Paleosols as An Alternative Method to Define Sequence Boundary in Fluvial System: A Case Study in Semberah Field, Kutei Basin

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Abstract

Difficulties in reconstructing sequence stratigraphic framework of the Semberah Area, East Kalimantan, have brought up an idea to use paleosols to solve the problems. The Semberah Area has dominantly fluvial deposits, which are characterised by the presence of many erosional channel bases. In a vertical sequence, the erosional channel base cannot be easily distinguished from a sequence boundary, therefore, in order to help in sequence stratigraphic interpretation, a research on paleosols of the Semberah Field, Kutai Basin, has been undertaken.

The research mostly utilizes outcrop data above the Semberah Field, where the equivalent of the producing units is exposed. The outcrops are correlated to subsurface well data (logs and cores) and seismic lines to analyze their significance in the Sequence Stratigraphic Framework. A total of 21 outcrops have been described sedimentologically and subsequently investigated for their paleosol occurrences. The research documents 52 discreet occurrences of paleosols in the Semberah outcrops with individual paleosol thickness ranges from 25 to 225 cm. The results of the research show that paleosols are found ubiquitously in deltaic sediments in the Semberah Field. The common distributions of paleosols in the Semberah area consist of Argilisol 16%, Histosol 16%, Oxisol 8%, Protosol 6%, Spodosol 50% and Vertisol 4%. The Gleysol, Calcisol and Gypsisol are not found. The occurrence of paleosols within a Highstand Systems Tract (HST) is 70.6% well-developed with maturity varies from weak to moderate (stage 2 to 4). The low accommodation space supports paleosols to develop well with its upper boundary most likely is associated with sequence boundary. The paleosol distribution within an Incised Valley Fill (IVF), Lowstand System Tract (LST) and Transgressive Surface of Erosion (TSE) are very well-developed with percentage of their occurrence as 3.9%, 1.9% and 1.96% with their maturity varies from moderate to strong (stage 4 to stage 5). In general, they will associate with an erosional channel base known as sequence boundary at the bottom end border. Paleosols are not found in the beginning of Transgressive System Tract (TST) in Semberah area which is commonly characterized by the occurrence of Hydromorphic Paleosol. During the Transgressive System Tract (TST), the paleosols are not well-developed or even obstructed with percentage of their occurrence within the area as 21.5% and the maturity varies from stage 2 to stage 3.

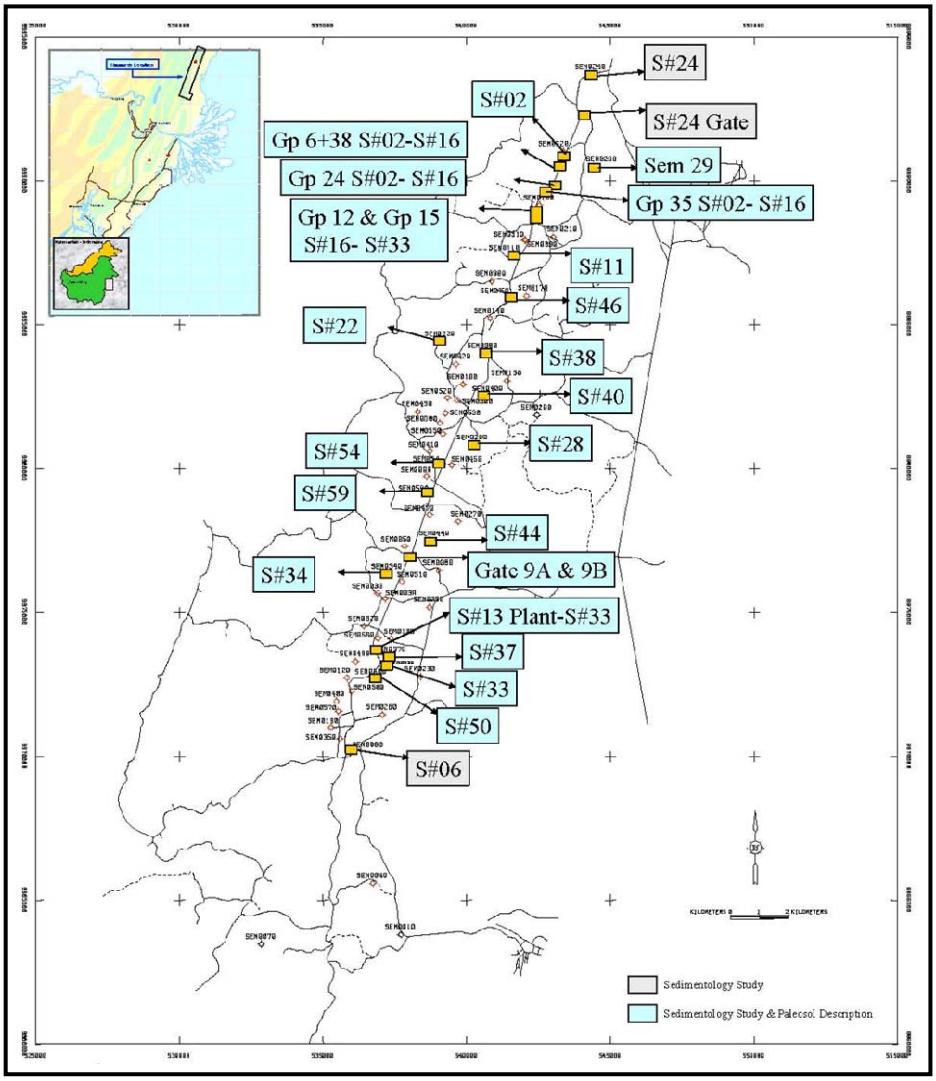


Figure 1. The research location of *Paleosols* study in Semberah Area, Kutei Basin.

Introduction

During the past decade, the research of Sequence Stratigraphy has progressed much, especially driven by practical need in oil & gas industry to reconstruct lateral continuity and reservoir character within time and space framework.

The application of Sequence Stratigraphy in fluvial deposits is still a topic of hot debate (Galeazzi and Vail, 1992; Wright and Marriott, 1993; Miall, 1996). The main problem is caused by the difficulties in recognising the indicator of sea level fluctuation, which is used as a basic indicator to divide the sequence stratigraphic components of fluvial or continental deposits. Many researchers (e.g.: Miall, 1996; Posamentier and Allen, 1993; and Posamentier and Allen, 1999) considered that in fluvial or land environment, local tectonic is the main and the most important factor that creates accommodation space and not sea level change.

Most of Indonesia's hydrocarbon reservoirs are of fluvial deposits, so understanding the model and character of reservoir within time and space is the most important and unconditional thing. One of the methods used as a tool in correlation and reconstruction to know the reservoir relationship in fluvial deposits is by relating paleosols to a sequence boundary.

The study of paleosols in fluvial deposits have not been done in Semberah Field or even in the Kutai Basin. The main difficulties in doing correlation with Sequence Stratigraphic method in fluvial deposits have been explained by Pangarso (2000), on his surface geological mapping of Lampake area. The explorationists of Kutai Basin also have the same difficulties when doing subsurface correlation of fluvial deposits in many oil & gas fields (Bachtiar, 2000, *personal communication*). Using and applying paleosols as a tool is necessary as an alternative method in solving such correlation problem.

As references, many publications that discuss about paleosols and fluvial sequence stratigraphy have been published, such as Galeazzi and Vail (1992), which discussed the sequence stratigraphy of fluvial environment; Kraus (1999) who published a lot of paleosol's applications; Retallack (1997) that published the color guide to paleosols; Wright and Marriott (1993), which discussed sequence stratigraphy of fluvial depositional system; and Miall (1996) that published special books of characteristics of fluvial environment. The studies of paleosols have been also applied to many depositional environments such as explained by Kraus (1999), including eolian, palustrine, and deltaic depositional environments. Paleosols can also be founded in marine environment if the sea level dropped until the marine deposit exposed and then followed by soil forming.

