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THE INFLUENCE OF SEDIMENTATION ON SALINITY VARIATION IN THE EAST KUTAI BASIN, EAST KALIMANTAN, INDONESIA

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ABSTRACT

The East Kutai Basin represents a major deltaic system formed under strong river-dominated sedimentary processes, characterized by long-term progradation from marine to terrestrial environments. In such deltaic settings, salinity distributions are generally expected to exhibit systematic lateral and vertical trends, with freshwater dominating proximal facies and saline water occurring in distal marine facies. Vertically, salinity typically increases with depth as a result of progressive progradation through time. This study investigates lateral and vertical salinity variations within the East Kutai Basin and evaluates their relationship with sedimentary facies distribution. Salinity data were obtained from formation water analyses and apparent water resistivity (Rwa) calculations derived from resistivity logs using Archie's equation. These datasets were integrated with net sand maps and electrofacies interpretations to examine salinity patterns across multiple stratigraphic intervals. The results show that while the general lateral trend of low salinity in channel facies transitioning to higher salinity in mouth-bar facies is preserved, significant anomalies are observed. Laterally, mouth-bar deposits locally exhibit unexpectedly low salinity values, approaching those of channel facies. Vertically, salinity decreases with increasing depth in several stratigraphic groups, contrary to the expected progradational model. These anomalies are interpreted to reflect lateral shifting of depositional environments during delta progradation and the expulsion of low-salinity compaction water from overpressured prodelta shales into adjacent sand bodies.

Keywords: East Kutai Basin; deltaic system; salinity anomaly; sedimentation; water resistivity

INTRODUCTION

Salinity distribution in sedimentary basins is closely linked to depositional environments, sedimentary processes, and post-depositional fluid migration. In deltaic systems, lateral salinity variation commonly reflects facies distribution, with freshwater typically associated with proximal fluvial or channel deposits and saline water associated with distal marine deposits such as mouth bars. Vertically, salinity is generally expected to increase with depth in progradational deltaic settings as older, more marine-influenced sediments are buried beneath younger terrestrial deposits. These concepts have been widely applied in deltaic basin analysis and reservoir characterization.

The East Kutai Basin is a major Tertiary sedimentary province located in Kalimantan, Indonesia, which initiated during the Middle to Early Eocene (Moss & Chambers, 1999; Permana, 2018). Structurally, the basin is bounded by the Mangkalihat High to the north, the Paternoster Ridge to the south, the Kuching High to the west, and the Makasar Straits to the east. Characterized as the deepest Tertiary basin in Indonesia, the East Kutai Basin accumulated significant sediment thickness of approximately 13,700 meters (Adli et al., 2021).

The basin represents a large river-dominated deltaic system that developed through repeated progradation cycles. Previous studies have described its depositional architecture, reservoir characteristics, and stratigraphic framework, yet detailed evaluation of salinity distribution and its deviation from conventional models remains limited. Observations from well logs and formation water analyses indicate that salinity patterns in the East Kutai Basin do not always conform to expected lateral and vertical trends.

Several anomalies have been identified, including low-salinity water occurring within mouth bar facies and decreasing salinity with increasing depth in certain stratigraphic intervals. Understanding the origin of these salinity anomalies is important for reconstructing basin evolution and for improving reservoir characterization in deltaic systems.

The objective of this study is to analyze lateral and vertical salinity variations in the East Kutai Basin and to interpret their relationship with sedimentary facies and depositional processes. By integrating salinity data derived from logs and fluid analyses with facies interpretation and net sand mapping, this study aims to identify the geological mechanisms responsible for salinity anomalies in the basin.

A. Research Area Setting

East Kutai Basin is a giant field that contains gas and condensate located on the Eastern boundary of the Mahakam Delta. This field is located in North-South direction, with a length of 75 km and 15 km wide, covers a surface of approximately 1000 km^2 along the median axis in the Mahakam Delta. East Kutai Basin located between the anticline axis trending NNE - SSW, and included in the median axis (Nugrahanto et al., 2023). This basin is also located broadly in the Eastern part of the Mahakam Delta and the direction of the axis syncline within 15 km towards the Western part of the basin. East Kutai basin geological structure consists of two main parts, as follows:

a. Northern part of East Kutai Basin is an anticline structure which extends along 30 km, separated from southern part of East Kutai Basin and adjacent to the fault structure on the northern part of the Mahakam Delta.
b. Southern part of East Kutai Basin is more flat anticlinal structure with a length of 40 km and 7km width.

