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A RECONNAISSANCE SEDIMENTOLOGICAL STUDY OF THE MIDDLE JURASSIC SHAUNAVON FORMATION, SOUTHWESTERN SASKATCHEWAN

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A reconnaissance sedimentological study of the Middle Jurassic Shaunavon Formation, Southwestern Saskatchewan

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Plates are placed at the end of the report

1. Introduction

This study was initiated whilst the author was a visiting scientist at the Institute of Sedimentary and Petroleum Geology in Calgary during the summer of 1984. Its purpose was to re-evaluate Christopher's (1964, 1966) descriptions and interpretations of the Shaunavon Formation in the light of more recent sedimentological knowledge.

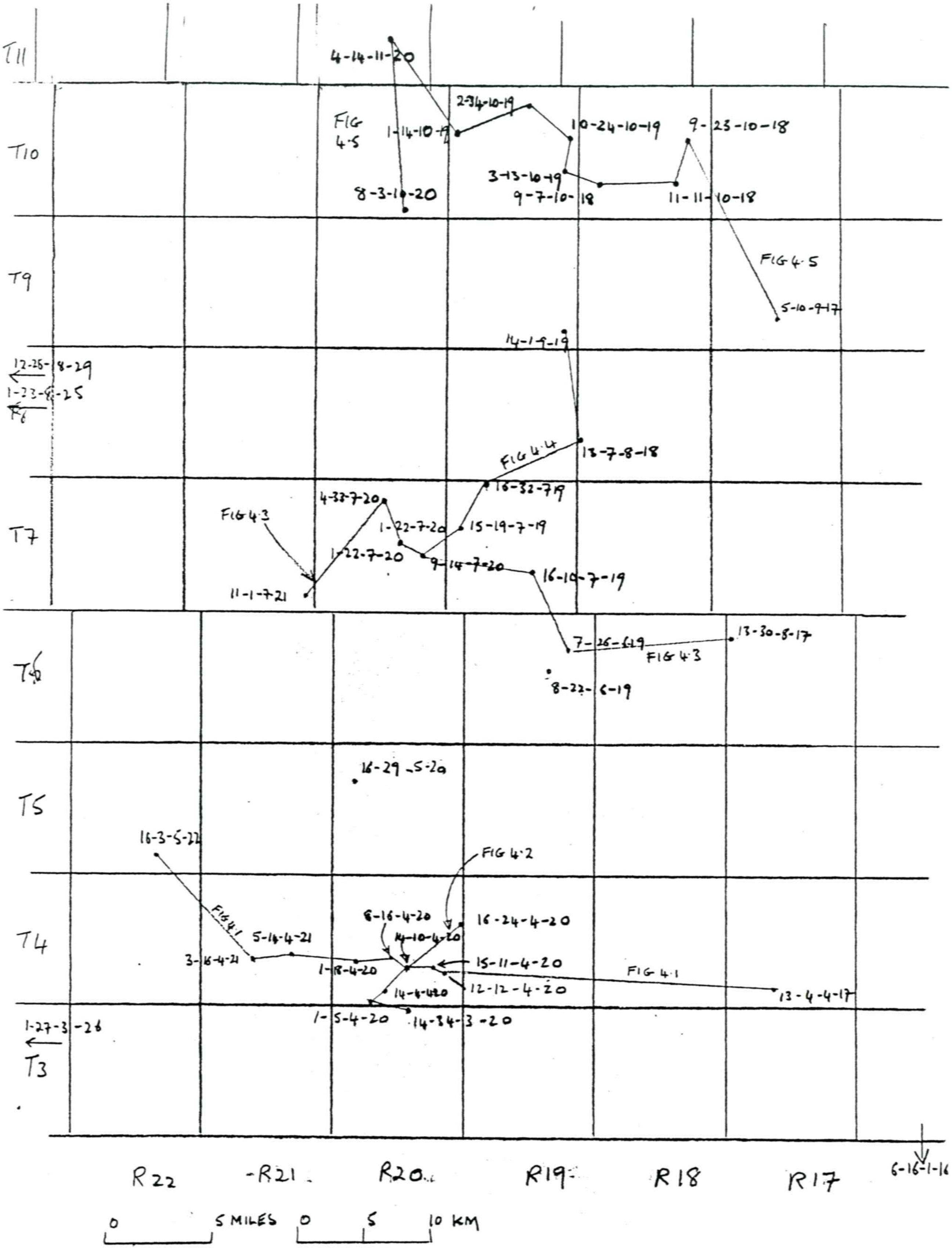
Fourteen working days were spent in the core repository in Regina. A total of 40 cored sections through the Shaunavon Formation were examined, and samples taken for more detailed petrographic study in the UK. The study is inevitably biased towards cores taken in producing fields, but an attempt was made to obtain some coverage not only between such fields, but also to the east and west of the oilfield trend. The location of the wells studied is shown in Figure 1.1. In addition, the thin section collection at the Regina core repository was also studied, and some of the illustrations in this report show these samples.

Given that Christopher (1964) suggested that the Upper Shaunavon was deposited in beach, shoal, tidal flat and channel environments, the original intention - before arriving in Regina - was to attempt a detailed study of the nature of cross stratification types present in the reservoir units. However, paucity of slabbed cores made this impossible during this initial study, and so more time was spent making a reconnaissance study of as many cores as possible in the time available.

2. Structural, stratigraphic and palaeogeographic setting of the Shaunavon Formation

The Shaunavon oil field trend is situated in the northwest quadrant of the Williston Basin. According to Christopher (1964), the Formation 'strikes northeast and dips southeast 13 to 16 feet per mile into the Shaunavon Syncline across an irregular step-like monocline' (p.3). The oil fields

Figure 1.1 Map showing the location of wells studied.



are situated along this north-south trending monocline, but in an unpublished report, McMillan (1966) suggested that in the Rapdan field, entrapment of the oil is essentially stratigraphic, 'as the height of the oil column exceeds that of the structure'.

Christopher (1964) suggested that the morphology of the Shaunavon depositional basin was influenced by four factors:

1 : draping over Precambrian topography;
2 : draping over the post-Mississippian erosion surface;
3 : subsidence due to solution of Devonian salt;
4 : long term epeirogenic factors:

However, the number of data points on Christophers structural and isopachous maps seem far too few to conclusively show the influence of factors 1 and 2 above. Christopher (1964) concluded that Shaunavon Formation spanned the Middle - Upper Jurassic boundary. However, in a recent review of the Jurassic of the Canadian western interior Poulton (1984) showed the Formation as Late Bajocian - Early Bathonian in age (see Fig. 2.1).

Figure 2.2a shows generalised facies maps for the Bajocian and Bathonian. From these maps, it seems likely that the Shaunavon sea was connected to the epi-continental seaway to the west, although the Sweetgrass Arch was a positive area over which Jurassic strâta thinned significantly (see Fig. 2.2b). If the Williston Basin was connected to the epi-continental seaway during the Middle Jurassic, then it is probable that the Williston 'sea' at this time was affected by tidal currents as it was during the Late Jurassic (see review by Bridges, 1982).

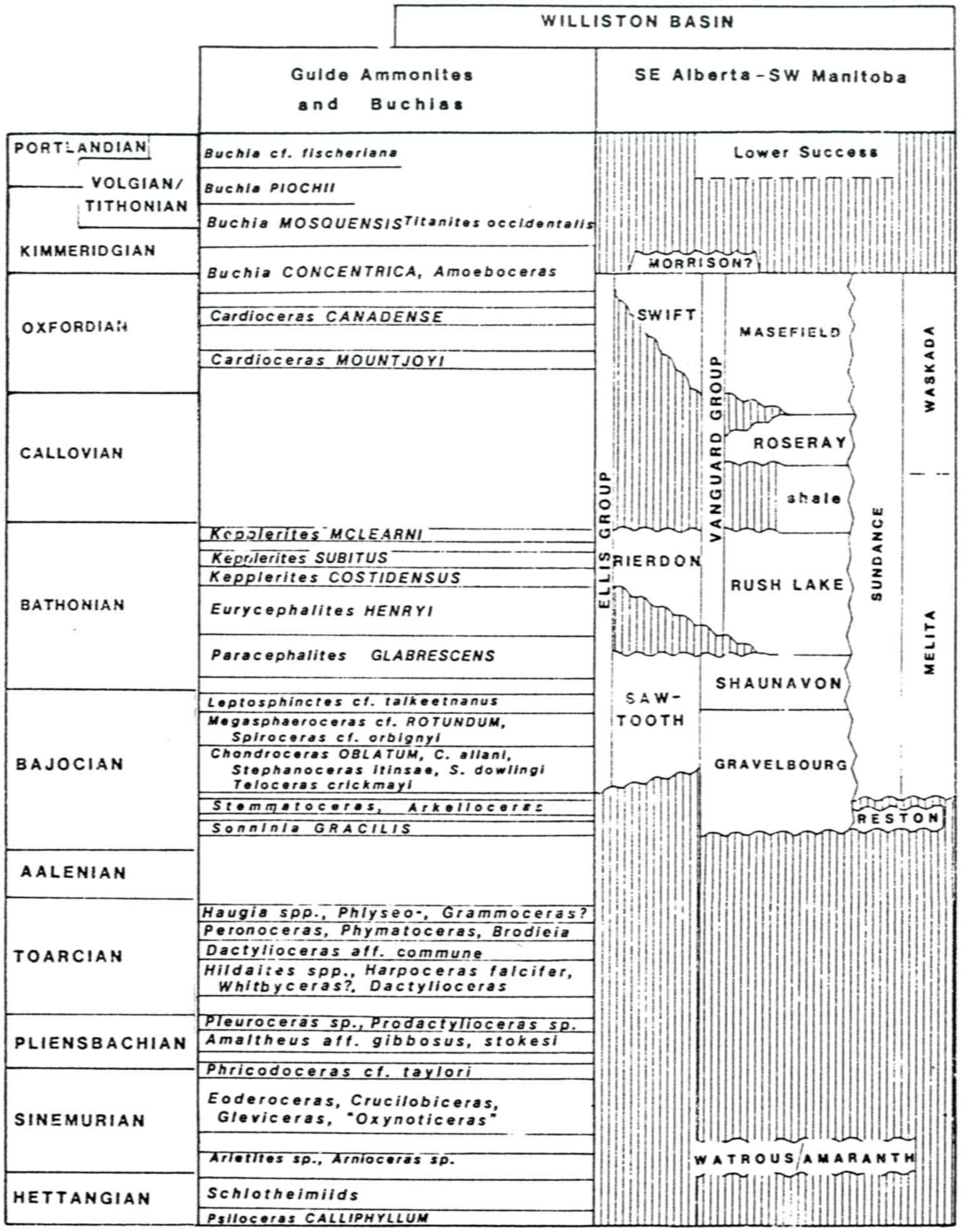
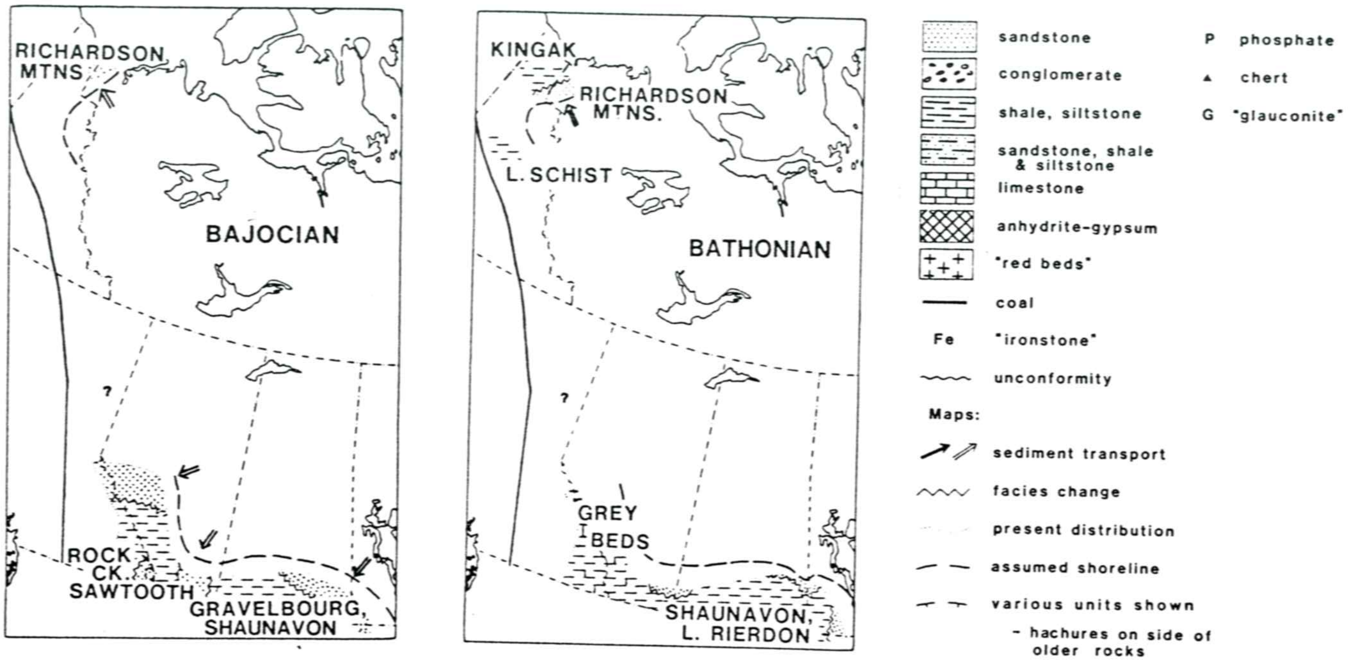
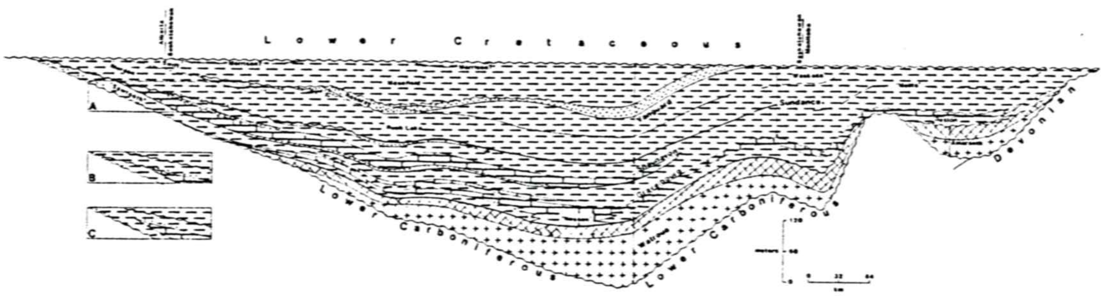


Figure 2.1 Jurassic Stratigraphy of Western Canada (from Poulton, 1984)





East-west stratigraphic cross-section across northern margin of the Williston Basin in southern plains of Canada, modified from Francis (1956) with additional data mainly from Stott (1955), Weir (1949), and Christopher (1964, 1974). Three alternative correlations (A, B, C) of the Sawtooth Formation are shown. The second (B) involving overstep of the Gravelbourg by the Shaunavon is most conventional.

Figure 2. 2. Generalised maps of lithofacies distributions in Western Canada and in cross section across the Williston Basin (from Poulton 1984).

3. The Lower Shaunavon

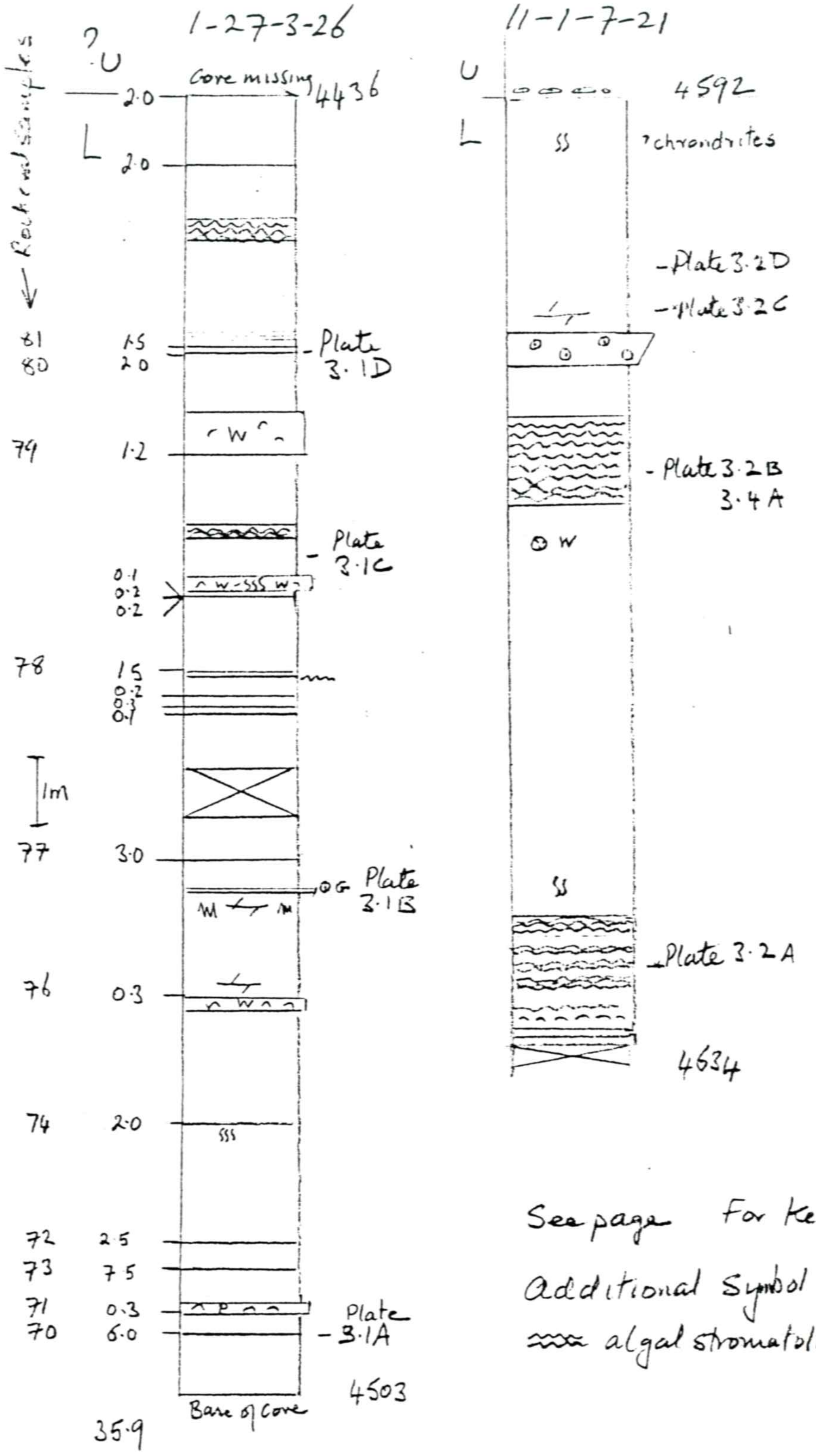
At an early stage during the examination of the cores it was decided to devote most of the time available to study the more lithologically variable Upper Shaunavon. Therefore, only two sections are shown here through the Lower Shaunavon (see Fig. 3.1). The following lithologies were recognised:

1. Micrites: usually cream to light grey in colour, with faint laminations. SEM examination revealed no traces of planktonic organisms contributing to the carbonate mud. Scattered layers of small bivalves are present along some bedding planes (Plate 3.1C).