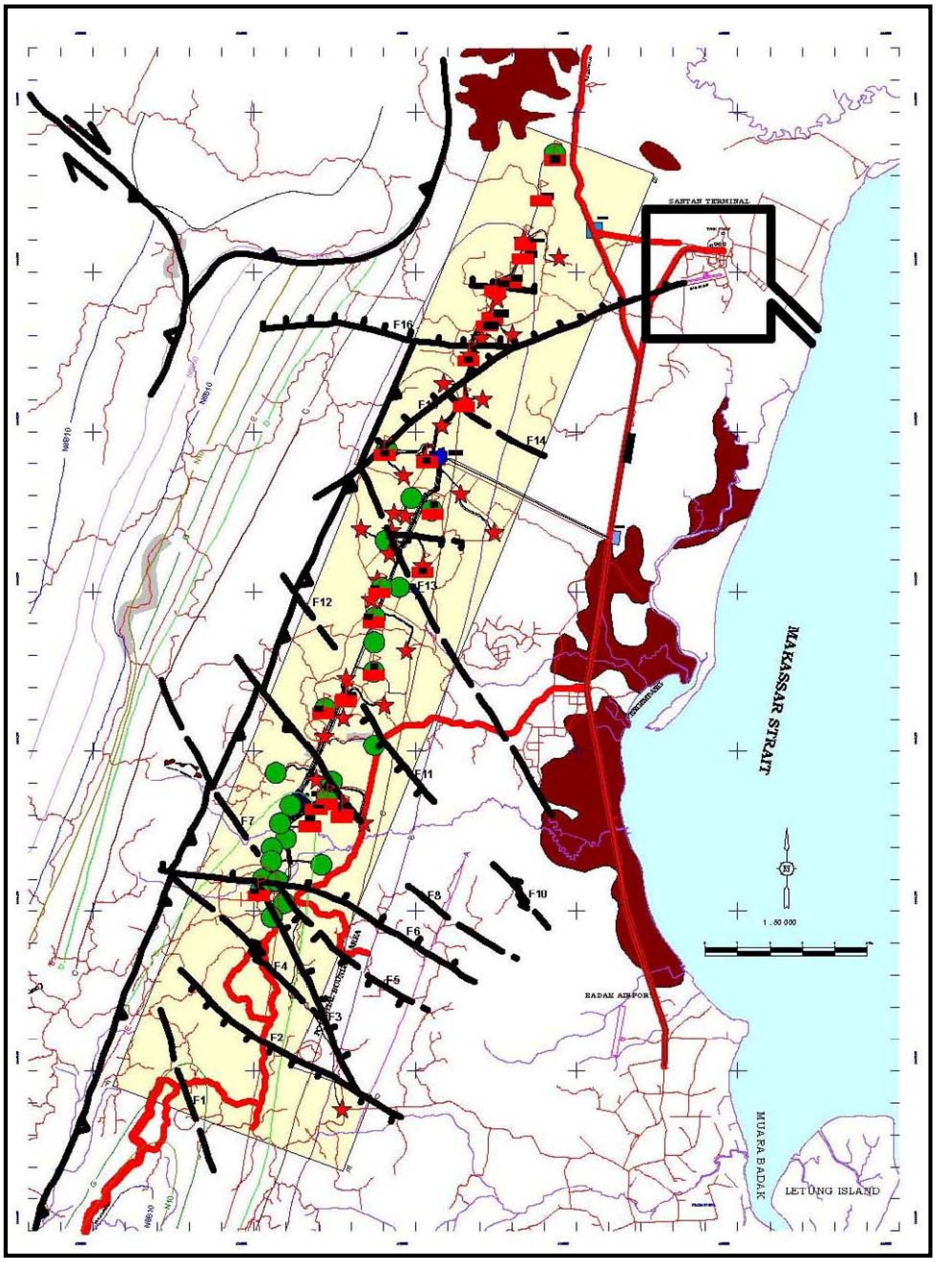


Figure 2. A Basemap showing well location (red star = gas & green circle = oil), outcrop & paleosols description location (red rectangle) and geological structure trends & pattern in Semberah Field - Kutai Basin. Interpreted from SAR data and Field mapping (modified from Bachtiar et.al., 1999).

The initial survey that have been done by VICO Indonesia (*unpublished*) and the authors (Kurniawan *et al.*, 2001) shows that there are at least 26 outcrops along the Semberah anticline that show good indication and ideal to sedimentological study. Some of them have suitable characteristics to be used in paleosol study in fluvial deposits. About 61 wells have been drilled and more than 100 km seismic lines have been recorded along the Semberah

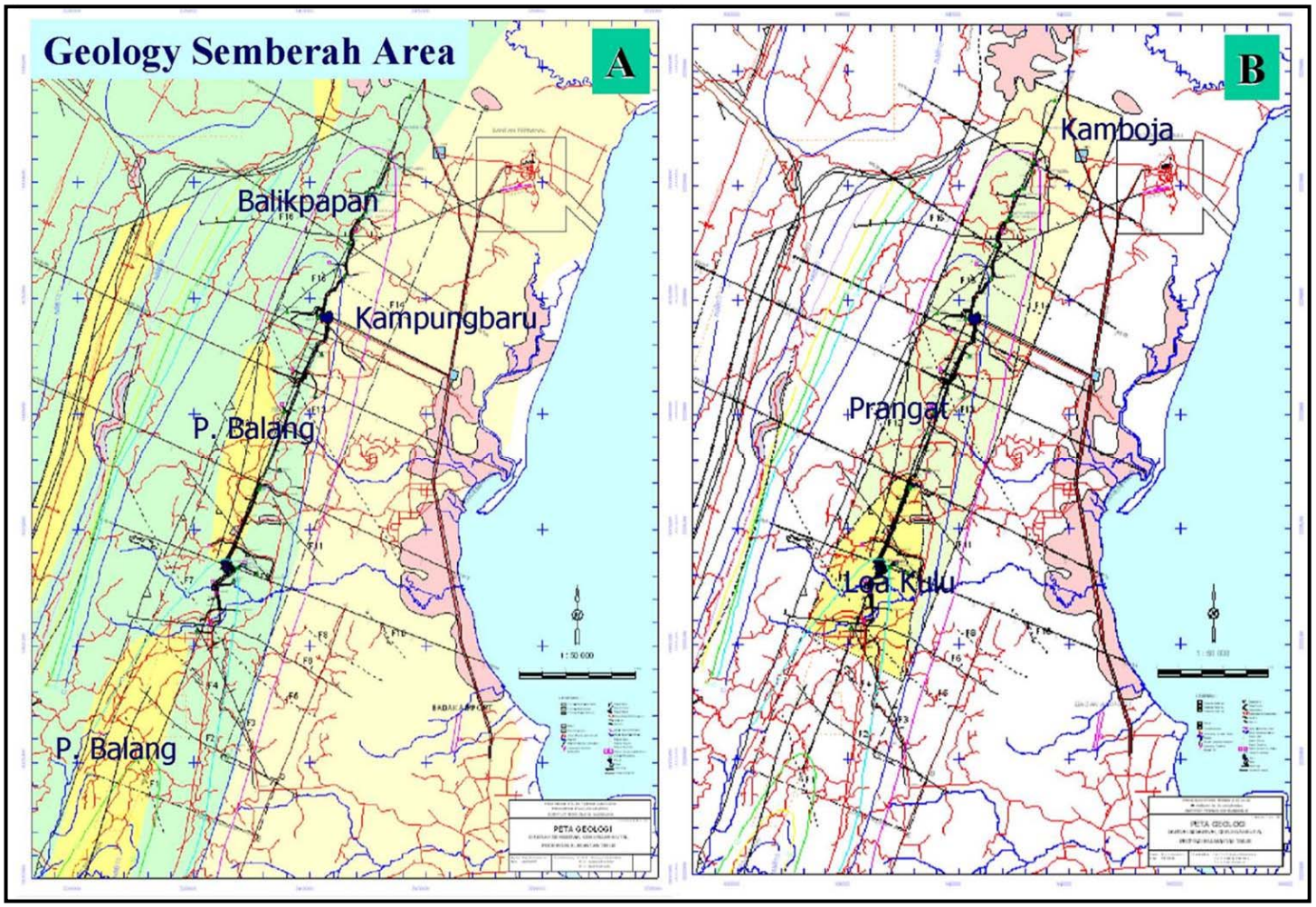


Figure 3. Geological map Semberah area; GRDC Bandung (A) and Chambers (B). The differences of both are in the formation name.

Anticlinal axis by VICO Indonesia, which permit the construction of outcrop correlation to subsurface data.

The purpose of the research are: 1) to document the occurrences of paleosols in the stratigraphic column, 2) to characterise the physical, chemical, and sedimentological features of the paleosols, and 3) to seek for their significance in Sequence Stratigraphic framework.

Geology of Semberah Field

The Semberah Field lies within Muara Badak sub district, Samarinda regency, East Kalimantan province, geographically spread out from 117° 15' 00" E – 117° 25' 00" E and 0° 10' 00" S to 0° 20' 00" S (Figures 1 & 2). The coverage of research area is about 150 km² (almost 86% of Semberah field acreage). The research area can be reached with land transportation using car or bus from Balikpapan to

GENERAL STRATIGRAPHY SAMARINDA AREA

From Chambers, et.al., 1992

Stratigraphy of Leupold and van der Vlerk (1931)	System		Blow Zone	Land and Jones, 1987 Formation	Thickness (m)	Environment	Chambers, et al, 1992 Formation	Environment
KAMPUNG BARU BEDS Tgh	Pliocene		N 19	(top not seen)				
			N 18					
UPPER BALIPAPAN BEDS Tf 3	Upper Miocene		N 17	KAMBOJA FORMATION	470	Alluvial floodplain	KAMBOJA FORMATION	Alluvial floodplain
			N 16					
LOWER BALIPAPAN BEDS Tf 2			N 15	PRANGAT FORMATION	1375	Alluvial floodplain	PRANGAT FORMATION	Alluvial floodplain
	Middle Miocene		N 9 to N 14	unconformity				
PULAU BALANG BEDS Tf	Lower Miocene	late	N 8	LOA KULU FORMATION	800	Deltaic to Marine Shelf	LOA KULU	Deltaic to Marine Shelf
				LOA DURI FORMATION	450	Deep Marine		
				Batuputih Limestone	2-50	Shallow Marine	BATU PUTIH / LOA DURI	
		Early	N 7				?	?
BEBULU BEDS Te 4-5			N 6				(Mud Volcano)	Bathyal
			N 5				?	?
PAMALUAN BEDS Te 1-3	Upper Oligocene		N 4					

The age of the top and bottom of the Prangat Formation is uncertain

Figure 4. The Equivalent of Kutai Stratigraphic Column (modified from Chambers, 1992).

Samarinda then from Samarinda to Muara Badak, and finally from Muara Badak, we can use a motorcycle to the research location.

Physiographically, the Semberah Area is located in the northern part of Samarinda Anticlinorium in the lower Kutai basin. Referring to the morphology of modern Mahakam Delta, the Semberah Field is located in the northern part mainland from the center of active delta development.

Based on lithostratigraphic nomenclature arrangement and similarity of formation name of Land and Jones (1987), the lithology that outcrops in the research area consists of Loa Kulu, Prangat and Kamboja Formation, and consists of continues sedimentation series of paleo-Mahakam deltaic sediments of Middle Miocene to Pliocene age (Figures 3B & 4). Fluvio-deltaic to shallow marine deposits generally dominate the clastic sediments. Paleosols are proved to be well-developed in the fluvio-deltaic deposits within all formations that exist in the research area. The geological structure developed in the Semberah area is a plunging anticline toward northeast along +/- 50 km and the equivalent production zones of the Semberah Field are exposed in the upper-end of this anticline (Figure 3). The Semberah anticline is the northern part of Samarinda anticlinorium, which is bordered by NE–SW thrust fault in the west and dipping abruptly to the east in the shoreline area. Some cross-faults were also documented crossing the axial crest of the anticline (Bachtiar *et al.*, 1999). There is no 3D seismic data to clearly identify these cross faults continuing in the deep subsurface, but we still can trace them with the available 2D seismic data.

