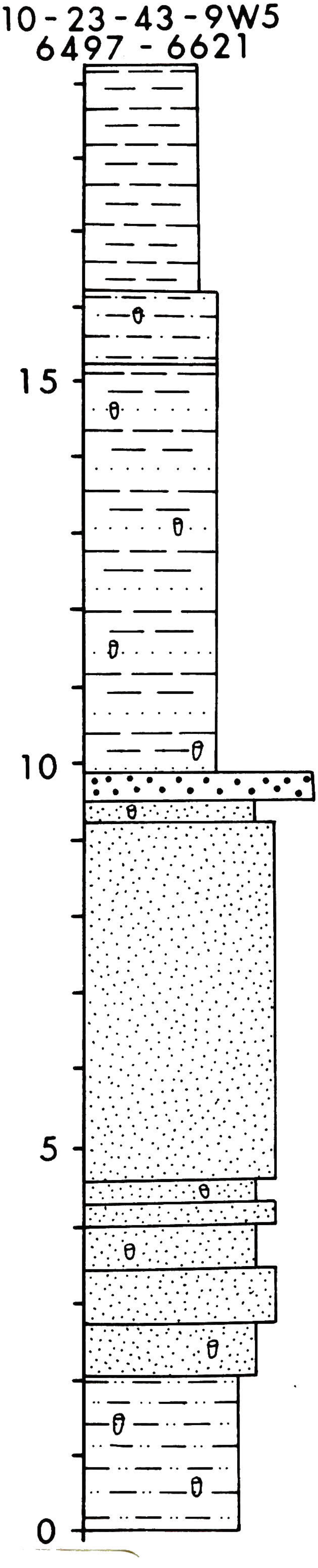
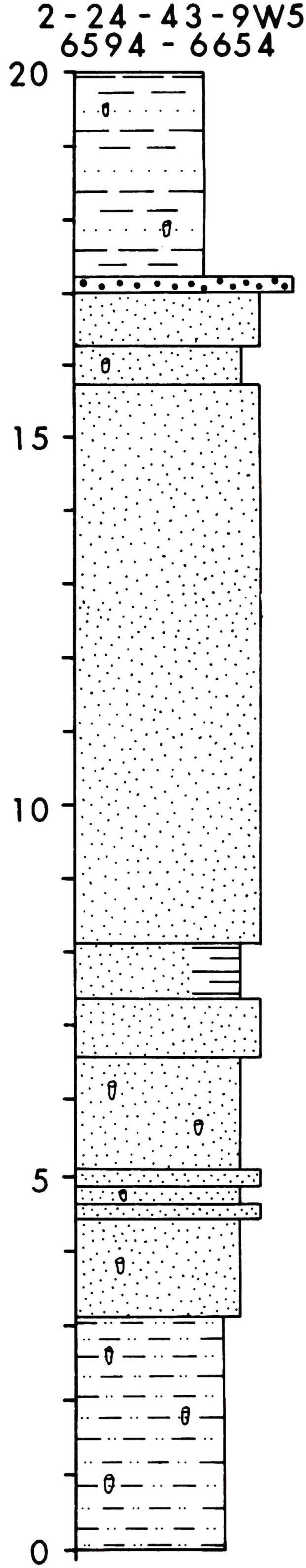
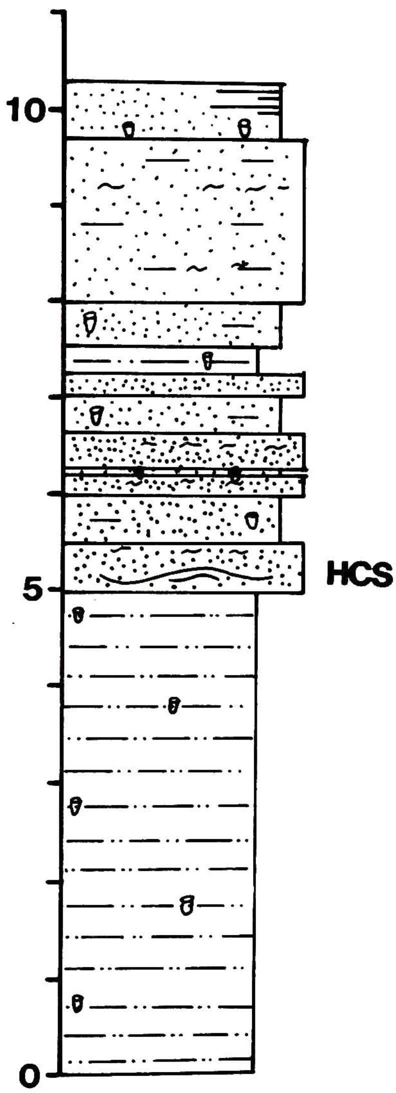
15
10
5
0

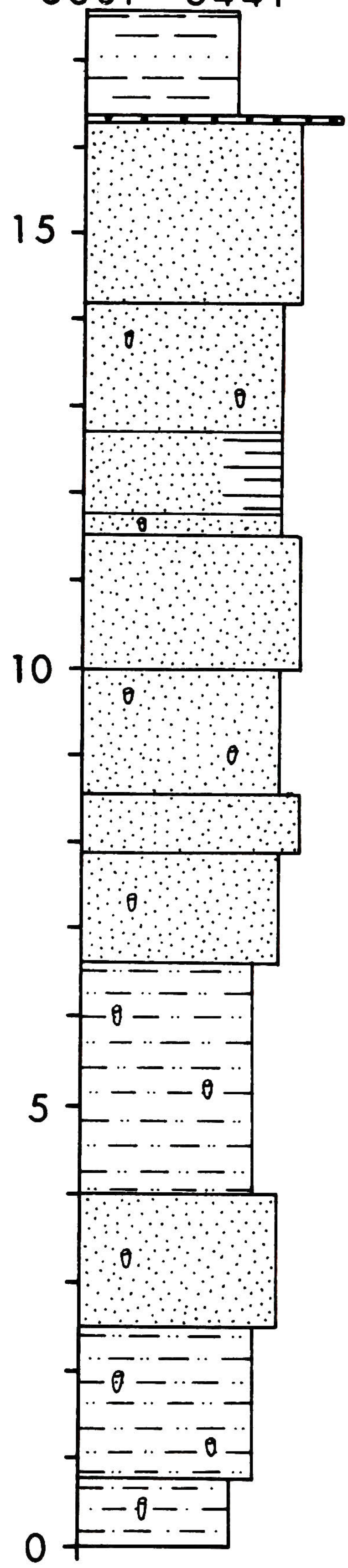

10-23-43-9W5
6497 - 6621
15
10
5
0

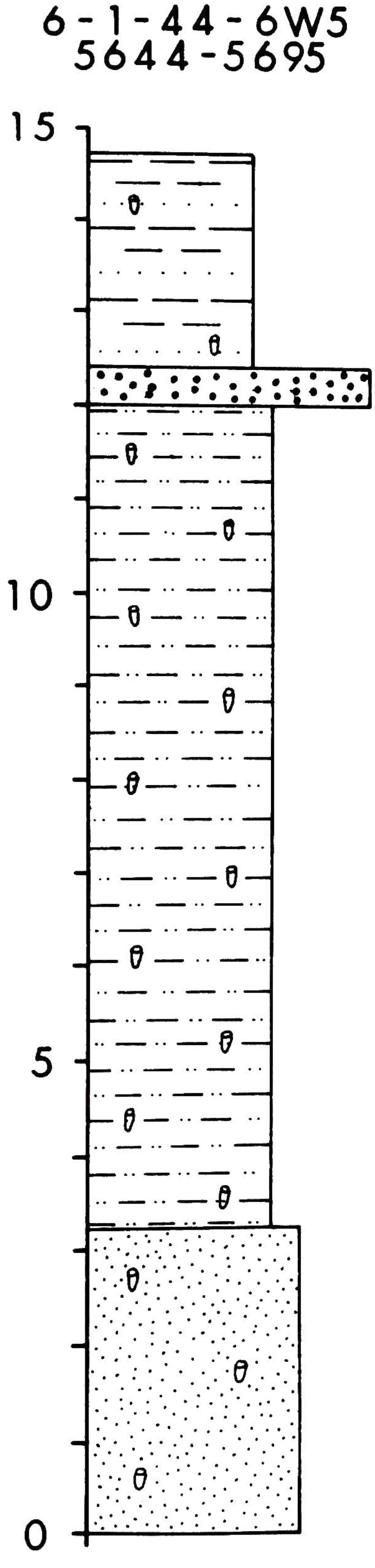

2-24-43-9W5