East Kutai Basin stratigraphy is divided into several zones:

a. Shallow zone: the zone from the surface to the base of Pliocene rocks.
b. Freshwater zones: the zone which lies between the upper Miocene sediment and unconformity surface at 7 Mya.
c. Main zone:
   Upper: between the flooding surface in 7.3 Mya until 9.5 Mya.
   Lower: between the flooding surface in 9.5 Mya until the unconformity surface at 10.5 Mya.

The main zone of East Kutai Basin can be found at a depth between 2,200 m to 5,000 m. The main zone is vertically divided into six stratigraphic units, with each thickness ranged from 300 m until 400 m. Each unit is divided into several sequences within 30-50 m of thickness which limited by flooding surfaces.

B. Depositional Environment and Reservoir Type in East Kutai Basin

Vertically, the whole of East Kutai Basin has progradation model, but on a smaller scale, the cycle pattern of sand retrogradation-progradation cycle are changing as the response of equilibrium between the eustatic variations (changes in sea level relative), the comparison of subsidence (decrease), and also sediment supplies (Permana, 2022). Laterally, most areas of western part in East Kutai Basin are represented by upper delta plain reservoir to delta front proximal part (the part near the delta plain) in the form of channel and mouth bar accumulations. On the east side, delta front sediment in distal part is more dominating. Mouth bar sediment in distal part is dwindling and isolated. Types of reservoirs at East Kutai Basin consist of:

a. Channel

Reservoir in the form channel is sand stone with grain size ranged from coarse sand to fine sand, medium rounded grain shape, well sorted, compact, good porosity (Walker, 1992; Serra, 1990). Coal is found in some areas and in little calcium carbonate is present in the upper part. Channel sediment has an average thickness of 7-20 meters. Cross-section channel sediment can have a thickness ranging up to 30 meters, and have been found at this East Kutai Basin. Channel sediment characterized by fining upward on gamma ray log. Average porosity of the channel sediment which has the thickest and the lowest shale is approximately 15%-27% with average permeability of 100 mD–maximum 1D (Sangree at all., 1993). The geometry model of channel reservoir currently resembles to lateral bar, which in the modern East Kutai Basin has length1-3 Km and width of 300-700 m.

b. Mouth Bar

Mouth bar is large sand stone composed of fine-very fine grain size with medium rounded grain shape, well-sorted, compact, and medium porosity (Walker, 1992). A reservoir in the form of mouth bar has thickness ranged between1 m to5m and average thickness of 3 meters. The maximum sediment accumulation in the mouth sediment can reach until 15meters of the thickness. This sediment facies usually has coarsening upward characteristics in gamma ray log. The thickest and the lowest shale-contain in mouth bar sediment is approximately 13%-18% with an average permeability of 10 mD to 200 mD maximum (Harsono, 1997).

C. Salinity and Facies in East Kutai Basin

In general, the content of salinity in East Kutai Basin varies from west (toward land) to east (toward sea) with the change in lateral facies types. Based on data from the current salinity, lateral variations show that salinity has a basic pattern change that associated to the type of facies. The area containing fresh water in proximal and the area containing saline water in distal. Channel facies generally has low salinity content and gradually increased to the marine environment which is characterized by mouth bar facies.

Based on geological overview, salinity content in East Kutai Basin should increase with depth as the progradation process that happens along the time. In reality, these conditions are not found as the discussion above. Based on the data that has been calculated (salinity from both log and fluid analysis) found the anomalies of salinity data. Lateral variations indicate anomalies such as mouth bar facies which have low salinity content approaching salinity content contained in the channel facies, as well as vertical variations indicate anomalies that show a decrease in the salinity content with increasing depth. These variations arise as a result of several possible factors from facies position and geological phenomenon that have occurred to date.