Problematic

The research was initiated from the difficulties of (1) applying sequence stratigraphy concept to correlate and reconstruct reservoir connectivity in fluvial depositional system. The main problem is caused by the difficulties in recognizing the indicator of sea level fluctuation, which is used as a basic indicator to divide the sequence stratigraphic components of fluvial and continental deposits, (2) most of Indonesian's hydrocarbon reservoirs are of fluvial deposits, so understanding the model and character of reservoir within time and space is the most important and unconditional thing, (3) there is no detail correlation where sequence stratigraphic concept was applied in the Semberah area, and (4) the importance of paleosols study in Semberah area as one of alternatives correlation methods and reconstruction of reservoir connectivity within fluvial depositional environment.

The utilisation of paleosols as a tool is necessary as an alternative method in solving the correlation problem mentioned previously. In order to understand very well the solution to this problem, the work to be done include: (1) introduction to soil in the field with specific understanding of the relationship between paleosols and indication of sequence boundary, (2) explaining the development, maturity, model, classification and detailed description of paleosols as indication of sequence boundary, (3) correlation and reconstruction the reservoir relationship within fluvial depositional environment by understanding the relationship of paleosols, and (4) evaluating the available paleosol classification (Mack *et al.*, 1993; Soil Survey Staff, 1975; 1998) to be applied in the Semberah area.

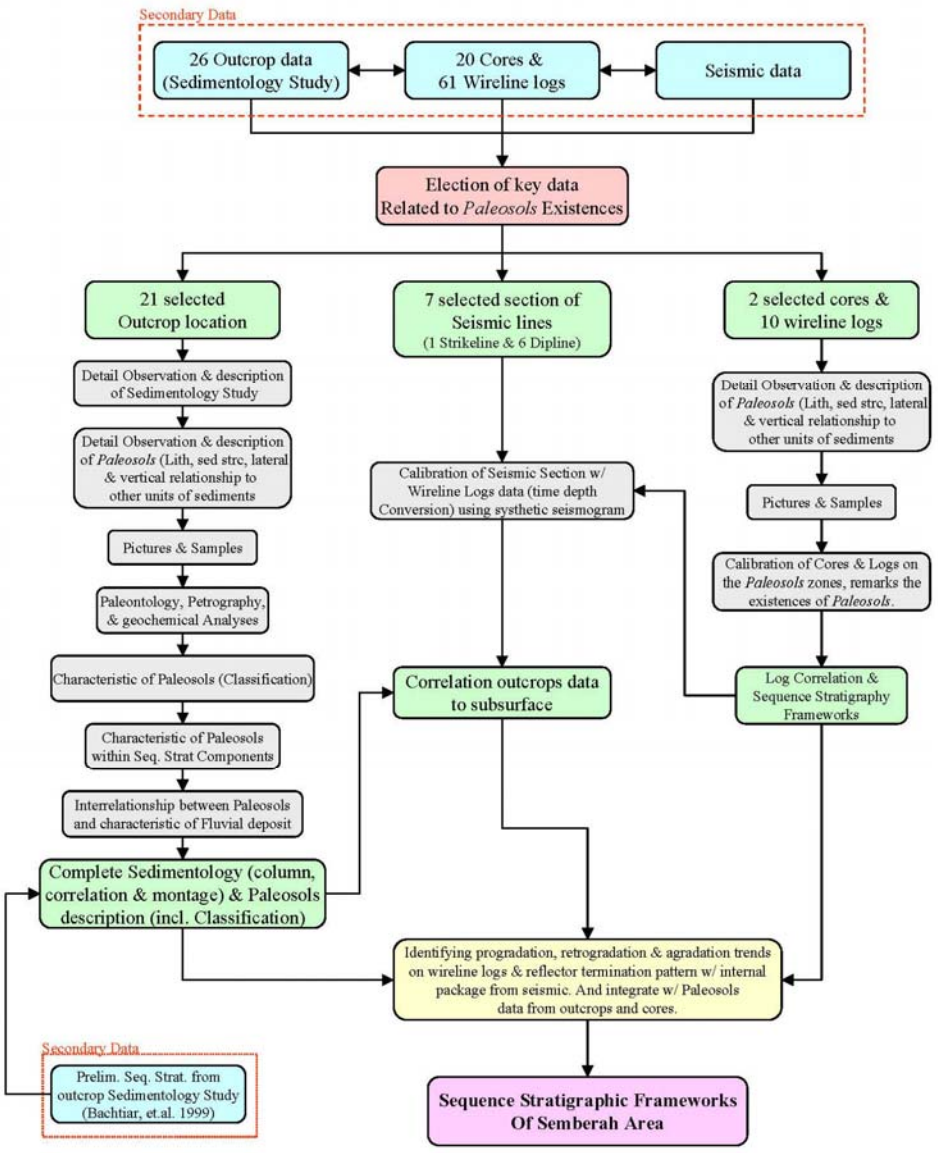


Figure 5. **Research Flow Chart, use primary data (21 outcrops, 7 seismic line, 10 wells, 2 cores) and secondary data (26 outcrop sedimentology study, seismic line, 61 wells, 20 cores, sequence stratigraphy framework from previous study).**

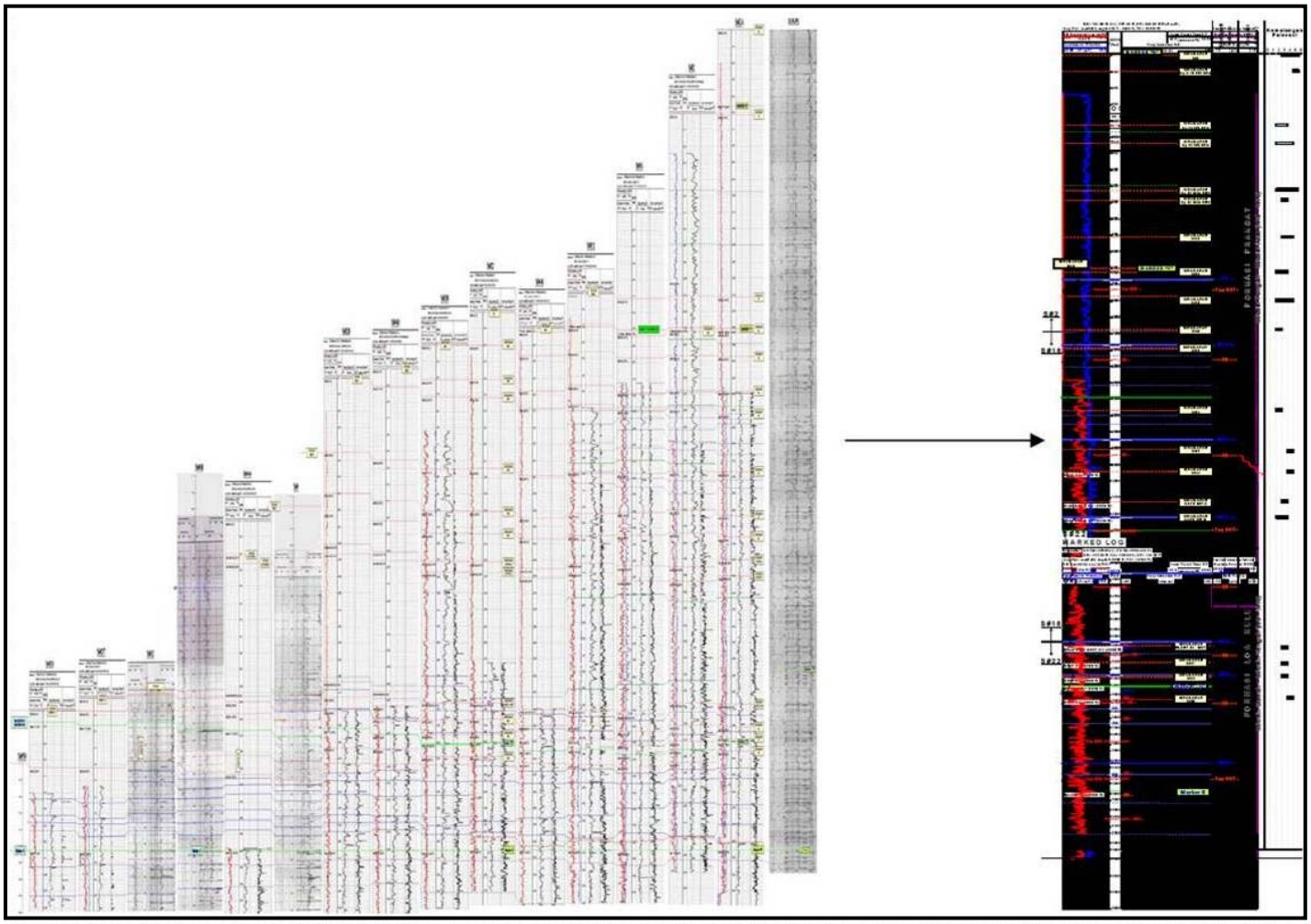


Figure 6. Wireline log correlation to place the 21 outcrops and 16 wells into sequence stratigraphic framework of Semberah area; resulted 8 sequences and then summarize into composite sequence stratigraphic log. All individual markers and outcrop then plotted to seismic correlation.