2. Skeletal wackestones show skeletal material ranging from complete shells or corals, to sand sized grains. Some beds show a sharp erosive contact with underlying bituminous shales (Plate 3b, C), and may grade upward into the latter rock type.

3. Bituminous shales are very finely laminated, and often contain skeletal material (oysters or echinoderm plates) around which the fine sediment has compacted (Plate 3.3A, E). The skeletal material is both scattered through the shales and concentrated in thin layers 1 - 2mm thick. It is possible that these layers were deposited as debris flows as perhaps were the skeletal wackestones overlying some bituminous shale intervals.

   Rockeval data from one well is shown below, and reveals quite high TOC values. However, the sediments have not yielded oil, as they are immature (T max < 435°), although further to the SE of this location they may be expected to be slightly more mature at greater depths. However, unless the Lower Shaunavon contains a significantly greater thickness of bituminous



See page for key

Additional symbol

〰 algal stromatolites

shales than Well 1-27-3-26 (which has a total of 36 cm) in this direction, the Lower Shaunavon is unlikely to have yielded significant amounts of oil.

Rockeval data from Well 1-27-3-26 (see Fig. 3.1 for sample locations).

	ORG.C	PI	S1+S2	TMAX	S1	S2	S3	HI	OI
S70	2.20	.09	13.85	429	1.28	12.57	.51	571	23
S71A	1.06	.08	3.60	427	.29	3.31	.29	312	27
S71B	1.09	.11	1.66	428	.19	1.47	.22	134	20
S72	3.52	.06	15.55	423	1.00	14.55	.59	413	16
S73	1.72	.08	6.38	423	.48	5.90	.38	343	22
S74	4.54	.08	16.35	419	1.33	15.02	.79	330	17
S76	.80	.12	1.00	437	.12	.88	.14	110	17
S77	7.12	.07	23.97	421	1.66	22.31	1.04	313	14
S78	2.48	.09	10.00	428	.92	9.08	.74	366	29
S79	3.56	.08	13.74	426	1.11	12.63	1.10	354	30
S80A	.73	.14	1.94	433	.27	1.67	.75	228	102
S80B	1.32	.10	10.42	422	1.05	9.37	.74	709	56
S80C	.19	.17	.23	436	.04	.19	.15	100	78
S81	2.35	.09	10.14	423	.91	9.23	.85	392	36

4. Ooid grainstones. Christopher (1964) reported that these are widespread near the top of the member, and may be up to 20 feet thick. They consist of well sorted grains up to 0.3mm in diameter, usually cemented by coarse equant calcite and showing significant intergrain dissolution features.

5. Boundstones. Stromatolitic layers are quite common in the Lower Shaunavon, and may consist of purely algal stromatolites (Plate 3.2A), or corals coated by algae, with some examples bored by bivalves (Plate 3.2B, 3.4A-C). Further work on these stromatolitic sediments will be undertaken in collaboration with Dr. V.P. Wright.

6. Dolomites in the Lower Shaunavon appear to be replacive, whereas those in the Upper Shaunavon occur as cement, and may have formed in a tidal flat environment. Dolomitisation has affected lime mudstones, and produces a mottled fabric (Plate 3.2C) in which

> the dolomite contains small amounts of oil. Partially dolomitised allochem limestones also occur (Plate 4.4, D & E). Christopher's map (1964, Fig. 11) shows that dolomitised Lower Shaunavon occurs to the west of the oilfield trend, except in the Instow - Bone Creek area, where it extends within the oilfield belt.

The most striking feature of the Lower Shaunavon is the virtual absence of siliciclastic material, in comparison to its abundance in the Upper Shaunavon. This suggests deposition during a major transgressive episode which prevented siliciclastic deposition. The laminated bituminous shales were deposited below fair-weather wave base in anoxic bottom conditions. The oyster and echinoderm remains found within this lithology appear to have been transported episodically into the anoxic bottom environment, perhaps due to storm activity. The occurrence of stromatolites, corals and a variety of bivalves suggests deposition in a shallower more aerated environment. Likewise, the ooid grainstones also indicate shallower more turbulent conditions, although the structureless thin beds of this lithology illustrated on the log in Figure 3.1 could have been resedimented into a deeper water environment.

4. The Upper Shaunavon

4.1 Principal lithologies

The main rock types identified in the Upper Shaunavon are tabulated below:

SILICICLASTICS	Sandstones	° with large scale cross stratification
		° with small scale cross stratification
		° bioturbated
	Mixed Sandstones and shale	° wavy bedded
		° bioturbated
	Shales	
CARBONATES	Dolomites	° dolomitic mudstones
		° dolomitic sandstones
		° dolomitic limestones
	Limestones*	° peloidal packstones
		° ooid packstone and grainstones
		° skeletal sands (a spectrum ranging from wackestones to grainstones)
		° oncolitic packstones and grainstones (see Christopher, 1964, Fig. 17).
		° micrites

* All limestones contain varying amounts of fine grade siliciclastic sand

Sandstones

Irrespective of the sedimentary structures present, consist of moderately to well sorted fine sand (~0.2mm), dominated by quartz grains that are subangular to subrounded. They range from entirely uncemented varieties, to sands with patchy calcite cements that seeded off scattered skeletal grains. Many non-porous sandstones either contain a fine grained dolomite matrix, or an admixture of clay. SEM studies reveal that many sandstones contain grains that exhibit varying developments of quartz overgrowths, particularly where carbonate matrices are absent, or poorly developed, as in many reservoir sands (see Plate 4.2). The paucity of slabbed cores rendered detailed study of the sedimentary and biogenic structures difficult, and so the simple tri-partite division of sandstones tabulated above was adopted when compiling logs of the sequences.

Sandstones in the Upper Shaunavon form the end member of two spectra of sediments leading to dolomitic sediments and the various types of limestone tabulated on the previous page.

Mixed sandstones - shales (Plate 4.1 A - C).

Although the proportion of sandstone and shale present in parts of the Upper Shaunavon is quite variable, in the absence of slabbed cores, no attempt was made to make detailed divisions such as those suggested by Reineck & Singh (1973). Most heterolithic sequences studied were dominated by wavy or lenticular bedding, and to aid speed of logging during this reconnaissance study they were grouped as one lithofacies on the logs presented in this report. Rare examples of wave ripples were seen, and several examples of wavy/lenticular bedded units exhibiting low angle master bedding, probably due to lateral accretion, were observed (Plate 4.1A).

Shales

Following McMillan (1966), no attempt was made to record subtle differences between different types of shale based on colour. After initially recognising six different categories, he found a division into calcareous, non-calcareous and red shales was a more practical definition. During this study, the majority of shales were found to be calcareous, and examples of shales that swelled when wetted were also quite common. As noted by McMillan, the non-calcareous and red shales contain slickensides; the present author believes these probably to be the result of pedogenic processes.

A few samples of dark grey green shales from the base of the Upper Shaunavon were collected to assess their petroleum source rock potential. TOC valves that ranged from 0.4 to 0.8% were obtained, confirming the impression gained from core examination that these shales are lean.

Dolomites

Dolomitic mudstones and sandstones usually occur as inter-laminated deposits (see Plate 4.3C, D). Under the SEM the mudstones usually exhibit idiotopic dolomite rhombs up to 10 m across. One example of laminated dolomitic mudstone with a brecciated interval was observed (Plate 4.3F). In core descriptions, Christopher (1966) noted contorted intervals in several dolomitic units. Dolomitic sandstones contain similar dolomite crystals (Plate 4.5,C,D), although in a few cases larger crystals are present which clearly formed as cement. Frequently, the quartz grains are seen floating in the dolomitic matrix, or quartz rich laminae are separated by dolomitic mudstone layers. In hand specimen, various combinations of dolomitic sandstones and mudstones can be seen:

(i) laminated sediments in which quartz rich layers show slight crenulations (Plate 4.3A). The origin of these features is uncertain, but the possibility that they formed as wind (adhesion) ripples cannot be ruled out;

(ii) drapes over ripples within ooid grainstones (Plate (4.6C);

(iii) mottled sediments (Plate 4.3B) due either to bioturbation or perhaps to adhesion ripples.

Dolomitic limestones consist of three main types:

(1) grainstones with an early (pre-compaction) drusy dolomite fringe, where the dolomite clearly developed as a cement (Plate 4.7F);

(2) dolomite partially replacing allochems, the packing of which suggests an original mud supported fabric, in which case the dolomite has also replaced an original matrix;

(3) packstones and wackestones with a dolomitic mudstone matrix, but showing no dolomitisation of allochems (Plate 4.7 G,H);

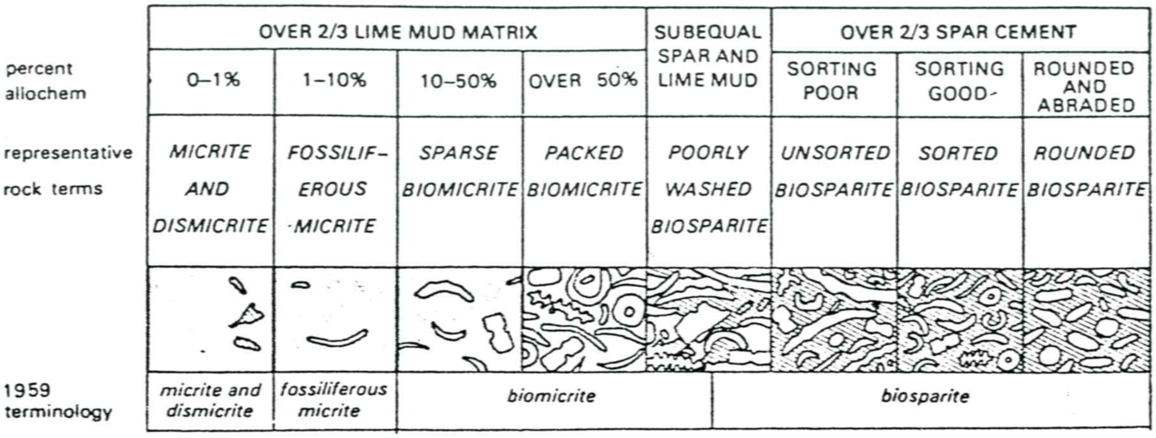
(4) dolomitic micrites (i.e. micrite only partially replaced by dolomite;

Limestones

Peloidal packstones consist of well sorted fine sand (0.1 - 0.2mm) grade peloids with some superficial ooids; the amount of quartz sand is variable, as high as 20% (Plate 4.7A). Skeletal debris also may occur, and is generally much abraded and micritised. In cores, this lithology usually shows wavy bedding (similar to that shown in Plate 4.8A,B).

Ooid packstones and grainstones. The grain size of this category ranges from 0.2 to 0.5mm. Sorting is usually good, but packstones show a greater variability of allochem size. Ooid nuclei consist of quartz grains, peloids or skeletal fragments. Skeletal debris is commonly present. Grainstones are cemented by early (pre-compaction) iron free drusy calcite fringes with late iron free equant calcite filling the remaining pores after compaction (Plate 4.7C-E). Dolomite fringes may occur instead of calcite drusy fringes in some grainstones, particularly in the Rapdan area (Plate 4.7F). Packstones commonly possess a dolomite mudstone matrix. Sedimentary structures within Upper Shaunavon oolitic rocks are generally indistinct, although high angle (up to 20°) 'master bedding' is quite common.

Skeletal sands. The Upper Shaunavon contains a textural spectrum of skeletal sands akin to that illustrated by Folk (1962). Figure 4.1 illustrates this spectrum, and cites examples illustrated in Plates 4.8, 4.9 and 4.10. Significant amounts of quartz grains of fine sand grade are always present in the skeletal sands. It is clear that skeletal debris forms a significant proportion of Upper Shaunavon limestones. However, intact fossils appear to be relatively rare in the Shaunavon, except where tests of burrowing bivalves are preserved as molds in wavy bedded siliciclastic and carbonate lithologies. The skeletal sands appear to be dominated by molluscan debris; echinoderm plates form a small but significant fraction of the sediments. Some limestones are completely dominated by shells which in life were secreted as calcite (Plate 4.10A); this may be due to sorting or ecological effects, or due to the diagenetic destruction of shells which in life were composed of aragonite. However, diagenetic processes cannot account for sands dominated by skeletal debris that was originally composed of aragonite (see Plate 4.10D). Skeletal sands form important reservoirs in the Upper Shaunavon; with submature and mature types (see Fig. 4.1) exhibiting the best porosity. It is perhaps surprising that supermature skeletal sands do not form good reservoirs, given that they would have possessed good depositional porosity However, both their depositional intra-particle porosity, and moldic porosity consequent on aragonite solution are today invariably filled with sparry calcite.



	OVER 2/3 LIME MUD MATRIX				SUBEQUAL SPAR AND LIME MUD	OVER 2/3 SPAR CEMENT		
percent allochem	0–1%	1–10%	10–50%	OVER 50%		SORTING POOR	SORTING GOOD-	ROUNDED AND ABRADED
representative rock terms	*MICRITE AND DISMICRITE*	*FOSSILIF-EROUS ·MICRITE*	*SPARSE BIOMICRITE*	*PACKED BIOMICRITE*	*POORLY WASHED BIOSPARITE*	*UNSORTED BIOSPARITE*	*SORTED BIOSPARITE*	*ROUNDED BIOSPARITE*
1959 terminology	*micrite and dismicrite*	*fossiliferous micrite*	*biomicrite*			*biosparite*		
Shaunavon examples illustrated in Plates:			4.10B	4.8E	4.8F	4.9A,B 4.10C		4.10D,E

Figure 4.1 Folk's textural spectrum of skeletal limestones, with Shaunavon examples illustrated in this report listed. Unsorted biosparites/skeletal grainstones appear to form the best carbonate reservoirs.

4.2 Limestone diagenesis

The diagenetic history of the Upper Shaunavon carbonates appears to have been relatively simple. The following general diagenetic sequence can be recognised in the majority of the carbonate sands:

1. dissolution of aragonite shell material;
2. precipitation of iron free drusy calcite as linings to intra particle pores, and to shell molds;
3. compaction: fracturing of grains and inter-particle solution;
4. precipitation of calcite spar (usually iron free) in remaining porosity;
5. continued compaction may occur enhancing earlier grain contact effects, and through the development of stylolites.

Good reservoir units, have, it seems, only suffered the first three stages listed above.

In the Rapdan Field, some oolite grainstones show dolomite crystals lining inter-particle pores instead of Stage 2 drusy calcite (see Plate 4.7F). Ferroan calcite is not commonly developed, and appears rarely in reservoir sands. It is, however, common as moldic fills in large shells present in skeletal wackestones. Occasional vuggy porosity occurs in some mature skeletal sands (Plate 4.10D) as a result of both calcite solution and the incomplete cement infilling to shell molds.

The presence of thin layers of shell debris within siliciclastic reservoir sands may result in a severe reduction of their gross vertical permeability, as carbonate cements develop within such layers. Echinoderm plates are particularly important in this regard, as they act as 'seeds' for the relatively rapid development of syntaxial overgrowths which quickly plug pore spaces.

4.3 Environmental interpretation

4.3.1 Introduction

Christopher (1964) suggested that Upper Shaunavon sediments were formed as beach, shoal, tidal flat and channel deposits. McMillan (1966) reached similar conclusions commenting, like Christopher, that the dolomitic sediments probably formed in tidal flats subject to arid conditions; he also suggested that the presence of red sediments indicated an interval of subaerial exposure. He postulated that the blue grey oolitic and coquinoidal limestones commonly found near the base of the Upper Shaunavon were deposited in non-evaporative bays or lagoons with reducing bottom conditions. He attributed a beach origin to the siliciclastic sands on the basis of their generally horizontal laminations and the absence of cross bedding. Today the industry view of the depositional environment (Godkin, personal communication, 1984), has much in common with the earlier conclusions, namely a belt of shelf and shallow marine sands trending NNE-SSW, traversed by tidal channels, and forming a barrier protecting lagoons to the west beyond which occur 'blanket' or 'fluviatile' sands. In an undergraduate thesis, Tritthart (1980) suggested that the Whitemud field developed as a 'marine sand bar' trending NE-SW.

The purpose of this section of the report is to review the evidence available concerning the lithofacies distribution of the Upper Shaunavon in the light of modern sedimentological knowledge concerning shoreline and shallow shelf sea sediments (see Elliott 1978, Johnson 1978, Reinson 1984 and Walker, 1984, for reviews of the sedimentology of these environments). The discussion is divided into sections dealing with (i) the broad palaeogeographic setting, (ii) environmental significance of selected depositional and diagenetic features (iii) sand body geometry and finally (iv) a brief review of the possible environments of deposition of the three larger oil fields.

4.3.2 Palaeogeographic setting

Poulton's (1984) generalised facies distribution maps suggest that the Jurassic 'Williston sea' was linked to a shallow sea that existed in southern Alberta (see Fig. 2.2a); it is not clear from these maps whether this western shelf sea was connected with the open ocean to the west, or north. Thus it is difficult to assess the extent to which the Shaunavon sea was subject to tidal currents. It is not improbable that it was a mesotidal sea, as suggested by Bridges (1982) for the Upper Jurassic and Upper Cretaceous North American epicontinental seaway.

Given the overstep of Jurassic formations around the margin of the Williston Basin (see Fig. 2.2b) it is probable that large areas bordering it during the Middle Jurassic comprised outcrops of Upper Palaeozoic carbonates. If this were the case, the amount of siliciclastic influx into the Williston Basin would have been relatively low at this time, but windblown carbonate detritus might also be expected to have contributed significantly to the sediments as is the case today along the southern margins of the Arabian Gulf. Christopher's (1964, Fig. 22) isopachous map of the Upper Shaunavon shows a general thickening of the unit to the SE which may indicate that the palaeoslope at the time was inclined gently in the same direction. Superimposed on this trend, Christopher showed a region of more complex variations in thickness which coincides with the NNE-SSW oil field trend. This second order pattern may partly be artificial due to the abundance of well data in this region in contrast to much greater well spacings elsewhere. It may also be due, as McMillan(1966) implied, to an irregular top Lower Shaunavon topography caused by pre-Upper Shaunavon erosion. If such a topography existed, then it would have exerted a considerable influence on the lithofacies distribution within the Upper Shaunavon. The control of sea-bottom topography on the nature and geometry of deposits deposited by Holocene transgressions has been demonstrated in many parts of the world, and so it is likely that similar effects have have effected the Upper Shaunavon.

4.3.3 Some depositional and diagenetic environmental indicators

No single sediment type can provide unequivocal evidence on which to base environmental interpretations. But a consideration of the nature of the sediments and accompanying diagenetic features present in the Upper Shaunavon can narrow down the choice of alternative depositional models. The following comments can be made:

(i) Fauna and flora: the microfauna (Wall, 1960) and macrofauna (Christopher 1964, Paterson 1968), indicate that the Upper Shaunavon is largely marine in origin. The abundance of echinoderm debris in some sands observed during this study suggests normal marine salinities, but other sediments containing an abundance of one or two bivalve species may indicate raised or lowered salinities. Wall

(1960) described charophytes from the Upper Shaunavon, and Paterson (1968) reported a charophyte marker band about 10 feet from the top of the member. Although charophytes can tolerate saline conditions, today they only flourish in freshwater.

(ii) Well sorted oolitic, skeletal and siliciclastic sands point to high energy conditions. The supermature texture of some of the skeletal sands suggest prolonged transport and abrasion, as does the quartz dominant composition of the siliciclastics.