RESEARCH METHOD

The object of this study is the salinity anomalies in the existed facies types, primarily in mouth bar facies and channel facies. Three data used in this study: salinity data, net sand maps, and completion of log data.

Salinity data found from log fluid analysis. This data serves as quantitative data and basic data which must then be connected in geology, especially towards the interpretation of depositional environments. Calculation salinity of log known as Rwa Method or apparent Rw. Salinity content can be searched by calculating Rwa (water resistivity) from Log Resistivity by using Archie formula (Maurice, 1982). Calculations based on resistivity logs can be done if it meets the following requirements:

a. Reservoir thickness > 2 meters.

b. Layer with a low clay content of volume (low Vsh)

c. Water bearing sand, Sw = 1 (it is believed that the reservoir is fully of water)

Net sand maps are used from selected layers in accordance with the adequacy of salinity data on each layer. Net sand maps are utilized as illustrations of facies, thickness, and overview of research areas for the spread of salinity content in each layer. Completion log data is a standard final display combined log that has been analyzed and used for geological purposes. In the study, the data used to determine the completion log facies types according to their characteristics and is also used as a log correlation of adjacent wells to determine the circumstances surrounding the well. 19 maps were chosen from East Kutai Basin. More than 700 salinity data from the calculation of resistivity logs used in this study.

RESULT

Based on the calculation of salinity data from log and fluid analysis, the range of salinity at each layer is presented in Figure 1. In this study, layer means there presenting delta cycle vertically based on the character electro facies. The layers are divided into three groups:

Group I consist of layers 1A, 1B, and 1C, Group II consists of layers1G and 3A, and Group III composed of layers of 4A up to 5C. The groups are divided based on the difference obtained from the analysis and geological interpretation.

No.	Layer	Salinity (kppm)
1	**1A**	2.48 – 20.91
2	**1B**	2.9 – 21.76
3	**1C**	2.82 – 19.98
4	**1G**	3.72 – 24.46
5	**3A**	5.34 – 18.87
6	**4A**	3.81 – 18.3
7	**4B**	2.74 – 18.25
8	**4C**	4.44 – 16.52
9	**4D**	4.79 – 17.15
10	**4E**	5.77 – 15.64
11	**4F**	4.47 – 16.66
12	**4G-1**	5.02 – 13.57
13	**4H**	5.93 – 13.88
14	**4H-1**	6.62 – 14.45
15	**4I**	3.76 – 13.58
16	**4J**	4.21 – 13.57
17	**5A**	4.91 – 11.04
18	**5A-1**	4.36 – 12.15
19	**5C**	3.62 – 10.36

Figure 1. Distribution of salinity values across stratigraphic layers in the East Kutai Basin based on log- and fluid-derived data.

A. Relation Between Facies and Salinity in Group I

This group is an ideal example of the variation in salinity and associated with the depositional setting from land to sea, also of geological events that affect the variation of the salinity content.

The spread of salinity content in the northern part of East Kutai Basin in this group generally has low salinity content compared to the south. The northern part is dominated by fresh water while the southern part has noticeable variations, even seen the high content of salinity in particular points.

The result of analysis through geological approach identifies that the sediment influx from fluvial is more dominant in influencing the northern area than in the southern area.

This is supported by nets and map layer 1A that represents this group (Figure 2), which shows the volume of accumulated sediment greater in the northern area than in the southern area. This group was likely a result of Nillam Lineament formation showing increased accommodation space for sediment deposition. Thus, it can be seen that the influence of fluvial sediment looks very dominant in the northern area even though the area is in the most distal position.