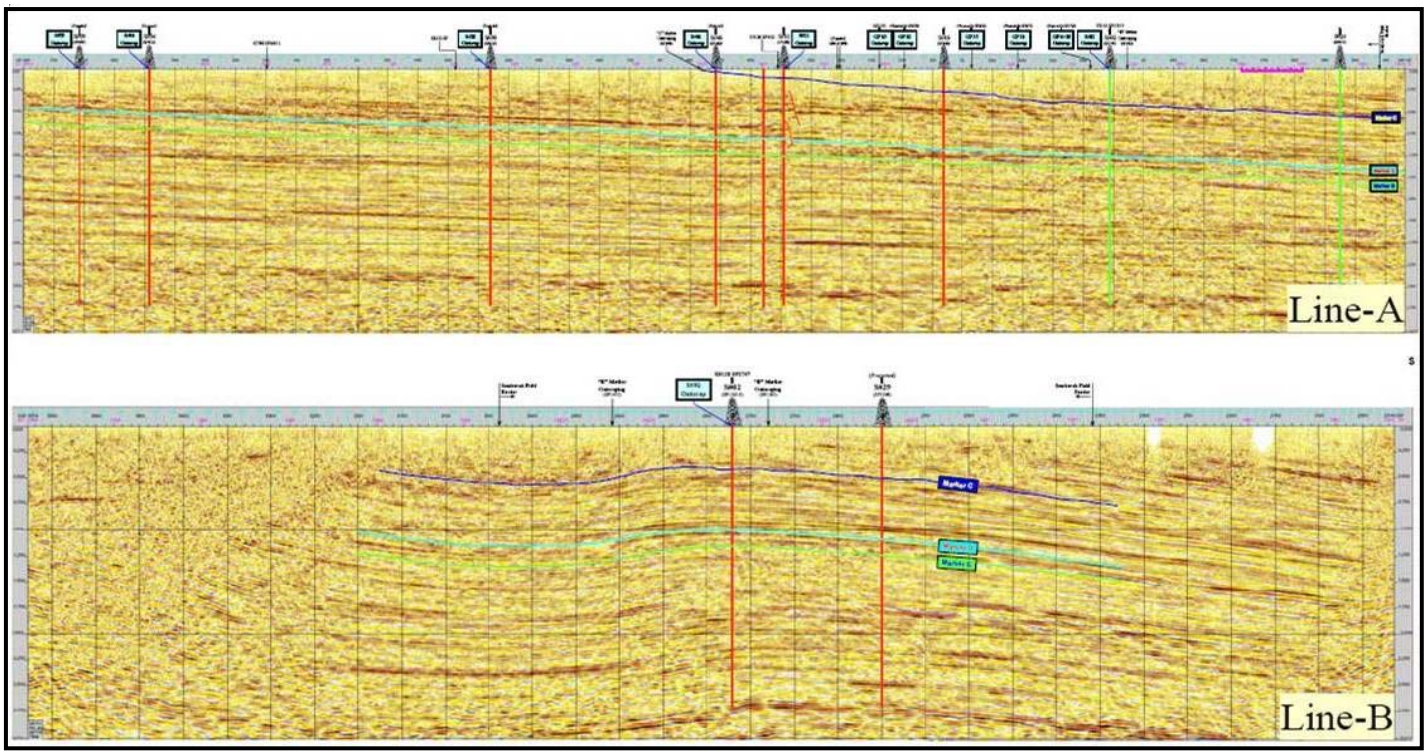


Figure 7. One of seven seismic correlation to place the 21 outcrops and 16 wells into sequence stratigraphic framework of Semberah area. This correlation was initiated by determining key seismic section line, which across drill hole points and chosen outcrops, calibration of seismic section with well logs data (Time depth conversion) using synthetic seismogram and correlation outcrops data to subsurface using chosen seismic section (final stacked / migrated hard copy) as guidance.

From previous studies and publications, it can be summarised that: (1) classification and type of paleosols represent the sedimentary process and rate of pedogenesis, (2) paleosols can develop well in HST due to low accommodation space, (3) paleosols can develop very well in LST and are associated with erosional channel base, (4) *hydromorphic paleosols* will develop only in the beginning of TST due to the increase of base level, accommodation space still low and overlap with channel sandstone, (5) as the accommodation space increases and sediment accumulation occurs faster in TST, paleosols will not develop or even will be obstructed.

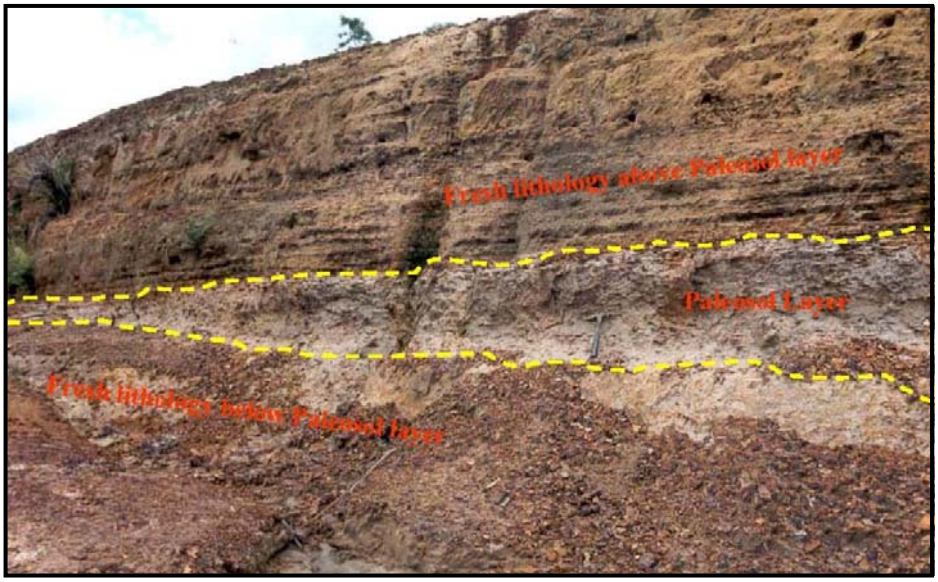


Figure 8. Step-1 in Paleosol description: describe Rock Type of paleosol; define fresh lithology within paleosols layer, fresh lithology above and below the paleosols layer (Mack, et.al., 1993).

Methods

The field study was undertaken in February 2001 for three weeks to document and describe many types of paleosols in the Semberah Field in order to find their similar characteristics, classify them and to apply this knowledge of paleosols within Sequence Stratigraphic framework in the Semberah Area.

The research uses outcrops, wireline logs, cores, seismic section and laboratory data (Figure 5).

1. Outcrop Data

- Determination of key outcrops by identifying the existences of paleosols from about 26 outcrops along the Semberah Anticline. About 21 outcrops are available to study paleosols (Table 1).
- Detailed observation and description of sedimentological study in the selected outcrops.
- Detailed observation and description of paleosols in the chosen outcrops including lithology description, sedimentary structures and the lateral & vertical relationship to the other units of sediments.
- Photo documentation and samples. Systematically, the samples are collected at three part of observation, i.e.: at the paleosol interval, upper part and lower part of the paleosol interval, the amount of samples depend on the variation of existences of paleosols in the outcrops, usually indicated by a clay to very fine sand grained size and reddish brown or Fe-oxides colors. The next step is data processing in laboratory.

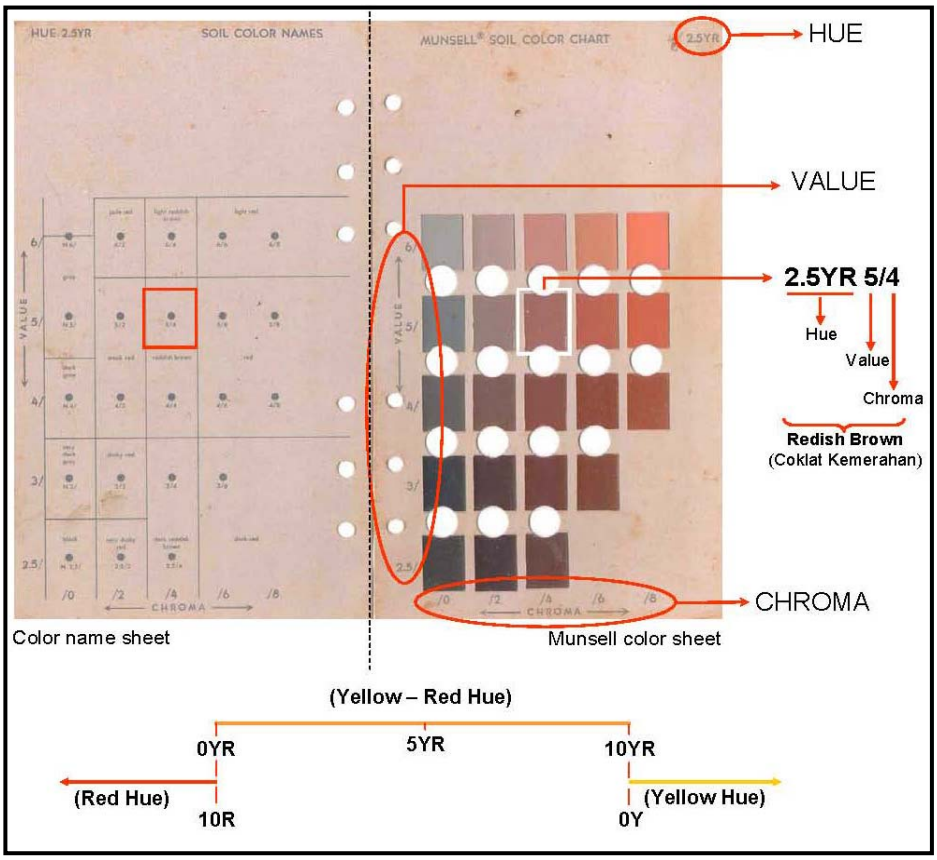


Figure 9. Step-2 in Paleosol description: define the Color, initiated with HUE then VALUE

2. Core and wireline log

- Determination of key cores by identifying paleosols in about 20 cores along the Semberah Anticline. It is difficult to find paleosols in the Semberah cores due to less lithological variation in core preservation (most of them are sandstones), but some

of them do have paleosols (Figure 6).

- Observation and detailed description of paleosols on selected cores, including detailed description of lithology, sedimentary structures and lateral & vertical relationship with other units of sediment.
- Calibration of cores with wireline logs on the zones, which have paleosols and note the existences of the paleosols (Ye, 1995).

3. **Seismic Section**
   - Determination of key seismic section lines that can be tide to borehole points and selected outcrops.
   - Calibration of seismic section with well logs data (Time-Depth conversion) by using synthetic seismogram.
   - Correlating outcrops data to subsurface by using selected seismic section (final stacked/migrated hard copy) as a guidance (Figure 7).