(iii) Dolomitic sediments. Both Christopher (1964) and McMillan (1966) interpreted these sediments as having been deposited in arid tidal flat environments. However, during the present study, few features characteristic of Recent tidal flat sediments, such as those known from Andros Island or the Persian Gulf, have been found. Algal mats and stromatolites are not present (apart from one stromatolitic dolomite, see Plate 4.6A), as are features characteristic of exposure such as fenestrae. A few examples of dessication cracks have been found together with brecciated dolomitic mudstone (see Plate 4.3F). One example of possible evaporite solution breccias was discovered (Plate 4.3G), and this is consistent with author's discovery of gypsum in the Suction Creek Dome section (described by Hearn et al, 1964) of Upper Shaunavon equivalent in Montana. Thus there is some evidence to support an evaporative tidal or wind flat origin for the dolomitic sediments. However, other origins for the dolomite must be considered, the two most plausible of which are detrital (wind-blown) origin, or replacement of calcium carbonate after burial. No unequivocal evidence for detrital dolomite has been found, although one SEM view (Plate 4.5A,B) shows slightly rounded dolomite rhombs. In addition, some structures in dolomitic sands could have been produced by adhesion ripples (see Plates 4.3A,B,C).

Evidence for dolomite replacement is present, both in the form of replacement fabrics and indirectly in the form of allochems being preserved as empty molds with fine grained dolomites (Plate 4.7H). However, fine grained dolomite also occurs as the matrix to ooid packstones, the allochems of which show no dolomite replacement. Some grainstones showing partial dolomite cements also exhibit small patches of fine grained dolomite, suggesting that dolomite cements may have developed as a fine grained fabric. Examples of early, pre-compaction dolomite cement lining pores also occur. To sum up, there is evidence in the Upper Shaunavon favouring three plausible modes of origin of dolomitic sediments:

- tidal flat dolomites : perhaps a mixture of evaporative and detrital dolomite.
- replacive dolomite, possibly produced by the mixing of marine and freshwater (see later discussion on diagenesis).
- dolomite cements, certainly as pore linings, and possibly as fine grained dolomite.

(iv) Aragonite solution and calcite cementation. Upper Shaunavon skeletal sands invariably show aragonite solution followed by the development of drusy fringe calcite cement within both the primary inter-particle and secondary moldic pore spaces. These features are characteristic of the freshwater phreatic diagenetic environment (Longman, 1980), implying a significant flow of freshwater soon after deposition (because the drusy calcite pre-dates any compaction features). Therefore it is probable that freshwater lenses developed in association with the Shaunavon reservoir sand bodies, which implies emergence. Other evidence for emergence is provided by red shales and apparently random slickensiding in shales probably caused by pedogenic processes. The abundance of charophytes at the top of the Upper Shaunavon also suggests the presence of freshwater.

If freshwater lenses did develop, then mixing zone dolomitisation might account for the origin of the dolomitic sediments, which, perhaps not coincidentally, occur beneath, or on the flanks of reservoir sands. In this context, it is interesting to note that Christopher (1964, Fig.11) shows that dolomitisation of the Lower Shaunavon occurs to the west of the oil field trend, and lies beneath it in the Instow - Leon lake area.

No evidence was found to indicate the development of marine cements that are characteristic of beach zones.

4.3.4 Sand body geometry

The NNE-SSW trend along which the Upper Shaunavon reservoir sands are concentrated has already been commented upon. The spacing of the wells examined during this study (Fig. 1.1) does not allow any original comments to be made about sand body geometries. The oil fields, which are usually elongate, are 1 - 3km across, and up to 20km long. From evidence cited earlier, it is clear that their shape is the result of depositional processes being overprinted by diagenetic effects. Clearly, the location of freshwater lenses which appeared to have been so important in both producing porosity (through aragonite solution) and occluding it (through calcite cementation) would have been controlled significantly by the geometry of units originally possessing high primary porosity. Thus the shape of the oil fields may offer some clues concerning the broad depositional environment of the Upper Shaunavon.

Shallow marine and barrier system sand bodies exhibit the following general characteristics (see reviews in Reading, 1978, and Walker, 1984).

Barrier islands. The barrier system is oriented parallel to the shore, but inlet fills (which are most likely to be preserved during transgressions) may be oriented perpendicular or oblique to this trend; they possess erosive contacts with underlying sediments. Barriers fringing microtidal seas are long and narrow, whereas those bordering mesotidal seas are short and stunted. Microtidal barriers are considerably affected by storms causing frequent washovers, whereas mesotidal barriers exhibit washover and tidal deltas.

Shallow marine sand ridges

(i) Storm sand ridges may be up to 10m high, 2 - 3km wide and a few tens of kilometres long and oriented obliquely to the shoreline.

(ii) Tidal sand ridges may be shore parallel or oblique, and those on the edge of the continental shelves (e.g. in the Celtic Sea) may be normal to the shelf edge. They are up to 40m high, up to 5km long, and range in length from 15 to 90km. Johnson (1978) has suggested that extensively cross bedded sandstone bodies probably have a tidal origin, whereas a broader range of structures indicates a storm origin.

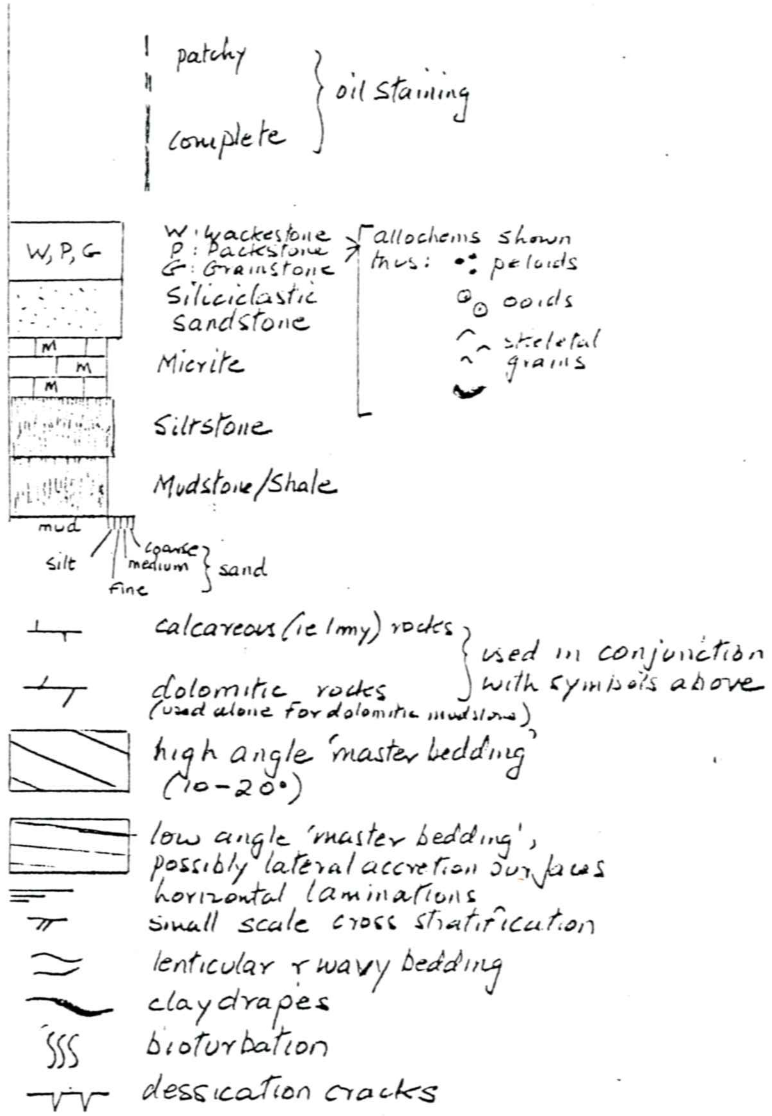
The dimensions of the larger oil field areas and their orientation with respect to the inferred palaeoslope preclude a microtidal barrier system. If they originated as a mesotidal barrier system, then evidence for tidal inlets and associated tidal deltas should be present, together with some of the characteristic features of shoreface, foreshore and backshore sands, with lagoonal sediments situated behind (to the west) of them. If the Shaunavon reservoir sands were deposited as tidal sand ridges, they should largely be encased in marine sediments, and oriented either parallel to the shoreline, or perpendicular or oblique to a shelf break of some kind.

The characteristic features of sequences in the three principal oilfield areas studied are reviewed in the next section in the light of the previous discussion.

Summary sections of cored intervals are depicted on Figure 4.2 - 4.6. Although previous reports describing the Shaunavon have used fence diagrams, this practice is not adopted here, for the well spacing on the Figures is seldom less than a kilometre, and usually much more. Given the dimensions of modern barrier sands and shallow marine sand ridges, only the well spacing achieved in producing areas is likely to reveal the true nature of the geometry of the Shaunavon reservoir sands.

EXPLANATION TO FIGURES 4.1 - 4.6

The symbols below are used to depict the broad features of Upper Shaunavon cores studied. The successions are hung arbitrarily on the basal Vanguard. The logs were completed from original measurements of the cores, with the only allowance for missing core being made when gaps were left in the core boxes (unfortunately no percentage recovery is given on the core boxes). This has resulted in the thicknesses of the successions depicted not corresponding to the true thicknesses. As the main purpose of this work was a rapid reconnaissance study, it was decided not to waste time trying to adjust the logs to give true thicknesses.



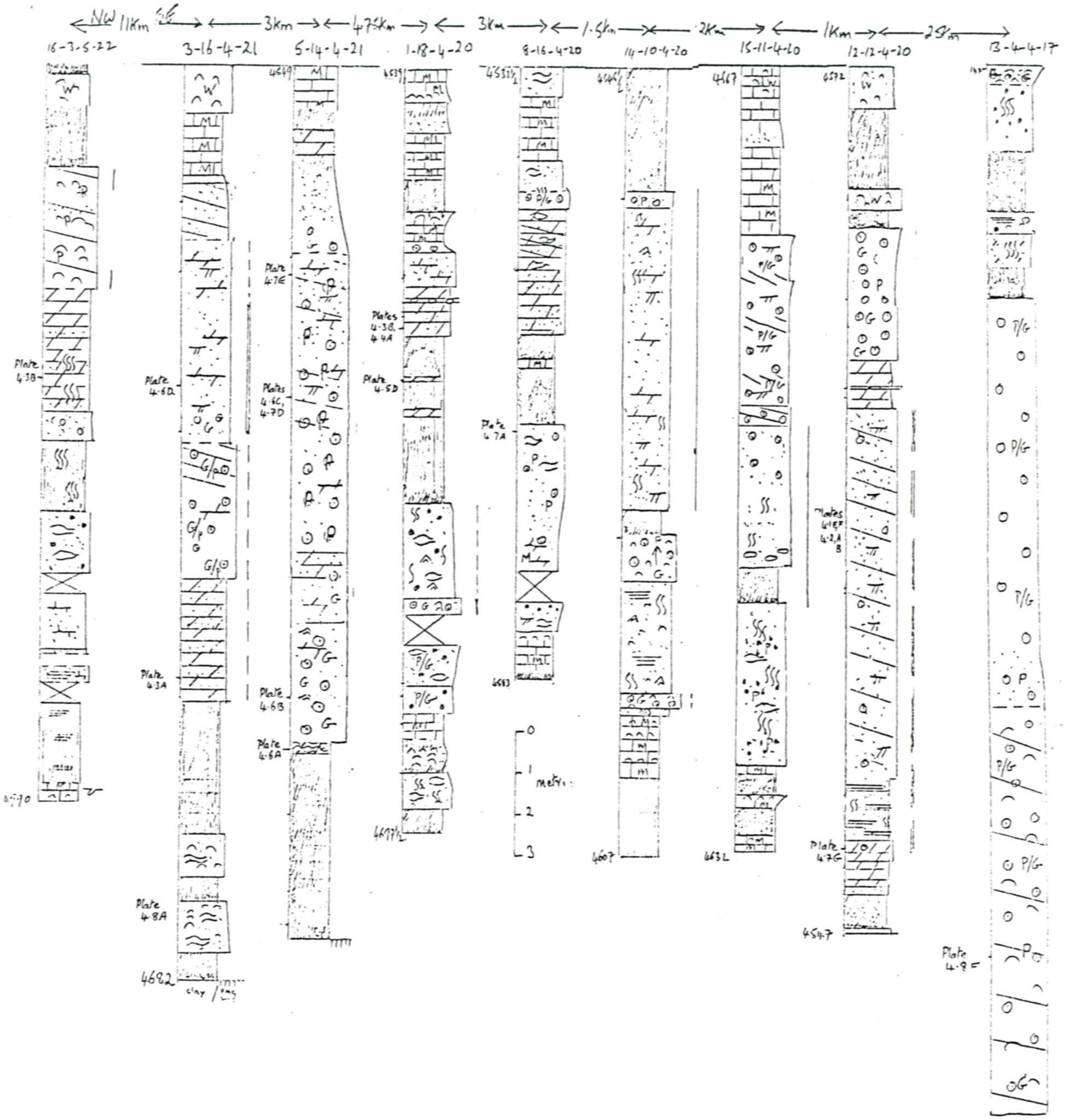


Figure 4.2 Sketch logs of cores from the Rapdan oilfield and nearby areas (for location see Fig. 1.1).

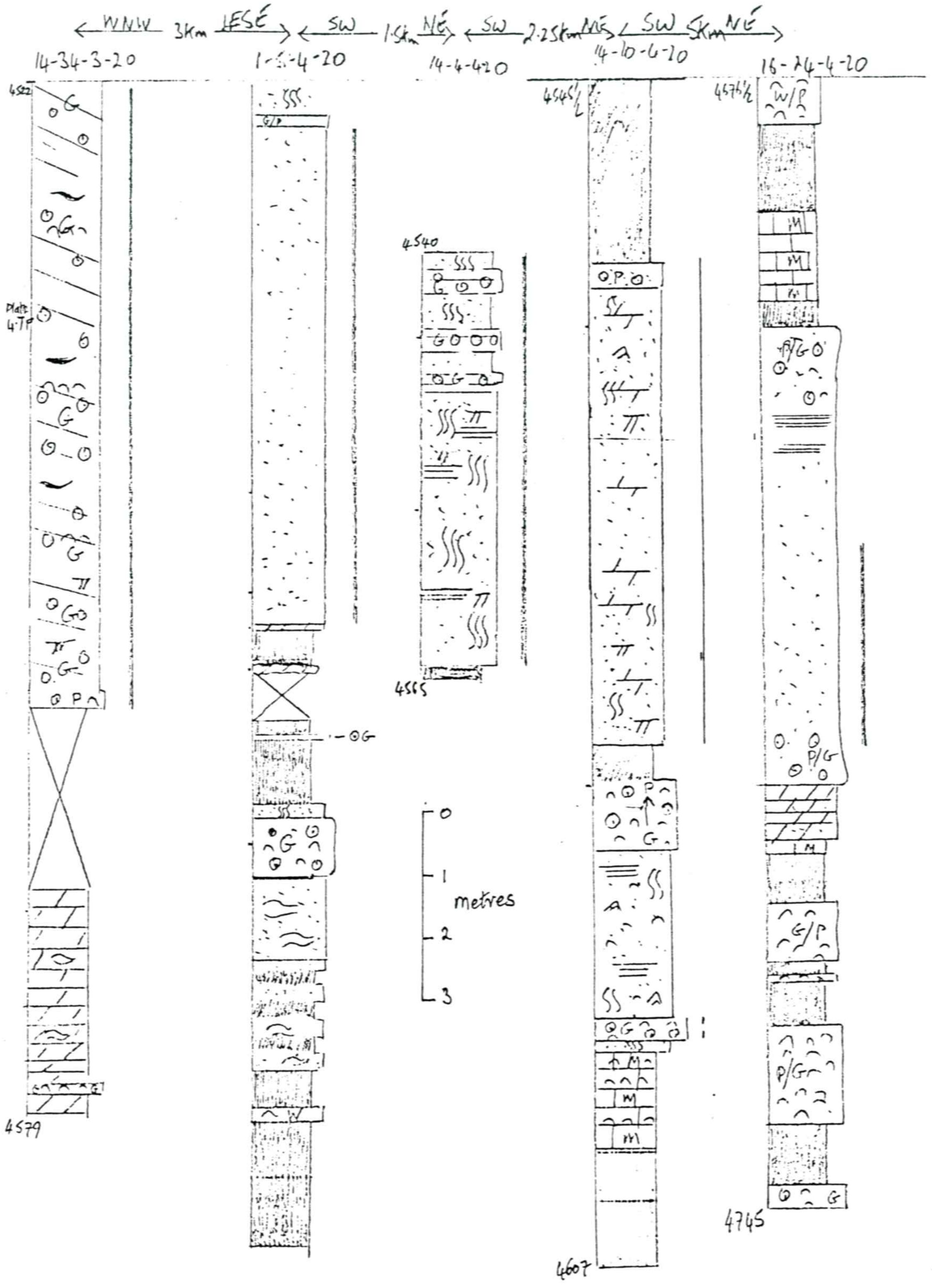


Figure 4.3 Sketch logs of cores from the Rapdan oilfield and nearby areas (for location see Fig. 1.1).

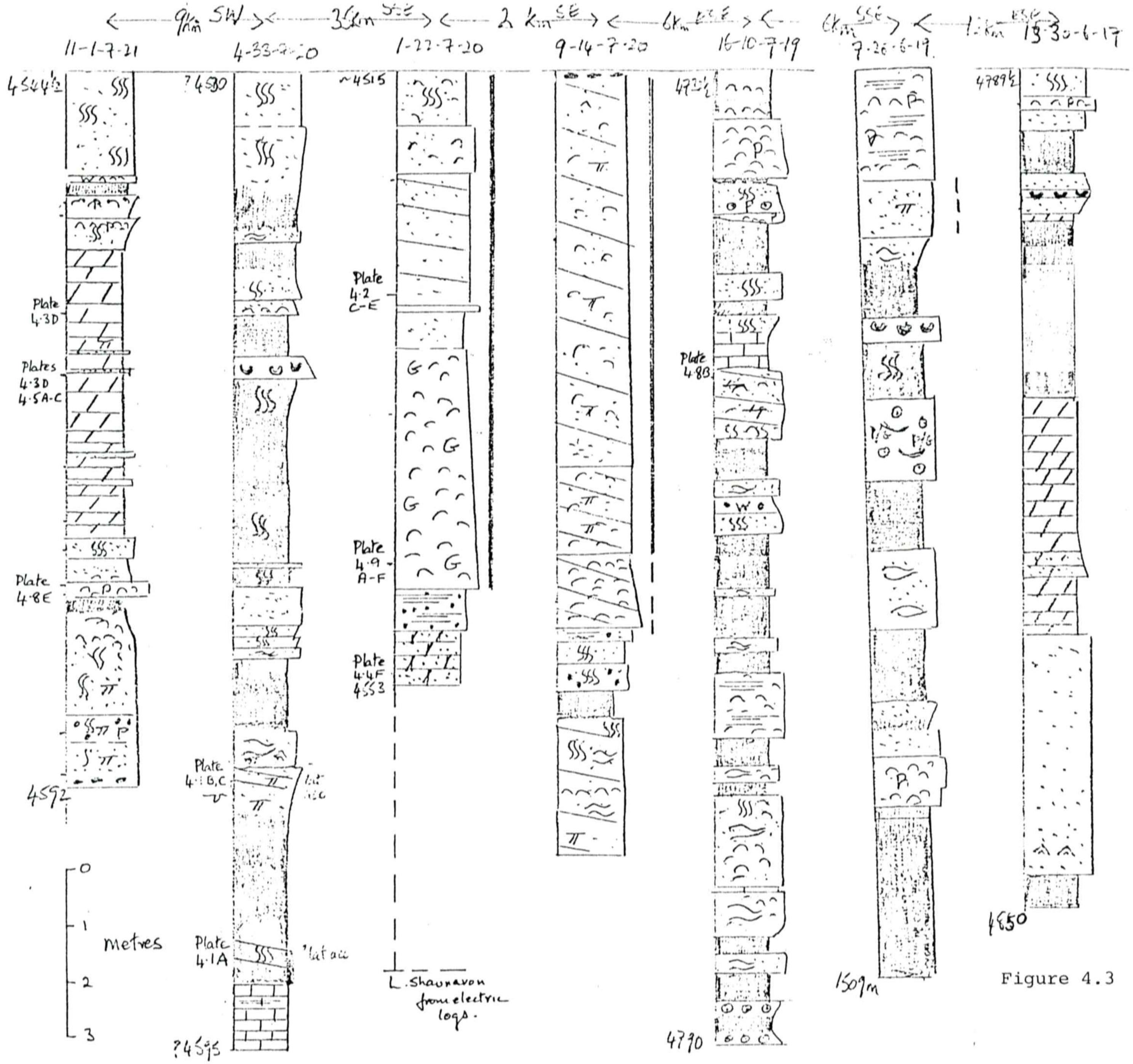


Figure 4.3 Sketch logs of cores from the Dollard oilfield area and nearby areas (for location see Fig. 1.1).