6594 - 6654
20
15
10
5
0

10-33-43-9W5
2012-2025m



2 - 36 - 43 - 9W5
6381 - 6441




6-1-44-6W5
5644-5695
15
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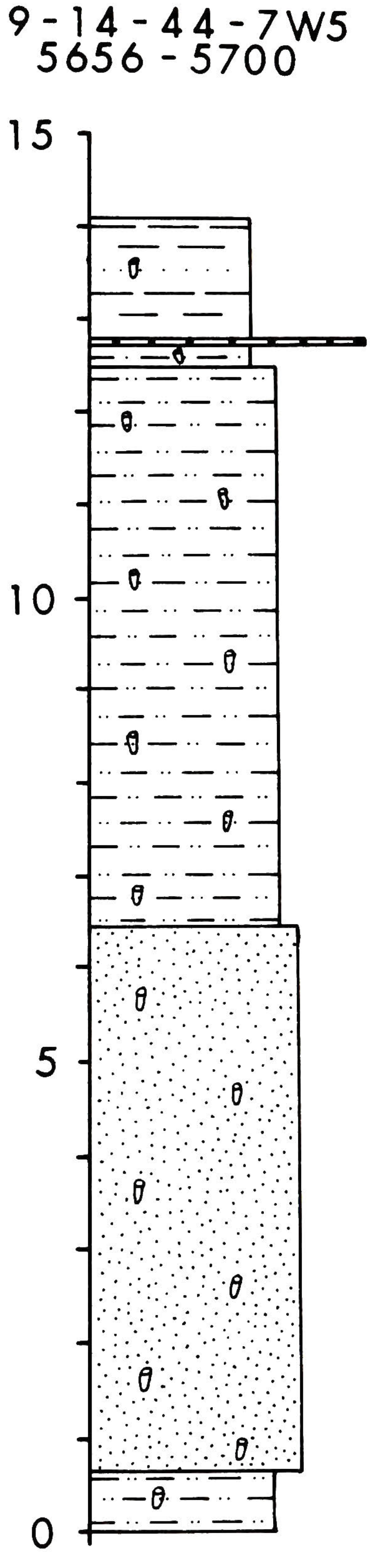
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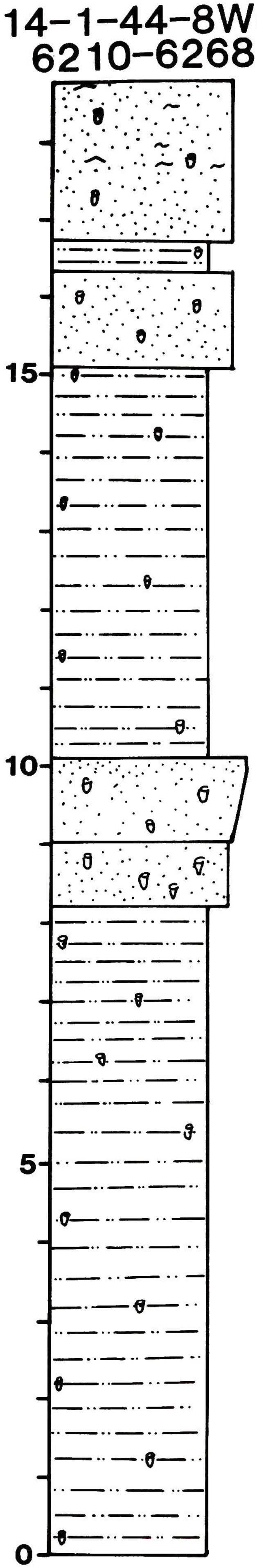