4. **Laboratory Data**
   - Paleontological analysis of selected outcrop to complete secondary data, which have been done previously by GDA team (Bachtiar *et al.*, 1999). The objective is to know the depositional environment from sediment units of the outcrops and later on will be applied to sequence stratigraphic frame-works.
   - Petrographic analysis of selected outcrop samples taken from paleosol intervals. The objective is to know the development degree, maturity, model and classification of paleosols.

Paleosols identification

Paleosols can be defined as soils that formed on a landscape in the past that were caused by a physical, biological and chemical modification from an exposed sedimentary rock (Kraus, 1999). According to Ailsa and Michael (1990), paleosols are soils that formed

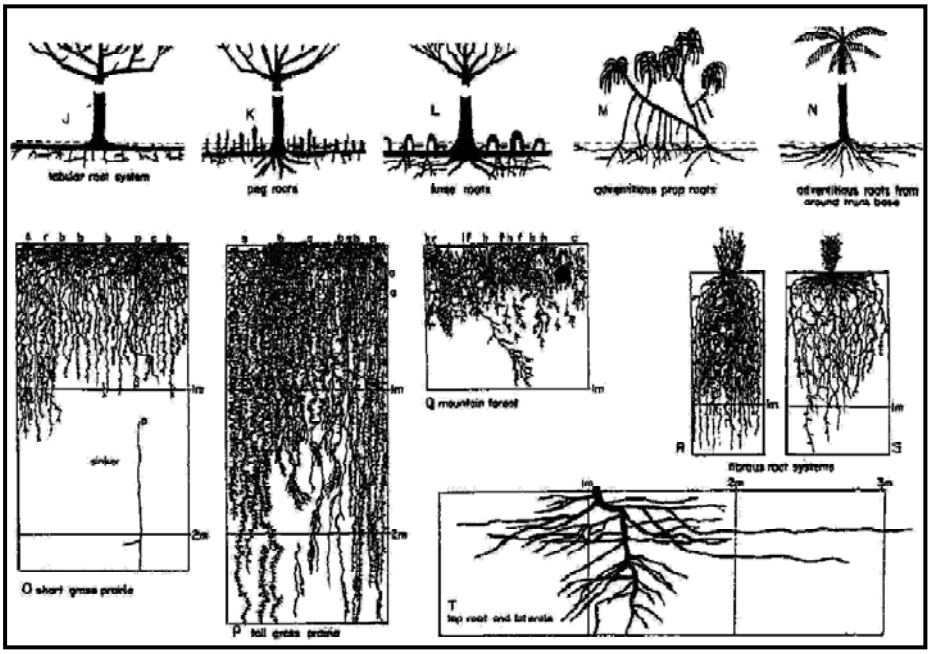


Figure 10. Step-3 in Paleosol description: describe Nature of Root Traces, with compare the appearance of root distribution in outcrop with model from Retalack, 1988.

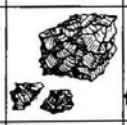
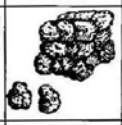
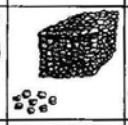
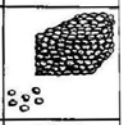
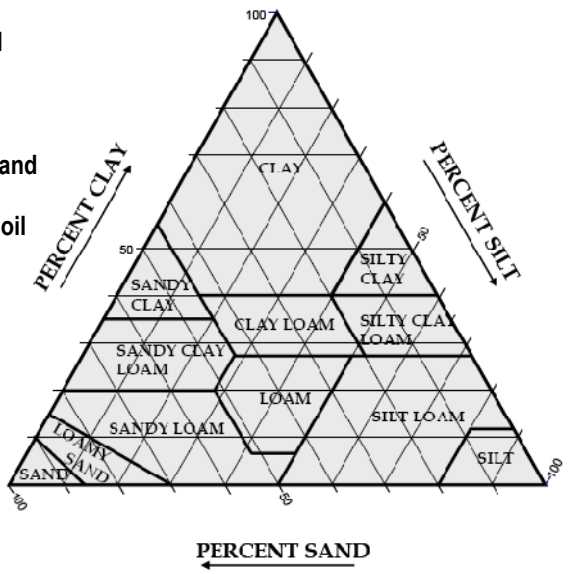
TYPE	PLATY	PRISMATIC	COLUMNAR	ANGULAR BLOCKY	SUBANGULAR BLOCKY	GRANULAR	CRUMB
SKETCH							
DESCRIPTION	tabular and horizontal to land surface	elongate with flat top and vertical to land surface	elongate with domed top and vertical to surface	equant with sharp interlocking edges	equant with dull interlocking edges	spheroidal with slightly interlocking edges	rounded and spheroidal but not interlocking
USUAL HORIZON	E,Bs,K,C	Bt	Bn	Bt	Bt	A	A
MAIN LIKELY CAUSES	initial disruption of relict bedding; accretion of cementing material	swelling and shrinking on wetting and drying	as for prismatic, but with greater erosion by percolating water, and greater swelling of clay	cracking around roots and burrows; swelling and shrinking on wetting and drying	as for angular blocky, but with more erosion and deposition of material in cracks	active bioturbation and coating of soil with films of clay, sesquioxides and organic matter	as for granular, including fecal pellets and relict soil clasts
SIZE CLASS	very thin <1 mm	very fine <1 cm	very fine <1 cm	very fine <0.5 cm	very fine <0.5 cm	very fine <1 mm	very fine <1 mm
	thin 1 to 2 mm	fine 1 to 2 cm	fine 1 to 2 cm	fine 0.5 to 1 cm	fine 0.5 to 1 cm	fine 1 to 2 mm	fine 1 to 2 mm
	medium 2 to 5 mm	medium 2 to 5 cm	medium 2 to 5 cm	medium 1 to 2 cm	medium 1 to 2 cm	medium 2 to 5 mm	medium 2 to 5 mm
	thick 5 to 10 mm	coarse 5 to 10 cm	coarse 5 to 10 cm	coarse 2 to 5 cm	coarse 2 to 5 cm	coarse 5 to 10 mm	not found
	very thick >10 mm	very coarse >10 cm	very coarse >10 cm	very coarse >5 cm	very coarse >5 cm	very coarse >10mm	not found

Figure 11. Step-4 in Paleosol description: describe the Soil Structure based on classification of soil peds above. It is simplified from classification from Soil Survey Staff (1975) and Birkeland (1984).

Figure 12. Step-5 in Paleosol description: classify the Soil Texture. The Chart showing the percentage of clay (below 0,002 mm), silt (0,002-0,005 mm), and sand (0,05-2,0 mm) in the basic soil textural classes (modified from Soil Survey Staff, 1992).



on past *pedogenesis*)* period, and have been buried, later on re-exposed, or continuously exposed on a landscape until present *pedogenesis* period.

Paleosols in outcrops can be recognized by identification of three main features of root traces, soil horizons, and soil structures (Retallack, 1988). Fenwick (1985) suggested some criteria in recognising paleosols in the field, i.e.: the presence of surface horizons enriched in organic matter, red-colored horizons that become more intense in color toward the top, marked decline in weather-able minerals toward the top of the soil profile, and disruption of original structures by organisms such as earthworms or by physical processes such as frost action and solifluction.

Paleosols can also be recognized in wireline logs by identifying the log responses of paleosol set and non paleosol set (Ye, 1995). Actually, it is not easy to recognize the individual of paleosols in wireline logs because the average thickness is only about 1–2 meters, which means it is not thick enough to see in the wireline log. However, the development of paleosol set is commonly within tens meters. Paleosol set means extensive development of paleosols, while non paleosol set means little or non development of paleosols.

The classification of paleosols used in this research is modified from the available classification and not all of the paleosols has been genetically applied as a regional sequence boundary, but only paleosols that are associated with the lower boundary of LST or the upper boundary of HST that can be used as alternative tool in sequence stratigraphic correlation within fluvial depositional environment. The profile, development and maturity of paleosols can help to identify the specific character of equivalent system tract and can be correlated.

New Term	Description	Old Term	
O	Surface accumulation of organic materials (peat, lignite, coal), overlying clayey or sandy part of soil	O	MASTER HORIZON
A	Usually has roots and a mixture of organic and mineral matter; forms the surface of those paleosols lacking an O horizon	A	
E	Underlies an O or A horizon and appears bleached because it is lighter colored, less organic, less sesquioxidic, or less clayey than underlying material	A2	
B	Underlies an A or E horizon and appears enriched in some material compared to both underlying and overlying horizons (because it is darker colored, more organic, more sesquioxidic or more clayey) or more weathered than other horizons	B	
K	Subsurface horizon so impregnated with carbonate that it forms a massive layer (developed to stage III or more of Table 4)	K	
C	Subsurface horizon, slightly more weathered than fresh bedrock; lacks properties of other horizons, but shows mild mineral oxidation, limited accumulation of silica carbonates, soluble salts or moderate gleying	C	
R	Consolidated and unweathered bedrock	R	
AB	Horizon with some characteristics of A and B, but with A characteristics dominant	A3	
BA	As above, but with B characteristics dominant	B1	
E/B	Horizon predominantly (more than 50%) of material like B horizon, but with tongues or other inclusions of material like an E horizon	A&B	
a	Highly decomposed organic matter	—	SUBORDINATE DESCRIPTORS
b	Buried soil horizon (used only for pedorelict horizons with paleosols; otherwise redundant)	b	
c	Concretions or nodules	cn	
e	Intermediately decomposed organic matter	—	
f	Frozen soil, with evidence of ice wedges, dikes, or layers	f	
g	Evidence of strong gleying, such as pyrite or siderite nodules	g	
h	Illuvial accumulation of organic matter	h	
i	Slightly decomposed organic matter	—	
k	Accumulation of carbonates less than for K horizon	ca	
m	Evidence of strong original induration or cementation, such as avoidance by root traces in adjacent horizons	m	
n	Evidence of accumulated sodium, such as domed columnar peds or halite casts	sa	
o	Residual accumulation of sesquioxides	—	
p	Plowing or other comparable human disturbance	p	
q	Accumulation of silica	si	
r	Weathered or soft bedrock	ox	
s	Illuvial accumulation of sesquioxides	ir	
t	Accumulation of clay	t	
v	Plinthite (in place, pedogenic laterite)	—	
w	Colored or structural B horizon	—	
x	Fragipan (a layer originally cemented by silica or clay, and avoided by roots)	x	
y	Accumulation of gypsum crystals or crystal casts	cs	
z	Accumulation of other salts or salt crystal casts	sa	

Figure 13. Step-6 in Paleosol description: classify the Soil Horizon based on the appearance of organic material, root, clay / sand content and other material in Master Horizon and subdivided with their subordinate based on their composition, concretion/nodule, and other parameter mentioned in classification above. The classification referred to Retalack, 1988.