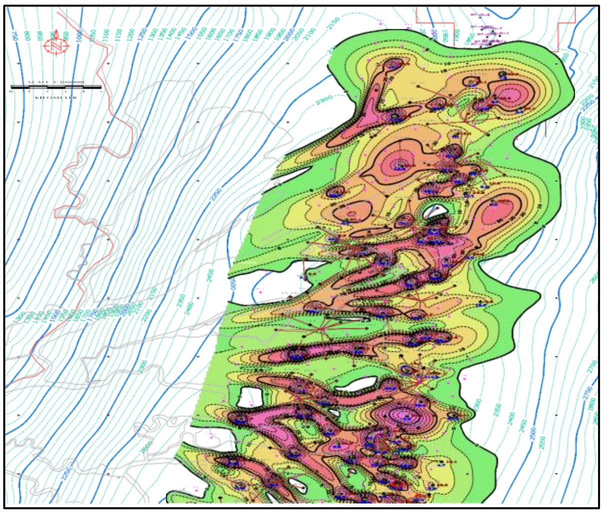

Figure 2. Net sand thickness map of Layer 1A showing sediment distribution and dominant depositional areas in the northern part of the East Kutai Basin.

In this group, anomalies appear as channel sediment that has high salinity content. This is opposite with the mouth bar sediment that has low salinity content. The channel sediment appears with the salinity content that varies depending on the position. The emergence of the channel sediment that has high salinity content is influenced by its own position in distal area, which effected by the sea (Figure 3.b and Figure 4.a).

The mouth bar sediment with low salinity content appears as the result of channel present influence on landward which then lowers the salinity content of the mouth bar sediment (Figure 3.a) and Figure 4.b). The influence of the river along with progradation causes the mouth bar sediment which previously formed in distal turns in median or proximal (landward).

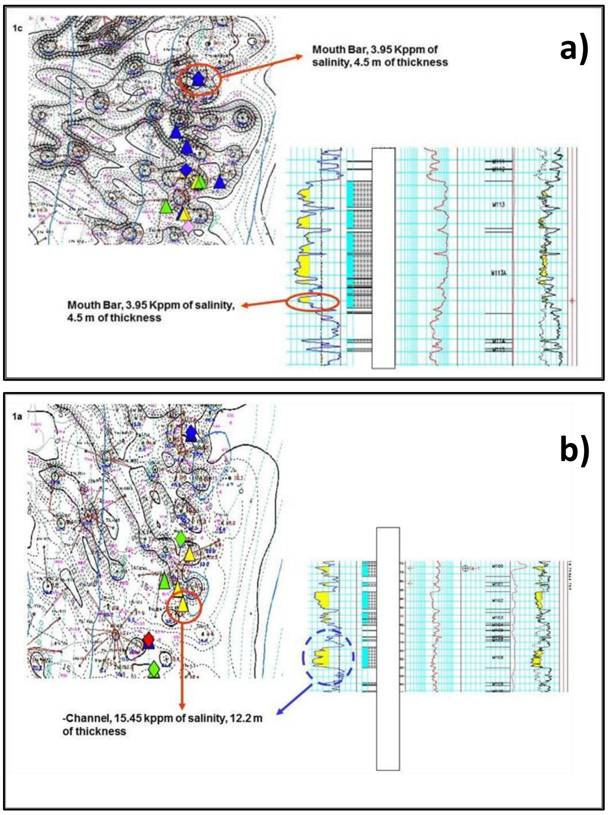

Figure 3. Example of mouth bar facies exhibiting a) low salinity and b) high salinity values in Group I stratigraphic interval.

B. Relation Between Facies and Salinity in Group II

In Group II, the spread of salinity content is varied. The 1G layer starts to change its salinity content spread pattern, whereas in layer 3A the salinity content looks more varied throughout the area. At this layer 1G, variations of salinity content in the northern part began to appear, but still more "fresh" compared to the south. Area with fresh water that looks a little more dominant still appears in the middle region with the distribution of low salinity content in distal position of this layer. This means that the influence of sediment from land or river is still dominant in this middle section. The thickness for the northern region is still thicker than the southern region in this 1G layer.

Channel sediment and mouth bar sediment relatively appear with high salinity content by way of average ranging between 11-16 kppm seen on layer 3A.

