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Depositional controls of reservoir thickness and quality distribution in Upper Miocene shallow marine sandstones (Stage IVD) of the Erb West Field, Offshore Sabah, NW Borneo

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Abstract: The Erb West field, situated offshore west Sabah, is a prominent NE-SW trending anticlinal structure containing substantial oil and gas reserves. The hydrocarbons are contained within a ca. 800 ft thick sequence of shallow marine sandstones and shales, belonging to the Upper Miocene, Stage IVD. The prospective reservoir interval is characterized by marked variations in thickness and rock quality across the field, which significantly influence hydrocarbon distribution and field development strategy; the nature and origin of these variations are discussed in terms of the depositional and tectonic setting of the Erb West field.

Facies analysis of ca. 1200 ft of core (from three wells) indicates that the reservoir sequence comprises five main facies with distinctive textures, sedimentary structures and porosity/permeability characteristics: (1) bioturbated mudstones (12%, 5 mD), (2) bioturbated sandstones (15%, 20 mD), (3) heterolithic sandstones (24%, 150 mD), (4) parallel laminated (hummocky cross-stratified) sandstones (25%, 350 mD) and (5) massive sandstone (26%, 2200 mD). The same facies can also be identified in uncored wells (total = 20) using a combination of GR, FDC, CNL and LLD log cut-off values, together with diagnostic HDT microresistivity curve shapes. Synthesis of these data, supported by regional geological and seismic data, has led to the identification of depositionally-related trends in sand thickness, facies and porosity/permeability.

Neritic microfaunas and abundant bioturbation indicate a shallow marine or shelf environment of deposition. The sandstones typically display parallel to wavy lamination (hummocky cross-stratification), wave ripples and grading, which are considered indicative of a storm-dominated depositional regime. This storm-dominated sand sequence onlaps against the Shallow Regional Unconformity and is believed to have been sourced by coastal erosion of the nearby, emergent and tectonically-active Erb High. Facies trends within the individual reservoir units support both depositional onlap and the conclusion that the Erb West reservoirs represent a transgressive sand complex.

Thickness and rock quality variations within the field reflect the interplay of depositional trends and subsidence patterns (caused by tectonics and/or relative sea-level changes). In the main N Sands reservoir the following depositional pattern is evident: (1) relatively condensed, "proximal" sequences to the E and SE, (2) well-developed, complete ("intermediate") sequences, with coarsening upward sand bodies, in the centre of the field, and (3) well-developed but finer grained, "distal" sequences to the W and NW, which includes a shale-out on the western flank. Superimposed on this facies trend is a subsidence trend which is manifested by a northward increase in the gross thickness of individual reservoir units (i.e. increasing towards the more distal part of the basin); the southward reduction in thickness reflects onlap against the Shallow Regional Unconformity. The resulting reservoir quality maps show optimum sand development in the central part of the field, seen as NE-SW trending sand "thicks", which decrease in both proximal (to E and SE) and distal (to W and NW) directions.

This reservoir geological model provides a basis for the following applications: (1) reserves estimates, (2) reservoir simulation studies, (3) monitoring well performance, (4) optimizing development well locations, and (5) further development planning.

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INTRODUCTION

The Erb West field is a major hydrocarbon accumulation, situated offshore west Sabah (Fig. 1), consisting of a 120 ft thick oil rim overlain by a large (550 ft thick) gas cap. The structural configuration of the field is relatively simple (Fig. 2), comprising a NE-SW trending domal anticline, which is cut by several normal faults, generally with only moderate throws (ca. 50 - 200 ft). In contrast, the field is stratigraphically complex, the prospective reservoir sequence of Upper Miocene shallow marine sandstones and shales (Fig. 3) displaying marked variations in sand body thickness and reservoir quality over the field.

Development strategy of the Erb West field is directed towards optimizing recovery of the oil rim and supplying gas to onshore utilities. Effective implementation of this strategy requires, amongst other things, a comprehensive knowledge of both reservoir thickness and rock quality distribution. This paper addresses this aspect of the reservoirs in the Erb West field in two ways:

(1) a depositional model is outlined, based on a synthesis of ca. 1200 ft of core supported by well log, seismic and regional geological data, and

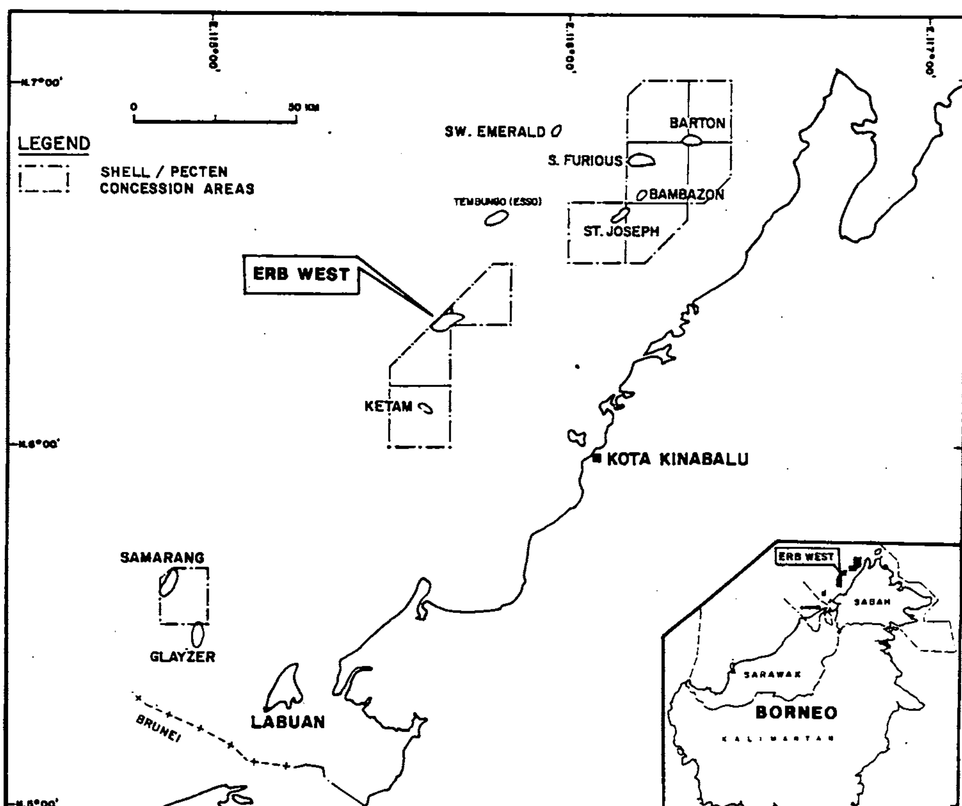


Fig. 1. Erb West Location Map

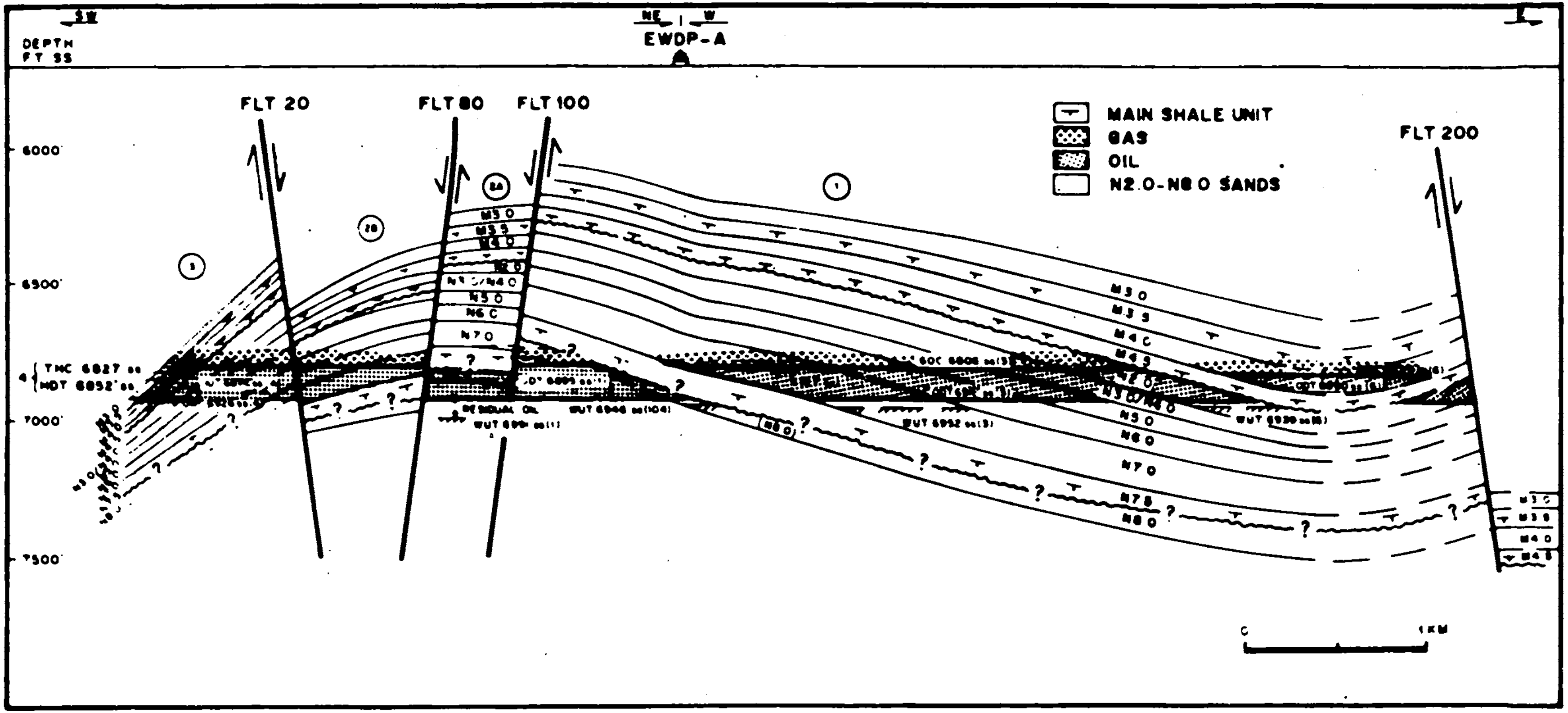
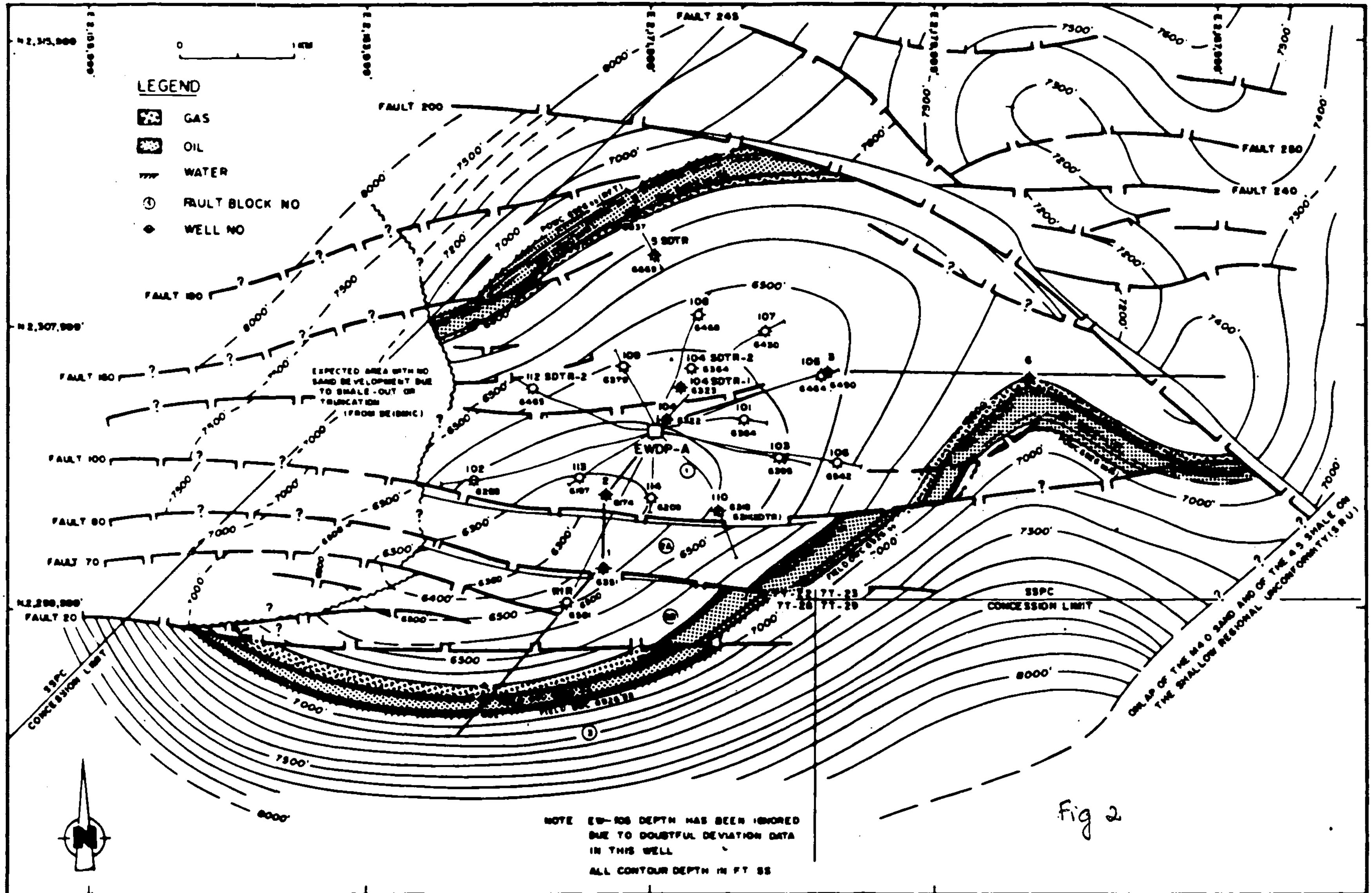


Fig. 2. Erb West Top M4.0 Map and Geological Cross-section of M3.0 – N8.0 reservoir


LEGEND
GAS
OIL
WATER
FAULT BLOCK NO
WELL NO
FAULT 245
FAULT 200
FAULT 280
FAULT 240
FAULT 180
FAULT 160
FAULT 100
FAULT 80
FAULT 70
FAULT 20
EXPECTED AREA WITH NO SAND DEVELOPMENT DUE TO SHALE-OUT OR TRUNCATION (FROM SEISMIC)
EWDP-A
SSPC
CONCESSION LIMIT
ONLAP OF THE M 4 0 SAND AND OF THE 4 5 SHALE ON THE SHALLOW REGIONAL UNCONFORMITY (S.R.U)
NOTE EW-108 DEPTH HAS BEEN IGNORED DUE TO DOUBTFUL DEVIATION DATA IN THIS WELL
ALL CONTOUR DEPTH IN FT SS
Fig 2

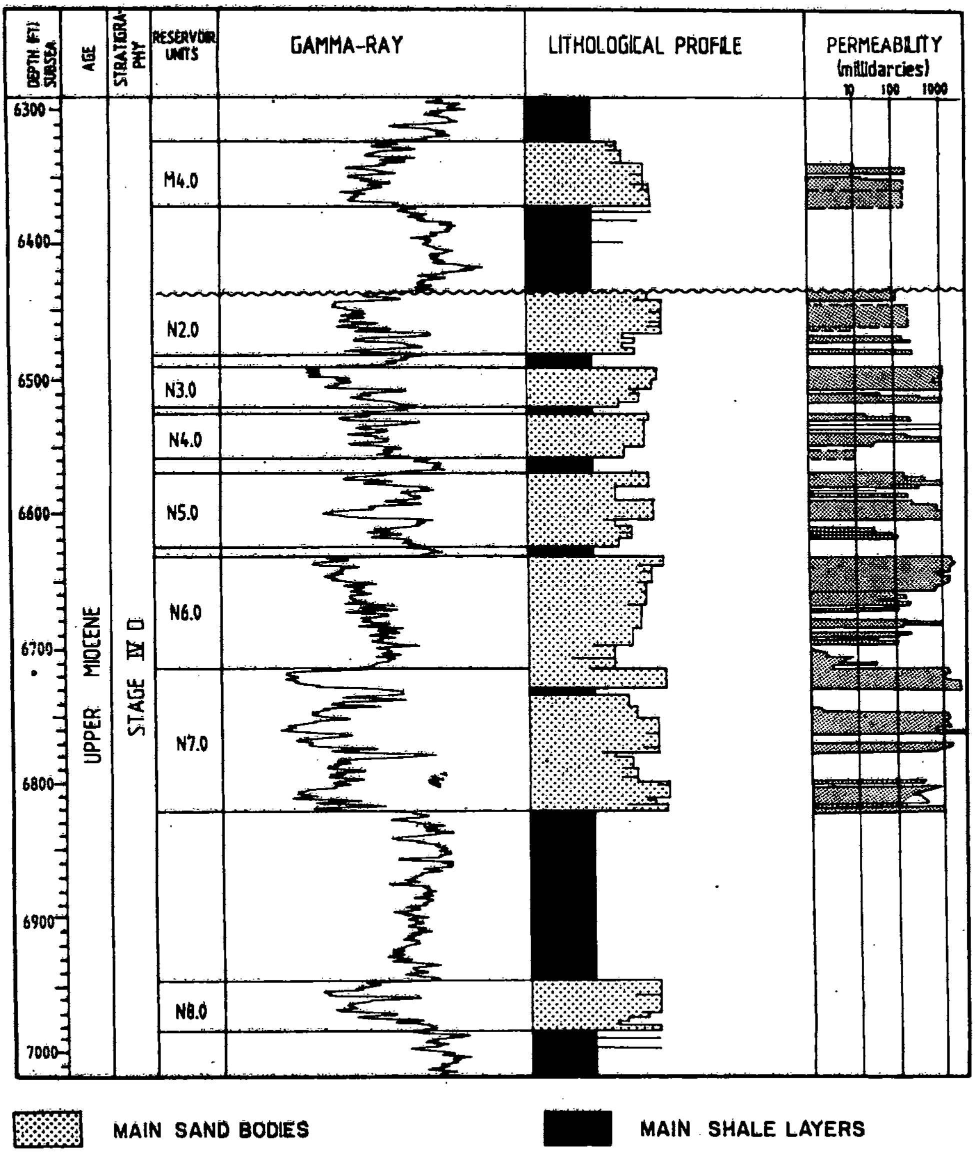


Fig. 3. Type Log through Well EW-104

(2) the reservoir geology of the field is discussed, which applies the depositional model to a description of sand thickness, facies and porosity/permeability distribution.