Carbonate Content	Reaction with Dilute Acid
Noncalcareous	Acid unreactive; often forms an inert bead
Very weakly calcareous	Little movement within the acid drop, which could be flotation of dust particles as much as bubbles
Calcareous	Numerous bubbles, but not coalescing to form a froth
Strongly calcareous	Bubbles forming a white froth, but drop of acid not doming upward
Very strongly calcareous	Drop vigorously frothing and doming upward

Figure 14. Step-7 in Paleosol description: classify the Reaction with Dilute Acid. Classification above explain the scale of Acid reaction to approximate Carbonate content of paleosols (Retalack, 1988).

***Pedogenesis** *is the natural forming of soil processes by many processes such as humidity, weathering, leaching and weathering in limestone.*

Paleosols description

The features that need to be described in detail during paleosol description of the outcrop and core are: rock type, color, nature of root traces, soil structures, soil texture, soil horizon, reaction with dilute acid, nature of contact (sharpness or lateral continuity), classification and maturity (Figures 8–17).

Paleosols in Semberah Area

The sedimentology study of Semberah area has described 26 outcrops and also subsequently investigated their paleosol occurrences. The outcrops represent age range of 10.5 Ma (Late Miocene) to 7 Ma (Late Miocene–Pliocene). Based on stratigraphic nomenclature of Land and Jones (1987), in the Kutai basin especially near to the locality type in Samarinda area, they all belong to the Balikpapan/Kampung Baru Formation. The lithology was dominated by sandstones, shales, siltstones, clays and coals, which spread out within various environments in deltaic system, e.g.: fluvial channel, distributary channels, floodplains, tidal channels, mudflats, and delta front bars.

In term of paleosol description, the research has documented 52 discreet occurrences of paleosols in 21 out of 26 outcrops in Semberah area. The individual paleosol thickness ranges from 25 cm to 225 cm. Based on the classification of Mack *et al.* (1993), the paleosols are classified as spodosol with typical character of having tabular root traces, heavily mottled A & C horizons, and granular peds structures with siderite nodules. Histosol and oxisol occurred in several places but not as ubiquitously as the spodosol. The spodosol occurrences are mostly associated with the swampy nature of the sedimentary depositional environments. The distributions of paleosols are found below the erosional surface at the bottom of channel sandstones, within channel

Category	Class	Features
Sharpness	Abrupt	Transition from one horizon to another completed within 1 in (2cm)
	Clear	Transition completed within 1-2.5 in (2-5 cm)
	Gradual	Transition spread over 2.5-5 in (5-15 cm)
	Diffuse	One horizon grading into another over more than 5 in (15 cm)
Lateral Continuity	Smooth	Horizon boundary forms an even plane
	Wavy	Horizon boundary undulates, with pockets wider than deep
	Irregular	Horizon boundary undulates, with pockets deeper than wide
	Broken	Parts of the adjacent horizon are disconnected, e.g., by deep and laterally persistent clastic dikes in Vertisols

Figure 15. Step-8 in Paleosol description: categorize the Nature of Contact with layer above and below, is it sharpness or lateral continuity contact. The classification above can be described based on the paleosol layer contact features in field (Retalack, 1988).

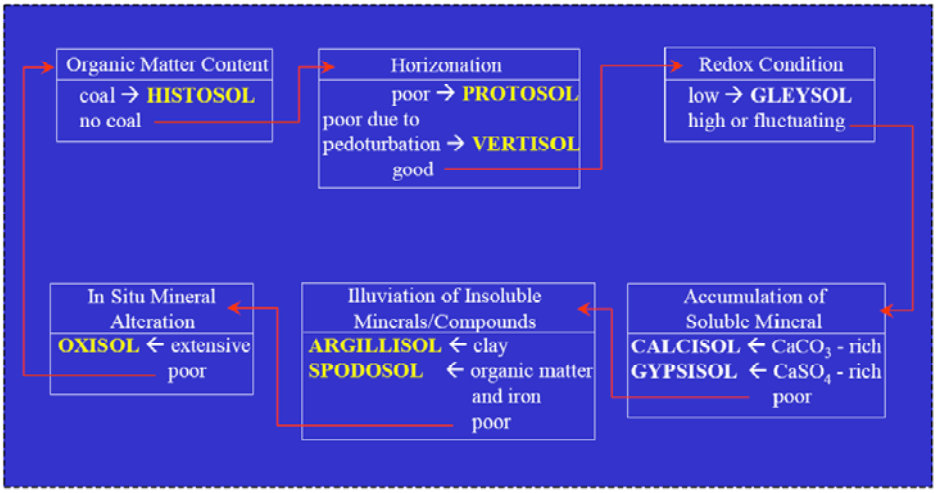
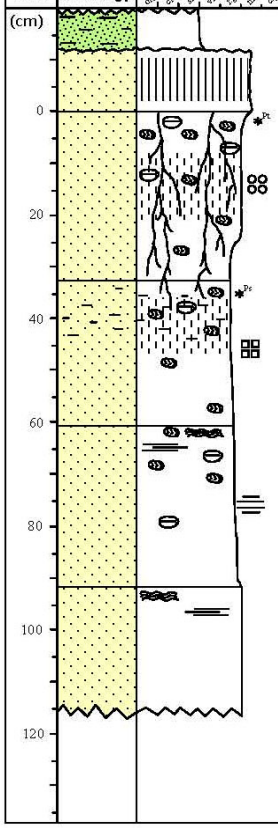


Figure 16. Step-9 in Paleosol description: Paleosols classification. The Classification above explain simple flowchart to determine Paleosols order based on pedogenic feature or process, adapted from Mack, et.al., 1993.

STAGE	0	1	2	3	4	5	6	7	8	9	10
Morphology Expression	No	not soil	weak ("band")	weak	moderate	strong	v. strong	v. strong	strong	moderate	weak
Morphology Description	geology	geology	weak solum	weak B	weak E or Bt	E and Bt normal	E and Bt thick	thick horizon	thick horizon	horizon can be disting.	horizon not clear
Horizon	D or R	C or Cr D R	A C D/R	A Bw C D/R	A E Bt C D R	A E Bt BCt C D/R	A E Bt Bt Ct D/R	A E Btt Bt Ct D/R	A E Bt Bto Ct saprolit R	E A Bto Bo Ct saprolit R	E A Bo Bo Ct saprolit R
Mineral Alteration	No	detected	v. weak	weak	weak	weak	moderate	moderate	strong	v. strong	complete
Key Development Character	No	Lab. evidence C	first evidence of horizon	first evidence of horizon B	first evidence E or Bt	E and Bt normal	E and Bt thick	Btt and strong weathering	Bto and strong weathering	Bo and strong weathering	v.strong weathering

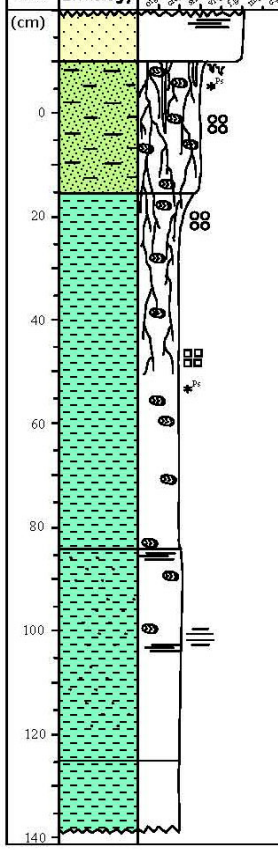
Figure 17. Step-11 in Paleosol description: categorize the Paleosols Maturity. The maturity stage above explain the sequence of the development scale of paleosol maturity, started with stage-0 for normal or fresh lithology to stage-10 for very strong maturity (Follmer, 1995).

S#02; PS-01 (SPODOSOL – Stage 3/Weak)



Thick-ness	General Lithology	Grainsize	Munsell color	Horizon design	Descriptive (rock type)	Nature of root traces	Soil structure	Soil teksture	Other Feature	Reaction with Dilute acid	Nature of contact		Remarks
											Sharpness	Lateral cont.	
			10YR5/4 (ylwsh brn)	R	Siltstone	-	-	-	-	Non calcareous	Abrupt	Smooth	Amber, coal frg., FeOx
			2.5YR4/4 (redsh brn)	O?	Sandstone (hard 'FeOx' layer)	Tabular (infrequently)	Granular	Loamy Sand	Distinct, Common, Fine	Non calcareous	Abrupt	Irregular	Hard, FeOx.
			10YR5/4 (ylwsh brn)	A	Sandstone (vf-fgr - muddy)	Tabular	Granular	Sandy Loam	Prominent, Many, Fine	Non calcareous	Clear	Wavy	FeOx, clay nodule
			10YR7/4 (v.pale brn)	B	Sandstone (vfgr - muddy)	Tabular (infrequently)	Sub angular blocky	Sandy Clay Loam	Prominent, Many, Fine	Non calcareous	Gradual	Wavy	FeOx, clay nodule, pH = 2
			10YR5/8 (ylwsh brn)	C	Sandstone (vf-fgr)	-	Platy	Sandy Loam	Prominent, Few, Fine	Non calcareous	Gradual	Irregular	FeOx, wavy lam, par lam, clay nodule
			10YR5/3 (brn)	R	Sandstone (fgr)	-	-	-	-	Non calcareous	Abrupt	Smoot	Wavy lam, par lam, clay drape, FeOx.