The spread of salinity relatively has uniform content in a linear line. Channel sediment and mouth bar sediment have adjacent range of salinity content, this happens because the deposition position is contiguous but both still have visible pattern of increase in salinity towards the sea (eastern part). In layer 3A is not found any striking anomaly. The spread of salinity

content and their relation to the facies type are still included as normal, which refers to the depositional environments.
The channel sediment with high salinity content appears as an anomaly. This is because the sediment is located on the distal position that is supported by depositional environment (Figure 5 and Figure 6).

Previous channel depositional environment dominated by the influence of fluvial then turned into environment dominated by the sea with the invisibility of shale sediment domination. The depositional environment change causes the increase of salinity value content on the channel sediment.

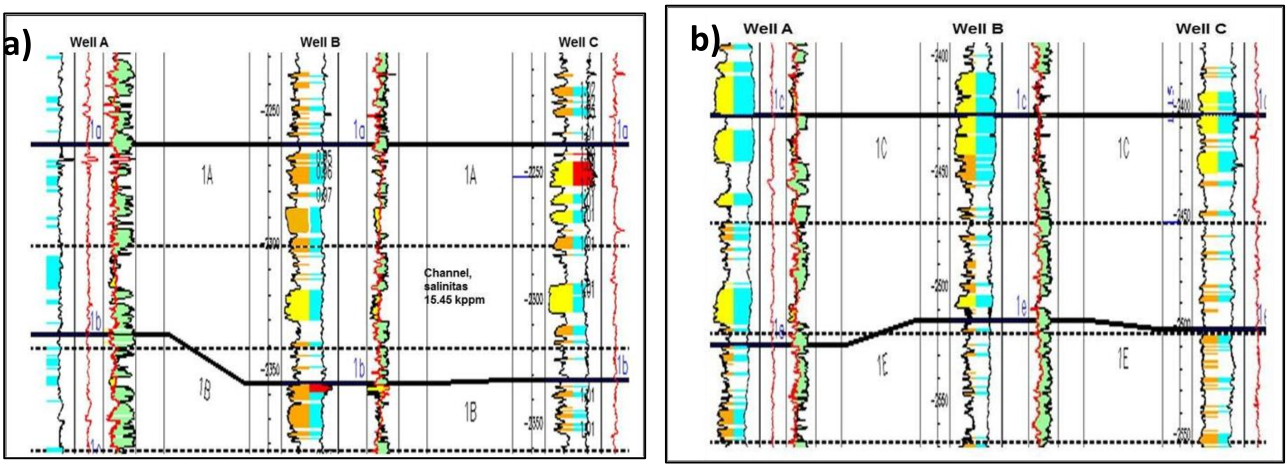

Figure 4. Well correlation illustrating a)channel facies distribution and salinity and b) mouthbar facies and salinity variation in Group I

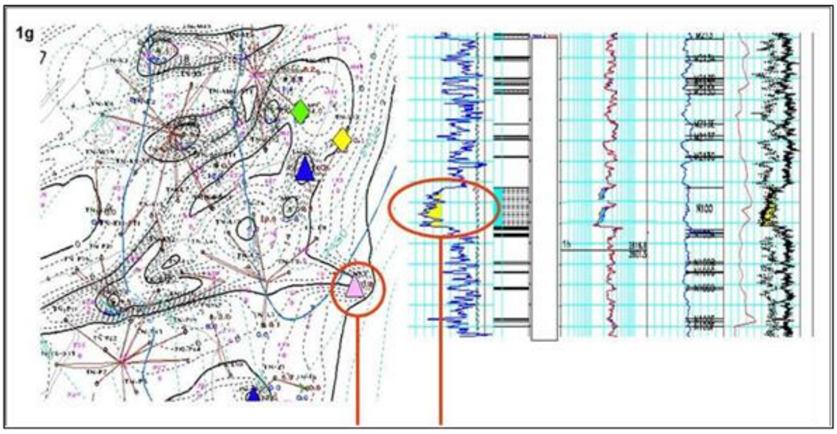

Figure 5. Example of mouth bar facies exhibiting high salinity values in Group II stratigraphic interval.