GEOLOGICAL SETTING AND CONFIGURATION OF THE ERB WEST FIELD

Location and discovery

The Erb West field was discovered in 1971 by the first successful offshore exploration well in Sabah. The field is located some 60 km NW of Kota Kinabalu and 125 km NNE of the island of Labuan, to where the hydrocarbons are transmitted by pipeline (Fig. 1). The field straddles three production blocks (7T-22, -23 and -28) and occurs in water depths of around 215 ft.

Stratigraphy and reservoir subdivision

The prospective interval occurs within Stage IVD, which is a ca. 4000 ft thick sequence of Upper Miocene, shallow marine sandstones and shales. Regionally this interval is defined by two seismic markers: (1) the extensive Shallow Regional Unconformity (SRU) at the base, and (2) seismic Horizon III at the top, which is an unconformity of more localized extent (Fig. 4).

The main prospective, hydrocarbon-bearing reservoirs occur within a ca. 700 ft thick interval towards the base of this Stage IVD sequence, close to the SRU. The reservoir sequence comprises an alternation of sandstones and shales which have been divided into several reservoir units (Fig. 3): (1) the majority of commercial hydrocarbons are located in six units within the N Sands (mainly N2.0 to N7.0), and (2) subordinate hydrocarbons are present in the M4.0 sand, which unconformably overlies the N Sands.

Structure

The structural configuration of the field is relatively simple, comprising a NE-SW trending, dome-shaped anticline (Fig. 4). The NE end of the field is terminated by a major, NW-SE trending normal fault (Fault 200, throw ca. 300 - 700 ft). The crestal part of the field is virtually unfaulted whereas the southern flank is dissected by several E-W trending normal faults with moderate throws (ca. 50 - 200 ft). The western flank of the field partly coincides with a major shale-out of the prospective reservoir interval.

This structural configuration is believed to be the result of deep seated wrench faulting which characterized the Sabah area during Miocene and Pliocene times. Two phases of deformation affected Erb West: (1) an Upper Miocene phase led to the formation of the Shallow Regionally Unconformity (Levell, 1987) and (2) a late Pliocene phase caused uplift of the anticline followed by subsequent crestal collapse.

Hydrocarbons

Hydrocarbons occur in a single column totalling around 670 ft in thickness (120 ft oil rim and a 550 ft gas cap). Under initial conditions common fluid contacts and pressure regimes were present in virtually all the reservoir units (seven separate sand complexes identified) and in all the different fault blocks. Since production started in 1981 (from a thirty slot, centrally located platform in the northern crestal area) the six main reservoir units (N2.0

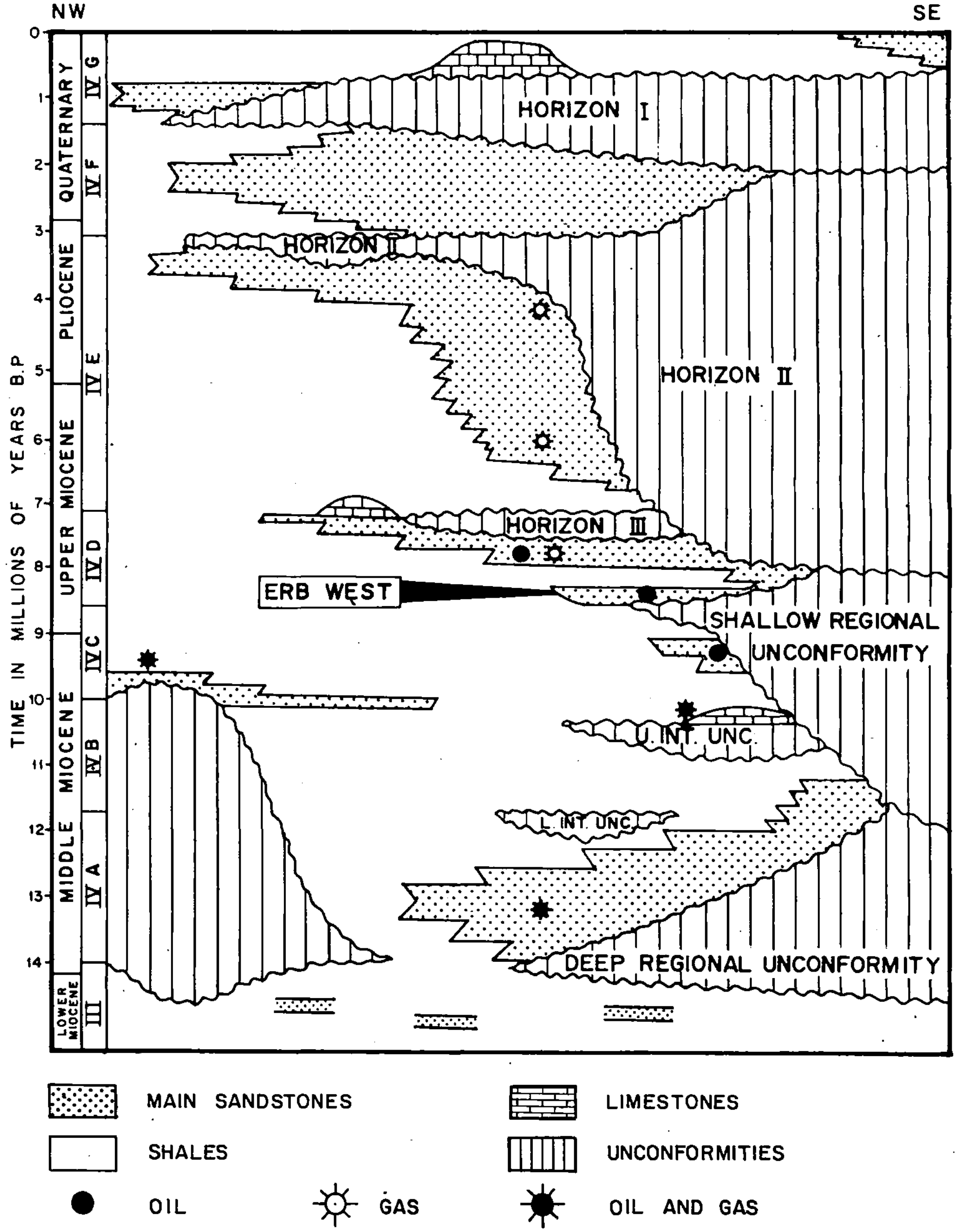


Fig. 4. Simplified Chronostratigraphy of Offshore Sabah

- N7.0 Sands) have remained in pressure communication, probably due to cross-flow through the normal faults of the crestal collapse zone. The uppermost sand (M4.0 Sand), however, which unconformably overlies the N-Sands, is separated by a major shale unit and contains undepleted pressures. This sand shares the field-wide OWC (= 6926 ft ss) but has a GOC some 23 ft deeper than the field-wide contact (= 6806 ft ss).

DEPOSITIONAL SETTING OF THE STAGE IVD RESERVOIRS

Regionally the Upper Miocene Stage IVD sands were deposited during a period of slow relative sea-level rise and/or a phase of increased clastic input. This resulted in rapid progradation of the fault-defined shelf edge, along which marked instability and slumping occurred (Levell and Kasumajaya, 1985).

The Stage IVD inner neritic to coastal deposits form a NE-SW trending, partly discontinuous, belt of sands, which was oriented parallel to the palaeocoastline (Fig. 5). These sands pass rapidly basinwards (to the NW) into deeper marine shales which, in places, contain turbidite sands (eg. in Esso's Tembungo field, Whittle and Short, 1978; Levell and Kasumajaya, 1985). To the SE, however, the shallow marine sands are absent, due either to non-deposition or to shallow marine erosion associated with the formation of the Shallow Regional Unconformity (Levell, 1987).

The Erb West field is situated close to the NW edge of the inner neritic-coastal sand sheet (Fig. 6). Within the vicinity of the field, seismic sections highlight two important large-scale features associated with the distribution and general setting of the prospective reservoir interval (Fig. 7):

(1) The reservoir sequence shows progressive onlap against the Shallow Regional Unconformity (Fig. 7a). which climbs progressively to the SE of the field towards the Erb High (Fig. 8). This trend persists regionally throughout offshore Sabah, as discussed by Levell, 1987.

(2) A change in seismic character in the western part of the field (from strong, parallel reflectors in the E, to weak discontinuous reflectors in the W) corresponds to a facies change from mainly sands (within the field) to mainly shales (on the western flank; Fig. 7b)

SEDIMENTOLOGY OF THE STAGE IVD RESERVOIRS

The characteristics of the Stage IVD reservoirs in the Erb West field are based on sedimentological studies on around 1200 ft of core taken from three main wells: EW-4, -5 and –104 (Fig. 2). The main results of these studies are outlined below.

Facies characteristics

The N and M Sands comprise five main genetically-related facies types identified on the basis of lithology (grain size, sorting, clay content), primary sedimentary structures, bioturbation and porosity/ permeability (Fig. 9). The facies reflect a broad range of reservoir properties and are summarized below:

(1) *Bioturbated mudstones* (MB) are usually biogenically mottled and relatively homogeneous. Additional features include thin (0.5 ft), sharp-based sandstone beds, shell-rich layers, plane lamination with graded bedding and common nodules of siderite and resin. Inner neritic microfaunas are abundant. This facies occurs in intervals of up to 200 ft thick and corresponds to the main shale units.