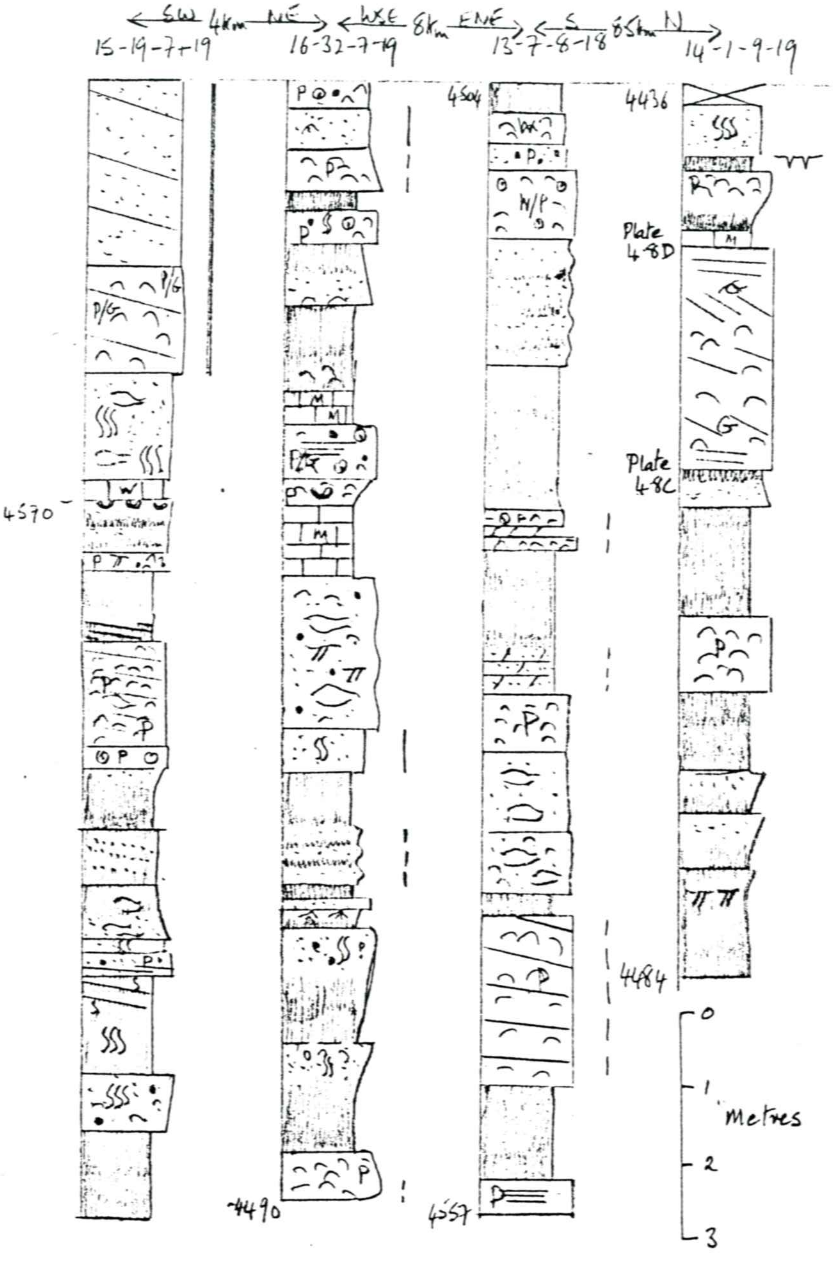


Figure 4.4 Sketch logs of cores from the Dollard oilfield and areas to the north of it (for location see Fig. 1.1).

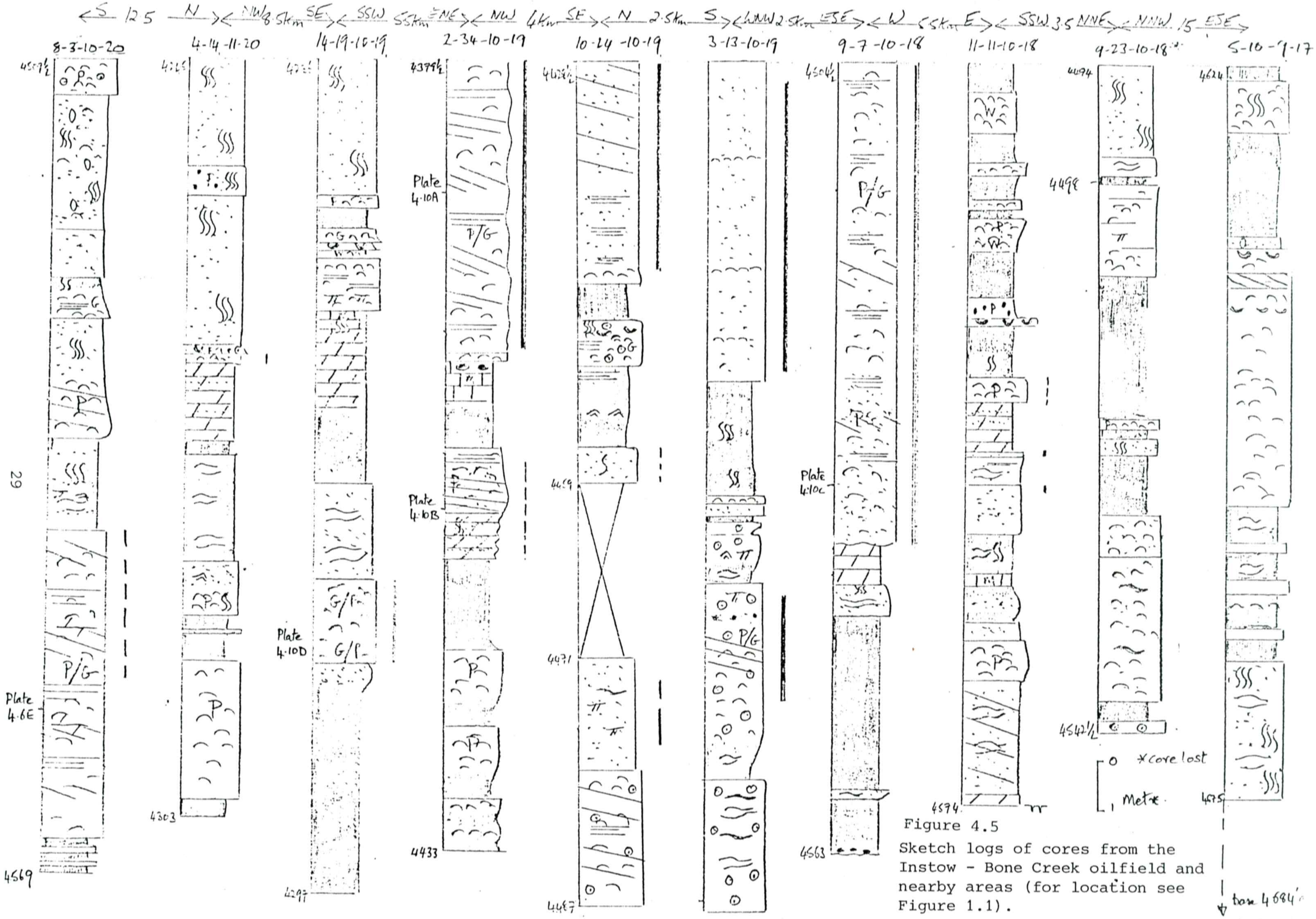


Figure 4.5

Sketch logs of cores from the Instow - Bone Creek oilfield and nearby areas (for location see Figure 1.1).

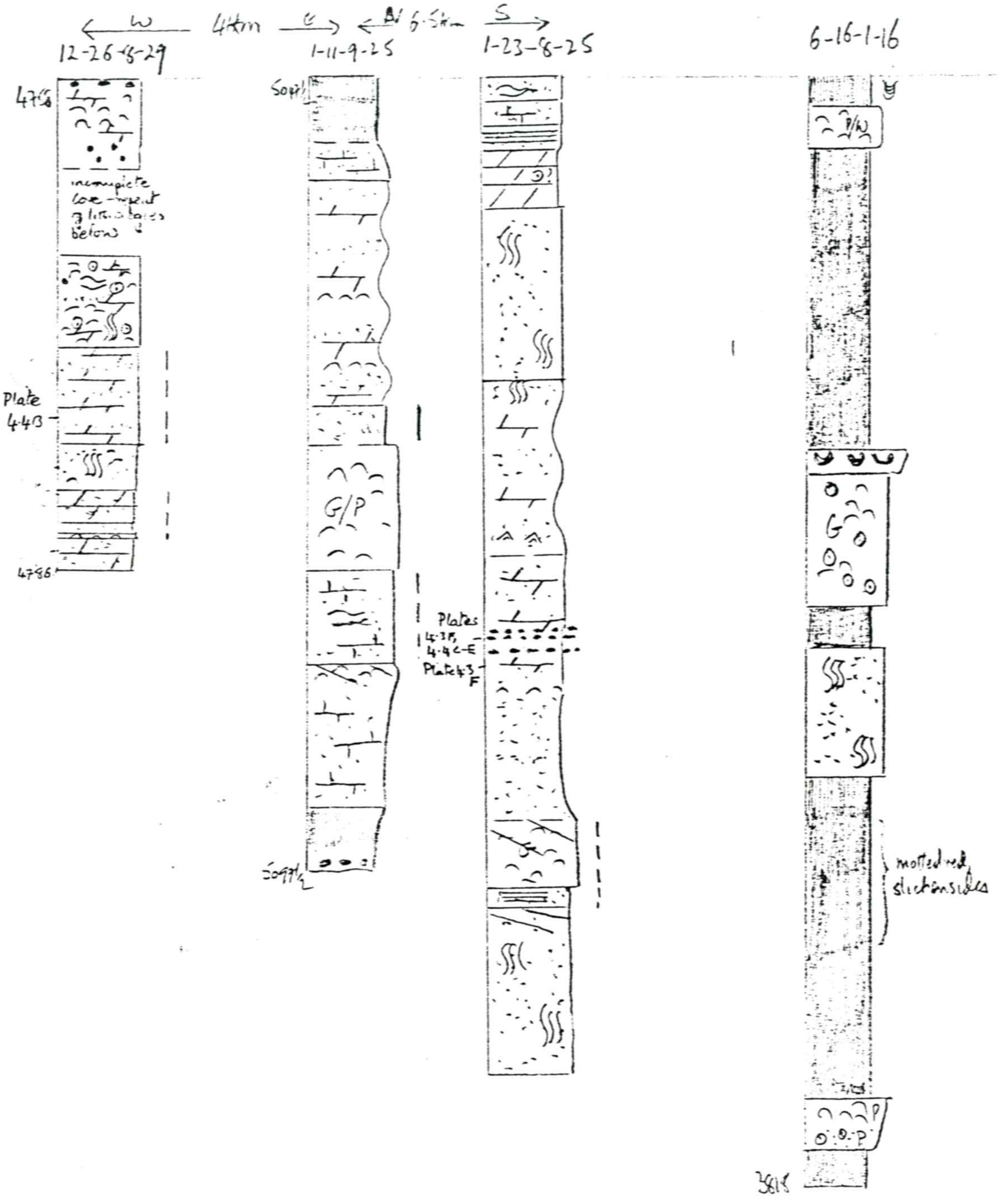


Figure 4.6 Sketch logs of cores from wells to the east and west of the oilfield trend.

Both Christopher (1964) and McMillan (1966) divided the Upper Shaunavon into three units. McMillan's division was quite simple, a lower blue grey limestone 'bundle' (oolitic, peloidal and conquinoidal limestones and grey calcareous shales), a middle sand 'bundle' (including dolomitic sediments), and an upper lithologically more heterogeneous interval. Christopher's division was as follows:

U3 : sandy coquinoidal channel fills of the Dollard and Instow - Bone Creek oilfields; variable lithologies elsewhere;

U2d : algal nodule bed, grading into sandstones with bright gray green laminae;

U2c : tan sandstone and dolomite, grading into oolites in the south;

U2b : green dolomitic and calcareous mudstone and shale, grading westward into dolomites;

U2a : blue-gray limestone;

U1 : very fine grained sandstone and bioclastic limestones (the most variable of the three units.

Christopher suggests that Unit 1 is capped by a disconformity, but cites no palaeontological evidence to support its presence. His use of these units to construct fence diagrams correlating successions over wide areas is open to doubt, as apart from the algal nodule horizon (which appears in about half the wells studied by McMillan), there appear to the present author to be no reliable marker horizons present.

4.3.5 Depositional environments

The lower part of the Upper Shaunavon

McMillan's lower bundle probably is roughly equivalent to Christopher's Units

U1 and U2a. In the Rapdan and Dollard areas (see Figs. 4.2 - 4.5) it consists of calcareous shales, sandy skeletal packstones and grainstones (the latter often supermature), peloidal grainstones, and sand-shale mixtures. The skeletal packstones (Plate 4.8E) are similar to the conquinoid sands described by Brenner and Davies (1973, 1974) from the Oxfordian of Montana, Wyoming and South Dakota, and interpreted as storm lag deposits. The skeletal grains in some limestones are very well rounded, yet set in a fine matrix of carbonate mud and fine quartz sand, suggesting rapid dumping of sediment, possibly as washover deposits. In contrast well sorted grainstones may have been winnowed over prolonged periods of time by storm or tide generated current activity. In the Dollard area, wavy bedded and bioturbated fine sand and silts show low angle bedding (Plate 4.1A) that was possibly caused by lateral accretion of tidal channels (Fig. 4.3, well 4-33-7-20, Fig. 4.4, well 15-19-7-19). Low angle bedding in skeletal sands is also seen in this area. In the wells studied in the Instow - Bone Creek area, the lower part of the Upper Shaunavon is developed mostly as skeletal and ooid grainstones, some of which form producing reservoirs (see Fig. 4.5, well 3-13-10-19).

On the evidence available, it is impossible to propose an environmental interpretation of the lower part of the Upper Shaunavon with any confidence. The most plausible interpretation is that it represents largely reworked relict sediments of a barrier system that transgressed across the region studied.

The middle and upper parts of the Upper Shaunavon are discussed below, treating in turn the three main oil field areas.

The Rapdan area (Figs. 4.2, 4.3).

The middle part of the Upper Shaunavon in this area contains dolomite mudstones, quartz rich dolomitic mudstones, and quartz and ooid sands. As commented earlier, the ooid sands contain early dolomite cement, and in places form packstones with a dolomitic matrix. At some intervals, the carbonate grains are only present as empty vugs in a dolomite matrix. The porosity of the sands seems largely to be inversely proportional to the amount of dolomite cement or matrix present.

The quartz and ooid sands often overlie dolomitic sediments, but in places they are absent and only the dolomites are present. In one case, dolomites occur within the sands (12-12-4-20). These relationships could be interpreted in terms of the sands forming in tidal inlets and deltas associated with a barrier system containing extensive wind flats or supratidal zones in which dolomites formed. Alternatively, the sands might have formed as tidal sand ridges after transgression had occurred across an extensive tidal/wind flat area in which the dolomitic sediments were deposited as a regressive cap to the underlying lower part of the Upper Shaunavon. This would imply that the later top Upper Shaunavon sediments, and also the Vanguard Formation, must have draped the sand-ridge topography.

Whatever the origin of the Rapdan sands they appear to be distinct from those of the oil fields to the north. They contain more ooids, are cemented by dolomite, and the trend of the individual oilfields in the area is generally NNE-SSW in contrast to the NW-SE trend of the Dollard and Instow - Bone Creek fields. This contrast in orentation suggests that the Rapdan ooid sands may be tidal sand ridges developed parallel to the barrier system in which the fields to the north formed. Another possibility is that the sand bodies formed during transgression of an earlier barrier - inlet system similar to that described by Swift et al (1972) from the eastern U.S.A. shelf. To the east of the Rapdan area there appears to be a belt of oolitic sediments that trends approximately at right angles to the oilfield trend. This pattern is similar to that described by Swift et al (1972) which they interpret to result from coastal retreat during transgression which leaves a shelf transverse sand body reworked by storm generated currents. The sediments overlying the sands (micrites, shales and bioturbated sands) could either represent lagoonal sediments formed behind a barrier system, or between sand ridges consequent on a sea level fall.

Dollard area (Figs. 4.4, 4.5)

In the wells studied, dolomitic sediments are less in evidence than they are in the Rapdan area, and apparently do not occur beneath the reservoir sands.

Christopher shows an isopachous map for his U3 unit in the Dollard area (1964, Fig. 26) which, from a review of data in his 1966 core descriptions appears to approximate to the thickness of skeletal and quartz sand in the field. The thickness distribution has a marked asymmetry, with very rapid thinning SW of the NW-SE axis of maximum thickness, but gradual thickening to the NE. The axis of maximum thickness coincides with a narrow zone along which the sands rest on the Lower Shaunavon (see Christopher, 1964, Fig. 25). This suggests that the sand unit has an erosive base, in which case it probably formed as a tidal channel. An alternative possibility is that the sand geometry was caused by a tidal sand body, for its size and asymmetry are appropriate for such an origin. However, this sand body would have to have been initiated at the beginning of the Upper Shaunavon transgression, as it rests on the Lower Shaunavon in places. To the north, the sand interval is situated above the pisolite horizon (see Fig. 4.4, well 15-19-7-19). Without being able to study slabbed cores, it is impossible to determine the extent to which the Dollard sand is in fact a composite body.

Instow - Bone Creek area

Some of the cross bedded reservoir sands in the Bone Creek field occur above the pisolite horizon (Fig. 4.5, wells 2-34-10-19, 10-24-10-19), and to the west (14-19-10-19) and northwest (2-34-10-19) sands overlying this horizon are extensively bioturbated - not a feature characteristic of a flood delta sequence which might be expected in these locations if the Instow - Bone Creek field developed as a tidal channel. In the wells further to the SE, along the axis of the field, the reservoir sands are thicker (3-13-10-19, 9-7-10-18) and the pisolite is absent. To the south east of the field, well 5-10-9-17 penetrated thick well cemented skeletal sands beneath the pisolite. Thus it is possible that the reservoir interval comprises stacked sand bodies, and that it does not have an erosive contact with underlying sediments. Dolomite sediments appear beneath the pisolite on both sides of the oil field trend.