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6210-6268
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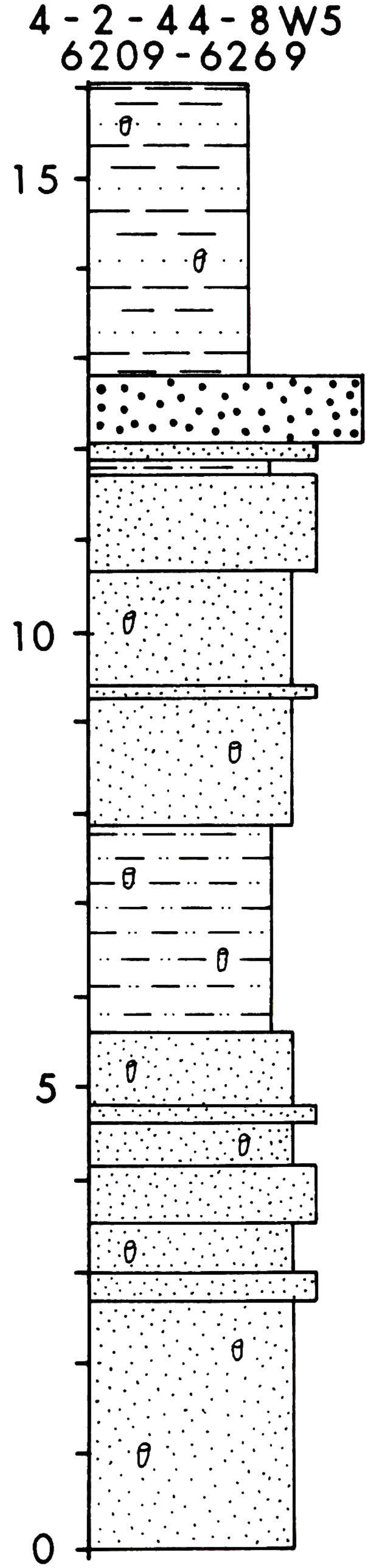
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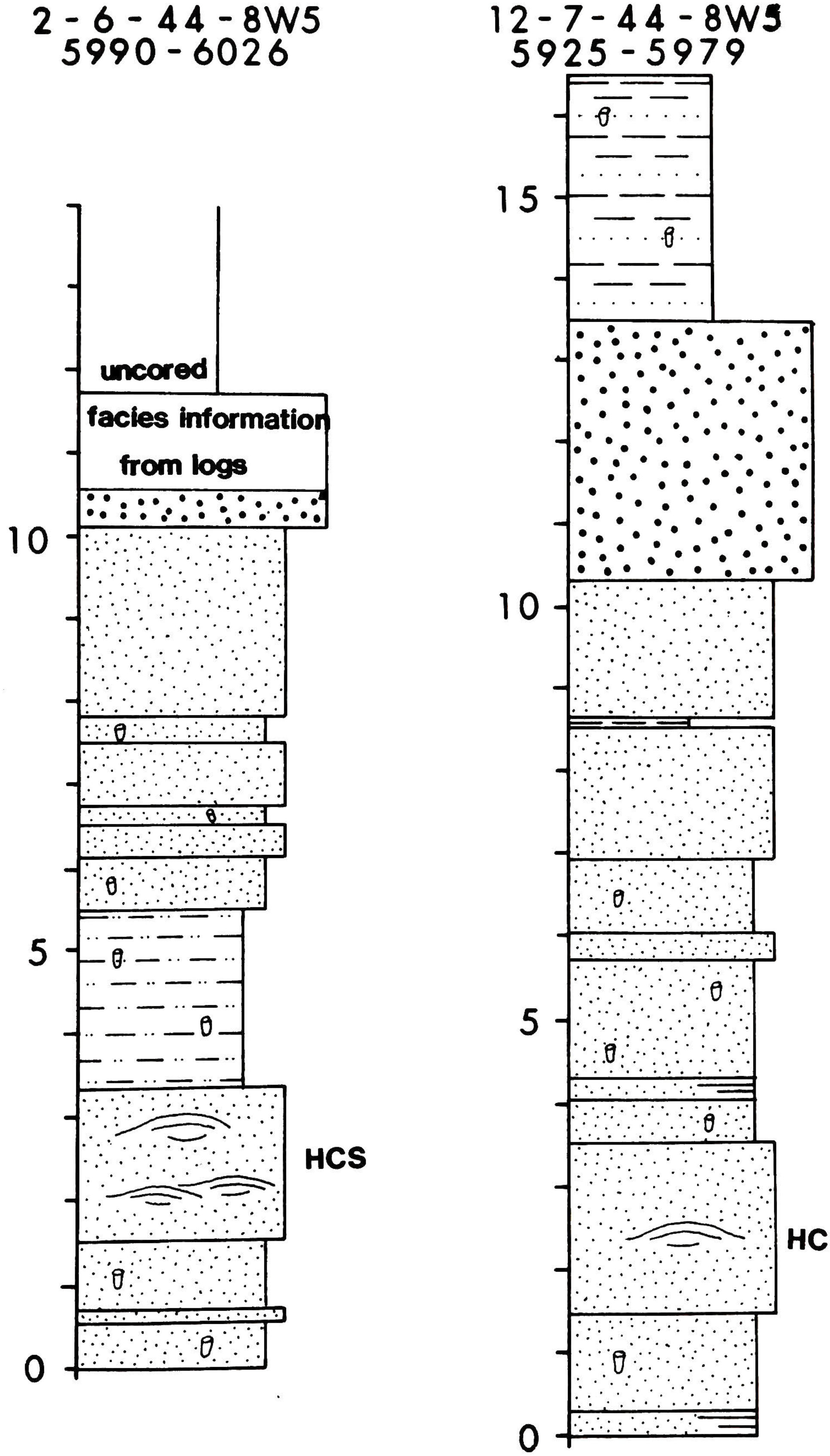