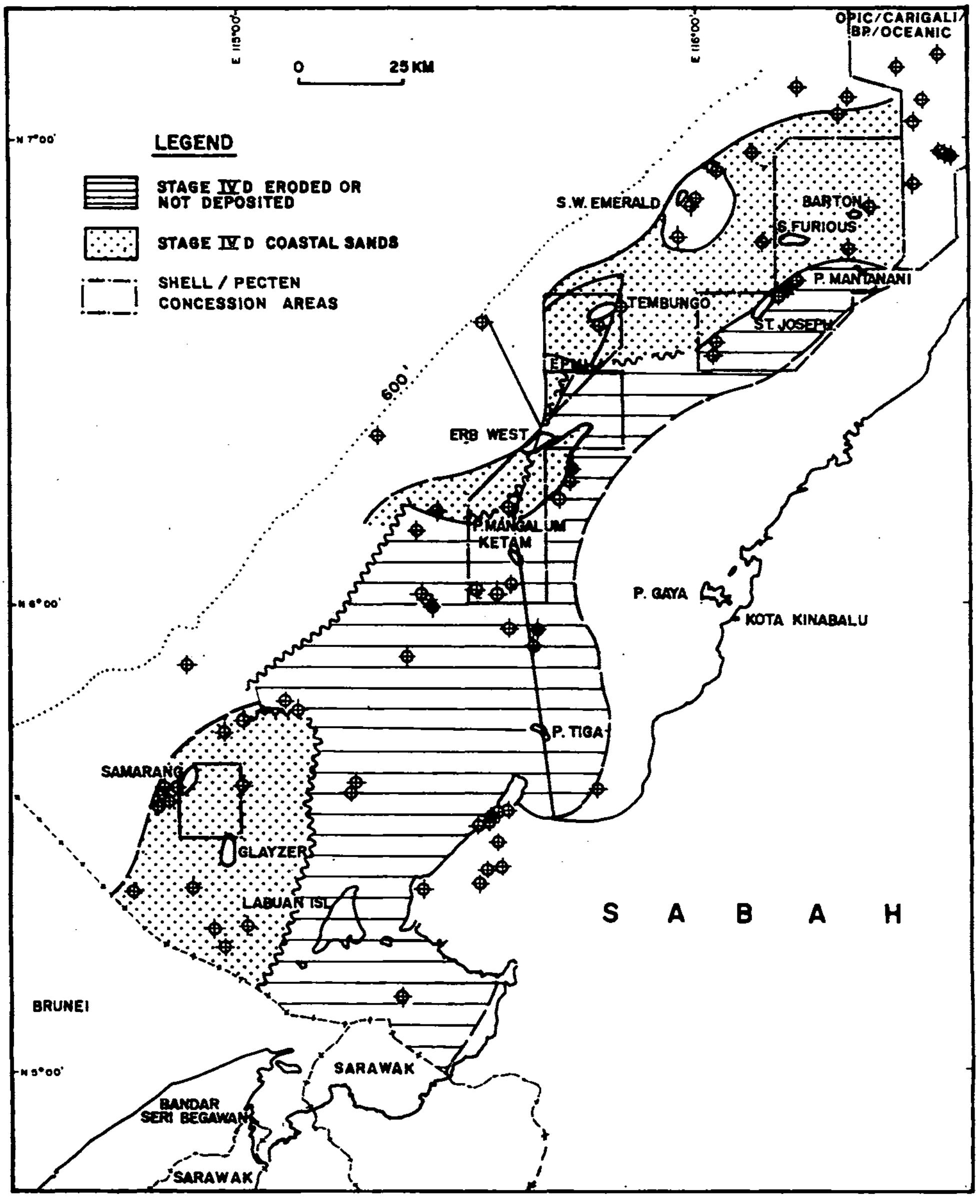


Fig. 5. Stage IVD Regional Sand Distribution Map

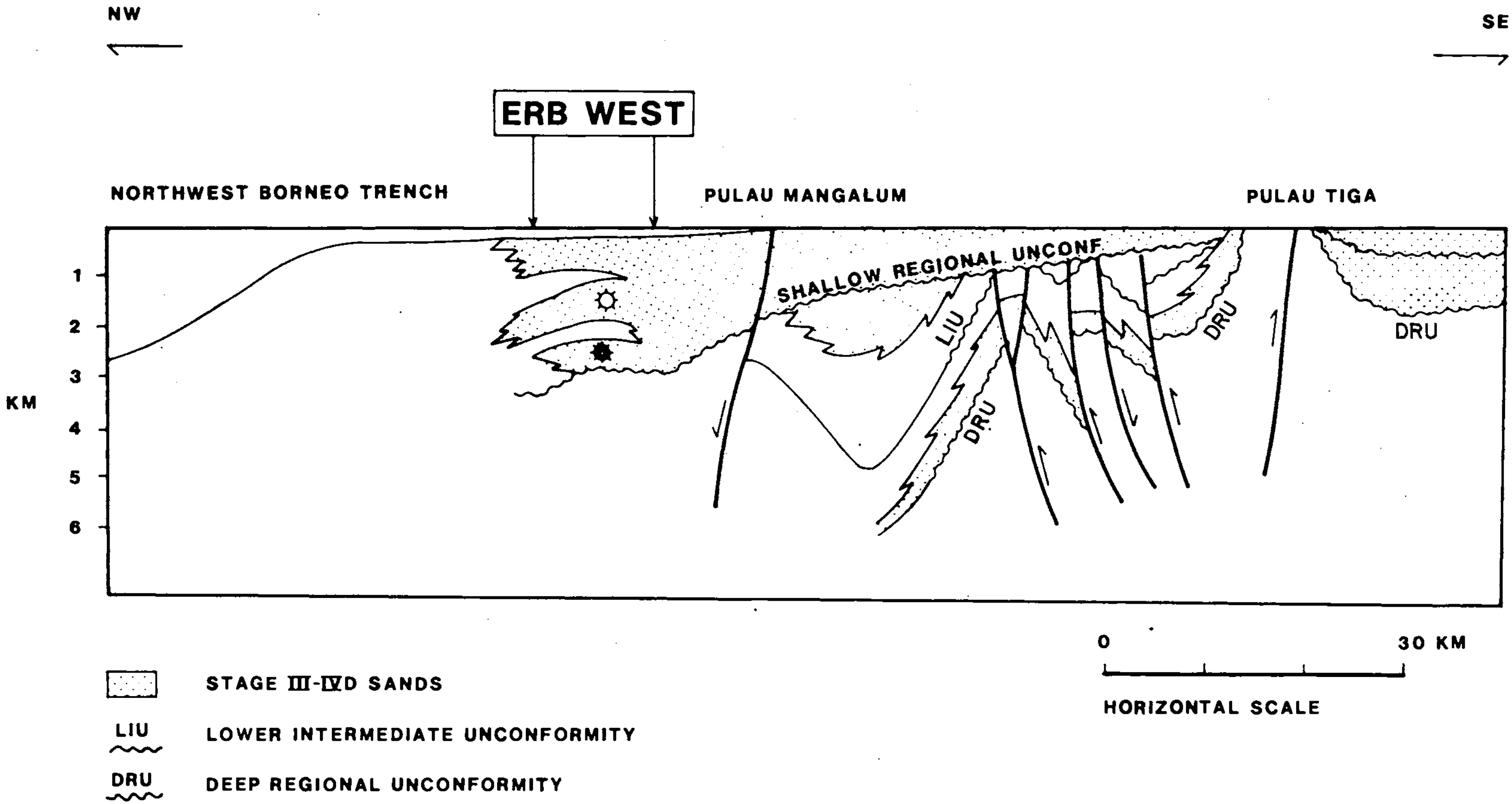


Fig. 6. Regional Geological Cross-section through West Sabah Offshore

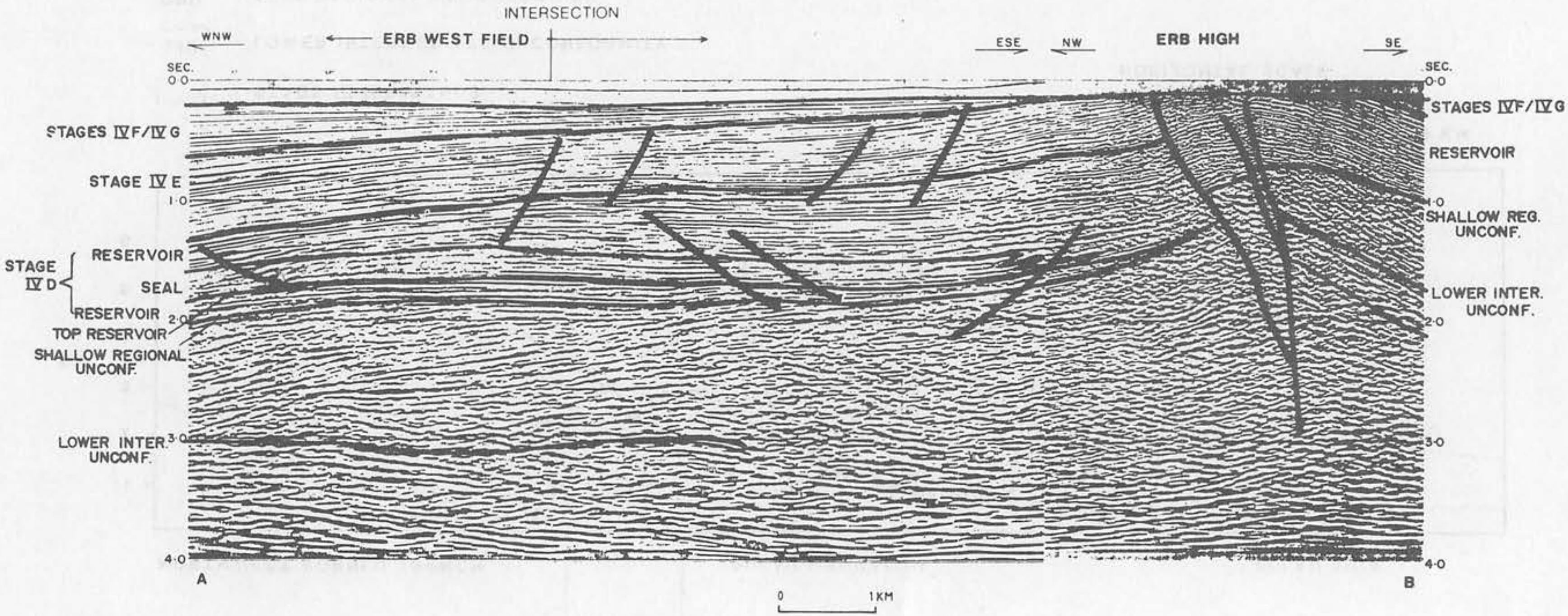


Fig. 7a. Erb West Migrated Seismic Section A-B

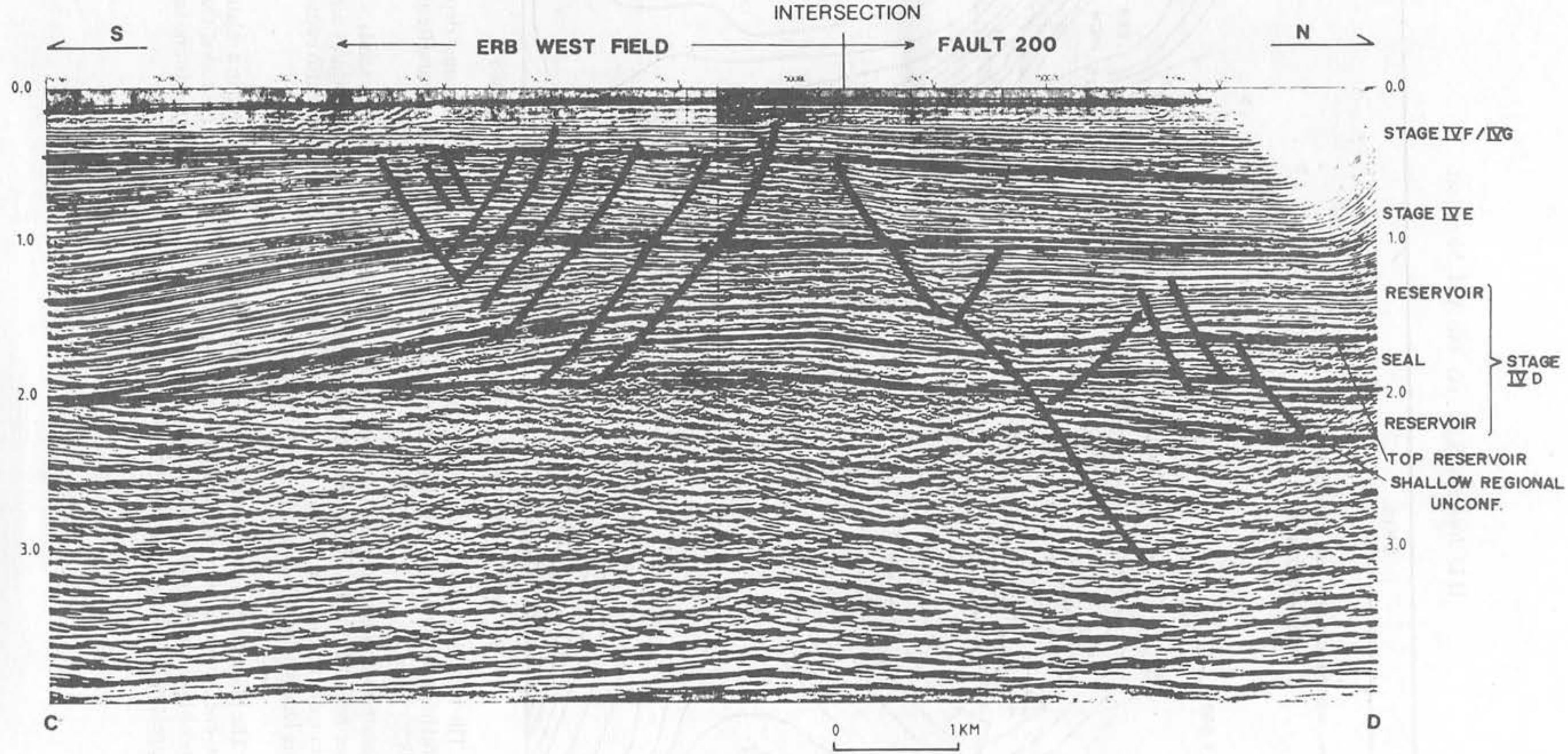


Fig. 7b. Erb West Migrated Seismic Section C-D

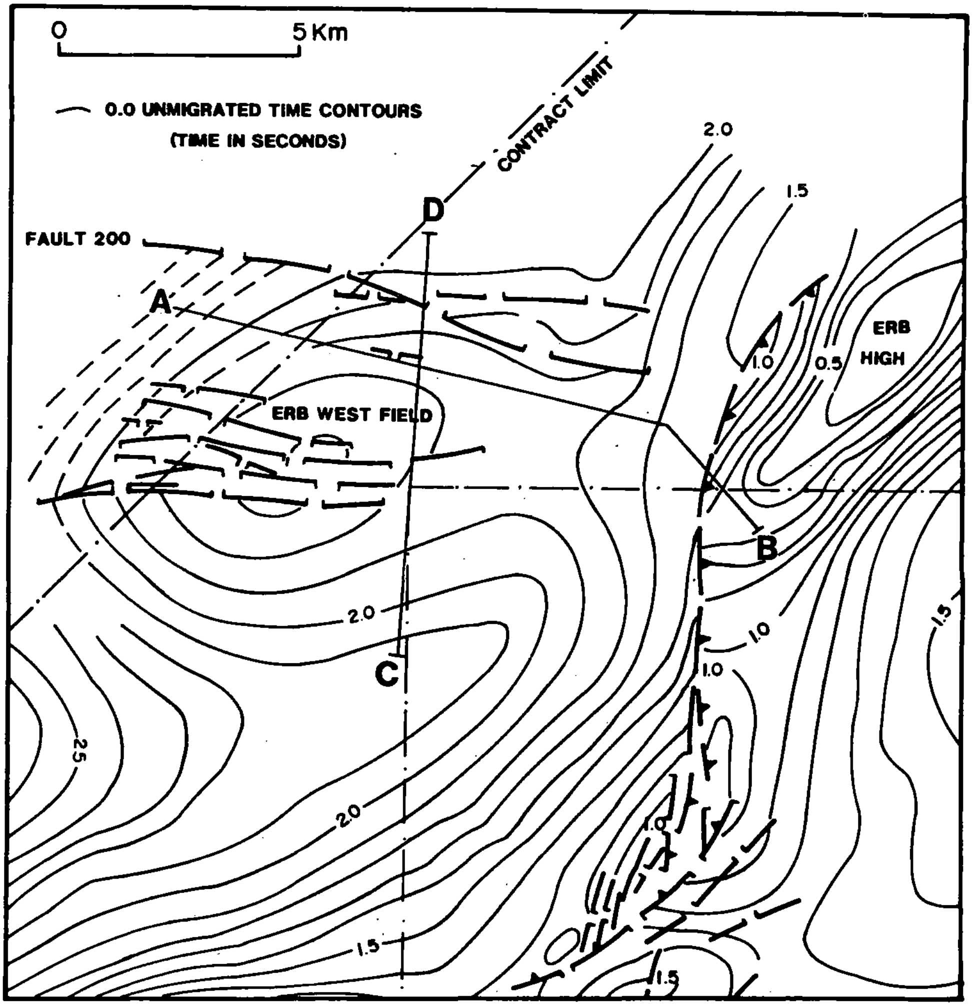


Fig. 8. Erb West Unmigrated Time Map of Shallow Regional Unconformity

The bioturbated mudstone facies is interpreted as a low-energy, shelf mud deposit, containing minor distal storm deposits (eg. sand and shell layers; cf. Aigner and Reineck, 1982).

(2) *Bioturbated sandstone* (SB) comprises mainly fine grained, argillaceous sands which have been thoroughly homogenized by biogenic reworking. Mottled textures are the dominant microscopic feature, but clay-lined *Ophiomorpha* burrows are also common. This facies occurs in intervals of 0.5 - 50 ft thick.

The bioturbated sandstone facies is interpreted as having accumulated in a relatively low-energy neritic environment in which the rate of bioturbation exceeded that of deposition. This facies is often closely associated with the bioturbated mudstone facies, suggesting a close genetic and environmental relationship.

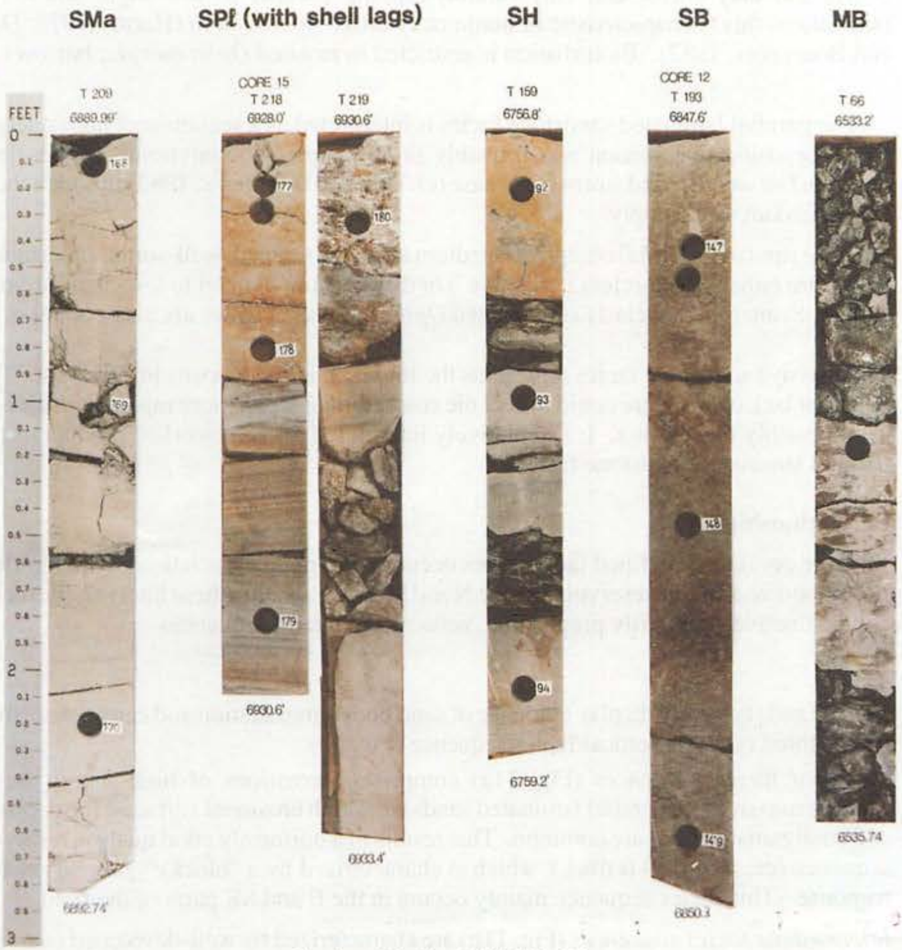


Fig. 9. Erb West Field EW-104

(3) *Heterolithic sandstone* (SH) comprises mainly sandstones with intercalations of relatively thin mudstones. The sandstones are fine grained, parallel to wavy laminated and occasionally wave rippled. Individual beds are usually 0.5 - 1 ft thick, sharp based, overlain by shell debris and/or shale clasts and grade upwards into finer laminated sand. Isolated *Ophiomorpha* burrows are common.

The heterolithic sandstone facies is interpreted as a sequence of storm-deposited sandstone beds separated by intervening, fair weather mudstone deposits. They accumulated in an inner neritic environment intermediate between the low-energy bioturbated sandstones and the high-energy, parallel laminated sandstones.

(4) *Parallel laminated sandstone* (SPl) consists of medium to coarse grained sandstone which occurs in intervals ca. 10 - 50 ft thick. These sandstones occur in cm-dm thick beds which display the following features: (i) erosional bases, (ii) basal lags of lignite, shell

debris and clay clasts, and (iii) variably-dipping parallel to low-angle and wavy lamination; this is characteristic of hummocky cross-stratification (Harms, 1979; Dott and Bourgeois, 1982). Bioturbation is restricted to isolated *Ophiomorpha* burrows.

The parallel laminated sandstone facies is interpreted as a sequence of high-energy, storm deposits. Deposition was probably in an inner neritic environment, possibly between fair weather and storm wave base (cf. Dott and Bourgeois, 1982) in which there was abundant sand supply.

(5) *Massive sandstone* (SMa) comprises medium to coarse grained, well-sorted sandstones, which are either structureless ("massive") or display faint parallel to low-angle stratification. Scattered clay clasts and isolated *Ophiomorpha* burrows are also common.

The massive sandstone facies represents the highest energy deposits in Erb West. The apparent lack of structure could reflect the coarser grain sizes, more rapid deposition or even possibly dewatering. It is tentatively interpreted as the reworked product of the parallel laminated sandstone facies.

Facies relationships

The five previously defined facies types occur in two main associations, which reflect the gross subdivision of the reservoir into the N and M Sands. Within these intervals the facies occur in distinctive, and partly predictable, vertical and lateral sequences.

The *N Sands* typically display evidence of sand body progradation and can be described in terms of three types of vertical facies sequence (Fig. 10):

(i) *Proximal facies sequences* (Fig. 11a) comprise alternations of high-energy sands (mainly massive and parallel laminated sands) in which erosional surfaces, lag deposits and amalgamated beds are common. This results in a uniformly good quality, reservoir sequence (ca. 50 - 130 ft thick), which is characterized by a "blocky" gamma ray log response. This facies sequence mainly occurs in the E and SE parts of the field.

(ii) *Intermediate facies sequences* (Fig. 11b) are characterized by well-developed coarsening upward sequences (funnel-shaped gamma ray log profiles) in which low-energy facies (eg. bioturbated mudstones and sandstones) are gradually replaced upwards by high-energy facies (massive and parallel laminated sands). Reservoir quality shows a similar upward improvement. This facies sequence is most characteristic of the central part of the field.

(iii) *Distal facies sequences* (Fig. 11c) mainly comprise low-energy facies types (bioturbated mudstones and sandstones, and heterolithic facies) and reservoir quality is relatively poor. They often occur in weakly developed coarsening upward sequences (poorly defined funnel-shaped gamma ray log profiles), which are mainly found in the W and NW part of the field.

The *M Sands* are characterlzed by fining upward, or retrogradational sequences (Fig. 12), and reflect a period of gradually diminishing sand supply. The M Sands, therefore, display a quite different facies sequence to the N Sands (cf. Figs. 10 and 12).