S#02; PS-02 (SPODOSOL - Stage-4/Moderate)



Thick-ness	General Lithology	Grainsize	Munsell color	Horizon design	Descriptive (rock type)	Nature of root traces	Soil structure	Soil teksture	Other Feature	Reaction with Dilute acid	Nature of contact		Remarks
											Sharpness	Lateral cont.	
			10YR5/4 (ylwsh brn)	R	Siltstone	-	-	-	-	Non calcareous	Abrupt	Smooth	Amber, coal frg., FeOx
			10YR6/4 (lgt ylwsh brn)	A	Sandstone, muddy (hard 'FeOx' layer)	Tabular	Granular	Sandy loam	Prominen, Many, Fine	Non calcareous	Abrupt	Irregular	FeOx
			10YR7/4 (very pale brn)	E-B	Tabular (jarang)	Tabular	Granular	Silty clay	Distinct, Few, Fine	Non calcareous	Gradual	Irregular	FeOx, pH = 4
			10YR6/3 (pale brn)	B	Tabular (jarang)	Tabular (infrequently)	Sub angular blocky	Clay	Prominent, Common, Fine	Non calcareous	Clear	Wavy	FeOx
			10YR6/4 (lgt ylwsh brn)	C	Tabular (jarang)	-	Platy	Silty clay	Faint, Few, Fine	Non calcareous	Gradual	Irregular	FeOx
			10YR5/4 (ylwsh brn)	R	Sandstone (fv gr)	-	-	-	-	Non calcareous	Abrupt	Smoot	Wavy lam, par lam, clay drape, FeOx.

Figure 18. An example of paleosol profile and description in Semberah Area. The paleosol unit PS-01 and PS-02 is located in Semberah-02 outcrop, a typical profile of Spodosol.

sandstones, in a series of crevasse splay deposits, and also below a transgressive surface. Sample of profile and description of paleosols in the Semberah area are shown in Figures 18 & 19.

Conclusions

1. Paleosols are found ubiquitously in deltaic sediments and can be well-documented on outcrops in the Semberah Field, Mahakam Delta, Kutai Basin. The individual occurrence varies on each outcrop.

2. The cores in the Semberah area do not have representative paleosols because these cores were taken

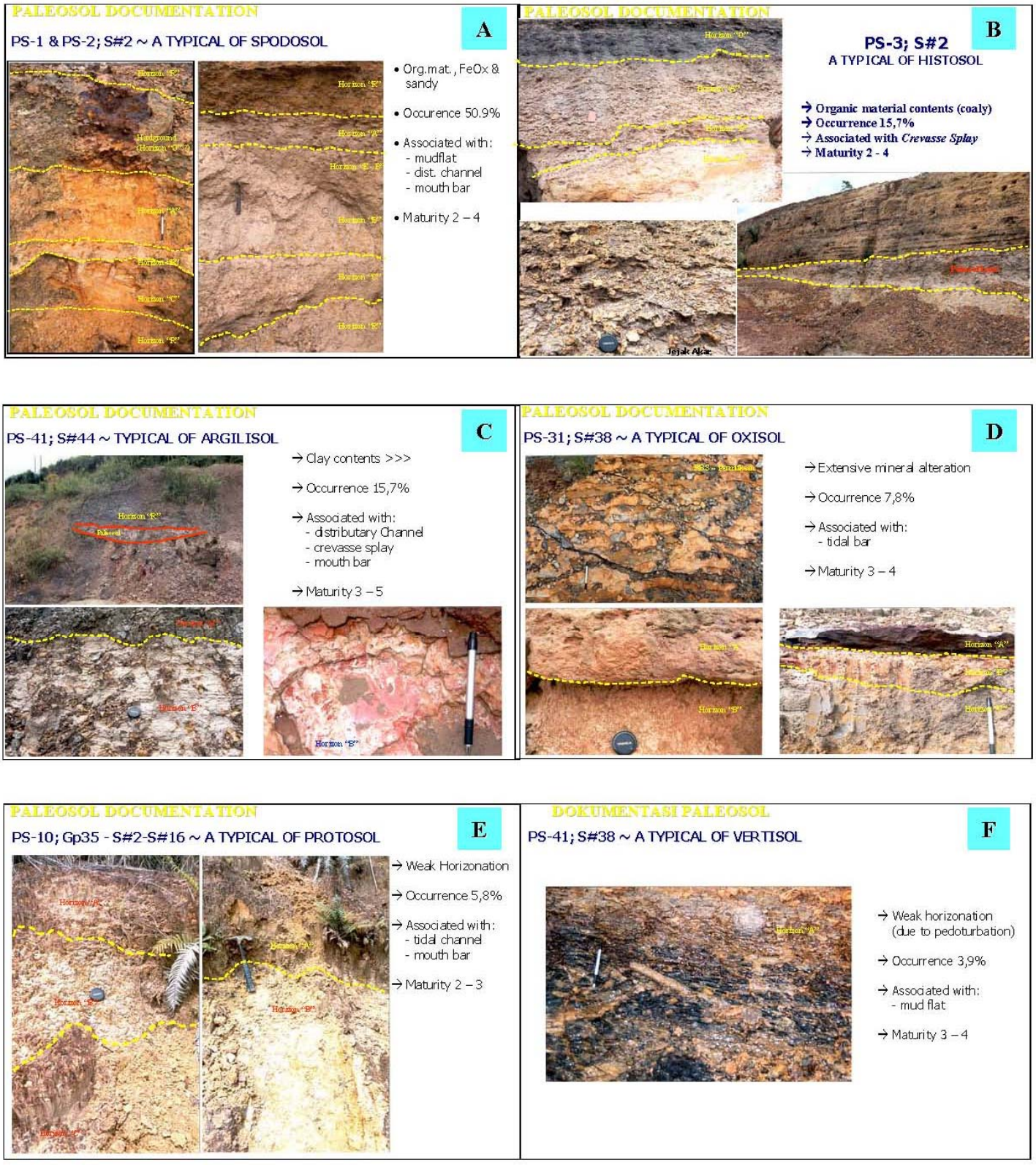


Figure 19. A typical paleosol profile in Semberah Area, (A) Spodosol, (B) Histosol, (C) Argilisol, (D) Oxisol, (E) Protosol, (F) Vertisol, using classification name from Mack et.al. (1993).

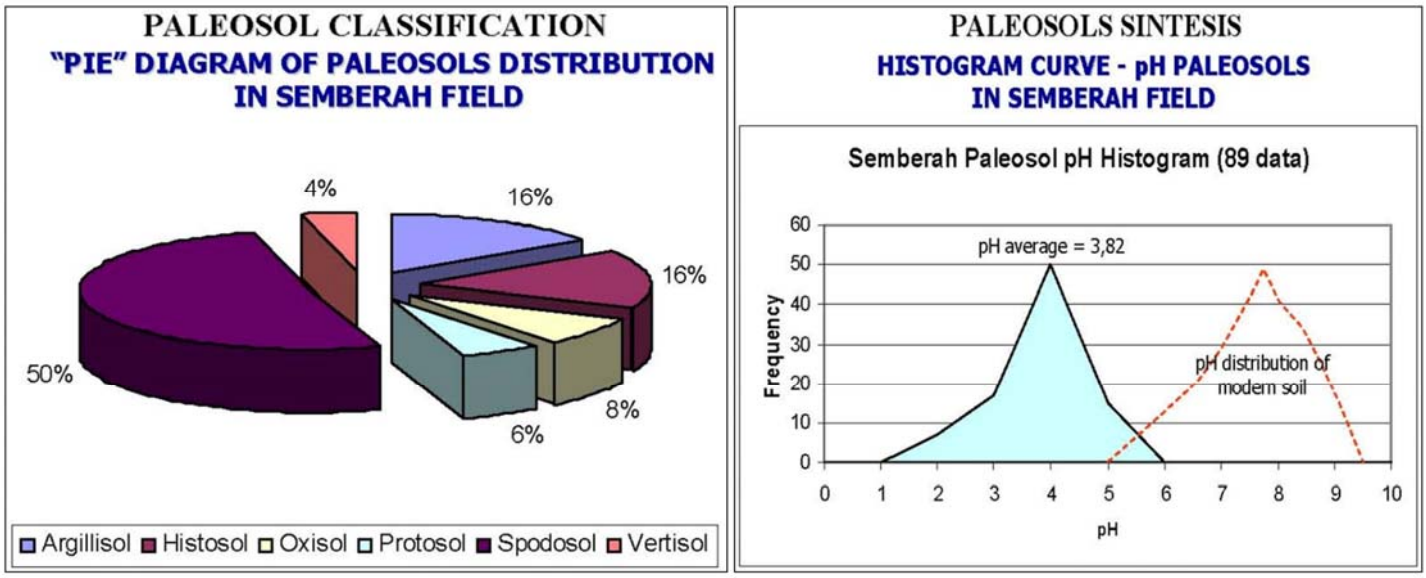


Figure 20. Pie diagram showing the percentage distribution of paleosols in Semberah area (left) and curve showing the pH average of paleosol and its related to pH of modern soil (right)