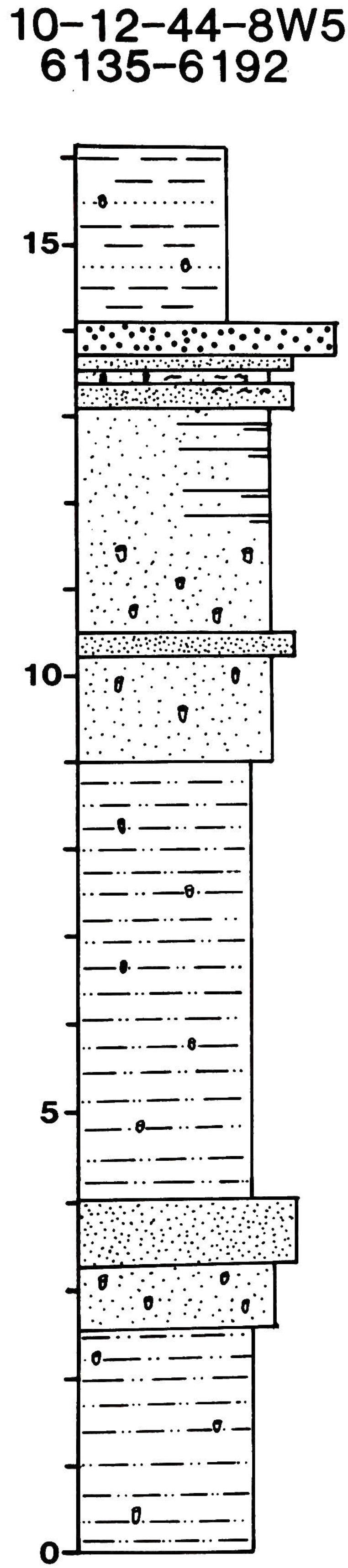

2-6-44-8W5
5990-6026
uncored
facies information from logs
HCS
10
5
0
12-7-44-8W5
5925-5979
HCS
15
10
5
0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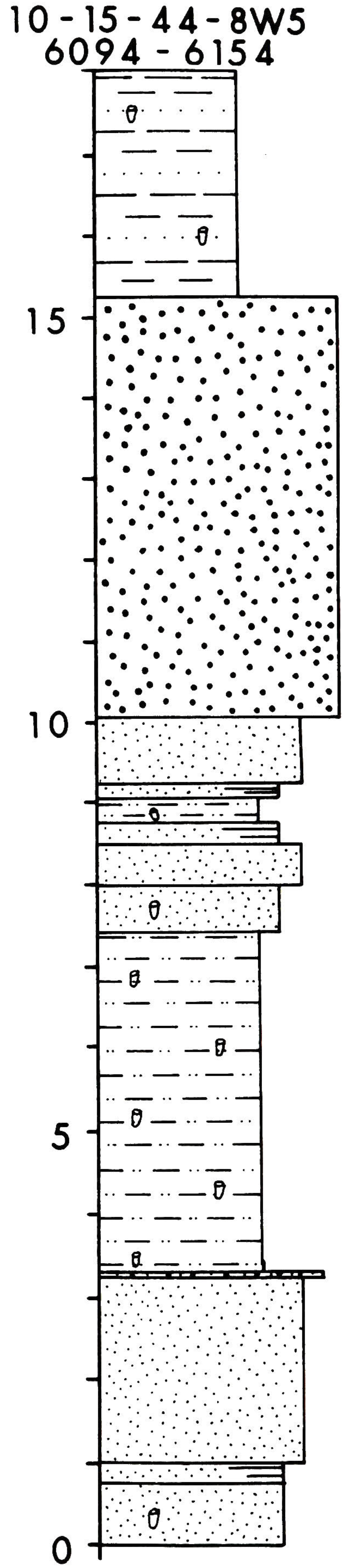