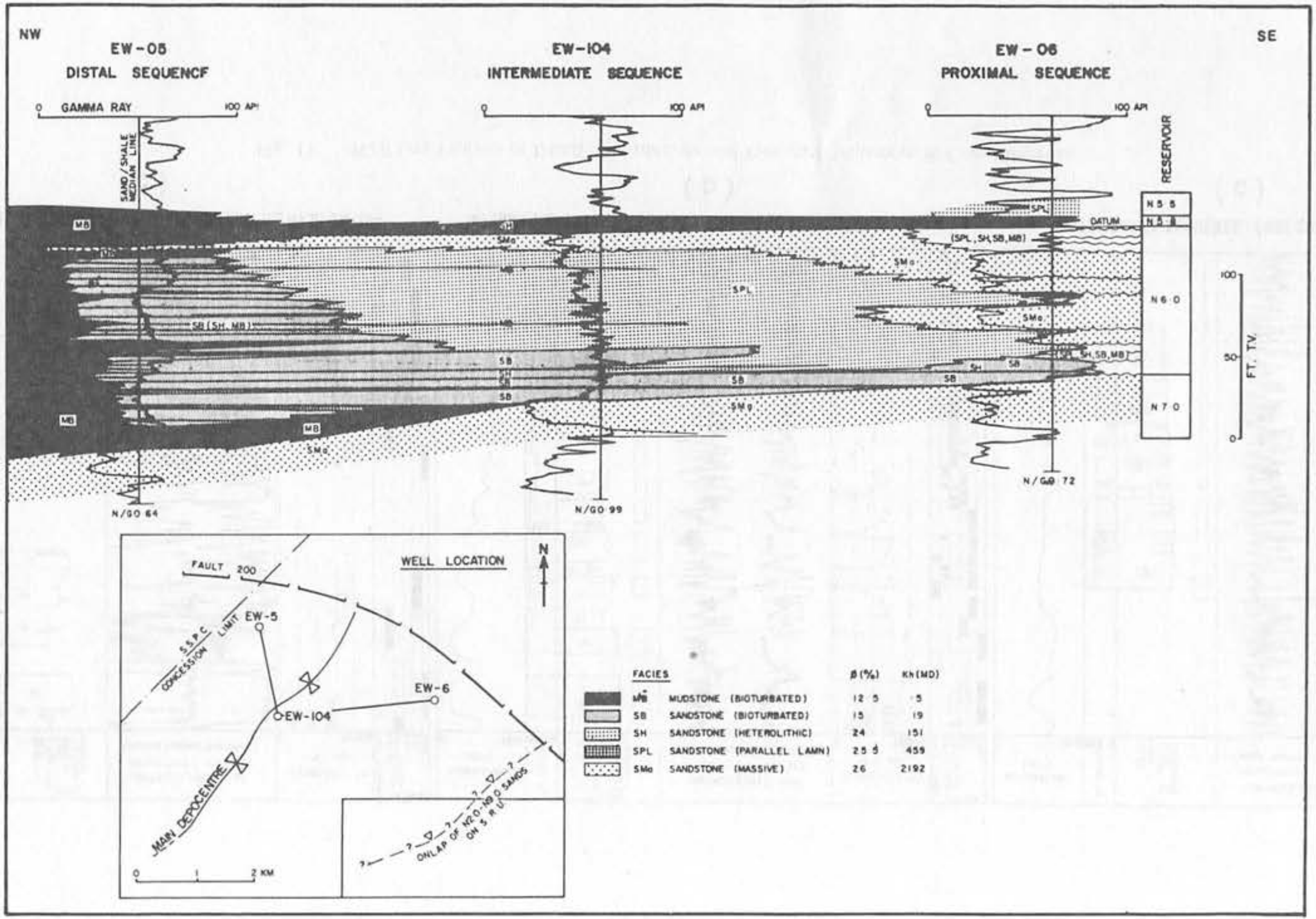


Fig. 10. Well Log Profiles and Facies Distribution for N6.0 Sand

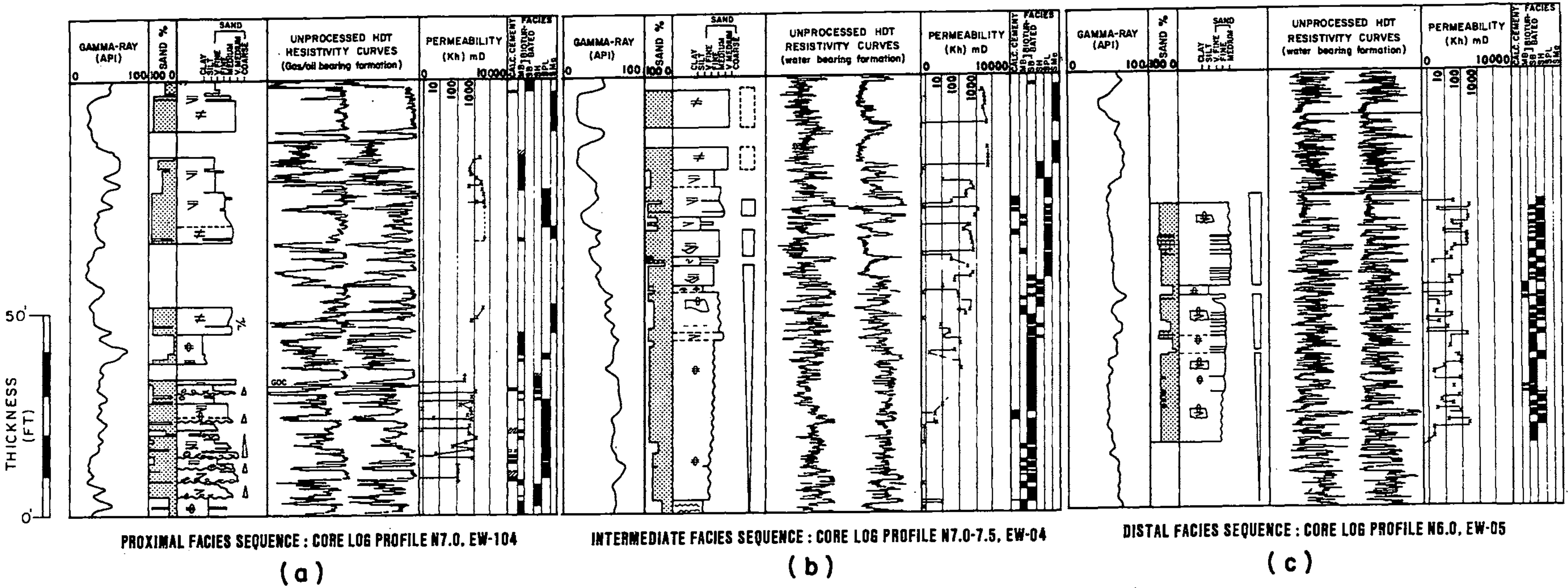


Fig. 11. Well Log Profiles of Distal, Intermediate and Proximal Sequences in Cored Intervals

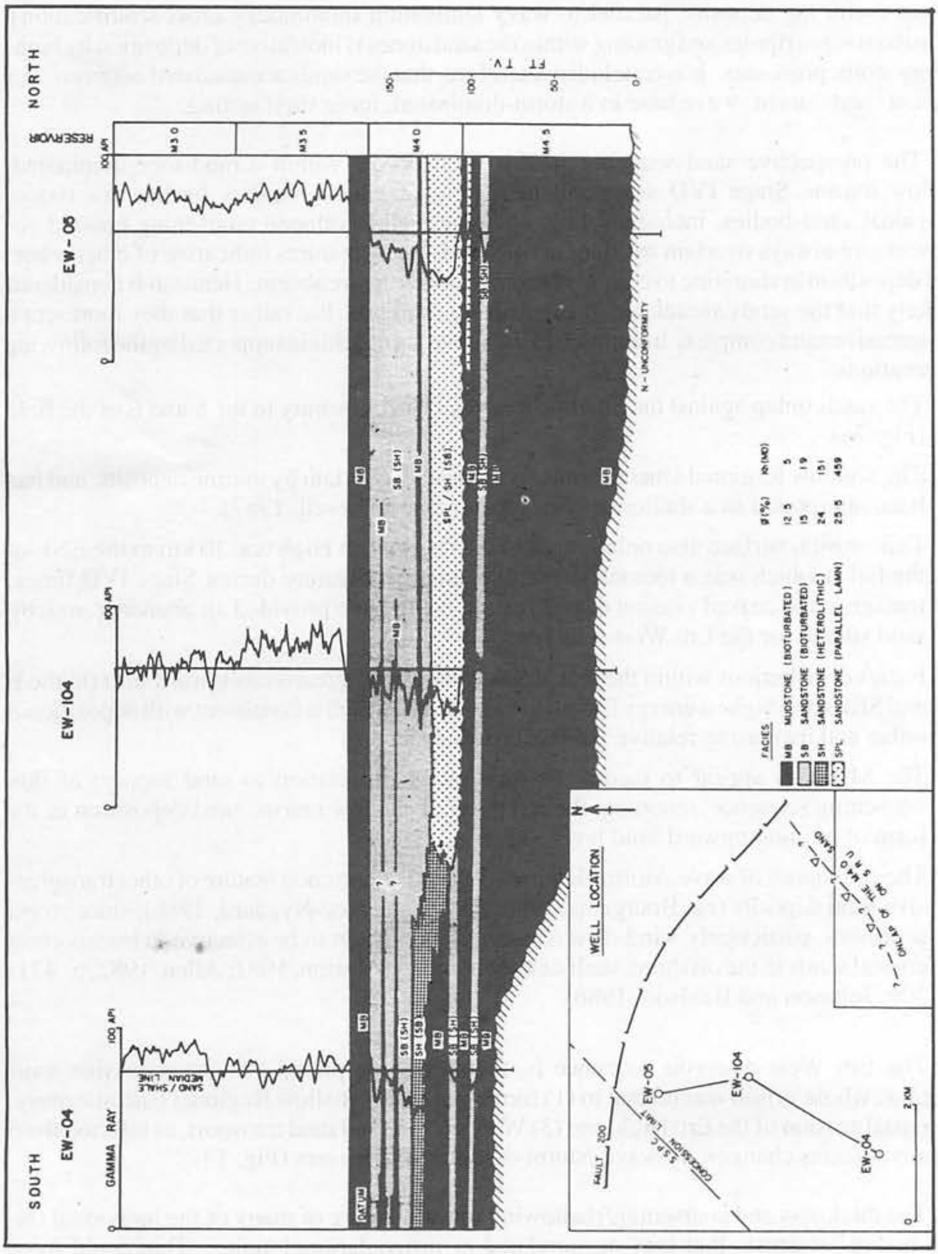


Fig. 12. Well Log Profiles and Facies Distribution for M Sands

Depositional model

The depositional environment of the cored intervals is broadly defined as inner neritic (fluviomarine) to coastal on the basis of the foram assemblage. The abundance of erosion surfaces with lag deposits, parallel to wavy lamination (hummocky cross-stratification), occasional wave ripples and grading within the sandstones is indicative of deposition by high-energy storm processes. It is concluded, therefore, that the sands accumulated between 'fair weather' and 'storm' wave base in a storm-dominated, inner shelf setting.

The prospective sand sequence in Erb West occurs within a mudstone-dominated, shallow marine Stage IVD sequence, the origin of which requires further discussion. Individual sand bodies, including those showing well-developed coarsening upward sequences, are always overlain by inner neritic mudstones; features indicative of emergence, or of deposition in shoreline to coastal plain environments, are absent. Hence, it is considered unlikely that the sands are related to a regressive shoreline, but rather that they represent a transgressive sand complex. In addition to the above points, this is supported by the following observations:

(1) The sands onlap against the Shallow Regional Unconformity to the S and E of the field (Fig. 7a).

(2) The Shallow Regional Unconformity is invariably overlain by marine deposits, and has been interpreted as a shallow marine erosion plane (Levell, 1987).

(3) This erosion surface also onlaps against the nearby Erb High (ca. 10 km to the ENE of the field) which was a tectonically-active, emergent feature during Stage IVD times; transgressive coastal erosion of this feature could have provided an abundant, nearby sand source for the Erb West reservoirs.

(4) Facies distributions within the mai N Sands show a progressive landward shift (to the E and SE) of the highest energy facies (SPl and SMa). which is consistent with depositional onlap and increasing relative sea level rise/subsidence.

(5) The M Sands appear to record the final phase (in relation to sand supply) of this deepening sequence, recording the last pulse of shallow marine sand deposition in the form of a fining upward sand layer.

(6) The abundance of wave-/storm-dominated sands is a common feature of other transgressive sand deposits (eg. Bourgeois, 1980; Surlyk and Noe-Nygaard, 1986), since storm processes, particularly wind-driven currents, are known to be effective in transporting coastal sands to the offshore, shelf environment (eg. Morton, 1981; Allen, 1982, p. 471-506; Johnson and Baldwin, 1986).

The Erb West reservoir sequence is, therefore, interpreted as a transgressive sand complex, whose origin was related to (1) formation of the Shallow Regional Unconformity, (2) coastal erosion of the Erb High, and (3) W to SW directed sand transport, as inferred from the lateral facies changes, by wave-/storm-dominated processes (Fig. 13).

The thickness and coarsening/shallowing upward nature of many of the individual 'N-sand bodies' suggests that they accumulated as progradational units. This could have occurred in the following ways: (1) sands could have been transferred from the shoreface onto the shelf via shoal retreat massifs (ie. transgressive shallow marine sand sheets, possibly

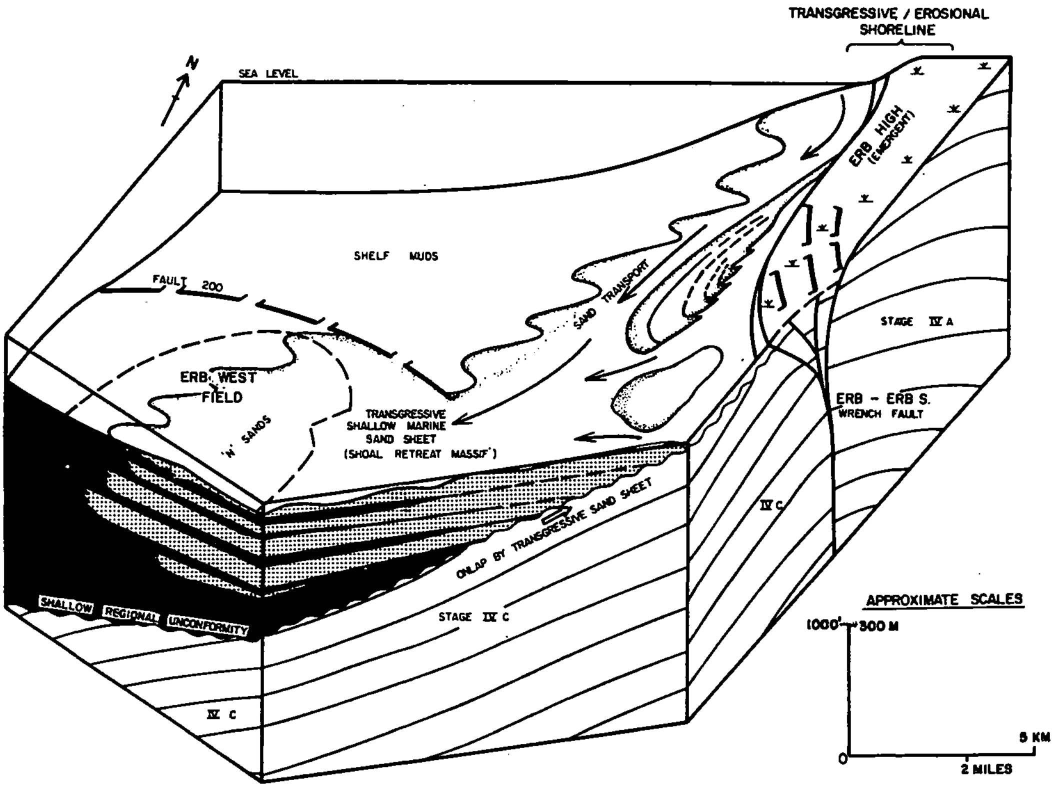


Fig. 13. Erb West Depositional Model for Stage IVD Sand Reservoirs

including the remnants of ephemeral deltas reworked by the transgressing sea), (2) reworked spits may have temporarily built-out from shoreline headlands, or (3) linear shelf sand bars may have migrated laterally. These features would act through time as temporary 'sinks' into which sediment would prograde.

RESERVOIR GEOLOGY OF THE STAGE IVD RESERVOIRS

To improve prediction of sand thickness and rock quality variations across the field, the following approach was applied: (1) summary of core-defined facies in terms of their porosity/permeability, (2) calibration of the core-defined facies with their well log response, (3) interpretation of all available uncored wells (twenty) in terms of genetically-meaningful log facies (using GR, FDC, CNL, LLD and HDT logs), and (4) nterpretation of the thickness/facies/poroperm trends within the framework of the depositional model, as previously outlined.

Reservoir properties

The five facies display a range in reservoir quality, which reflects their close genetic relationships (Fig. 14):

(1) *Bioturbated mudstone facies* has effectively zero reservoir potential although the thin, sandier intervals have some measureable porosity (0 - 13%) and permeability (0 - 6 mD).

This facies corresponds to the main shale intervals, which are probably capable of forming seals and/or baffles to vertical fluid flow.

(2) *Bioturbated sandstone facies* has relatively poor reservoir properties owing to the high proportion of interstitial clays introduced during bioturbation: porosity ca. 14 - 19%, permeability ca. 13 – 30 mD.

(3) *Heterolithic sandstone facies* displays moderate reservoir properties which, overall, are somewhat reduced by the frequent shale layer intercalations: porosity ca. 21 - 25%, permeability ca. 120 - 180 mD.

(4) *Parallel laminated sandstone facies* is represented by consistently good reservoir properties: porosity ca. 25 - 26%, permeability ca. 430 - 640 mD.