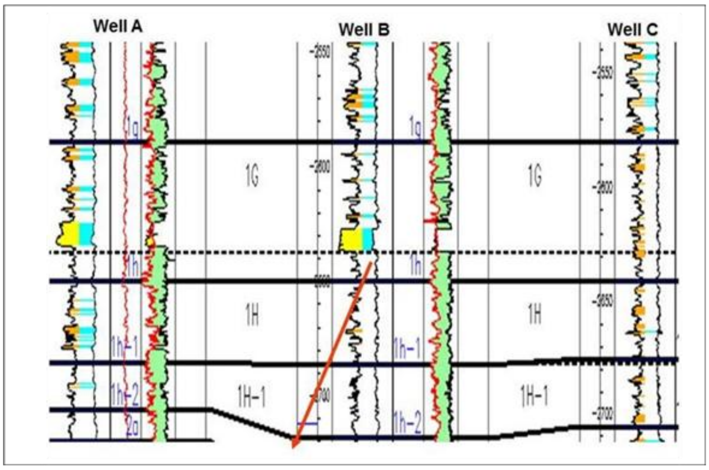

Figure 6. Well correlation illustrating channel facies and associated salinity variation in Group II.

C. Relation Between Facies and Salinity in Group III

In this group, the decreasing of salinity content along the increasing of depth is more visible. The decreasing of salinity content is contrary to the geological illustration of East Kutai Basin that indicates a pattern progradation from time to time which also shows the changing from marine to terrestrial environment.

Anomalies increasingly visible with the advent of channel sediment with high salinity and mouth bars sediment that has low salinity, both in proximal or distal position.

The channel sediment with high salinity value appears as described previously that this is caused by the deposition is in the distal position (adjacent to the mouth bar sediment), then the previous channel depositional environment dominated by the influence of the river turned into an ocean is most likely caused by a relative sea level rise (Figure 7 and Figure 8). This was shown by the change in sandstone sediment as channel facies becomes dominated by claystone. The depositional environment of channel that previously in lower delta plain, turn laterally into delta front depositional environment by the appearance of mouth bar and the claystone accumulation. The anomaly in the form of mouth bar sediment which has low salinity content is also more visible, both in proximal and distal of this East Kutai Basin.

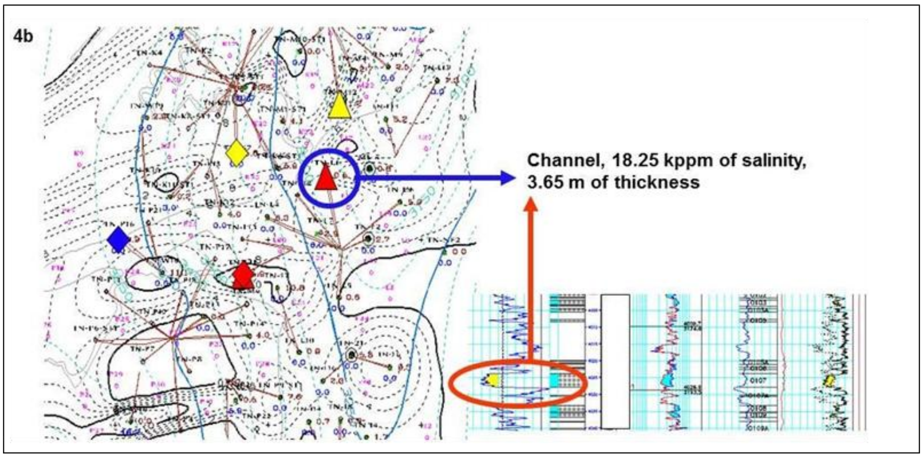

Figure 7. Example of channel facies with elevated salinity values in Group III stratigraphic interval.