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6094-6154
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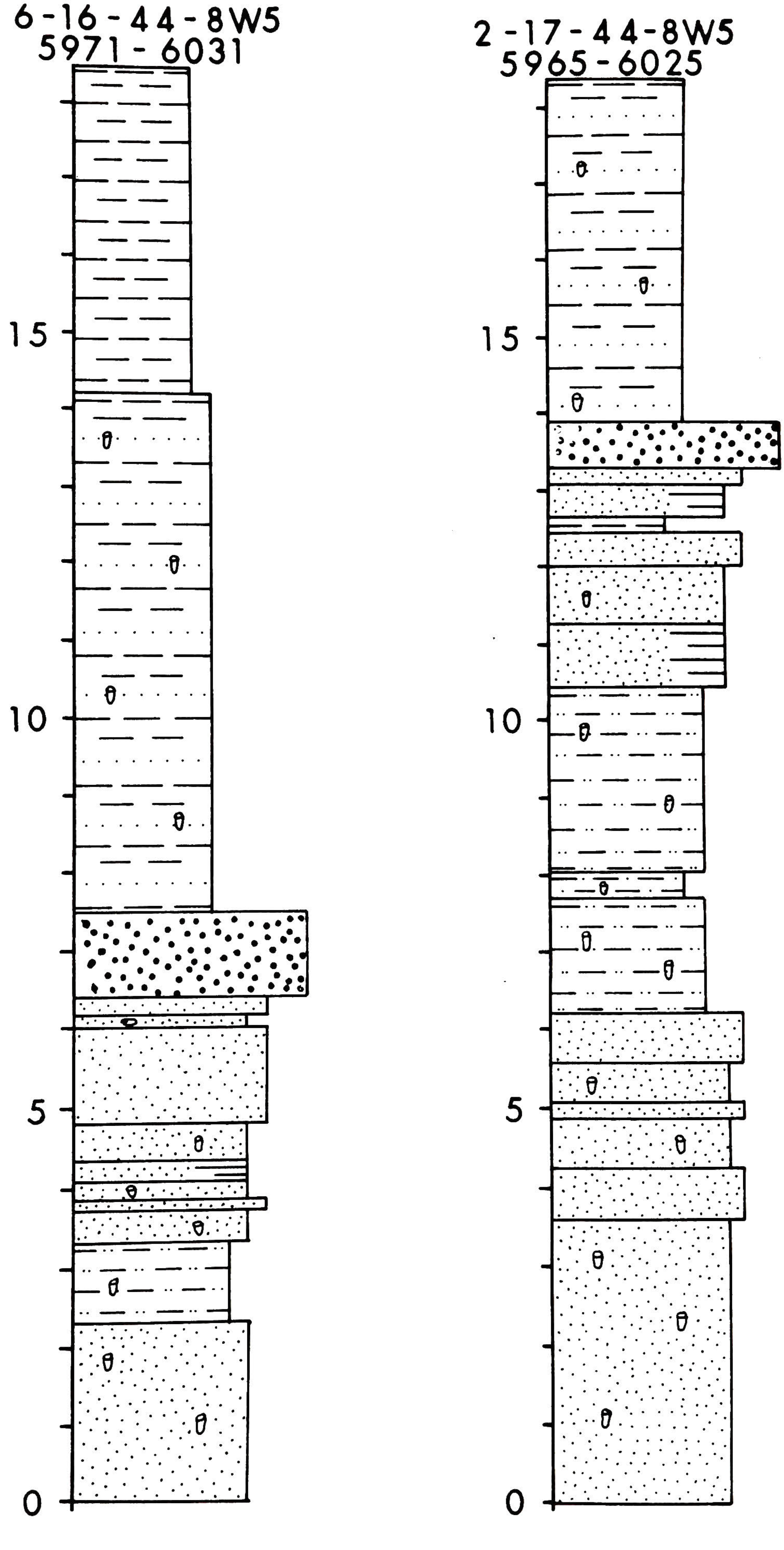
6-16-44-8W5
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2-17-44-8W5
5965-6025
15
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