(5) *Massive sandstone facies* displays uniformly excellent reservoir properties: porosity ca. 25 - 26%, permeability ca. 1500 - 2500 mD. The better porosity/permeability relationship of these sandstones (Fig. 14) reflects their improved textural properties, compared to the other sandstones, and supports the inference that they partly reflect the reworked product of the parallel laminated sandstones.

Core-log facies calibration

In terms of well log response, the five core-defined facies display the following significant differences: (1) sediment texture (grain size, sorting and dispersed clay content), (2) stratification (sand/mud interbeds, parallel lamination, structureless intervals - eg. SB ,nd SMa facies). and (3) porosity/ permeability. These variations allowed the core-defined facies intervals in wells EW-4, -5 and -104 to be calibrated with the GR, FDC, CNL and LLD logs and cut-off values established for the various types of pore-fill (ie. in gas, oil and water; Fig. 15). In many cases the cut-off values allowed recognition of specific facies types. In other cases, however, a combination of GR and HDT microresistivity curve shapes was required to make a final facies discrimination (Fig. 16).

In the Erb West reservoirs the HDT microresistivity curves proved to be particularly useful in facies identification because of their sensitivity to changes in grain size and hence permeability contrast, which allowed recognition of the following: (1) distinction between the massive (blocky response) and parallel laminated (serrate response) sandstone facies, and (2) identification of the sand-shale alternations in the heterolithic sandstone facies (Fig. 15).

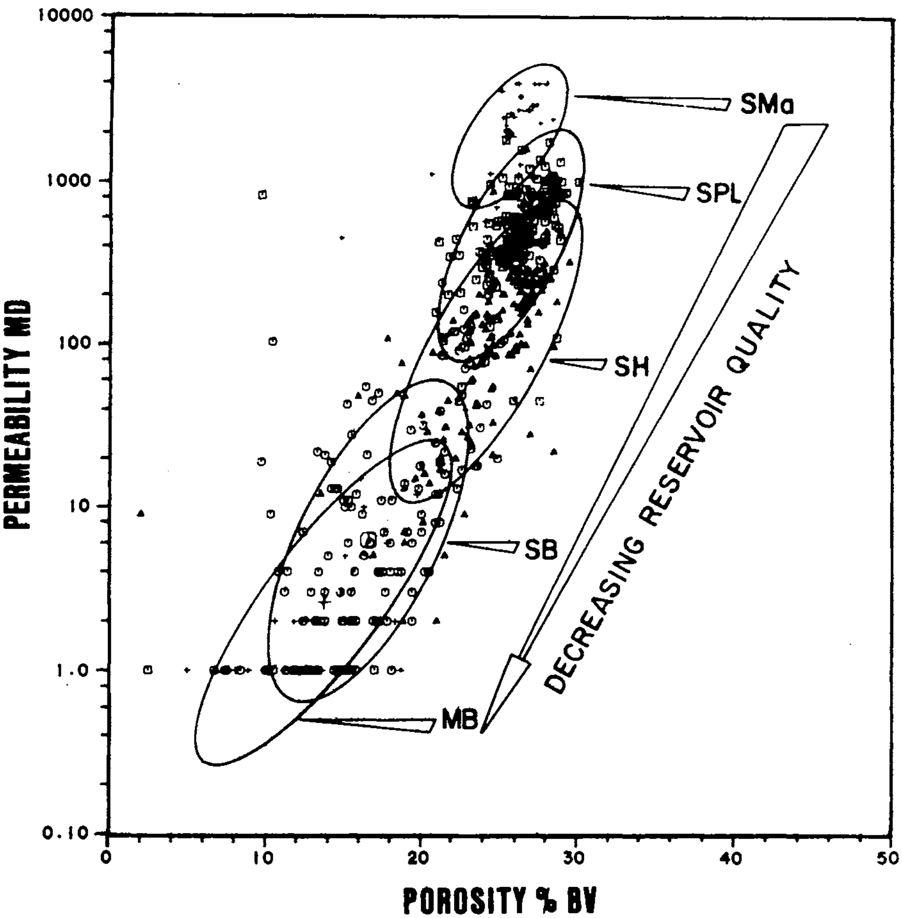
As a result all available wells (twenty-three) could be evaluated in terms of the five previously described facies.

Reservoir geological model: nature and origin of thickness/rock quality trends

Detailed well log correlation and interpretation of facies distribution in the framework of the depositional environment provides the basis for developing a reservoir geological model (eg. Sneider *et al.*, 1976). The aim of this model is to describe and predict reservoir thickness and quality distribution within the Erb West field. In this context the two main reservoir intervals, the N and M Sands, are treated separately because of their different geological histories.

(1) *N Sands*

The N Sands have a combined gross thickness of ca. 550 ft and contain six main



(MEAN) CORE PLUG VALUES

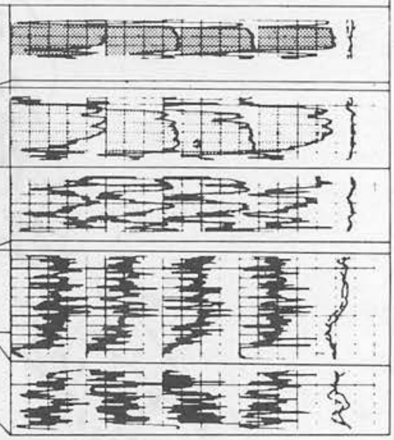
LITHOFACIES		EW-04 N=291		EW-104 N=198		EW-05 N=110		PROCESS
		0%	KmD	0%	KmD	0%	KmD	
	COQUINAS (CARB CEMENTED)	–	–	–	–	–	–	'TRANS-GRESSIVE' REWORKING
MB	BIOTURBATED MUDSTONE	12	6	(13)	(1)	(12)	(1)	BURROWING FOLLOWING 'STORM' EVENTS
SB	BIOTURBATED SANDSTONE	14	18	15	31	19	13	
SH	HETEROLITHIC SANDSTONE	21	120	24	138	25	184	WAVE INDUCED PARALLEL LAMINATIONS BY 'STORM' EVENTS
SPL	PARALLEL LAMINATED SANDSTONE	25	437	26	453	26	642	
SMA	MASSIVE SANDSTONE	26	2556	25	1577	–	–	'TRANS-GRESSIVE' REWORKING

( ) LESS THAN FIVE PLUGS

Fig. 14. Reservoir Quality of the Five Main Lithofacies

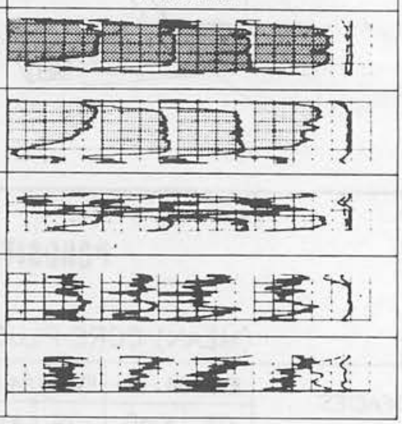
LOG-FACIES CUT-OFF IN GAS BEARING INTERVALS OF M & N RESERVOIRS (BASED ON EW-104)

LITHO-FACIES \ LOG-FACIES	G R Vsh (Av)	F D C G/CM³ (Av)	C N L %SV (Av)	L L D Ohmm	MSFL Ohmm	HDT Characteristic Log Curves (Unprocessed)
SMa	0.16	2.17	10.49	52.04	39.74	
SPL	0.34	2.27	15.22	63.84	237.5	
SH	0.50	2.28	21.53	18.87	13.85	
SB	0.52	2.42	19.72	5.34	5.15	
MB	0.69	2.4	25.8	—	—	



LOG-FACIES CUT-OFF IN OIL BEARING INTERVALS OF M & N RESERVOIRS (BASED ON EW-4,5 & 104)

LITHO-FACIES \ LOG-FACIES	G R Vsh (Av)	F D C G/CM³ (Av)	C N L %SV (Av)	L L D Ohmm (Av)	MSFL Ohmm (Av)	HDT Characteristic Log Curves (Unprocessed)
SMo	0.15	2.26	23.5	10.38	2.69	
SPL	0.29	2.27	25.30	5.97	2.07	
SH	0.35	2.35	25.5	7.85	3.04	
SB	0.47	2.4	25.57	7.37	2.90	
MB	0.69	2.46	26.11	4.06	1.4	



LOG-FACIES CUT-OFF IN WATER BEARING INTERVALS OF M & N RESERVOIRS (BASED ON EW-4 & 5)

LITHO-FACIES \ LOG-FACIES	G R Vsh (Av)	F D C G/CM³ (Av)	CNL % SV (Av)	L L D Ohmm (Av)	MSFL Ohmm (Av)	HDT Characteristic Log Curves (Unprocessed)
SMo	0.12	2.29	25.74	2.45	1.25	
SPL	0.26	2.30	25.5	3.07	2.4	
SH	0.39	2.36	25.0	3.25	2.33	
SB	0.47	2.44	22.49	4.59	3.46	
MB	0.62	2.46	28.9	2.7	2.3	

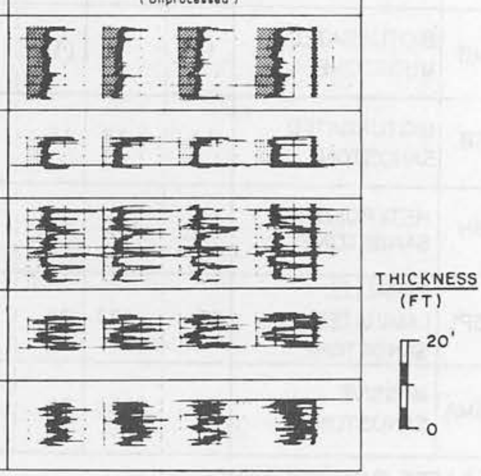


Fig. 15. Log Facies cut-off in Gas Bearing Intervals of M and N reservoirs (based on EW-104)

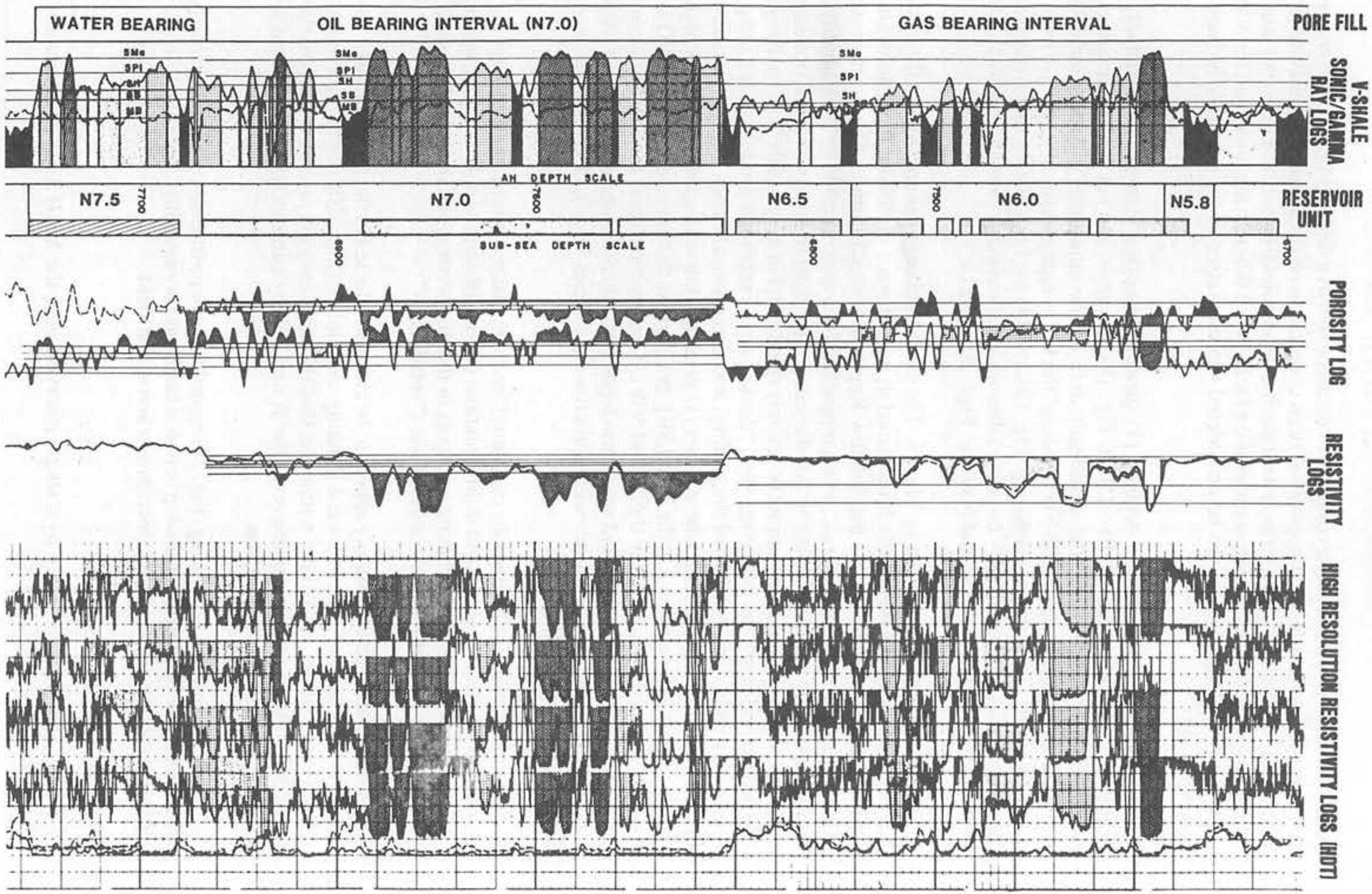


Fig. 16. Wireline Log/Lithofacies Calibration

reservoir sands (N2.0 - N7.0) separated by laterally extensive shales (Fig. 17). Reservoir thickness/facies/ poroperm mapping has been undertaken on each reservoir unit and all display similar trends, which reflects their similar depositional histories. Gross, net sand and massive sand facies thickness maps and a facies fence diagram are presented for one unit, the N6.0 Sand, which can be considered representative of all the other N Sand reservoir units.

The following patterns are evident: (1) gross thicknesses increase progressively northwards (mainly from ca. 10 - 150 ft; Fig. 18). (2) gross and net sand thicknesses decrease westwards (towards the seismically-defined "no sand zone"), (3) net sand distribution occurs as a series of NE-SW trending "thicks", ranging from ca. 40-80 ft in axial zones to ca. 10 - 60 ft on the flanks (eg. Fig. 19), and (4) the high quality massive sand facies occurs as E-W or SE-NW trending lobes which always decrease in thickness and/ or wedge-out towards the W and NW (eg. Figs. 20 and 21).

These trends are interpreted as follows. The gross thickness patterns reflect the subsidence history of the basin which increased in a northward direction; the southward thinning reflects onlap against the Shallow Regional Unconformity. The westwards thinning, as identified on seismic, is accompanied by a deterioration in rock quality, which supports a major shale-out in this direction. Alternative interpretations, notably non-deposition or truncation, cannot be entirely ruled-out, but are considered less likely. The nature and geometry of the net sand "thicks" are a combined product of the gross thickness trends (i.e. northward thickening) and depositional facies trends. Net sand thicknesses are at a minimum where either (1) gross thickness is small but N/G is high (eg. in proximal facies areas in the E and SE). or (2) gross thickness is large but N/G is low (eg. in distal facies areas in the W and NW). Optimum net sand thicknesses occur within the central part of the field where moderate gross thicknesses are combined with moderate to good N/G ratios (ie. within intermediate facies areas). This is illustrated graphically in Fig. 22.