4.3.6 Conclusions

From the limited number of wells studied in this report, no precise conclusions can be reached about the environment of deposition of the Upper Shaunavon reservoir sands. There is no doubt that they are marine sands that suffered later emergence during which freshwater phreatic diagenesis occurred. The Rapdan sands are more ooid rich than those to the north, and are apparently situated at the eastern end of a belt of thick, but non-porous ooid sands that extend to the south east, suggesting the formation of ooid shoals, possibly during a transgression which caused coastal retreat to the west.

The dolomitic sediments formed either as tidal or wind flat sediments, with the dolomite having an evaporative origin, or deposited as wind blown detritus from Upper Palaeozoic outcrops around the Williston Basin, or as mixing zone diagenetic dolomite replacing micrites and micritic sandstones. A tidal channel origin for the Dollard and Instow - Bone Creek sands seems probable, but no clear evidence for tidal deltas has been found. It is possible that they formed during a relative sea-level stillstand after the transgression during which the Rapdan sands were deposited, or possibly during a slight regressive episode when the coast began to advance eastwards due to sediment progradation.

If sufficient dip-meter data were available it would enable a much clearer interpretation of Upper Shaunavon depositional environments to be made. However, in its absence, more precision might be possible if a careful study was made of cross stratification types present in the reservoir sands; this would require many of the cores to be slabbed.

The industry view of the Upper Shaunavon oil field trend being a barrier system separating dominantly marine shales to the east from fluviatile/ blanket sands to the west is clearly oversimplified. Reddened shales occur to the east of the oilfield trend in several wells (see Christopher 1964, McMillan 1966, and Fig. 4.6 well 6-16-1-16 of this study). In the few wells studied west of the trend, dolomitic sands are common (see Fig. 4.6), but skeletal debris is also present, suggesting that transgressive episodes may have spread far to the west, temporarily inundating coastal flat environments.

5. Further work

Further work is needed to enable detailed environmental interpretations to be made, both to resolve whether the Upper Shaunavon reservoir sands were deposited as barrier or tidal sand ridge system, or some combination of these environments. The following tasks could usefully be accomplished in the short term:

1. The construction of detailed isopach maps for the Upper and Lower Shaunavon, and for the Mesozoic formations beneath. These should enable a better evaluation to be made of the extent to which Upper Shaunavon sedimentation was controlled by differential subsidence caused by compactional drape over the top Palaeozoic topography (Christopher, 1964) or by an irregular top Lower Shaunavon surface (McMillan, 1966).

2. Further sampling of Lower Shaunavon bituminous shales to the east and southeast of the oilfield trend to ascertain whether the oil window was reached in this area, and whether a significant amount of Shaunavon source rock is present.

3. Stable isotope work on the dolomitic sediments already collected to evaluate the alternative hypotheses for dolomite formation (i.e. evaporative, mixing zone replacement and detrital origins).

4. Detailed study of cores along several NE-SW traverses across the Dollard and/or Instow - Bone Creek fields preparatory to detailed studies of cross stratification types (see 5 below).

5. If more cores could be slabbed, detailed studies of the cross stratification types present in either the Bone Creek - Instow or Dollard fields.

6. Detailed study of the top part of the Upper Shaunavon containing charophytes in order to ascertain whether a lacustrine phase occurred; such an episode could account for the extensive freshwater phreatic diagenesis of the reservoir sands.

6 References

Bridges, P.H. 1982. Ancient offshore tidal deposits. In A.H.Stride (ed.), Offshore tidal sands, Chapman & Hall, London, p.172-192.

Christopher, J E. 1964. The Middle Jurassic Shaunavon Formation of southwestern Saskatchewan. Rept. 95, Sask. Dept. Mineral Resources, 95 pages.

Christopher, J.E. 1966. The Middle Jurassic Shaunavon Formation of southwestern Saskatchewan. Lithologic descriptions of selected cores sections. Rept. 110 Sask. Dept. Mineral Resources, 308 pages.

Elliott, T. 1978. Clastic shorelines. In : Reading, H.G. (ed.), Sedimentary environments and facies, Blackwell, Oxford, p.43-177.

Folk, R.L. 1972. Spectral subdivision of limestone types. In : W.E. Ham (ed.), Classification of carbonate rocks. Am. Assoc. Petrol. Geol. Mem. 1, 62-84.

Hearn, B.C., Pecora, W.T., & W.C. Swadley, 1964. Geology of the Rattlesnake Quadrangle, Bearpaw Mountains, Blaine County, Montana. U.S. Geol. Surv. Bull. 1181-B.

Johnson, H.D. 1978. Shallow siliciclastic seas. In : Reading, H.G. (ed.), Sedimentary environments and facies, Blackwell, Oxford, p.207-258.

Longman, M.W. 1980. Carbonate diagenetic textures from near surface diagenetic environments. Am. Assoc. Petrol. Geol. Bull. 64, 461-487.

McMillan, N.J. 1966. Sedimentation of the Upper Member of the Shaunavon Formation(southwest Saskatchewan). Internal report, Teneco Oil and Minerals Ltd.

Paterson, D.F. 1968. Jurassic megafossils of Saskatchewan with a note on Charophytes. Rept. 120, Sask. Dept. Mineral Resources, 135 pages.

Poulton, T.P. 1984. The Jurassic of the Canadian Western Interior, from 49°N latitude to Beaufort Sea. In : D.F. Stott & D.J. Glass (Eds.). The Mesozoic of Middle North America. Can. Soc. Petrol. Geol. Mem. 9. 15-41.

Reading, H.G. (ed.) 1978. Sedimentary environments and facies. Blackwell, Oxford, 557 pages.

Reinson, G.E. 1984. Barrier Island and associated strand plain systems. In : Walker, R.G. (ed.) Facies Models, Geoscience Canada, Reprint Ser.1., 119-140.

Swift, D.J.P., Kofoed, J.W., Saulsbury, F.P. & P. Sears, 1972. Holocene evolution of the shelf surface, central and southern Atlantic shelf of North America. In : Swift, D.J.P., Duane, D.B. & O.H. Pilkey (eds.), Shelf Sediment transport : process and pattern, Dowden Hutchison & Ross, Stroudsburg, 499 - 574.

Tritthart, A.D. 1980. The lithologies and depositional environment of the Upper Member of the Shaunavon Formation of the Whitemud field. Geology 400 Thesis, University of Regina.

Walker, R.G. (ed.) 1984a Facies Models. Geoscience Canada Reprint Series 1, 317 pages.

Walker, R.G. 1984b. Shelf and shallow marine sands. In Walker 1984a, 141-170.

Wall, J.H. 1960. Jurassic microfaunas from Saskatchewan. Rept. 53, Sask. Dept. Mineral Resources, 299 pages.

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Old expatriate friends (Colin Dunn and Geoff Parslow) are thanked for their professional help and hospitality during my stays in Regina.
I thank colleagues at the Open University for their assistance and patience (Beryl West: typing; Dick Carlton: SEM; Ian Chaplin: thin sections; John Taylor: plates; Jane Turner: SEM and section staining).

PLATE 3.1

Lower Shaunavon cores, Well 1-27-3-26 (for location of photographs see Fig. 3.1)

a Laminated bituminous shale seam with faintly laminated cream micrites above and below.

b Virtually intact *Camptonectes* tests in thin ooid grainstone seam.

c Bedding surface in micrite crowded with small bivalves (?*Protocardia*).

d Two laminated bituminous shale seams; lower one is overlain erosively by cream micrite.

Plate 3.1

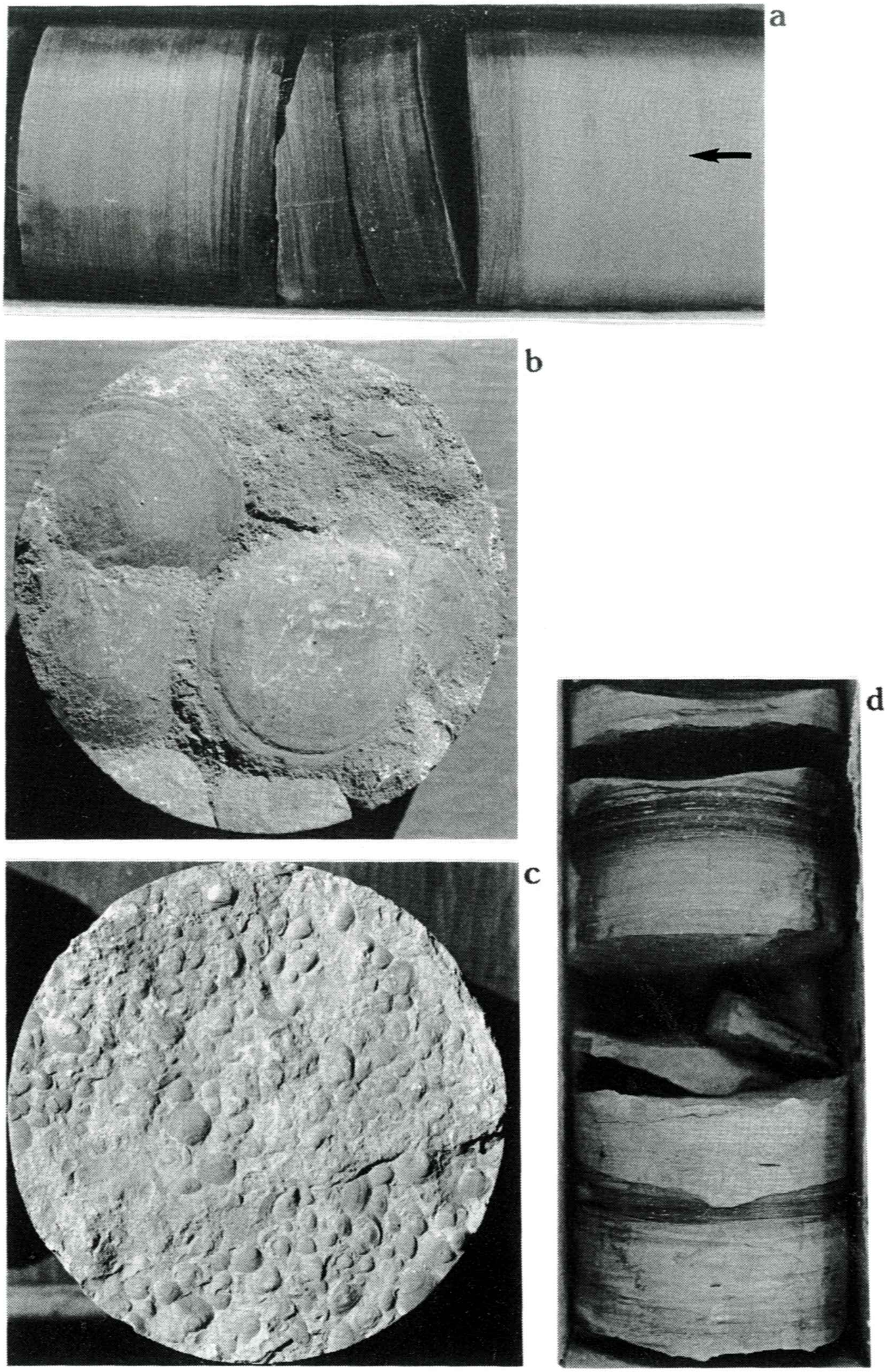


PLATE 3.2

Lower Shaunavon cores, Well 11-1-7-21

(for location of photographs, see Fig. 3.1; all cores shown in correct orientation - top uppermost).

a Algal stromatolite showing clear simple concentric/columnar growth pattern, overyling laminated micrite.

b Two layers of coralgal boundstone with complex internal fabric (see Plate 3.4) separated by light by micrite.

c Partially dolomotised micrite showing mottled fabric, with darker parts consisting of slightly oil stained dolomite.

d Laminated micrite; the thicker darker bands consists of bituminous shale.

Plate 3-2

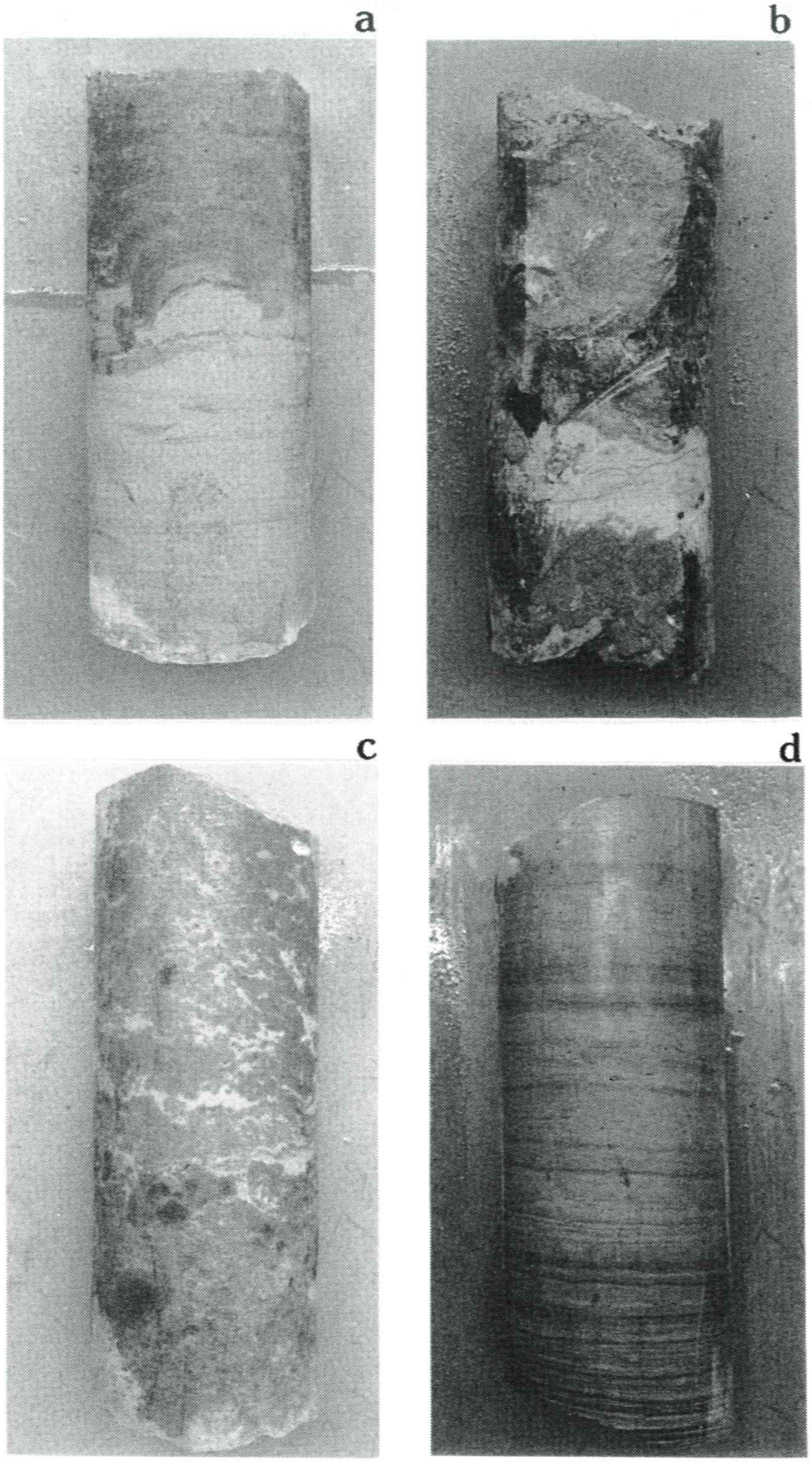


PLATE 3.3

Polished surfaces of Lower Shaunavon samples from Well 11-1-7-21 (for locations of samples, see Fig. 3.1)

A. Sample 71. Bituminous shale with lighter limestone streaks, scattered oyster fragments, and one larger oyster shell around which early diagenetic carbonate formed prior to compaction of the shales.

B. Sample 78. Cor~~y~~al-oyster skeletal wackestone overlying, possibly erosively, bituminous shale.

C. Sample 80. Skeletal wackestone erosively overlying a bituminous shale seam which grades downward into micrite, where lenticular inter-mixing of the two lithologies may be due to burrowing activity.

D. Sample 81. Bituminous shale seam with lime rock centre and skeletal rich seams sandwiched between micrite.

E. Closer view of part of Sample 81.

All scales are in millimetres.

Plate 3.3

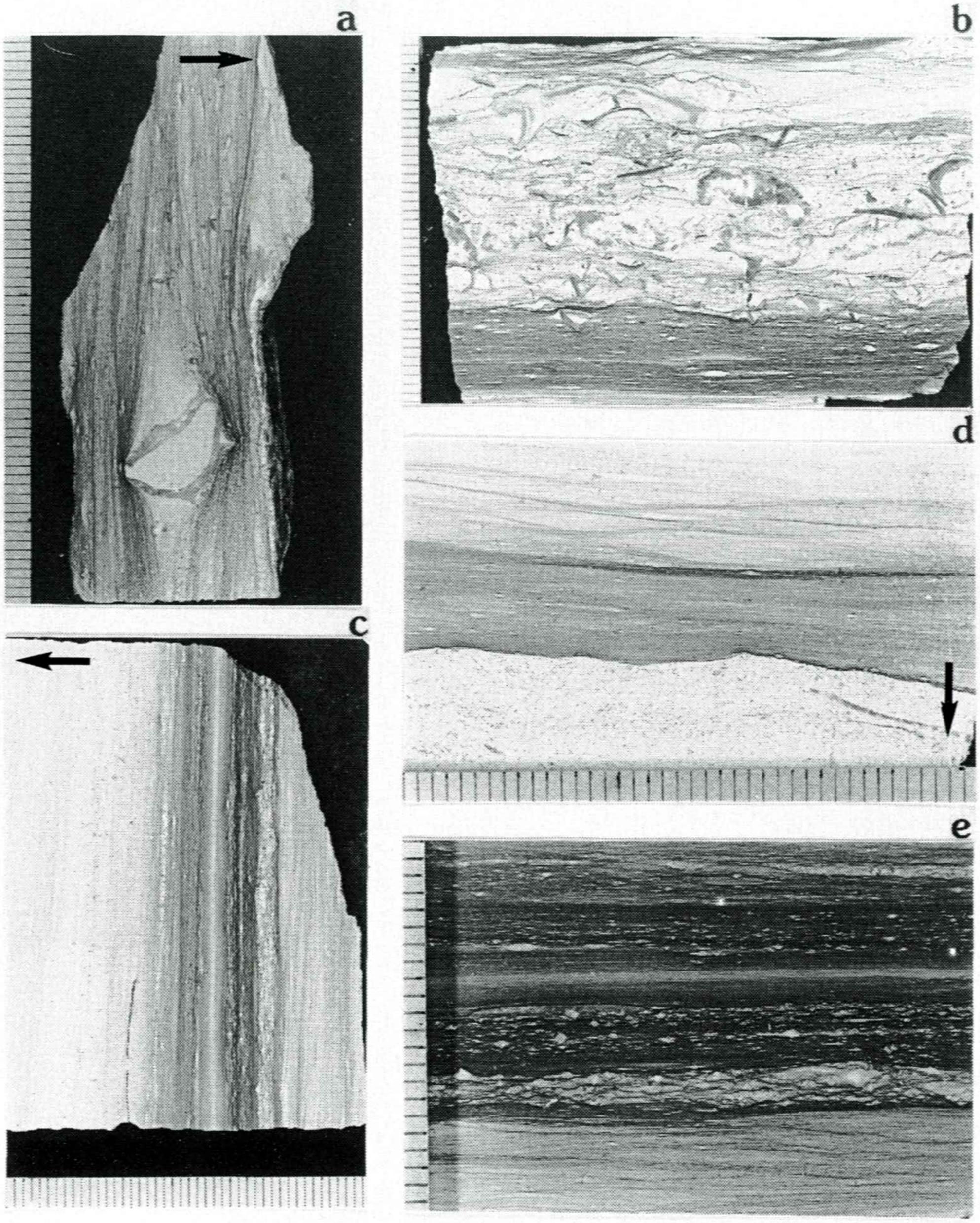


PLATE 3.4

Lower Shaunavon Carbonates

a	Detail of part of coralgal boundstone shown in Plate 3.2B. C: Coral, D: bivalve borings (Well 11-2-7-21, see location on Fig. 3.1); millimetre scale.
b & c	Coralgal framestone; branching corals (C) some of which have algal coatings (A). In enlarged view (3.4C), some vuggy porosity is visible within corals (P), and skeletal wackestone matrix between the corals can be seen (1-11-9-25); millimetre scale.
d & e	Photomicrographs of dolomitised allochem (?ooid) packstone/grainstone, Well 3-13-10-19, 4538.5 feet.