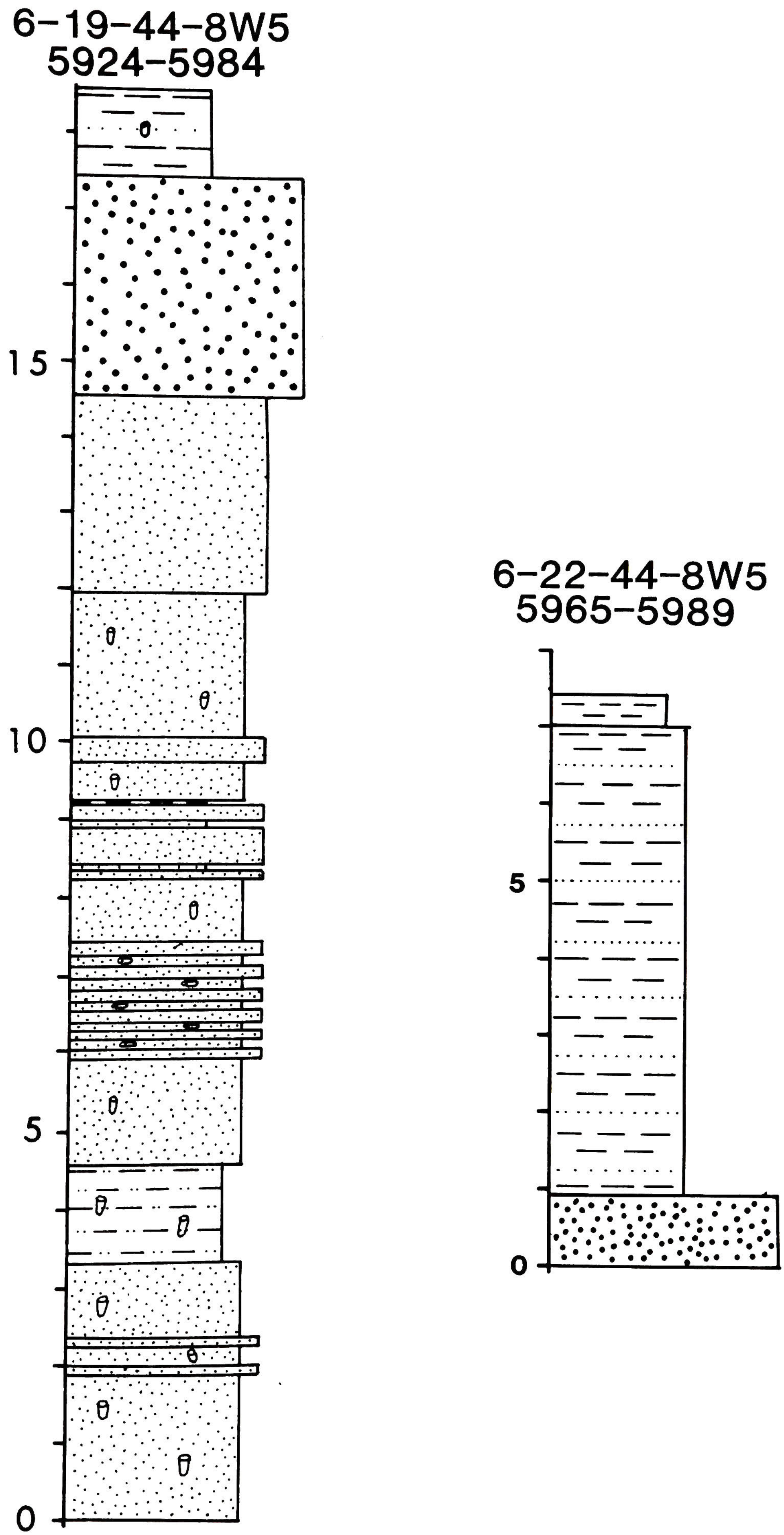
5
0
15
10
5
0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6-22-44-8W5
5965-5989
5
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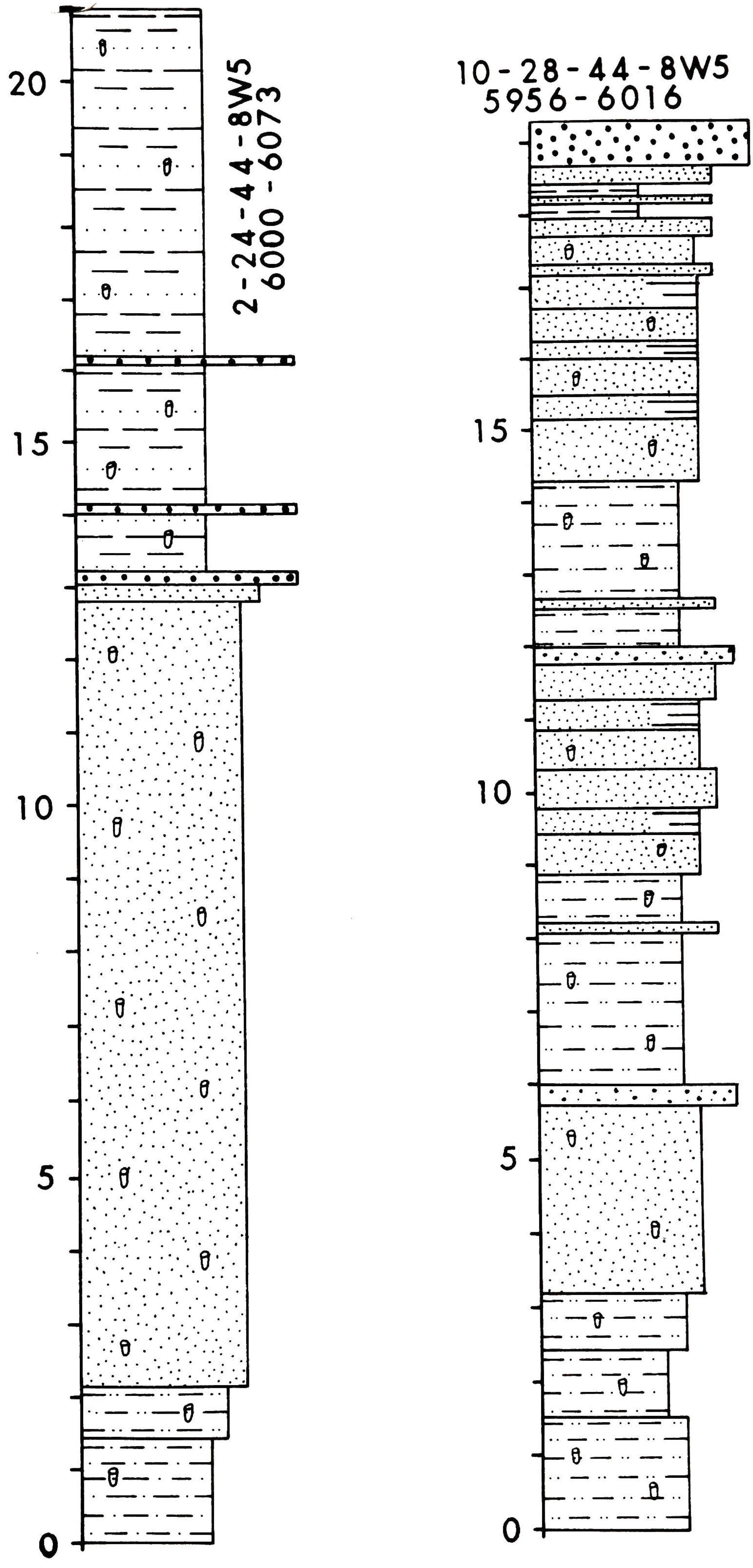
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6000-6073