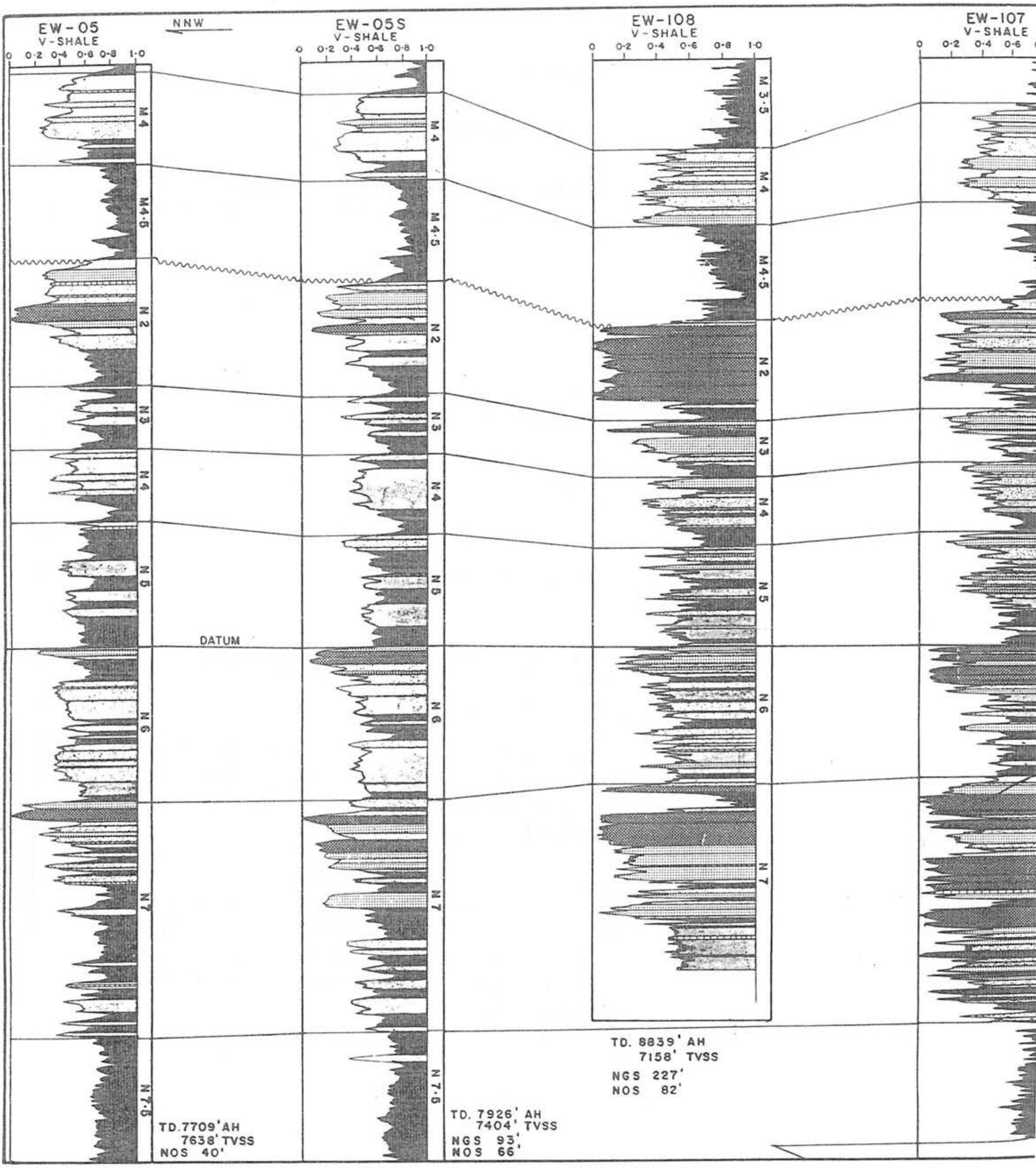
Net sand thickness distributions can, therefore, be explained in terms of the following controls on shallow marine sand sedimentation: (1) rate of sand supply from the coast, (2) rate of reworking and offshore transport in the high-energy, coastal to inner shelf zone, and (3) rate of relative sea-level rise ("subsidence").

Trends relating to sand supply appear to be closely reflected in the distribution of the massive sand facies. The westward thinning sand lobes (Fig. 20) are interpreted as reflecting maximum reworking within the shallow, high energy, proximal areas to the E and SE, followed by sand transport to the W and NW by currents which decreased in strength in a basinward direction.

The facies fence diagrams (eg. Fig. 21) record these depositional rock quality trends and, because of the close relationship between facies and permeability, give a reasonable representation of permeability distribution across the field.

(2) *M Sand*

The M Sand is represented by a single reservoir unit, the M4.0 Sand. This sand is



p 219 : Johnson, Kuell + Mohamad

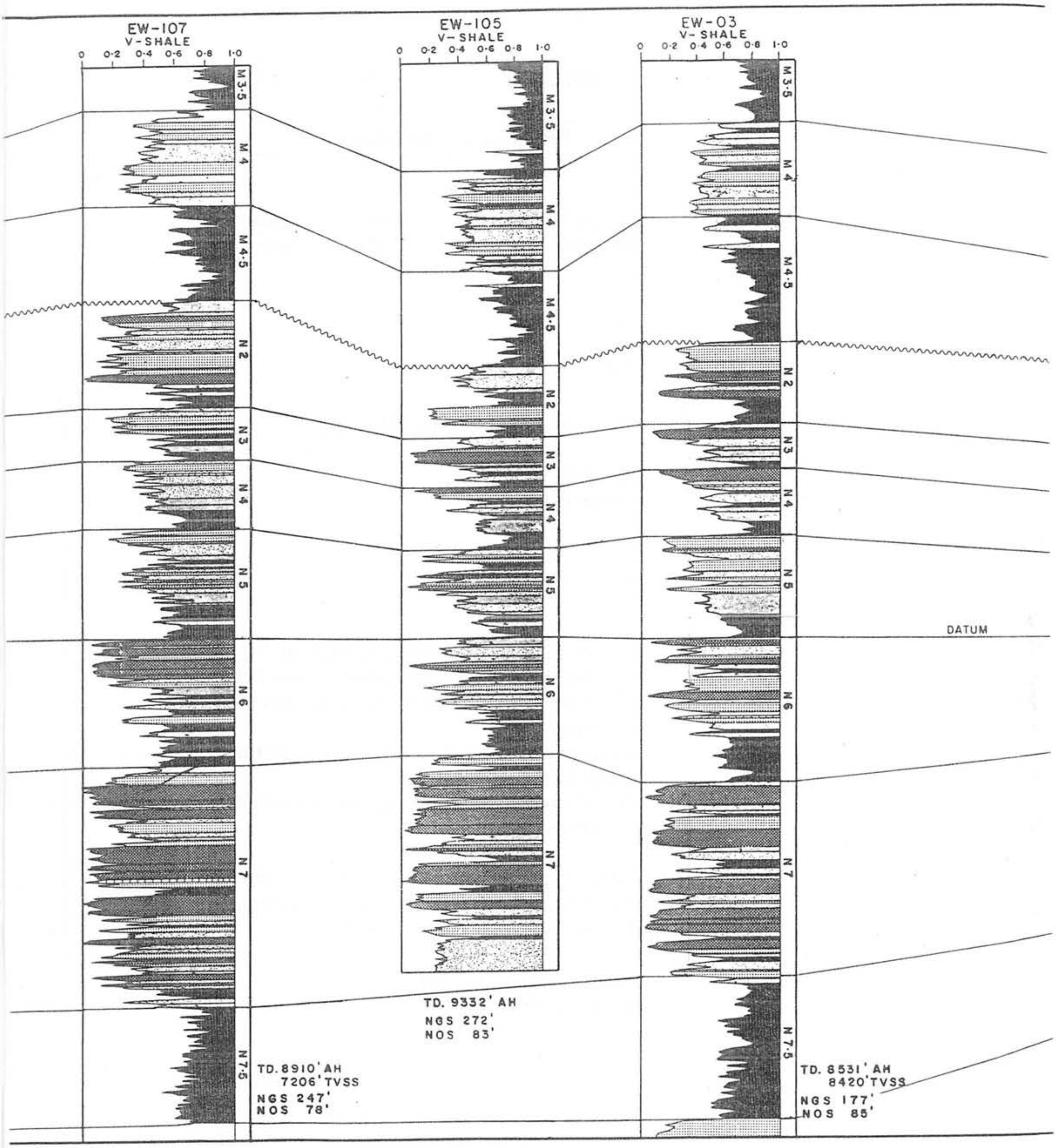
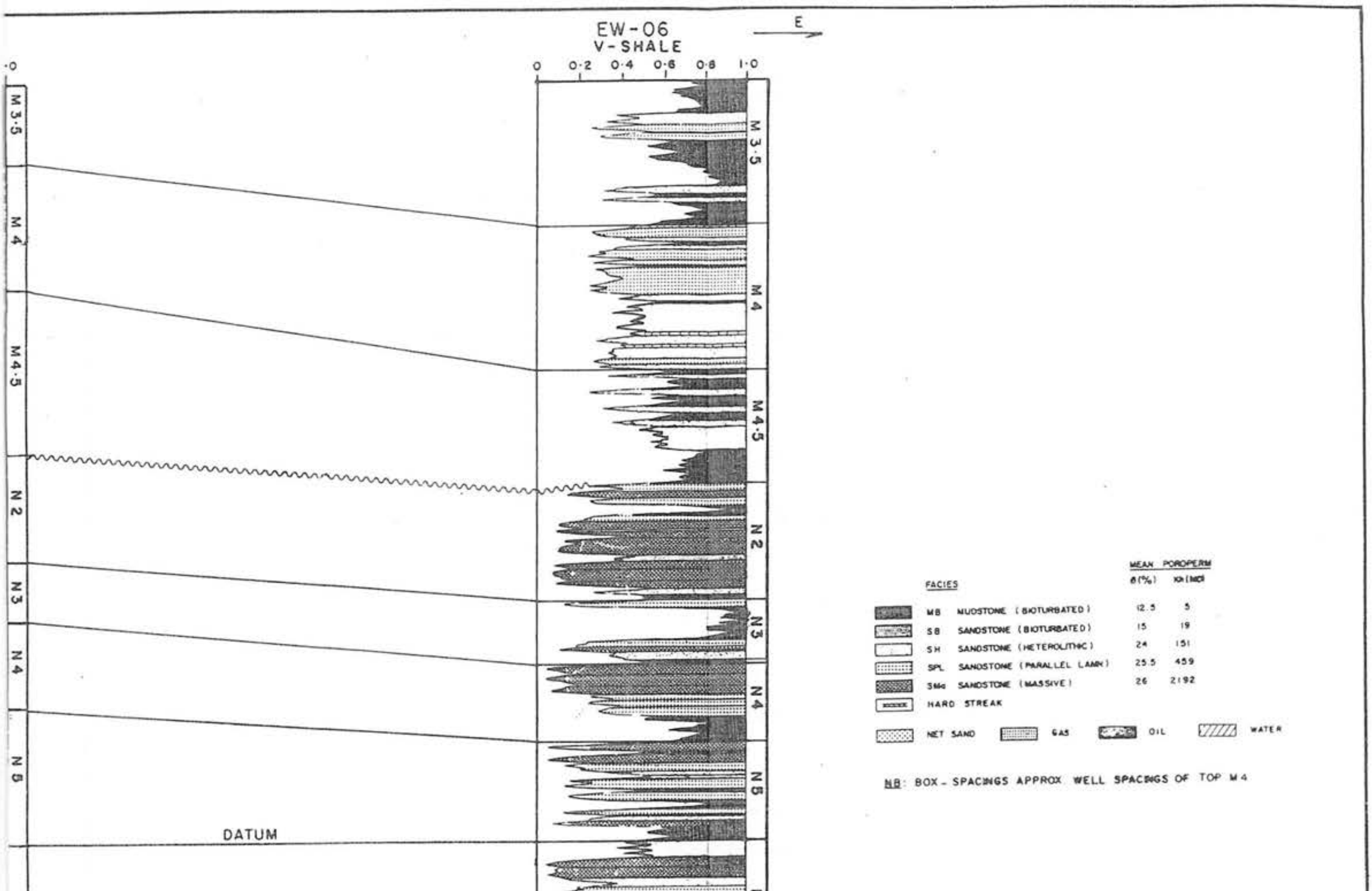