Plate 3·4

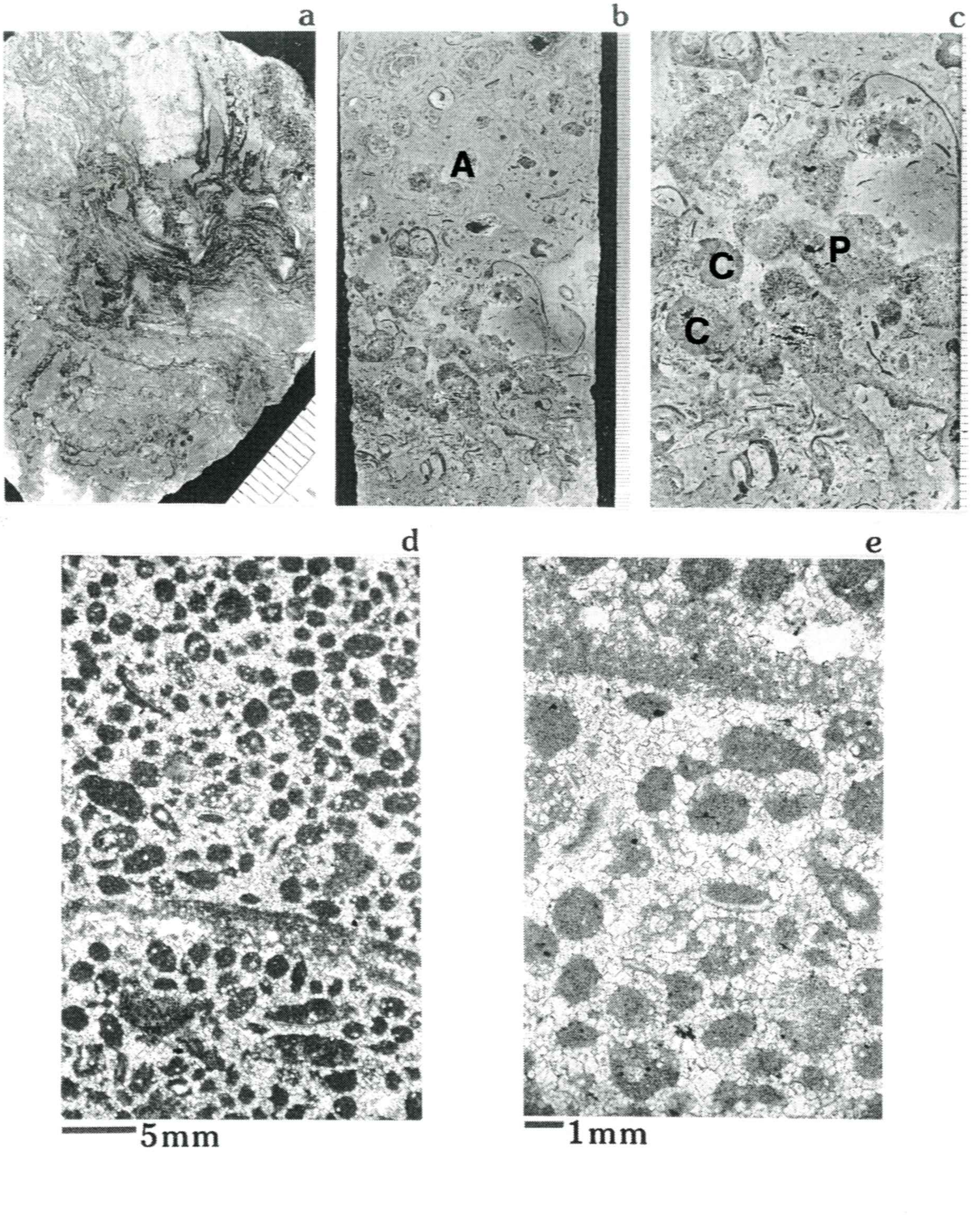


PLATE 4.1

Cores of siliciclastic sediments

a Mixed shale and siltstone (lighter), partly laminated and partly burrowed, showing inclined layers possibly indicating lateral accretion surfaces (4-33-7-20, see Fig. 4.1).

b & c Mixed shale and fine sand, with possible slump interval at top. In B, lower part of core is slabbed; in C, small scale cross stratification is visible (4-33-7-20, see Fig. 4).

d Small scale cross stratification, probably caused by migration of wave ripples (4-14-11-20. see Fig. 4.5).

e Massive, largely oil impregnated fine sand, showing 'master bedding' inclined up to 10°; very flat horizontal surfaces are saw cuts. The lighter intervals are calcite cemented. Note that no other sedimentary structures are visible on core surfaces (12-12-4-20; see Fig. 4.1).

f Polished surface of sandstone from cores illustrated in B, showing small scale planar cross stratification.

Plate 4·1

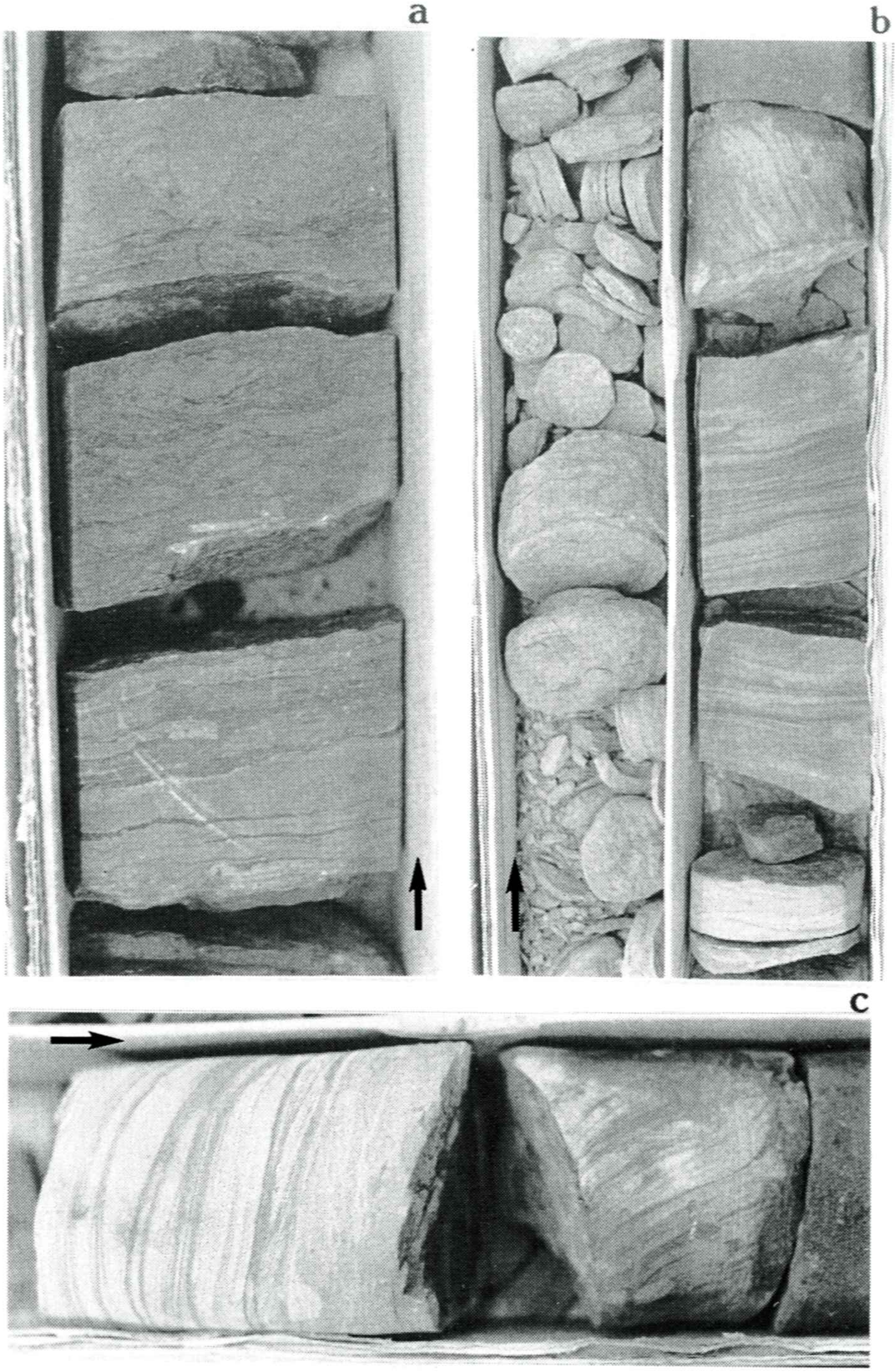
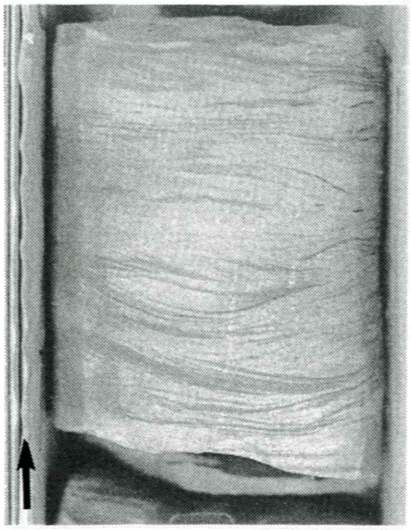


Plate 4.1 Contd

d



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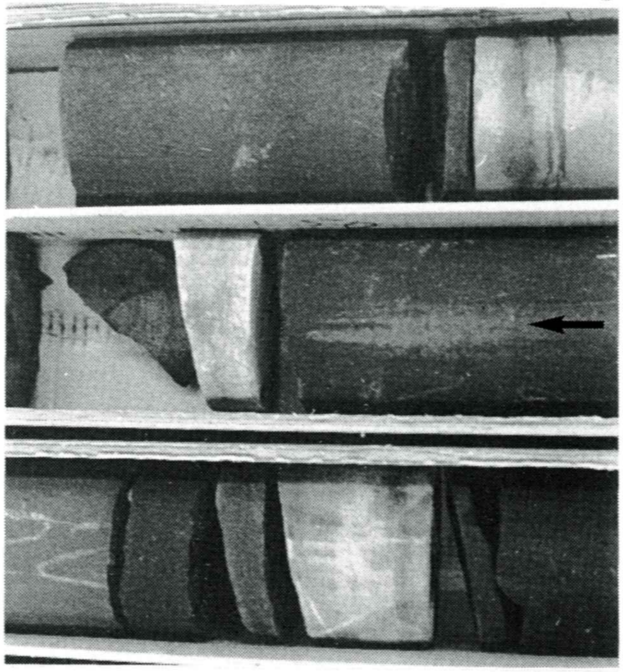


f

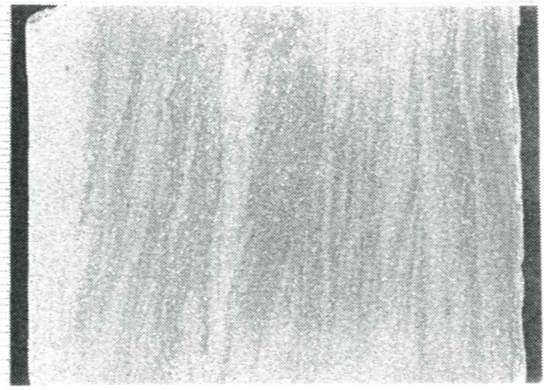


PLATE 4.2

Thin section and SEM photographs of siliciclastic reservoir sands

a, b	Quartz grains with slightly developed overgrowths, and loosely cemented by scattered dolomite rhombs. B shows closer view of grain with thin oolitic coating (top); to bottom left calcite drusy cement developed over another grain shows later scattered dolomite rhombs (12-12-4-20, see Fig. 4.1).
c	Subrounded to subangular well sorted fine sand and scattered allochem (dark grains). Intergranular porosity is only occluded by scattered development of syntaxial overgrowths to echinoderm fragments (arrowed). (1-22-7-20, see Fig. 4.3).
d, e	SEM views of sands shown in c showing lack of any cement. E shows development of overgrowth on quartz grains with the particle on the right having well developed straight crystal facies.
f	Well developed overgrowth on quartz-sand grain, with later dolomite crystals (1-22-7-20, see Fig. 4.3, see Fig. 4.3).

Plate4·2

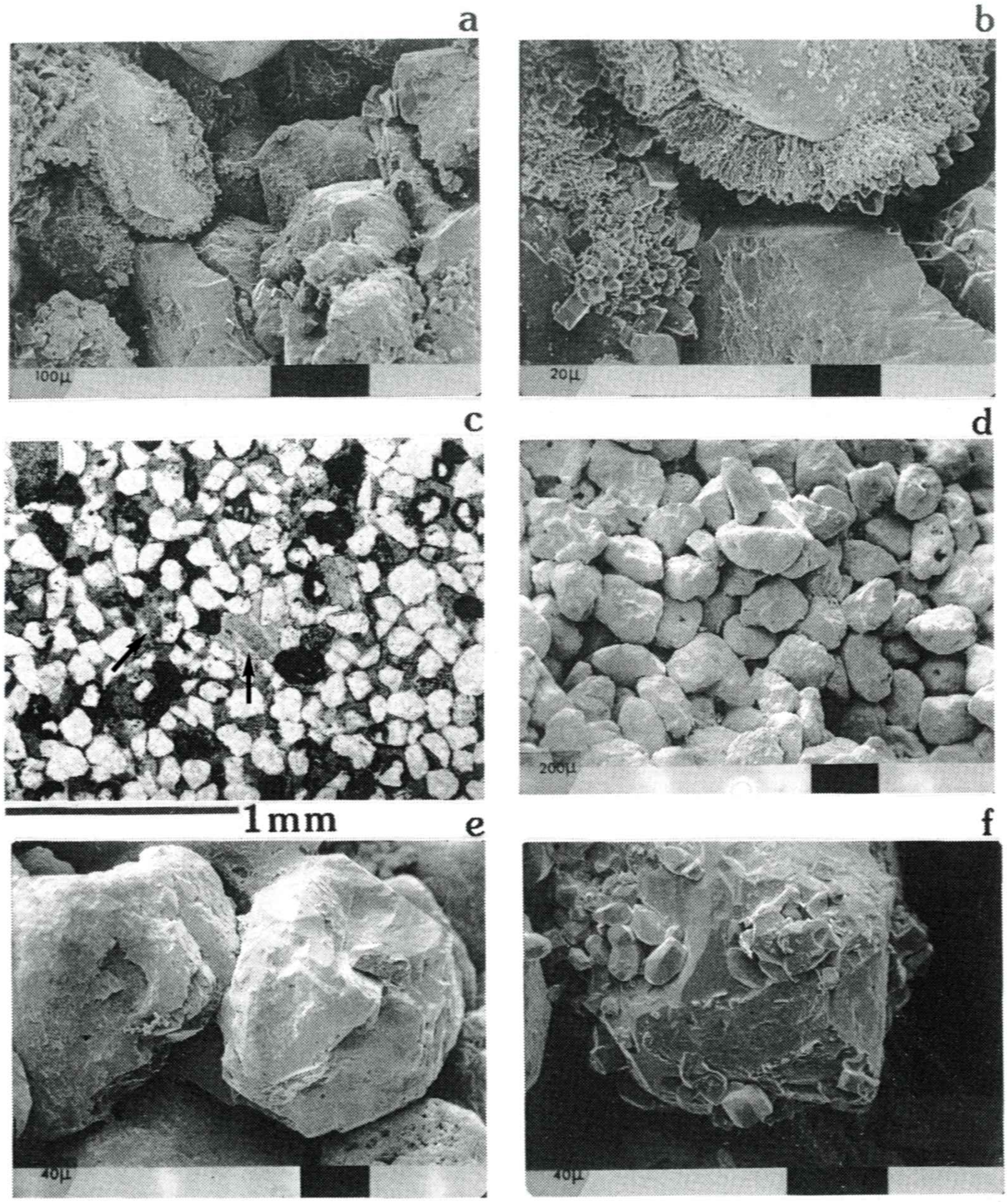


PLATE 4.3

Core and polished slabs of dolomitic sediments

a Finely laminated dolomite mud (light) and fine sand (dark); the laminae develop crenulations in parts of the core. (3-16-4-21, see Fig. 4.1).

b Mottled dolomitic sand (light) and dolomite poor sand, probably caused by burrowing; although the structure is similar to that caused by wind ripples developed in coastal sabkhas (1-18-4-20, see Fig. 4.1).

c Dolomitic sand (light) and dolomite free sand (dark), showing faint cross stratification similar to that produced by wind ripples (11-1-7-21, see Fig. 4.3).

d Dolomitic sand and dolomitic mud (light) and sands (dark) showing parallel and disrupted laminae of uncertain origin. The sands in the lower half are oil impregnated.

e Conglomerate of dolomitic mud clasts set in matrix of oil impregnated sand (1-23-8-25, see Fig. 4.6).

f Laminated and brecciated dolomitic mudstone; the brecciated interval contains some vuggy porosity. The specimen is patchily impregnated with oil (1-23-8-25, see Fig. 4.6).

g Breccia, possibly produced by dissolution of evaporite minerals, overlying irregularly laminated dolomitic sands and mudstones (width of sample is cm). (8-9-10-15).