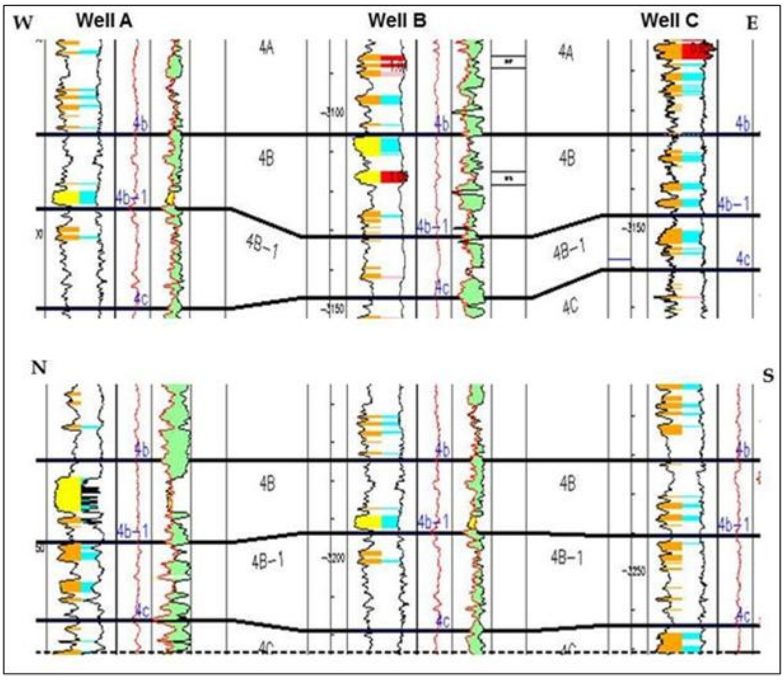

Figure 8. Well correlation panel illustrating channel facies with high salinity values in Group III.

Based on the geological interpretation, the anomalies emergence in the form of mouth bar sediment that has lower salinity content is caused by two main factors. The first factor is caused by channel influx dominated by the fluvial process in connection with progradation at East Kutai Basin (Figure 9 and Figure 10). This mouth bar formation causes the forming of branched river and created the new channel and mouth bar sediment toward the sea along with progradation. This process occurs continuously, which can be seen in the modern East Kutai Basin deposition today. The sediment of mouth bar that previously located in the distal position and has a high salinity content then changed into proximal or median sediment of East Kutai Basin today.

The second factor is the influence of very high pressure that drives the discharge of water with low salinity content derived from prodelta shale otherwise known as expelled compaction water prodelta from shale. This phenomenon occurs mechanically and also chemically. The mechanical process that led to the expelling of water from prodelta shale is caused by the high pressure as the result of the progradation. The water that comes out must pass through the sand grain which is very fine (silt or sandy shale are not included in the criteria as a reservoir because it has a porosity of less than 5%), which acts as a semipermeable membrane that can filter water. Semipermeable membrane has the ability to trap the salt crystals and release the freshwater solution along with the presence of high pressure, then the water intruding the closest channel sediment or mouth bar sediment to the prodelta shale. The passed fresh water make the levels of salinity lowered in mouth bar sediment positioned at the distal.

Chemically, prodelta shale has water content with higher composition of salt than on mouth bar sediment. NaCl solution is then broken into molecules with different diameters, which is due to the very high pressure. Water molecule (H2O) has a smaller diameter than the Sodium metal (Na+). Therefore, the water molecule which has been separated from the salt crystals will be pushed out through the layer and intruded the nearest sand sediment. Ultimately, it reduces the content of salinity on such deposits.

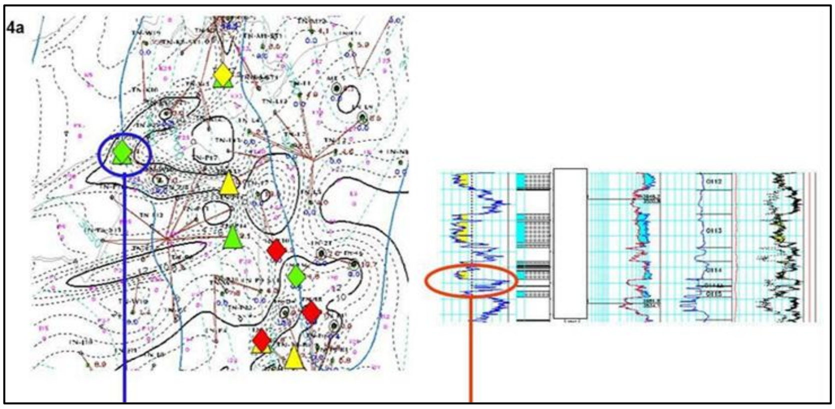

Figure 9. Example of mouth bar facies exhibiting low salinity values in Group III stratigraphic interval