Fig. 17. Correlation Panel of M4.0 - N8.0 reservoirs

p. 219. Johnson, Levi



p. 219. Johnson, Levell & Mohamad

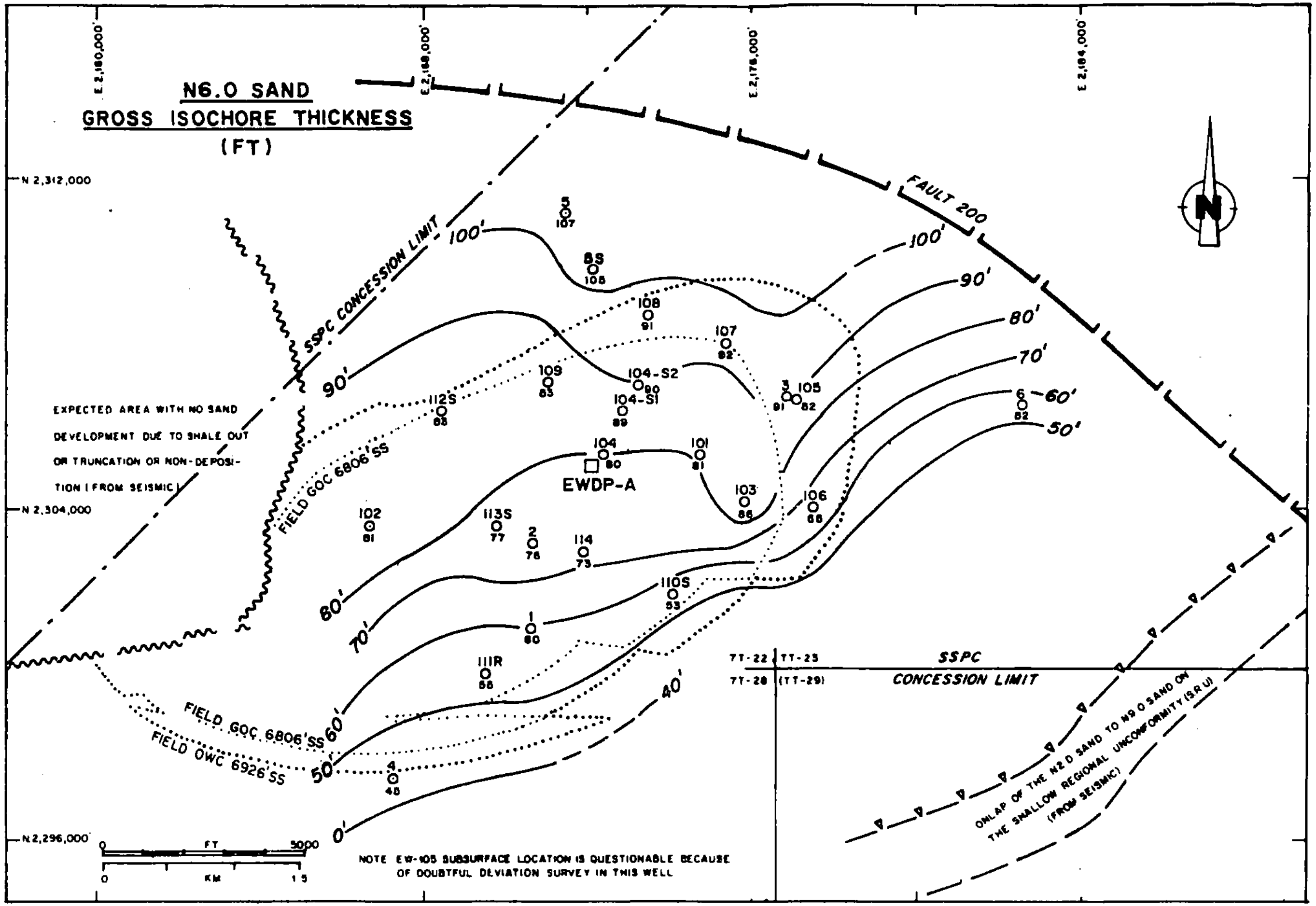


Fig. 18. N6.0 Sand Gross Isochore Thickness

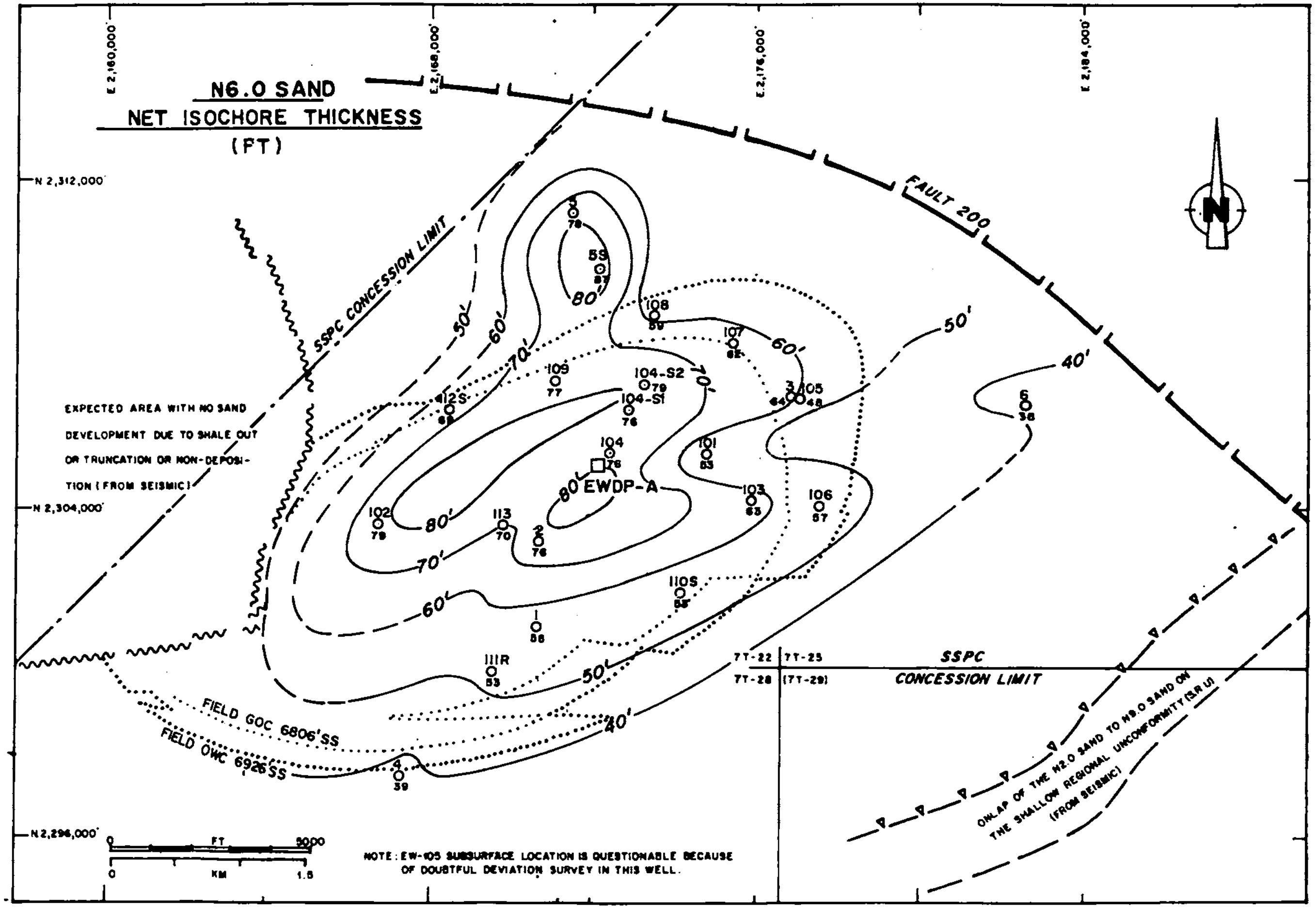


Fig. 19. N6.0 Sand Net Isochore Thickness

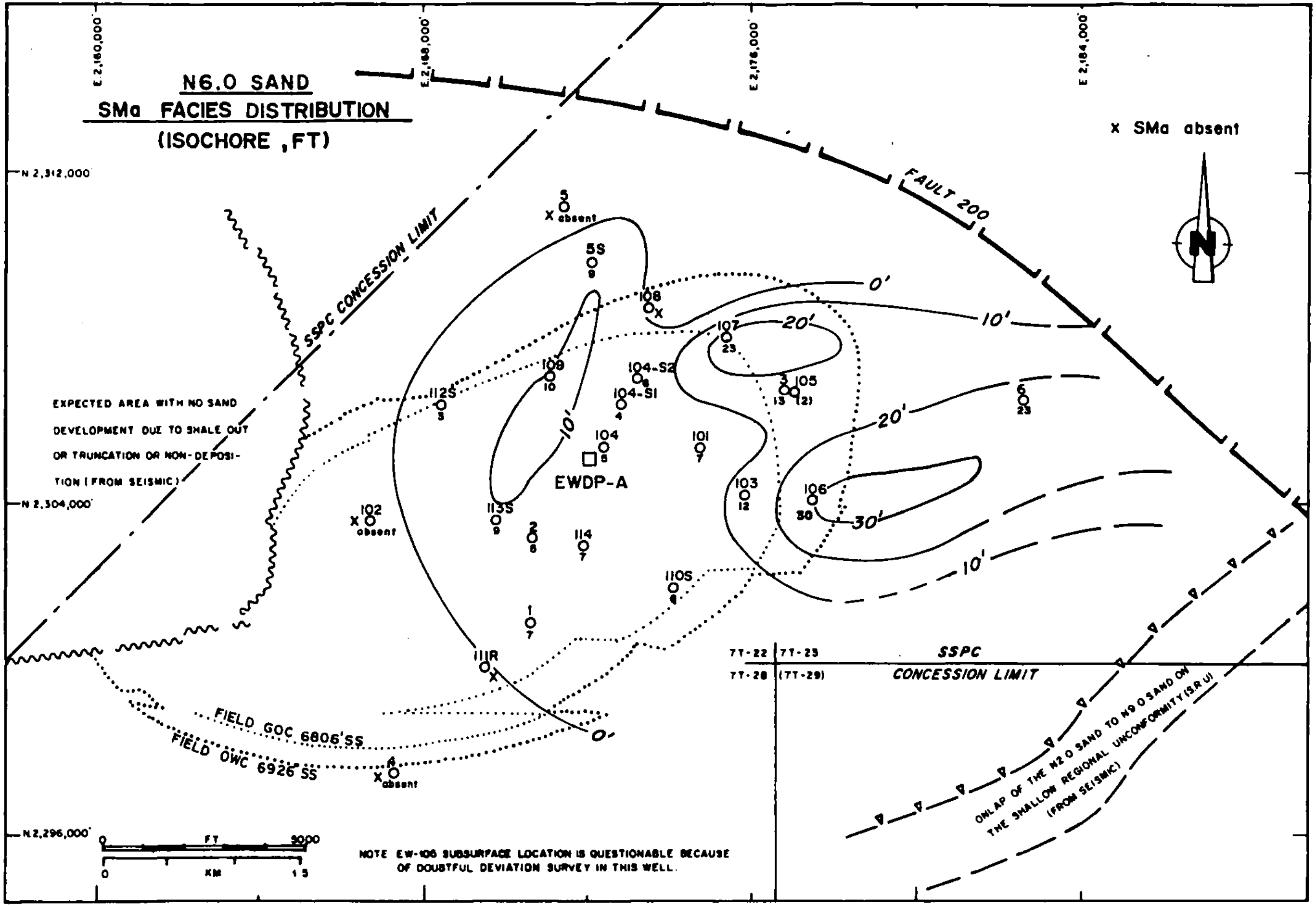


Fig. 20. N6.0 Sand SMA Facies Distribution

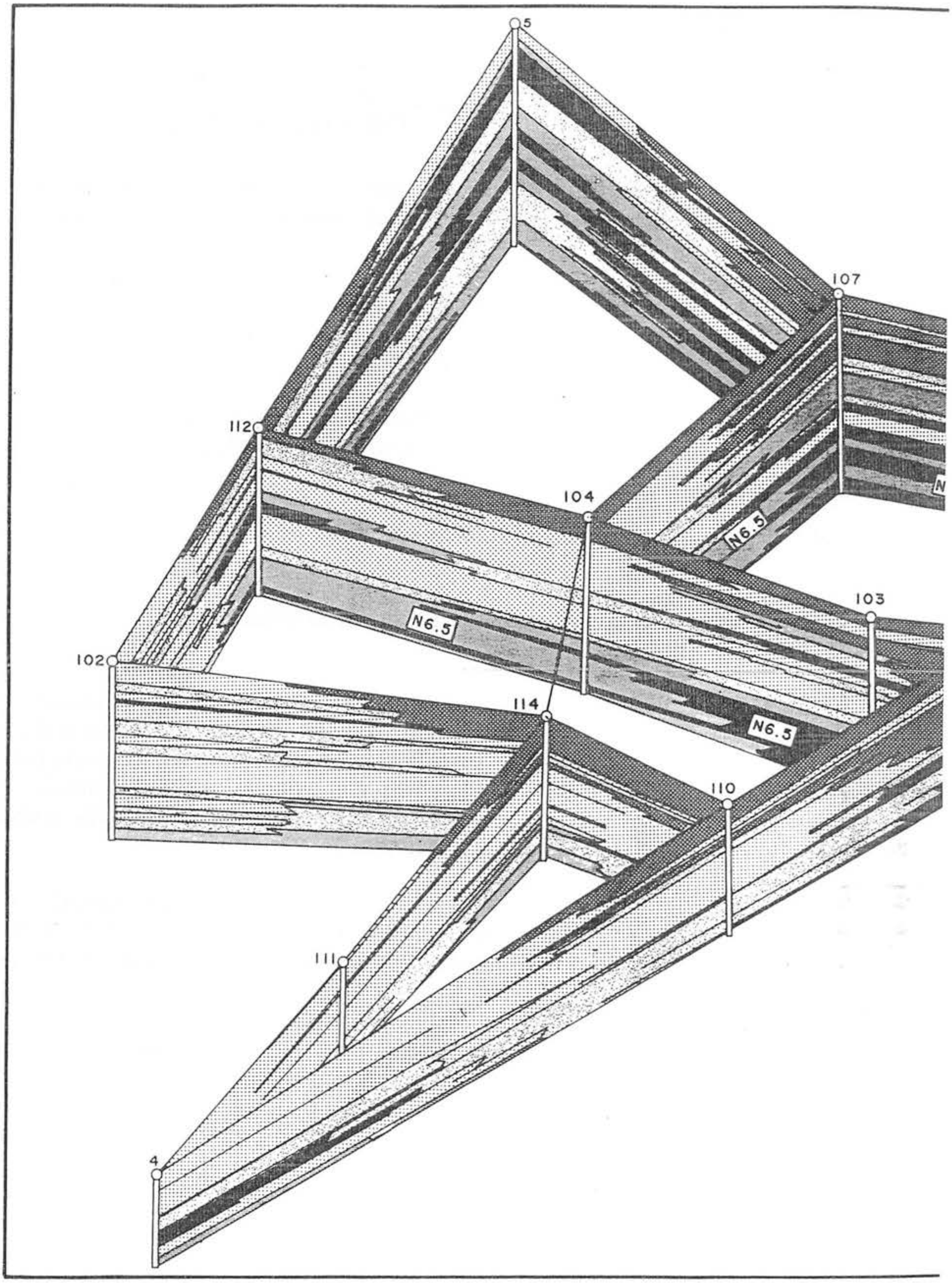


Fig. 21. Fence Diagram of Facies Distribution for the N6.0 reserv

p.223 Johnson, Levell & Mohamed

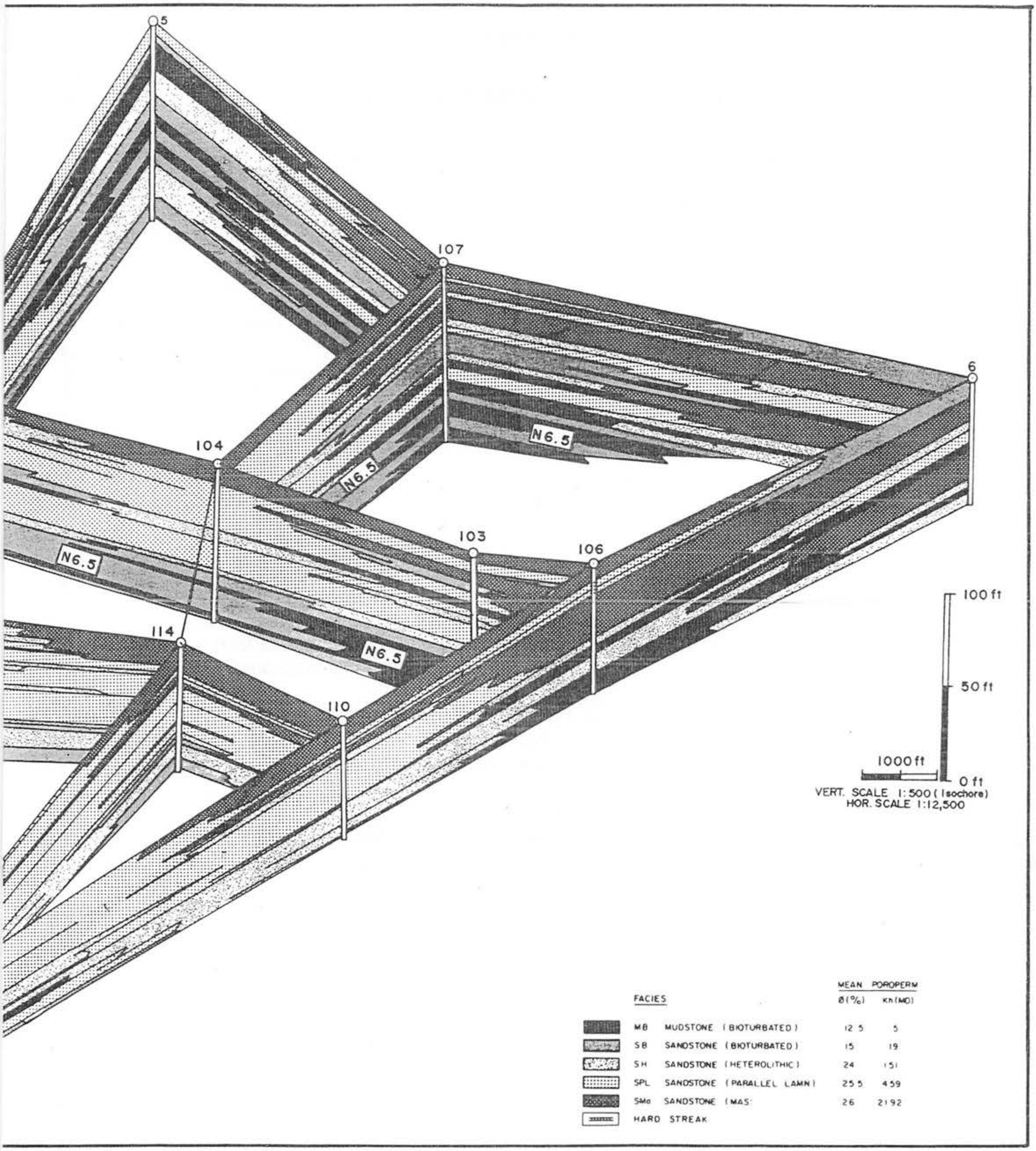


Fig. 21. Fence Diagram of Facies Distribution for the N6.0 reservoir sands

p. 223: Johnson, Levell & Mohamad

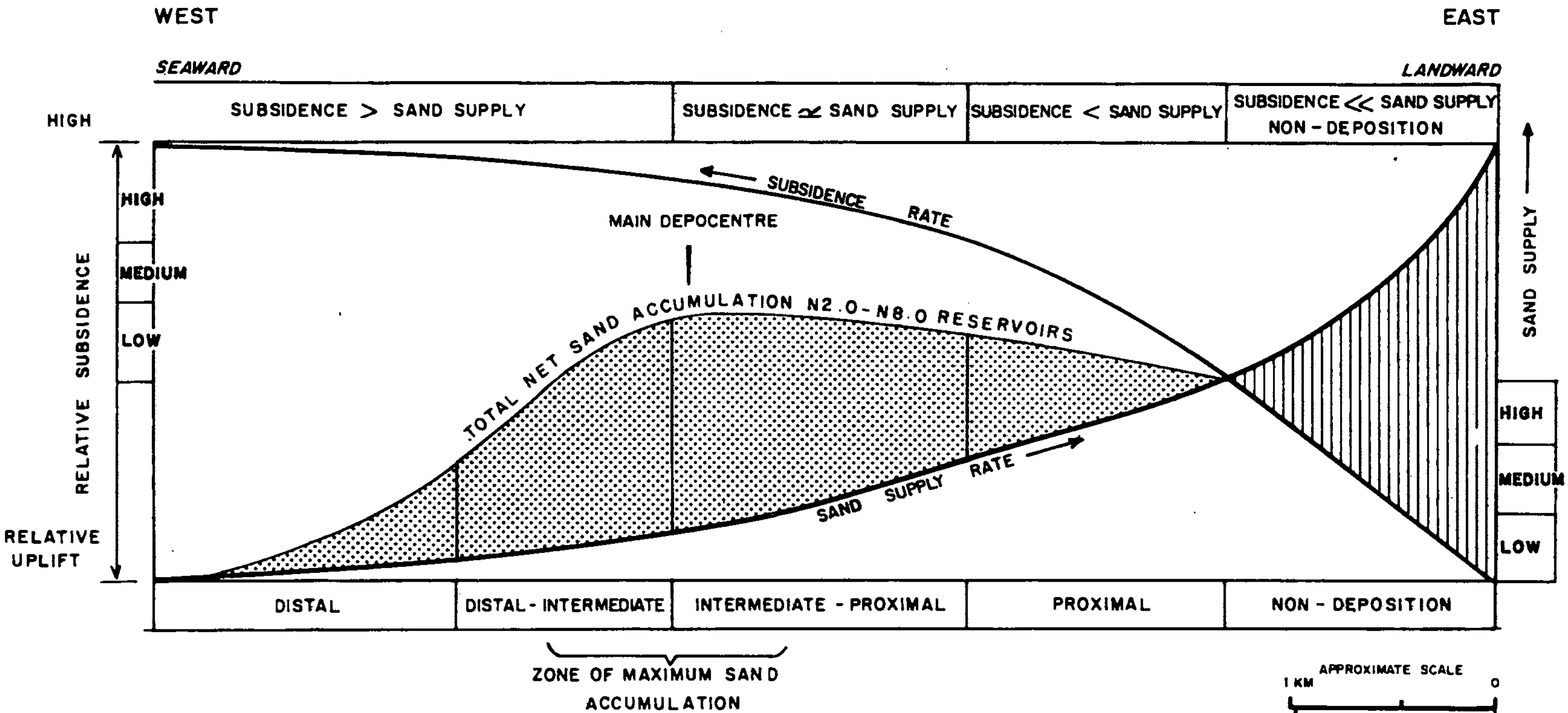


Fig. 22. Net Sand Thickness Model

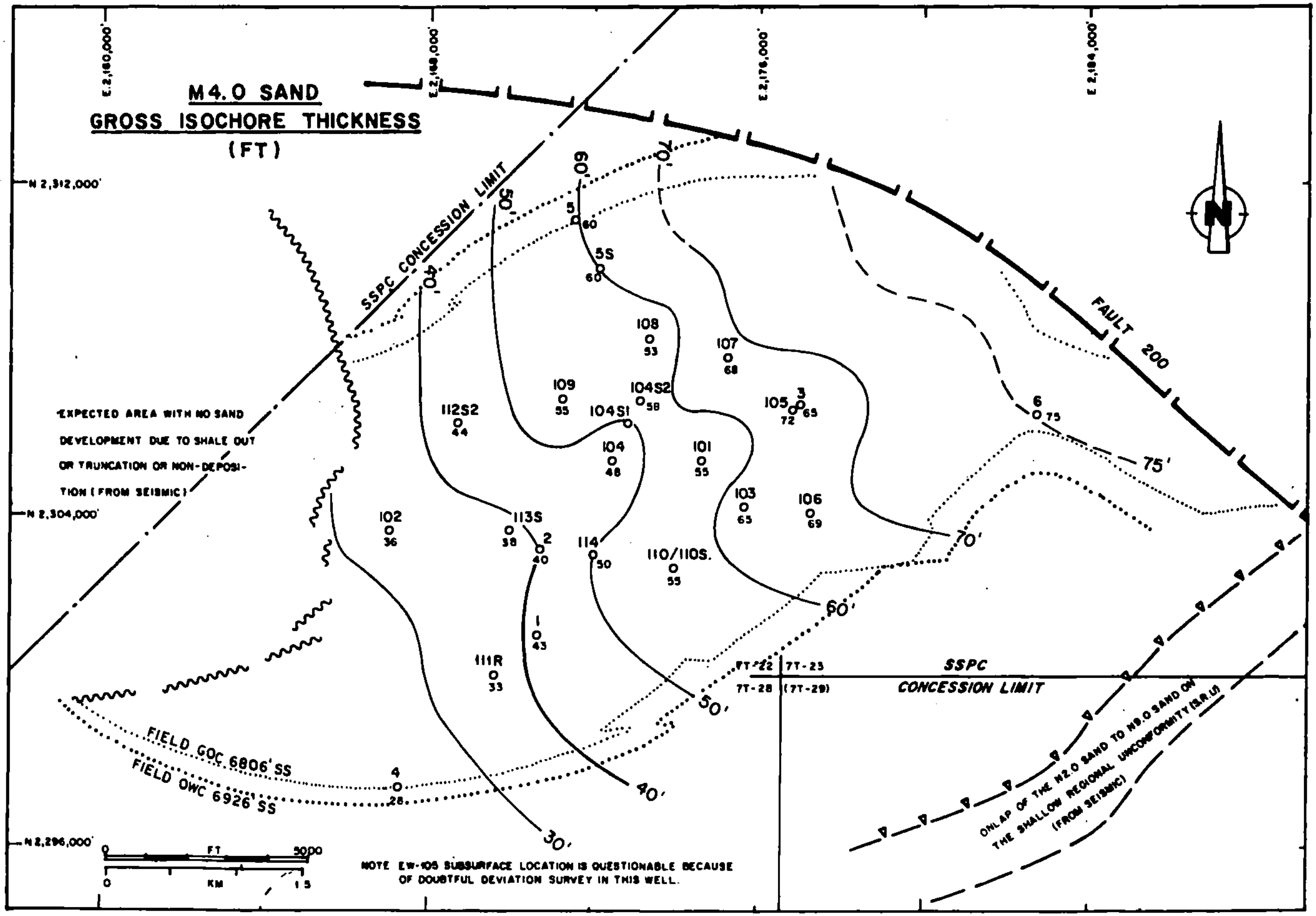


Fig. 23. M4.0 Sand Gross Isochore Thickness

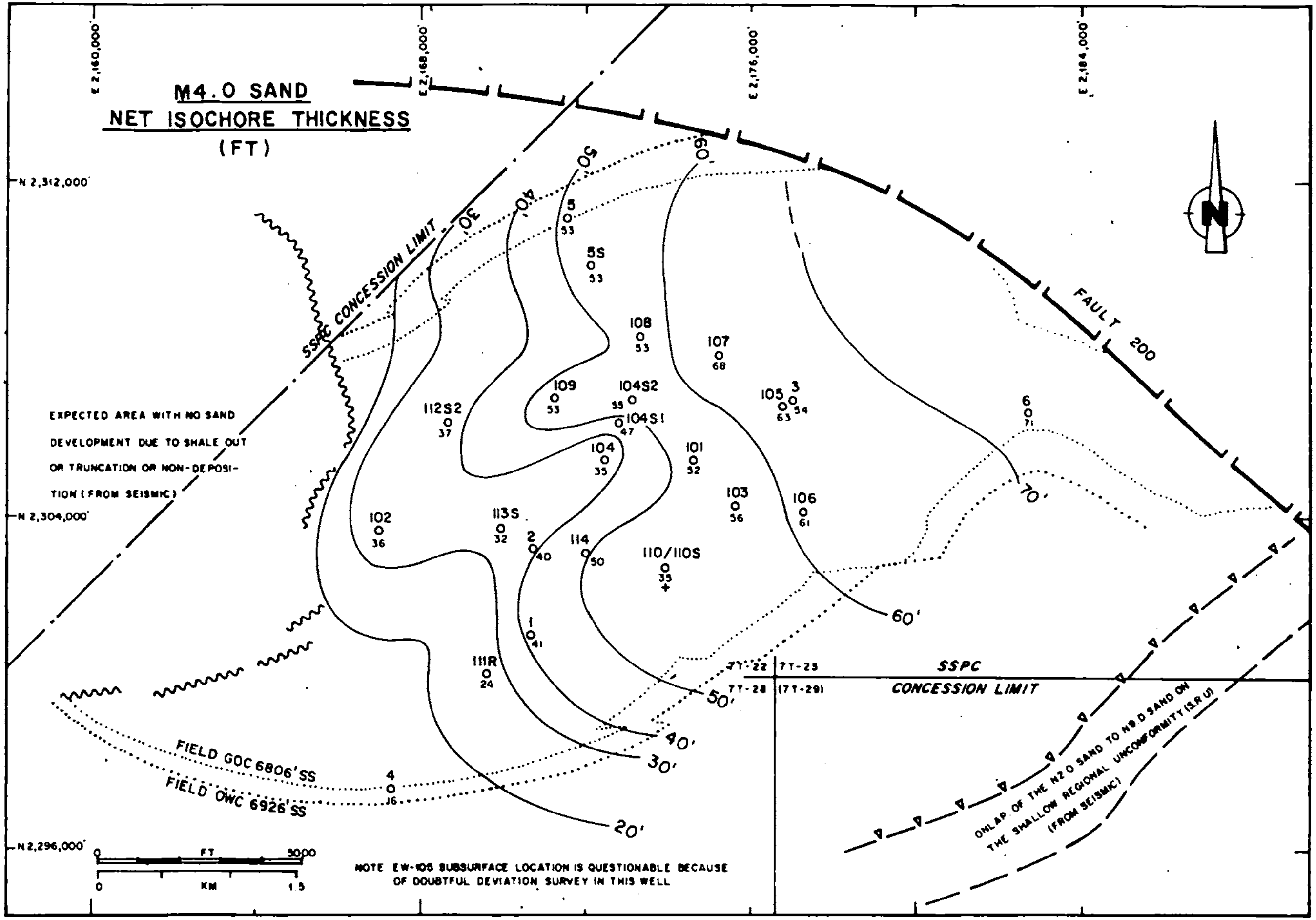


Fig. 24. M4.0 Sand Net Isochore Thickness

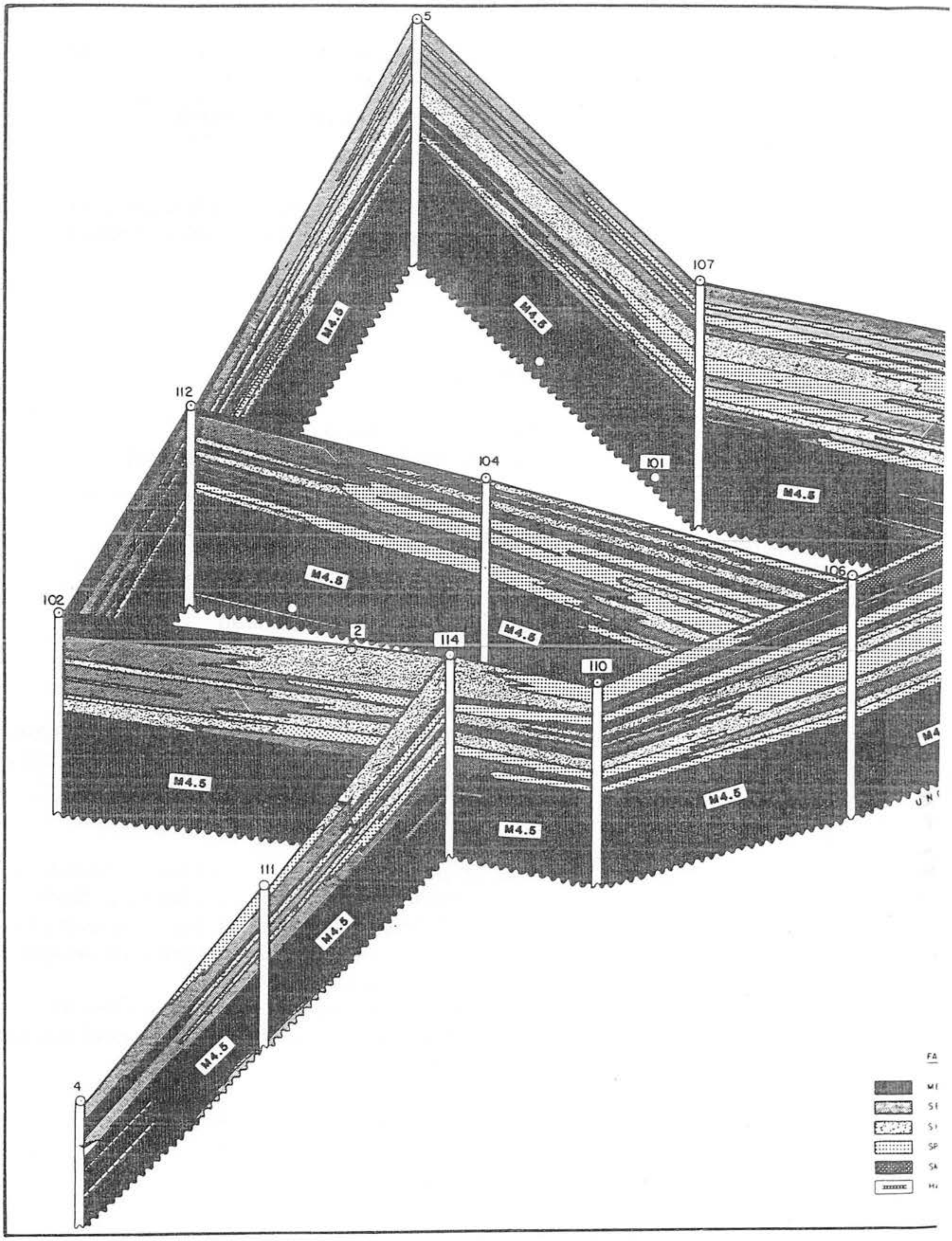


Fig. 25. Fence Diagram of Facie, Distribution for the M4.0/M4.5 reservoir sands an

P 227: Johnson, Well & Mohamed

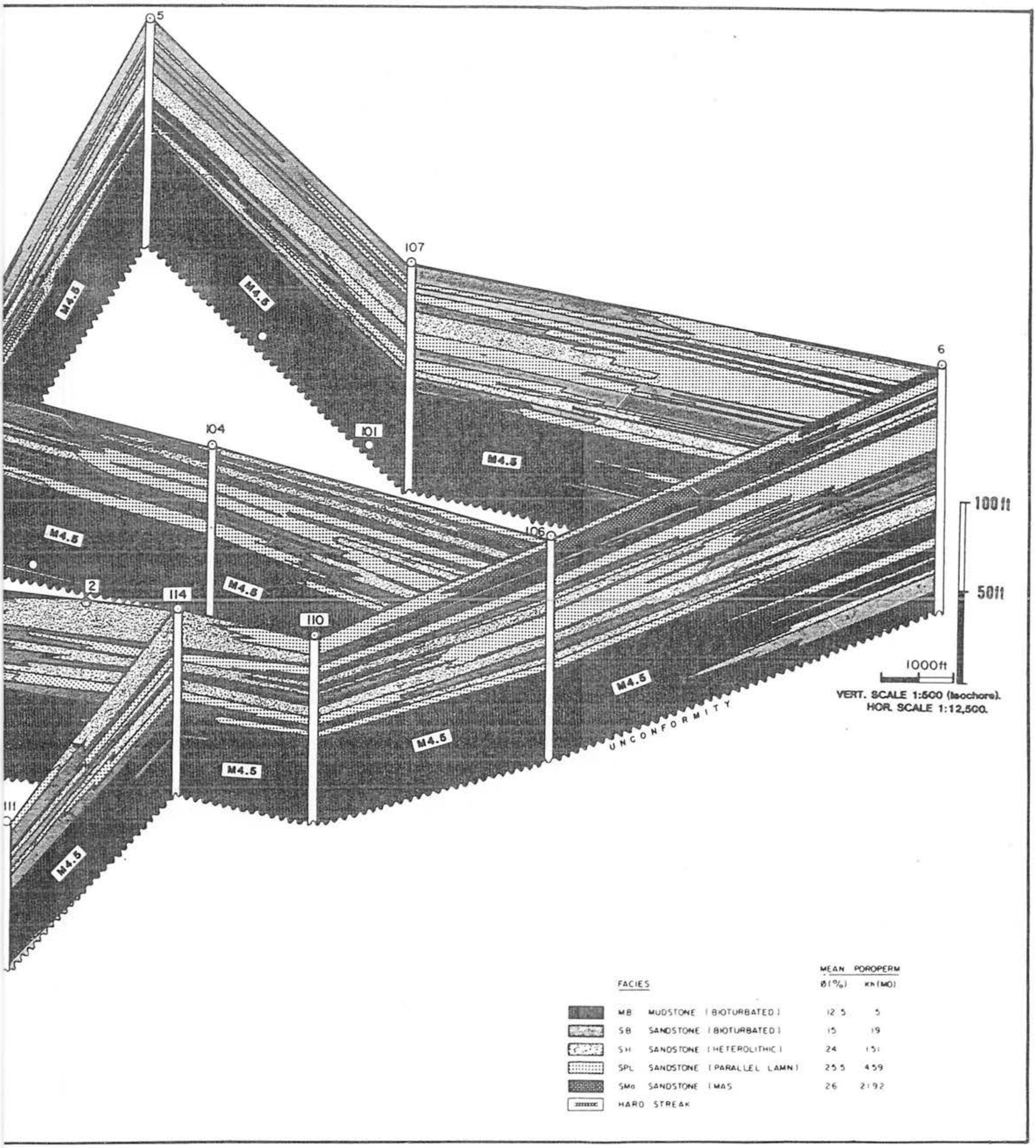


Fig. 25. Fence Diagram of Facie, Distribution for the M4.0/M4.5 reservoir sands and shales

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p. 227: Johnson, Lewell & Mohamed

underlain by the extensive M4.5 shale, which unconformably overlies the N Sands (Fig. 12).

The main features of this sand are as follows: (1) gross isochore decreases gradually from ca. 75 ft in the NE to ca. 30 ft in the SW (Fig. 23). (2) net sand thickness also changes progressively along the same trend varying from ca. 70 ft in the NE to ca. 20 ft in the SW (Fig. 24), (3) the SMa facies is virtually absent from this unit (Fig. 25), apart from a limited area in the SE, and (4) N/G ratios vary from mainly 0.6 to 1.0.

The dominant facies sequence in the M4.0 Sand comprises a fining upward, or retrogradational (ie. decPening) sequence. Sand quality trends, however, continue to reflect the N Sands palaeogeography, and associated depositional trends, with finer grained, more argillaceous sands increasing to the NW. The northward thickening of the M4.0/M4.5 (from 50 to 120 ft) is interpreted as representing the final onlap of the N Sands basin.

CONCLUSIONS

This sedimentological/reservoir geological evaluation of the Stage IVD reservoirs in the Erb West field has resulted in the development of a depositional model which provides a genetic framework for more accurately delineating sand thickness and reservoir quality trends within the field. Some of the main conclusions concerning the nature and origin of these reservoirs are summarized below:

1. The reservoir interval can be described in terms of five facies with distinctive textures, sedimentary structures and porosity/permeability characteristics. These variations have allowed recognition of the same facies on well logs using a combination of GR, FDC, CNL and LLD log cut-off values, and characteristic HDT microresistivity curve shapes. Facies mapping, therefore, has been applied across the whole field (using twenty-three wells).