Plate 4.3

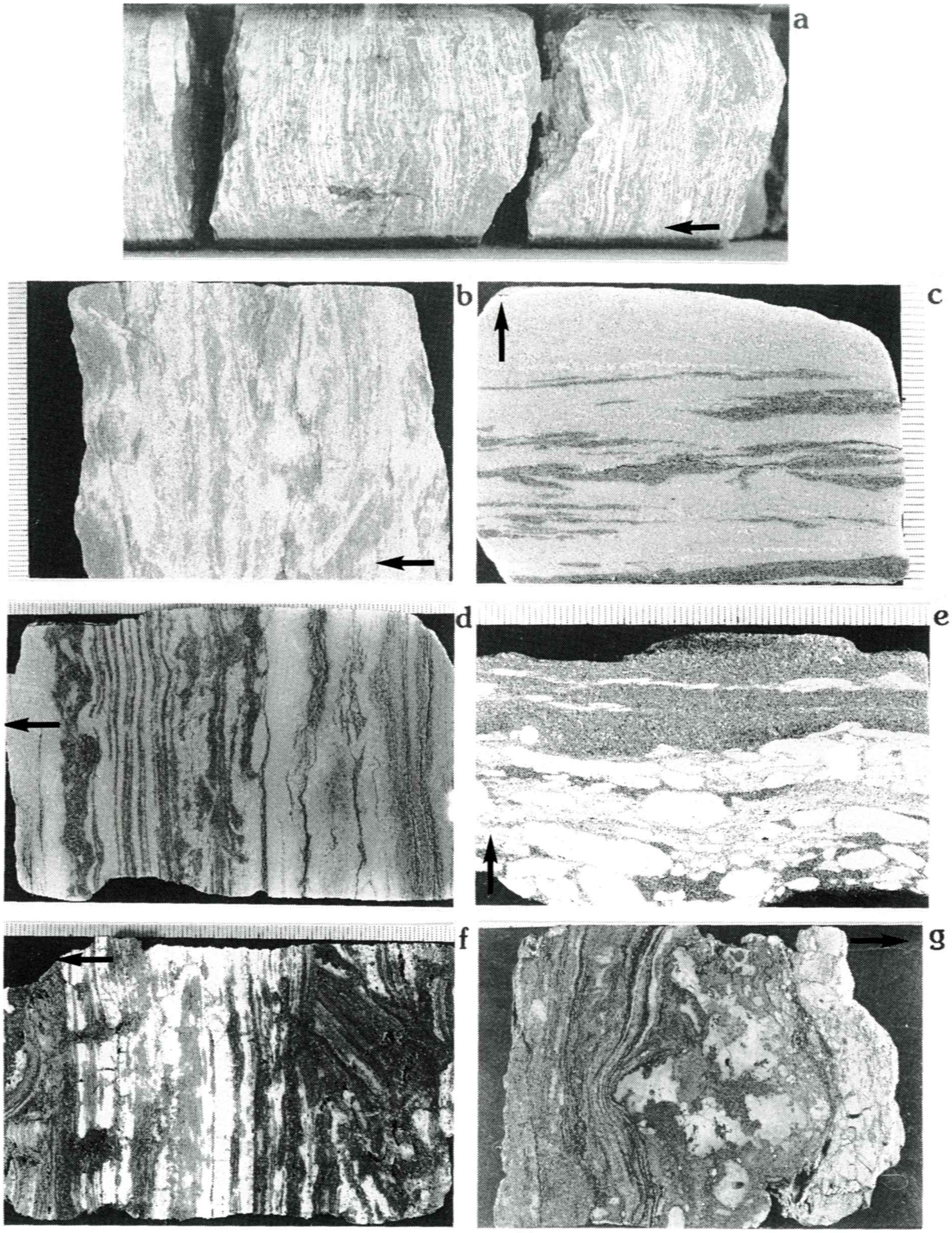


PLATE 4.4

Polished specimen, thin section and SEM photographs of dolomitic sediments

a Fine quartz sand grains in a matrix of dolomitic mud; large dark areas are irregular clasts of dolomitic mud that is finer grained than that in the matrix. (1-18-4-20, see Fig. 4.1).

b Fine quartz sand, with some intergranular porosity (P) partially occluded by large dolomite rhombs; elsewhere matrix is fine grained dolomite. (12-26-8-29).

c Polished specimen of cross stratified sands alternating with dolomitic muds; top half of specimen is oil impregnated. (1-23-8-25, see Fig. 4.6).

d SEM photo of oil free sand at base of specimen shown in c. Quartz grains with overgrowths are loosely cemented by dolomite rhombs which block pore throats.

e SEM photo of sand from oil impregnated part of specimen shown in c. Dolomite cement is absent, but quartz grains show well developed overgrowths.

f SEM photo of tight sand, showing well developed dolomite matrix and some remaining intra granular porosity (1-22-7-20. see Fig. 4.3).

Plate 4.4

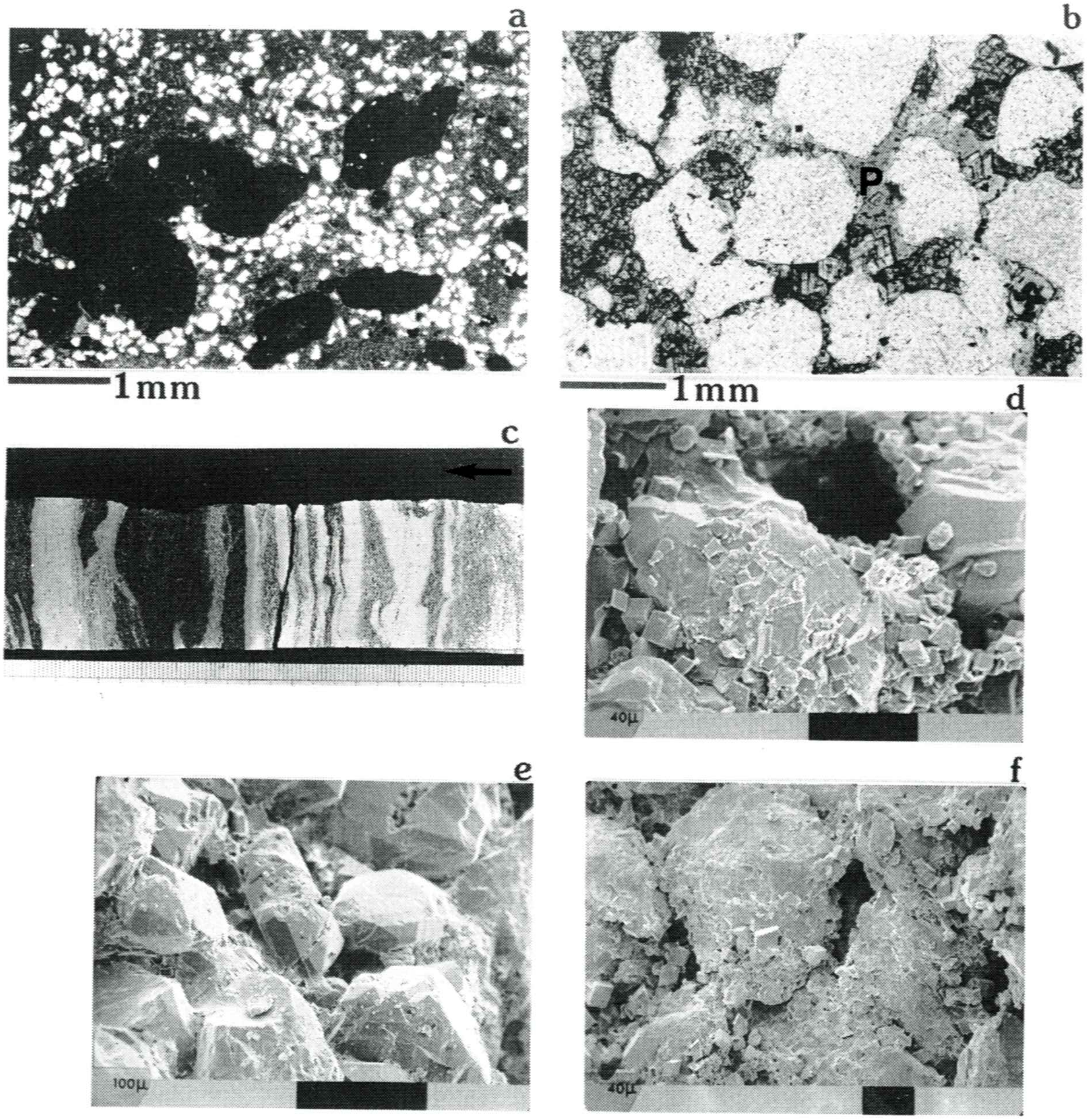


PLATE 4.5

a, b	Dolomite rhombs showing some rounding of edges suggestive of a detrital origin (11-1-7-21, see Fig. 4.3).
c	Well developed dolomite rhombs; sample taken 2cm above that shown in a & b.
d	Very fine grained dolomite (1-18-4-20).

Plate 4·5

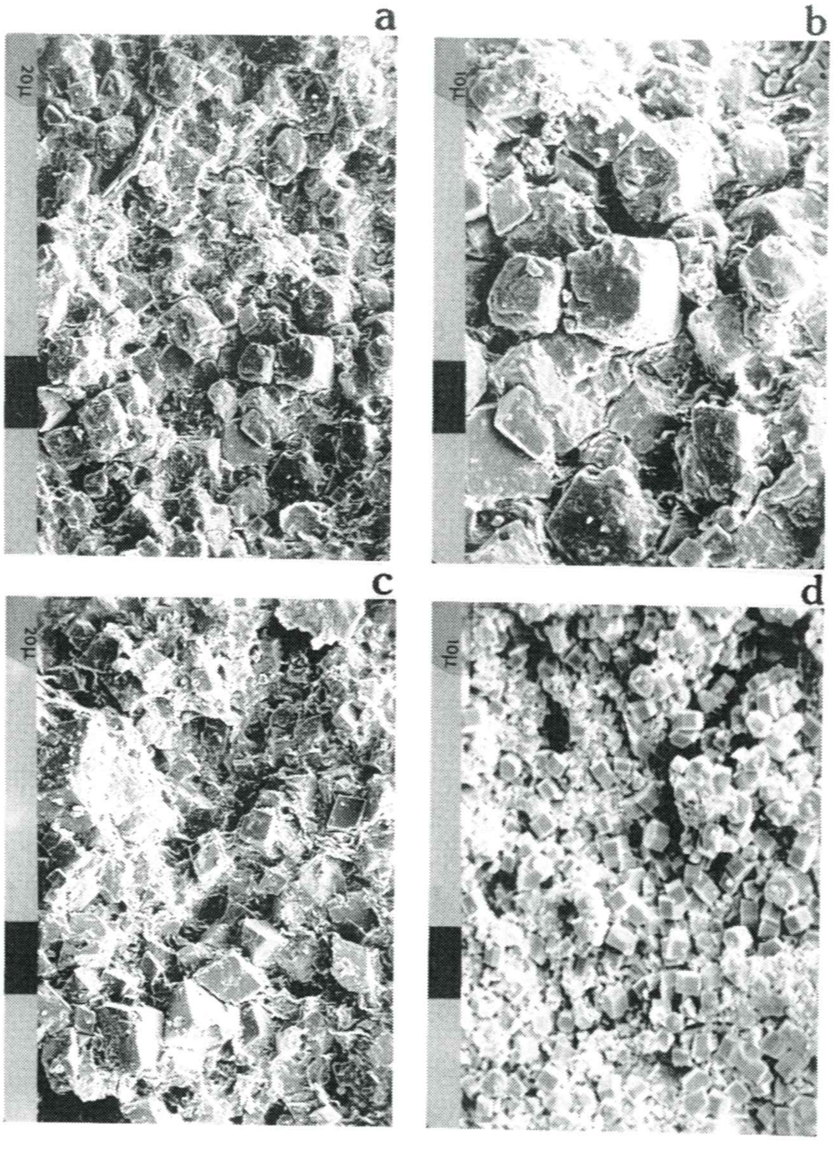


PLATE 4.6

Polished slabs of oolitic and dolomitic sediments

a	Stromatolitic sediment, composed entirely of dolomite, showing possible dessication cracks in centre of sample (5-14-4-21, see Fig. 4.1).
b	Ooid grainstone (with dolomite cement) and 'clay drapes' composed of dolomitic mudstone (5-14-4-21, see Fig. 4.1).
c	Ooid grainstone with scattered bivalve shells and lithoclasts of cemented ooid grainstone (ligher coloured large grains up to 5.-0mm across). (5-14-4-2, see Fig. 4.1).
d	Dolomitised ooid packstone with large dolomite and mud clasts containing scattered replaced allochems (3-16-4-21, see Fig. 4.1).

Plate 4·6

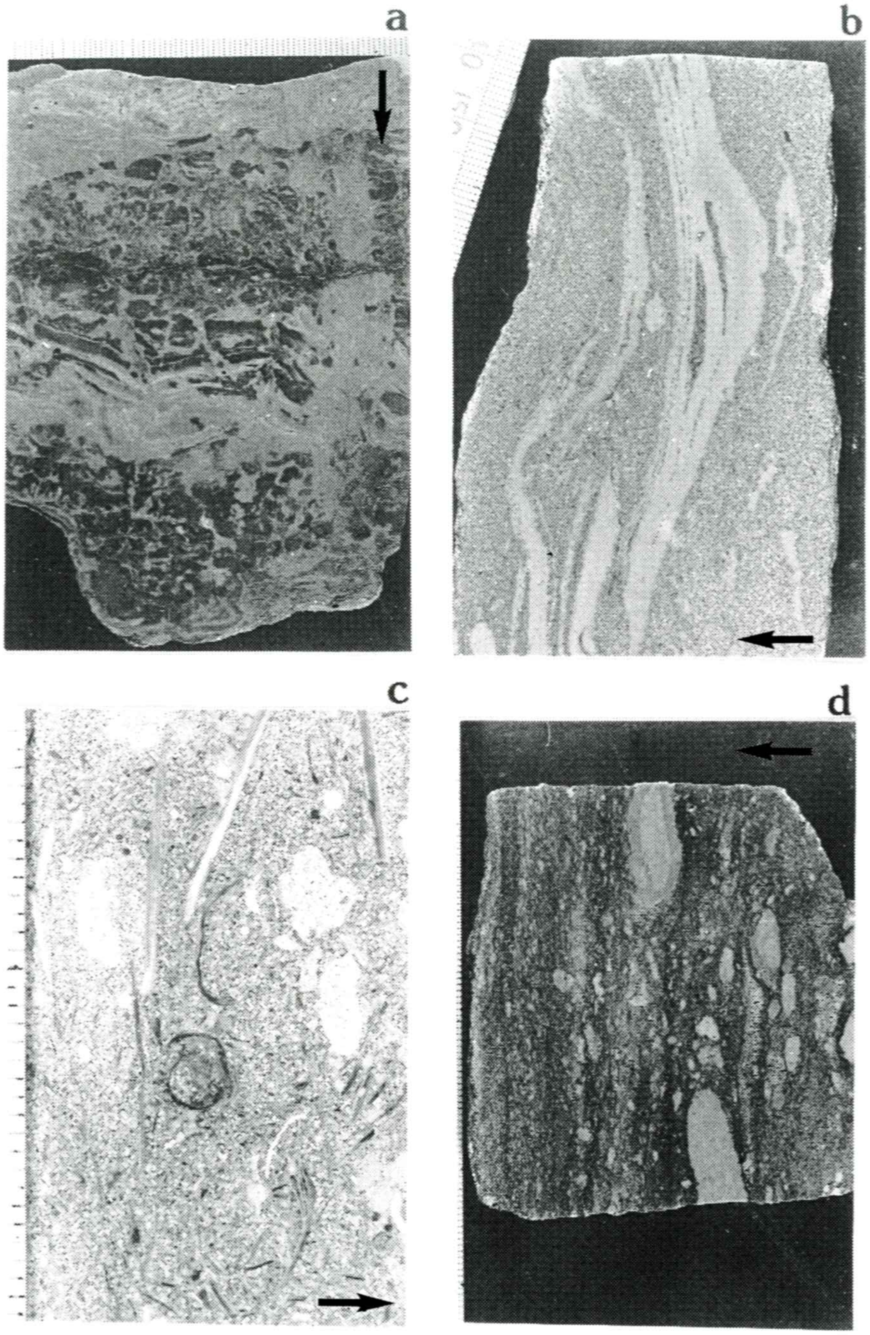


PLATE 4.7

a	Peloid packstone with subsidiary quartz grains (8-16-4-20, see Fig. 4.1).
b	Quartz rich ooid grainstone, with numerous peloids; ooids show thin oolitic envelopes (i.e. superficial ooids) (5-18-4-19, 4655').
c	Ooid grainstone showing compaction features; allochems are fringed by drusy calcite cement which formed before intergrain solution between grains. Note also collapse of skeletal mold (arrowed) (5-18-4-19, 4647').
d	Ooid grainstone, with drusy calcite fringe formed before inter grain solution (5-14-4-21, see Fig. 4.1).
e	Ooid grainstone, with similar features to that shown in d; note how quartz grains are pressed into allochems due to grain dissolution during compaction (5-14-4-21, see Fig. 4.1).
f	Ooid grainstone with dolomite drusy fringe pre-dating inter-grain dissolution; some porosity remains (P). (14-34-3-20, see Fig. 4.2).
g	Dolomitised grainstone/packstone in which the allochems appear to have suffered little dolomite replacement. (8-3-10-20, see Fig. 4.5).
h	Quartz rich dolomitic packstone in which the alochems are partially dissolved to leave pin-point porosity (12-12-4-20, see Fig. 4.2).