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5
0
10-28-44-8W5
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5
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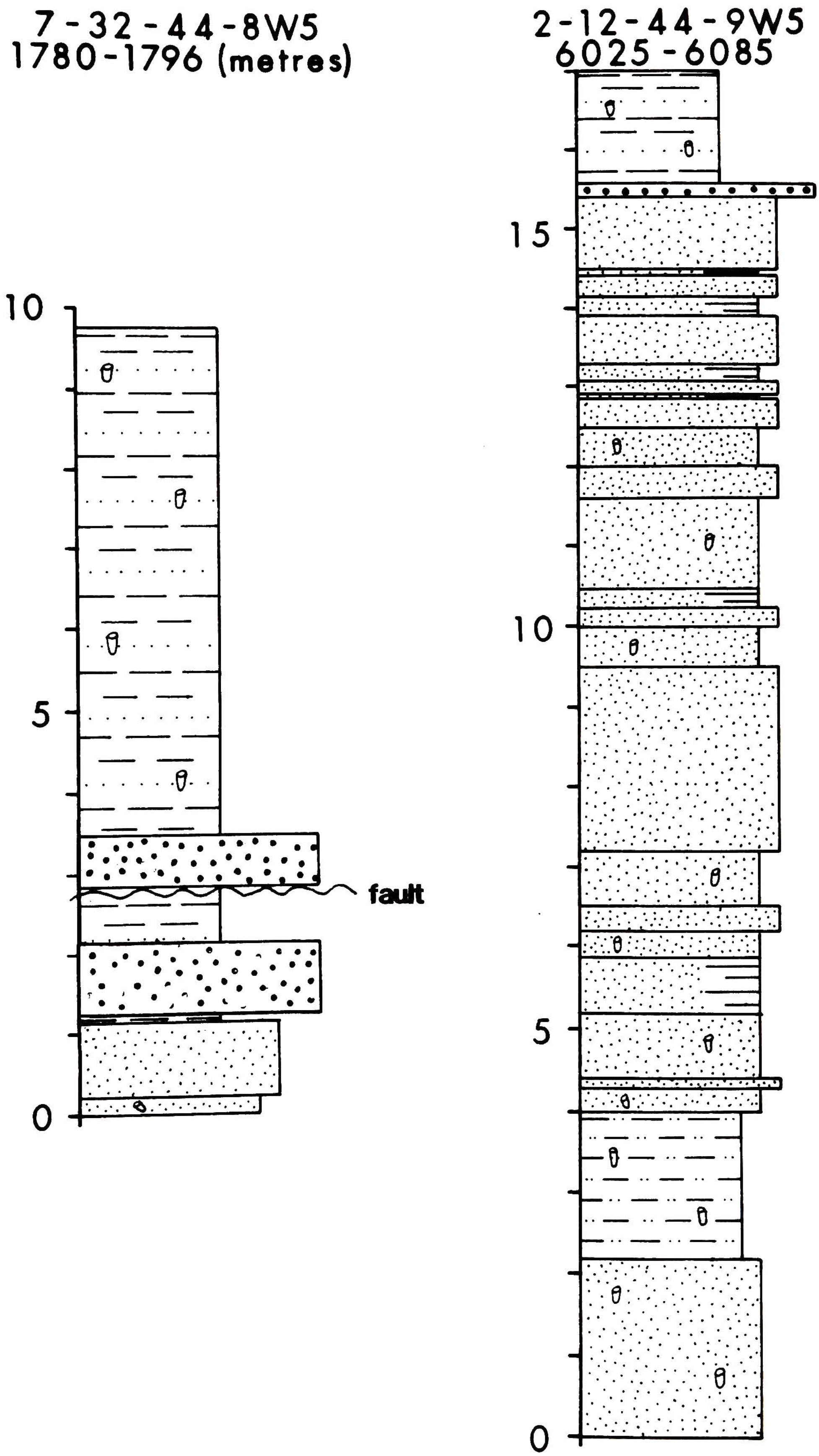
7-32-44-8W5
1780-1796 (metres)