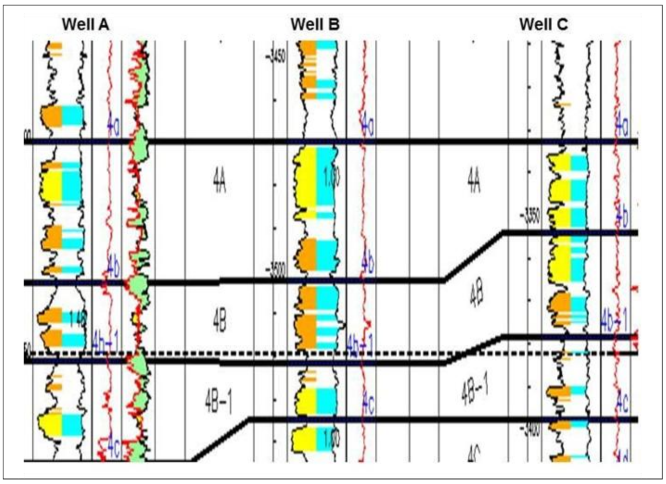

Figure 10. Well correlation illustrating mouth bar facies and associated salinity anomalies in Group III.

DISCUSSION

The observed salinity patterns in the East Kutai Basin reflect the combined influence of depositional processes and post-depositional fluid migration (Figs. 7–10). In Group I, the dominance of low-salinity water in the northern area is interpreted as the result of strong fluvial sediment influx, which supplied freshwater-dominated deposits even in relatively distal positions. The presence of high-salinity channel facies in some areas represents an anomaly caused by channel deposition occurring in positions influenced by marine conditions.

In Group II, salinity distribution is relatively uniform, indicating transitional depositional environments where fluvial and marine influences were balanced. The limited occurrence of anomalies suggests stable depositional conditions during this phase of basin evolution.

Group III exhibits the most pronounced salinity anomalies, with decreasing salinity observed with increasing depth (Figure 9–12). This pattern contradicts the expected progradational salinity model and is interpreted to result from the expulsion of low-salinity compaction water from overpressured prodelta shale. High pressure generated during progradation forced freshwater to migrate into adjacent sand bodies, reducing salinity in both channel and mouth bar facies. In addition, lateral migration of depositional environments due to continuous progradation caused formerly distal mouth bar deposits to become influenced by fluvial processes, further contributing to low-salinity anomalies.

The change of salinity has a basic pattern laterally from terrestrial (with lower salinity content) to marine (with higher salinity content), and this pattern can still be found in the research area. The effect of sedimentation is more dominant in the northern area of East Kutai Basin than in southern area of Group I. The salinity content decreases with the increasing of depth and is particularly evident in Group III as a result of the dominant influence of expelled compaction water from prodelta shale. The factors that cause the salinity anomalies in facies are as follows:

a. Channel sediment containing high salinity caused by its position in distal area of East Kutai Basin, which is dominated by the influence of the sea. Depositional environment of channel is also changed laterally from lower delta plain into delta front.
b. Mouth bar sediment that has low salinity content is a result of influx channel influence that is dominated by fluvial influence in connection with the process of progradation of East Kutai Basin, as well as the influence of expelled compaction water from prodelta shale.

CONCLUSION

Salinity distribution in the East Kutai Basin generally follows a lateral trend from low salinity in proximal fluvial deposits to higher salinity in distal marine deposits. However, significant lateral and vertical anomalies are present. Vertically, salinity decreases with depth in deeper stratigraphic groups, contrary to the expected progradational model. These anomalies are primarily caused by lateral shifts in depositional environments associated with progradation and by the expulsion of low-salinity compaction water from prodelta shale into adjacent reservoir sands. The results emphasize the importance of integrating sedimentological and hydrodynamic processes when interpreting salinity patterns in deltaic reservoirs.

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