Plate 4.7

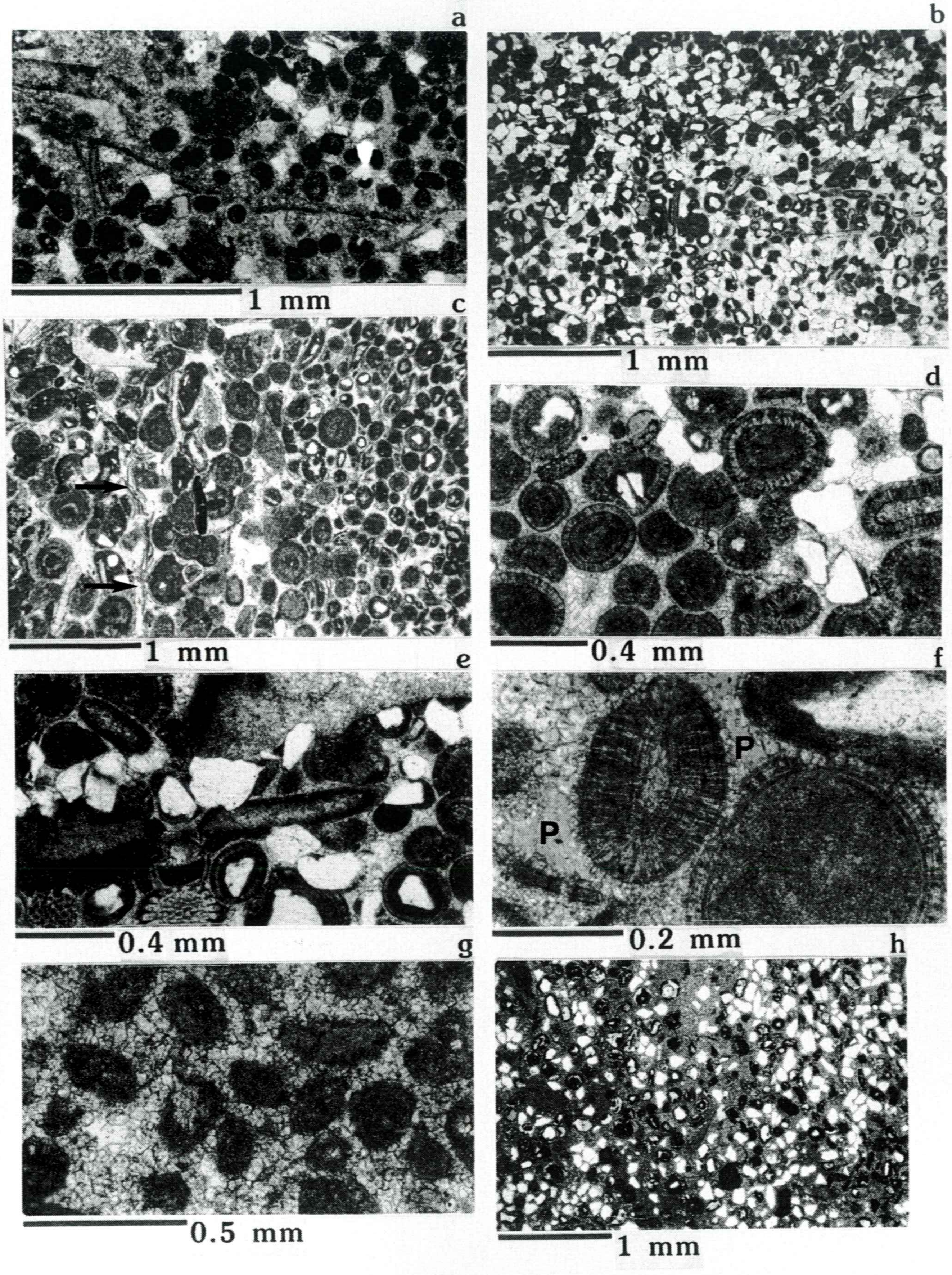


PLATE 4.8

Skeletal sands and associated sediments

a Wavy bedded skeletal packstone with shale partings. Skeletal sand grains comprising this sediment are highly abraded and micritised. (3-16-4-21, see Fig. 4.1).

b Wavy bedded skeletal packstone (similar to A) overlain (in bottom core) by horizontally laminated mudstones (16-10-7-19, see Fig. 4.3).

c Burrow mottled silts and marls (top core) overlain by skeletal grainstones showing low angle cross-bedding. (14-1-7-19, see Fig. 4.4).

d Skeletal grainstones (bottom core) showing low and high angle cross stratification, overlain by fractured micrites (soil horizon?) capped by erosion surface (top core). (14-1-9-19, see Fig. 4.4).

e Skeletal packstone: thin shelled bivalves packed convex up in a micrite matrix. (11-1-7-21, se Fig. 4.3).

f Skeletal grainstone (darker) and packstones (lighter) consisting of well rounded shell debris. Peloids and ooids are scater through the sediment. (13-4-4-17, see Fig. 4.1).

Plate 4.8

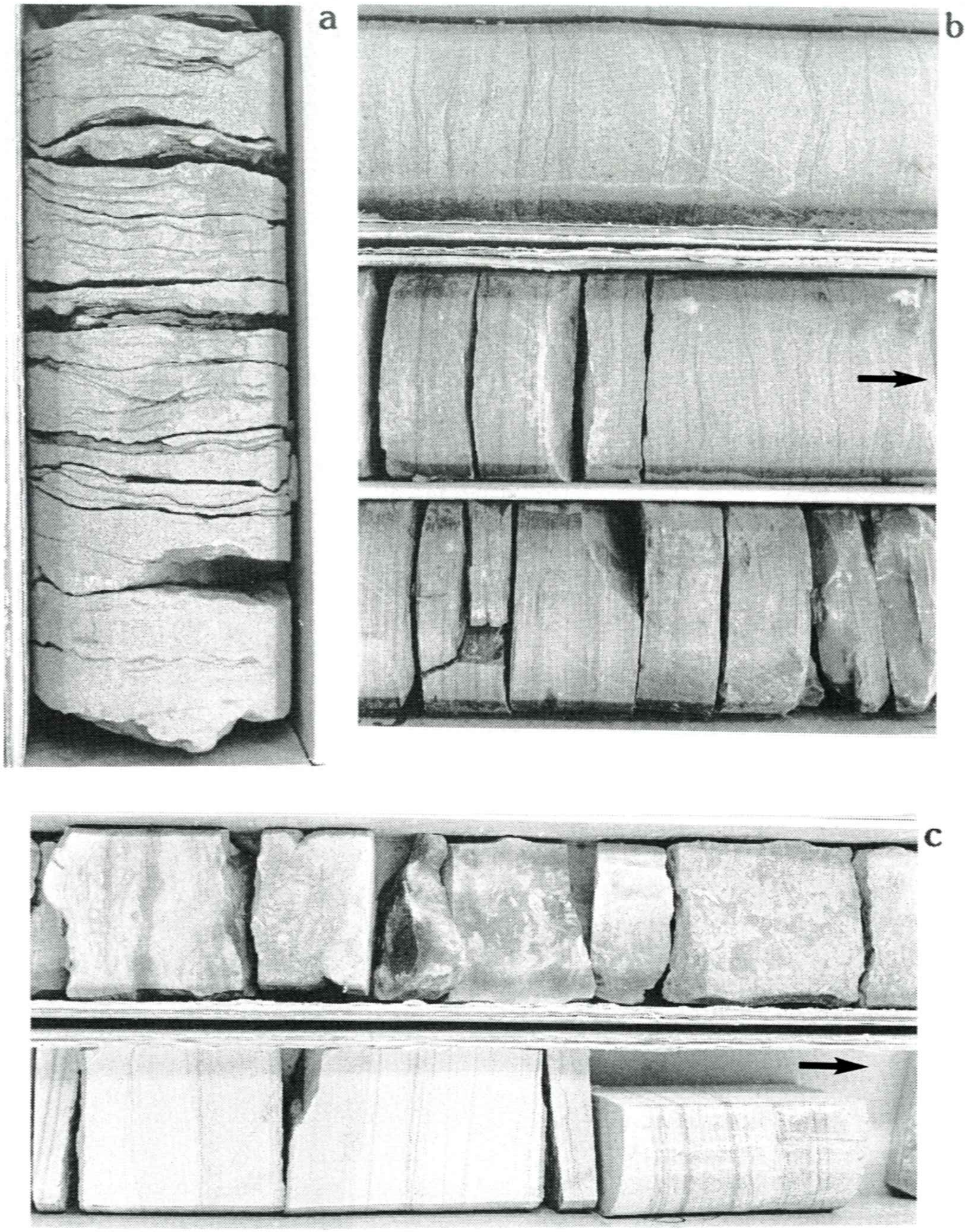


Plate 4.8 contd

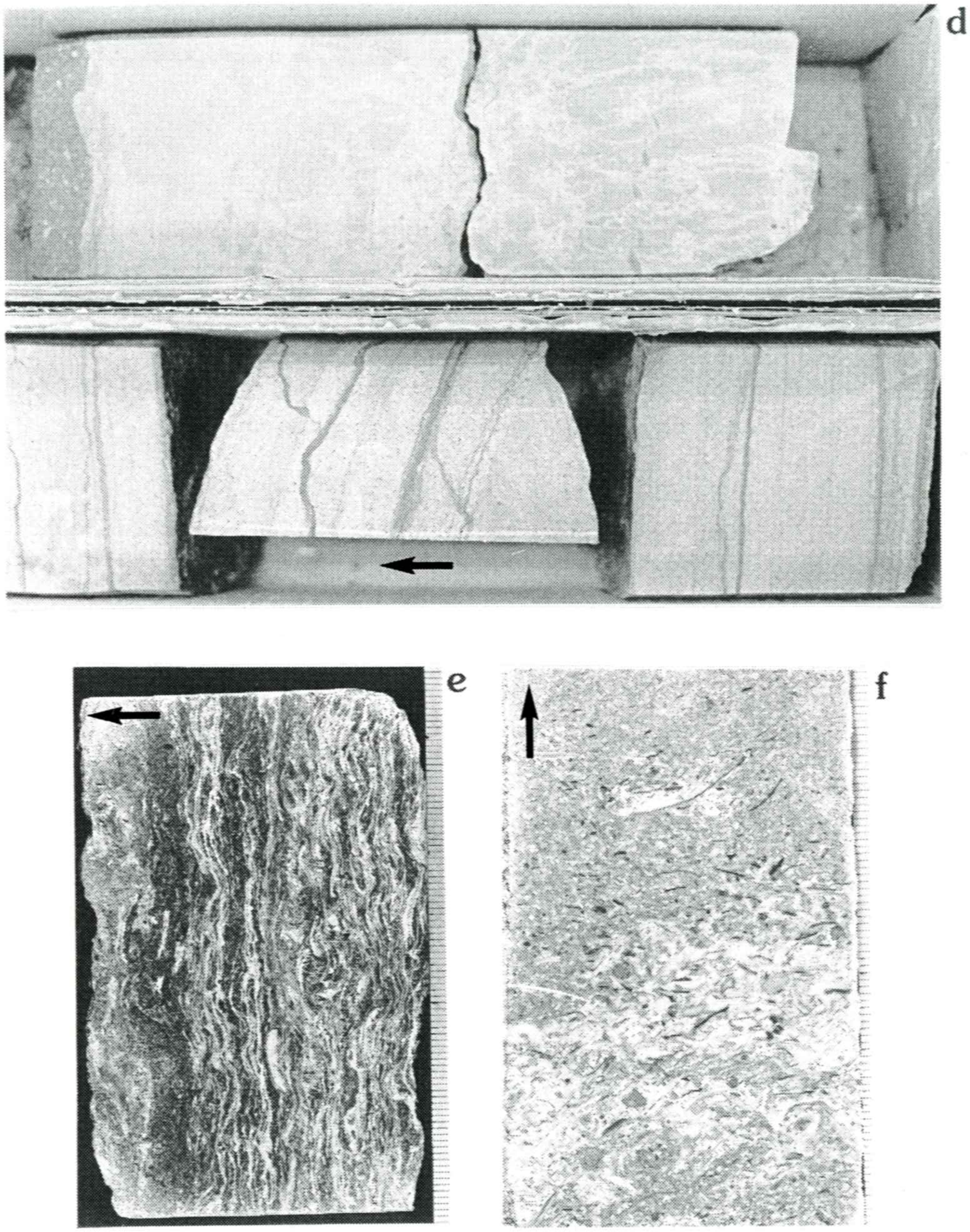


PLATE 4.9

Thin section and SEM photographs of porous skeletal sands from Well 1-22-7-20 (see Fig. 4.3), Dollard Field

a,b Skeletal grainstone, with calcitic (in life) tests (C), and mass of collapsed micritic envelopes (M). All the allochems are coated by a drusy calcite fringe that cemented the rock prior to compaction of the micritic envelopes and fracture of the large allochem at the top of the photograph.

c Micrite envelope to skeletal grain, with interior showing algal boring preserved by micrite and projecting into moldic porosity. The rock is cemented by drusy calcite fringe which has not developed inside skeletal grain preserving borings.

d, e, f SEM photographs of shell fragment preserved by micrite envelope and inter- and intra- particle porosity lined by drusy calcite fringe. Note the large pore spaces between this skeletal fragment and other grains.

Plate 4.9

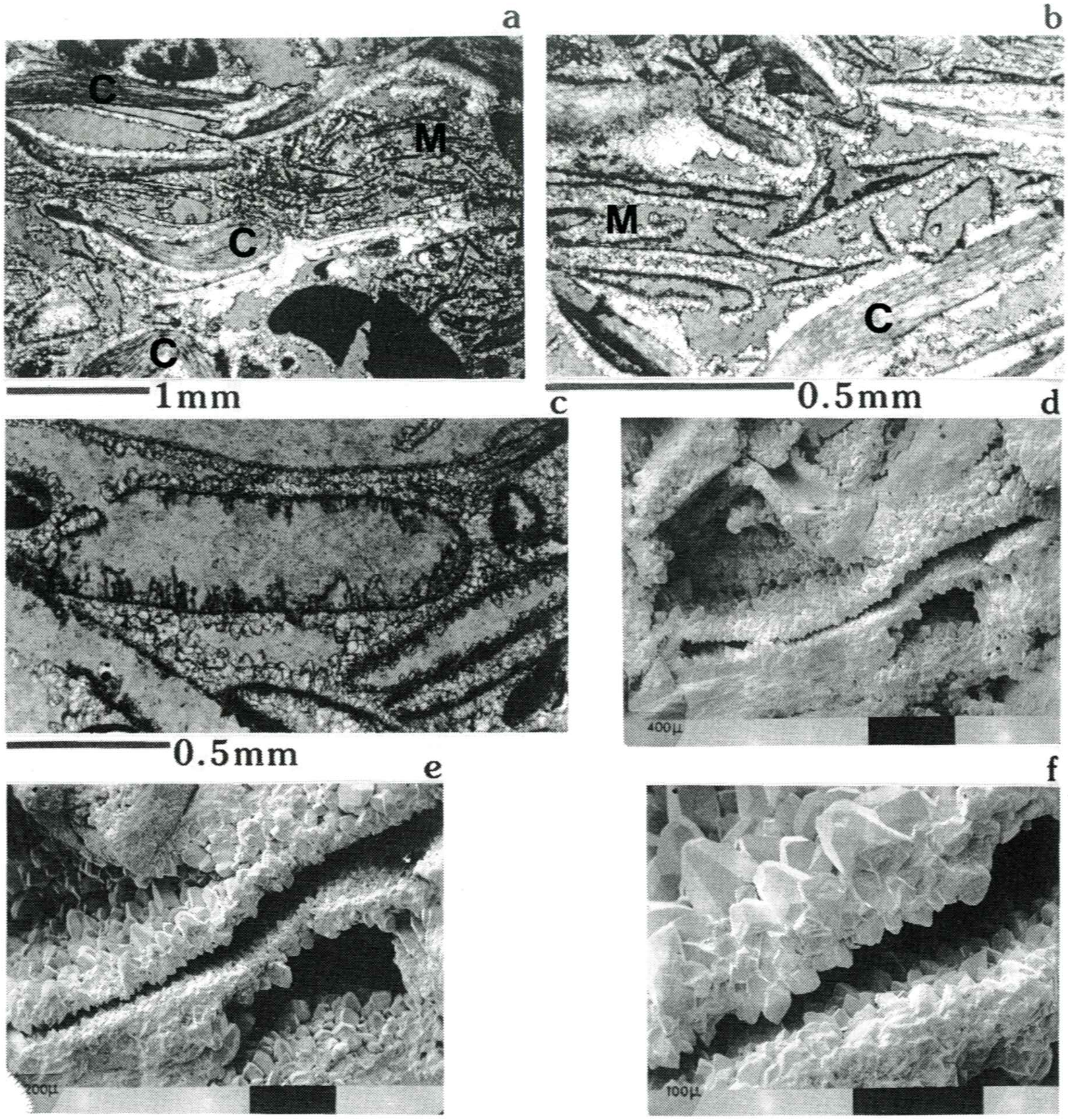


PLATE 4.10

Photomicrographs of skeletal packstones and grainstones from the Instow - Bone Creek oilfield

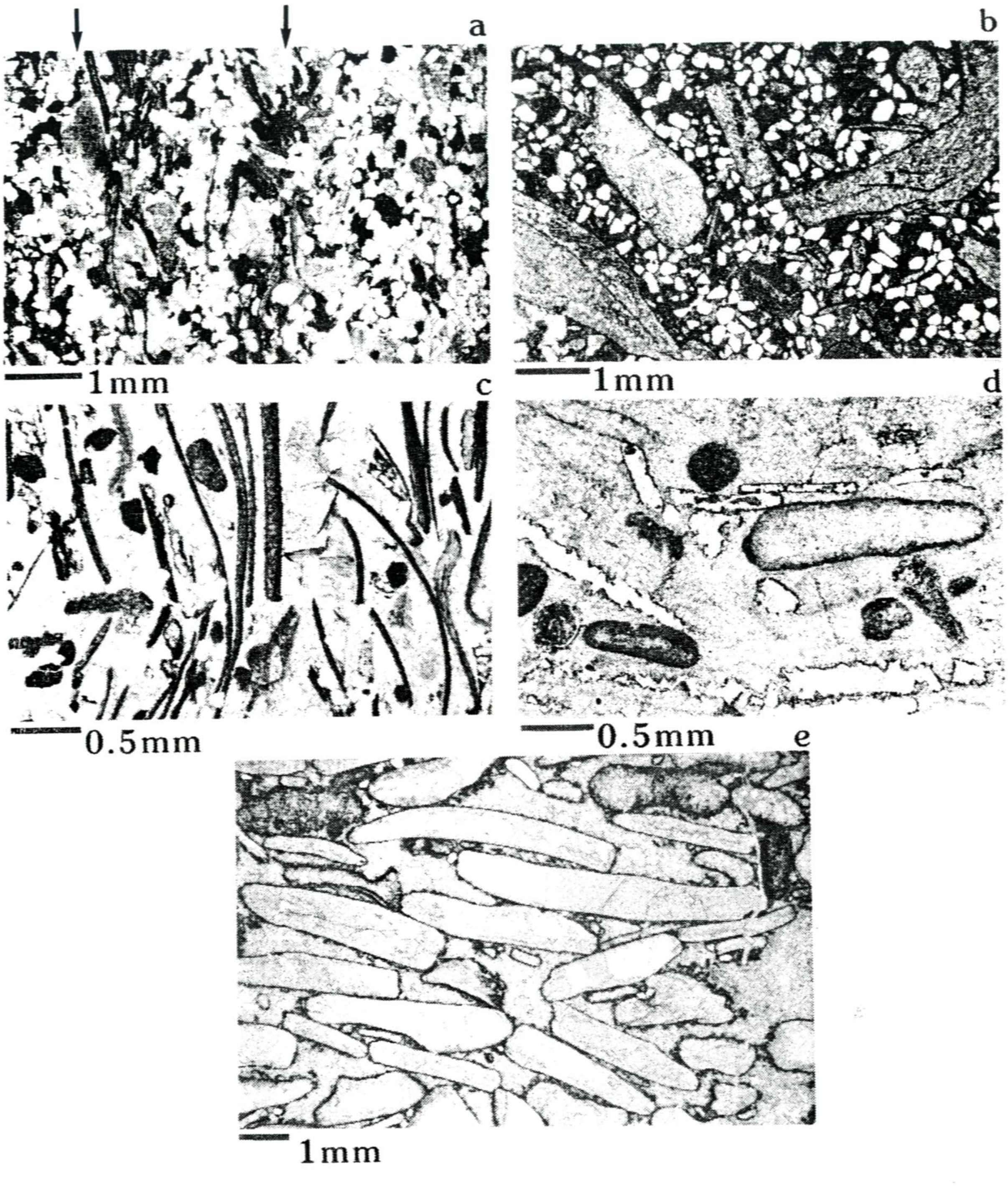
a Mixed quartz - skeletal peloid grainstone. Calcite overgrowths over echinoderm debris occlude porosity in discrete levels (arrowed). (2-34-10-19, see Fig. 4.5).

b Quartz rich skeletal wackestone. The skeletal fragments are lined with iron free drusy calcite, and filled with large ferroan calcite crystals (2-34-10-19, see Fig. 4.5).

c Quartz rich skeletal grainstone. No originally aragonitic shells are present, which suggests either ecological or diagenetic sorting. (9-7-10-18, see Fig. 4.5).

d Skeletal grainstone with subsidiary content of ooids (?); vuggy porosity is present within skeletal grains only partially filled with calcite cement. (14-19-10-19, see Fig. 4.5).

e Skeletal grainstone composed entirely of elongate grains originally composed of aragonite; shells are lined by drusy fringe of calcite, and filled with very large calcite crystals. (5-19-9-17, 4638.5').



4.10