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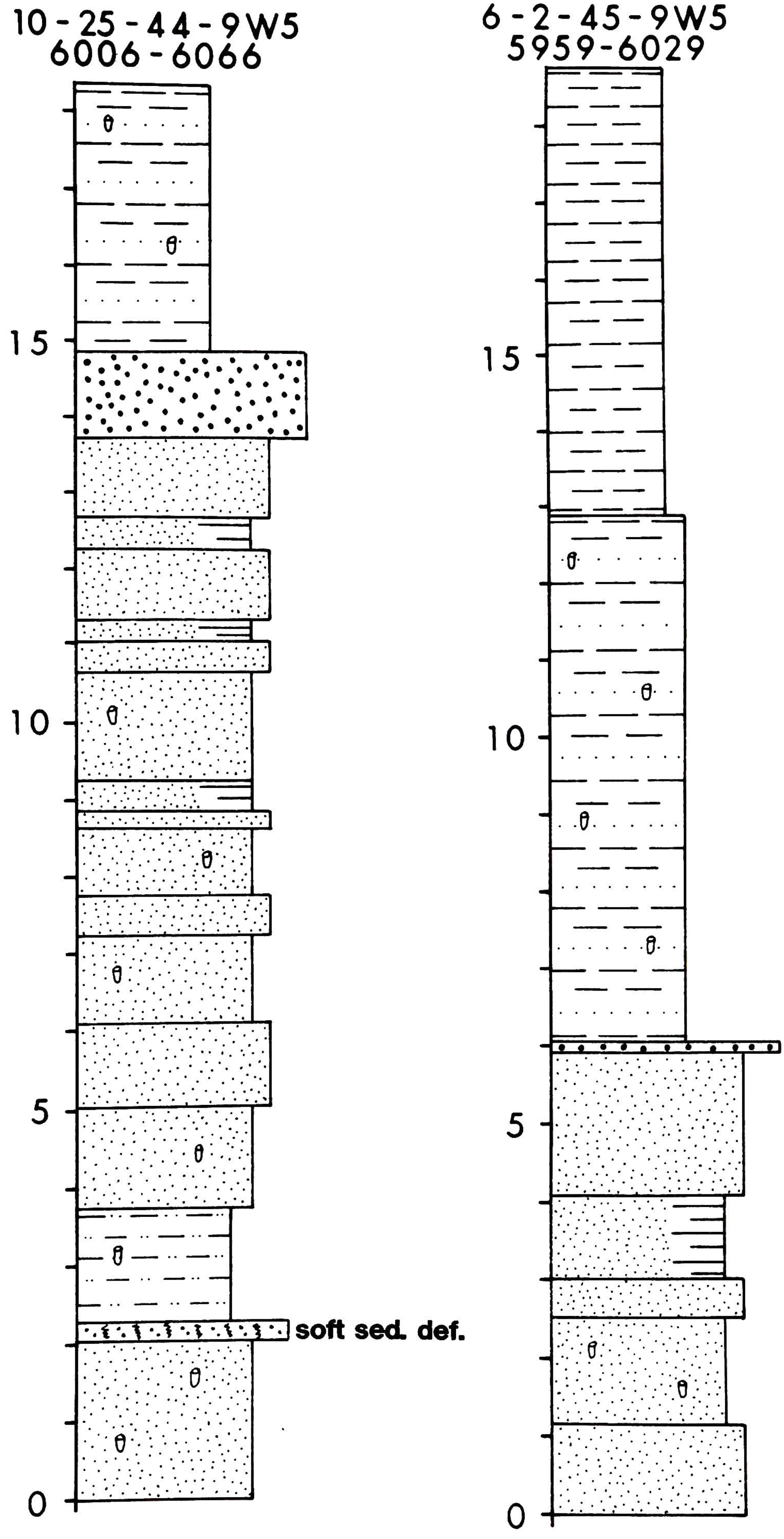
5
0
fault
2-12-44-9W5
6025-6085
15
10
5
0



10-25-44-9W5
6006-6066
6-2-45-9W5
5959-6029
15
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0
soft sed. def.
15
10
5
0