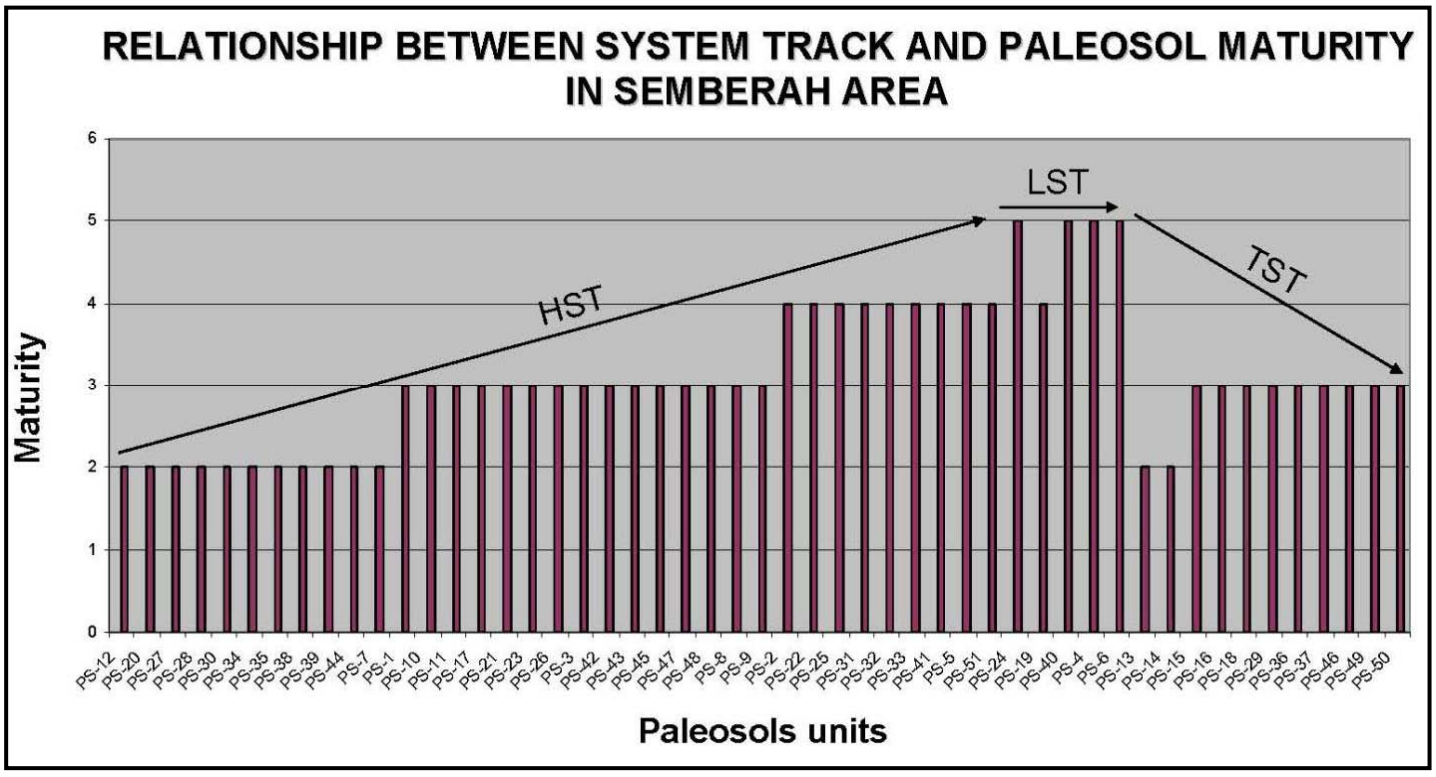


Figure 21. Paleosols Synthesis; A relationship between System Track and paleosols maturity in Semberah area. Their occurrence in HST represent to 70.6%, IVF : 3.9%, LST : 1.9%, TSE : 1.96% and TST : 21.5%

from a deep part and only within production reservoir only.

3. The paleosol description methodology refers to Retallack (1993) with small modification and efficiency, while the paleosol classification uses Mack *et al.* (1993). The paleosol maturity development is defined based on paleosol development degree of maturity from Follmer (1998), where stage 0 to stage 6 scale use only morphological expression parameters while stage 7 to stage 10 need mineralogical parameter.

4. The composition of paleosols in the Semberah area consists of Argilisol 16%, Histosol 16%, Oxisol 8%, Protosol 6%, Spodosol 50% and Vertisol 4%. The Gleysol, Calcisol and Gypsisol are not found. The average pH is 3.82 which is slightly lower than modern soil (Figure 20).

5. The occurrences of paleosols within sequence stratigraphic framework are (Figure 21):

a. ***Highstand Systems Tract (HST)*** is 70.6% well-developed with maturity varies from weak to moderate (stage 2 to 4). The low accommodation space supports paleosols to ***develop well*** with its upper boundary most likely associated to sequence boundary.

b. The paleosol distribution within Incised Valley Fill (IVF), Lowstand System Tract (LST) and Transgressive Surface of Erosion (TSE) are ***very well-developed*** with percentage of their occurrence as 3.9%, 1.9% and 1.96% with their maturity varies from moderate to strong (stage 4 to stage 5). In general, they will associate with an erosional channel base known as sequence boundary in the bottom part border.

c. Paleosols are ***not found*** in the beginning of Transgressive System Tract (TST) in Semberah area which is commonly

Table 01. The result of paleosols research, documented 24 outcrops of sedimentology study and 51 units paleosols within 21 outcrops.

No.	Outcrop Name	Paleosol			Classification	Dep. Env	System	Maturity	None	Not Soil	Weak	Weak	Moderate	Strong
		Units	pH	Color	(Follmer '95)	Association	Track		0	1	2	3	4	5
1	Semberah-24													
2	Gate S#24 to S#2													
3	Semberah-2	PS-1	2	10YR7/4	Spodosol	Upper Tidal DP	HST	3						
		PS-2	4	10YR7/4	Spodosol	Tidal Mouth Bar	HST	4						
		PS-3	3	10YR7/3	Histosol	Crev. Splay	HST	3						
		PS-4	4	5YR6/3	Argillisol	Crev. Splay	LST	5						
		PS-5	4	10YR7/3	Histosol	mudflat	HST	4						
4	Gp 6+38 - S#2 to S#16	PS-6	4	10YR6/3	Argillisol	Dist. Channel	TSE	5						
5	Gp 24 - S#2 to S#16	PS-7	4	10YR7/4	Spodosol	Dist. Mouth Bar	HST	2						
		PS-8	4	10YR7/6	Spodosol	mudflat	HST	3						
		PS-9	4	10YR7/4	Argillisol	Dist. Channel	HST	3						
6	Gp 35 - S#2 to S#16	PS-10	4	10YR7/2	Protosol	Mouth Bar	HST	3						
		PS-11	5	10YR7/6	Spodosol	Mouth Bar	HST	3						
		PS-12	4	7.5YR7/4	Spodosol	Tidal Flat	HST	2						
7	GP 12 - S#16 to S#33	PS-13	5	10YR7/6	Spodosol	Dist. Channel	TST	2						
		PS-14	4	10YR7/6	Spodosol	Dist. Channel	TST	2						
		PS-15	4	5YR7/3	Spodosol	mudflat	TST	3						
		PS-16	5	10YR7/6	Oxisol	mudflat	TST	3						
8	GP 15 - S#16 to S#33	PS-17	5	10YR7/4	Histosol	mudflat	HST	3						
9	Semberah-11	PS-18	3	10YR6/4	Histosol	Fluv. Channel	TST	3						
		PS-19	4	5YR5/8	Histosol	Fluv. Channel	IVF	4						
10	Semberah-46	PS-20	4	10YR6/4	Argillisol	Mouth Bar	HST	2						
		PS-21	4	10YR6/6	Spodosol	mudflat	HST	3						
		PS-22	5	7.5YR7/6	Argillisol	mudflat	HST	4						
		PS-23	3	5YR6/3 - 10YR7/4	Spodosol	Tidal Flat	HST	3						
		PS-24	4	10YR7/3	Argillisol	Dist. Channel	HST	5						
		PS-25	4	5YR5/3	Spodosol	Dist. Channel	HST	4						
11	Semberah-22	PS-26	2	5YR4/3	Spodosol	mudflat	HST	3						
		PS-27	3	10YR6/2	Spodosol	mudflat	HST	2						
		PS-28	5	5YR5/2	Spodosol	mudflat	HST	2						
		PS-29	3	10YR6/4	Spodosol	mudflat	TST	3						
12	Semberah-38	PS-30	4	10YR6/2	Histosol	Tidal Flat	HST	2						
		PS-31	3	10YR6/2	Oxisol	Tidal Bar	HST	4						
		PS-32	4	10YR6/1	Oxisol	Tidal Bar	HST	4						
		PS-33	4	10YR7/6	Oxisol	Tidal Bar	HST	4						
13	Semberah-40	PS-34	3	10YR6/4	Spodosol	mudflat	HST	2						
		PS-35	5	5YR5/3 - 10YR6/6	Spodosol	mudflat	HST	2						
14	Semberah-28	PS-36	4	10YR7/4	Spodosol	Mouth Bar	TST	3						
		PS-37	4	10YR6/3	Spodosol	Mouth Bar	TST	3						
15	Semberah-54	PS-38	4	10YR6/6	Protosol	Tidal Flat	HST	2						
		PS-39	3	10YR6/2	Protosol	Tidal Channel	HST	2						
16	Semberah-59	PS-40	5	10YR7/4	Argillisol	Tidal Flat	IVF	5						
17	Semberah-44	PS-41	4	10YR4/3	Argillisol	Crev. Splay	HST	4						
18	Gate 9A	PS-42	3	10YR7/4	Histosol	Dist. Channel	HST	3						
		PS-43	4	10YR7/4	Spodosol	Tidal Channel	HST	3						
19	Gate 9B	PS-44	4	10YR7/4	Spodosol	Tidal Channel	HST	2						
		PS-45	3	10YR6/2	Spodosol	Tidal Channel	HST	3						
20	S#13 to S#33	PS-46	4	5YR7/4	Histosol	Tidal Channel	TST	3						
21	Semberah-37	PS-47	5	10YR5/3	Vertisol	mudflat	HST	3						
		PS-48	3	10YR6/3	Spodosol	mudflat	HST	3						
22	Semberah-33	PS-49	4/5?	7.5YR7/6	Spodosol	Tidal Bar	TST	3						
		PS-50	2	10YR4/2	Spodosol	Tidal Bar	TST	3						
23	Semberah-50	PS-51	4	5YR5/2	Vertisol	Crev. Splay	HST	4						
24	Semberah-6													

characterised by the occurrence of ***Hydromorphic Paleosol***.

d. During the Transgressive System Tract (TST), paleosols are ***not well-developed*** or even ***obstructed*** with percentage of their occurrence within the area as 21.5% and the maturity varies from stage 2 to stage 3

6. In oil and gas industries, paleosols are very useful to support the sequence stratigraphic interpretation, especially within the areas that are dominated by fluvial depositional environment that have many reservoir compartment.

7. Paleosols can be used to define the Sequence Boundary and also can avoid miss-leading interpretation based on their maturity.

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