2. Neritic microfaunas, abundant bioturbation and storm-generated sandstone beds indicate deposition in a storm-dominated inner neritic (or shelf) environment.
3. The reservoir sequence represents a transgressive sand complex which is reflected on seismic by onlap against the Shallow Regional Unconformity, and in the wells by an upward reduction and eastward (landward) migration of the highest energy sand facies.
4. Sand supply is believed to have been provided from coastal erosion of the nearby emergent and tectonically active Erb High, followed by offshore and alongshore sediment transport, across the Erb West field, by wave-/storm-induced currents.
5. The main N Sands reservior units (N2.0 to N7.0) display the following depositional facies changes across the field:
   - (i) *proximal facies sequences* in the E and SE comprise high-energy, good-quality storm sands with frequent erosion surfaces, lag deposits amd amalgamated beds;
   - (ii) *intermediate facies sequences* in the central part of the field are characterized by coarsening upward sand bodies with a range of facies types which increase in reservior quality upwards; and
   - (iii) *distal facies sequences* in the W and NW comprise low-energy facies types (eg. mudstones and bioturbated sandstones) with generally poor reservior properties; in

addition the western flank of the field appears to be marked by a major shale-out of the reservoirs.

6. Thickness distributions reflect both this depositional trend and a superimposed subsidence pattern. *Gross thicknesses* of the reservoir units increase basinwards (to the N) and decrease landward (to the S), the latter due to onlap against the rising Shallow Regional Unconformity. *Net sand thickness* occurs as NE-SW sand "thicks" which correspond to areas where subsidence and sand supply rates were optimally balanced. Lower net sand thicknesses occur in both (1) proximal areas due to the lower subsidence rates (reduced gross thicknesses), and (2) distal areas due to poor reservoir quality (low N/G) which did not compensate for the higher subsidence rates (larger gross thicknesses).
7. The uppermost, subordinate reservoir unit, M4.0 Sand and its underlying M4.5 shale, unconformably overly the N Sands. This sand reflects the final phase of sand deposition, within the Erb West reservoir sequence. Thickness trends are different and the sand body fines upwards in response to basin deepening/sand supply reduction.
8. The resulting reservoir geological model provides a valuable basis for ongoing field development studies, including: (1) reserves estimates, (2) reservoir simulation modelling, (3) monitoring well performance, (4) optimizing development well locations, and (5) further development planning.

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