Problem Solving of Hole Enlargement in Shale Formation Using XRD and CEC Analysis Approach: A Case Study of Well HES-003 in the North West Java Region, Indonesia

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Abstract

Hole enlargement in shale formations poses significant challenges in the drilling industry, particularly in maintaining wellbore stability and preventing operational delays. This study focuses on addressing these challenges through the application of X-ray diffraction (XRD) and Cation Exchange Capacity (CEC) analysis in well HES-003, located in the North West Java region of Indonesia. By employing XRD and CEC analysis, we aim to identify the mineralogical composition of the shale and understand its impact on hole enlargement. The study reveals that certain clay minerals within the shale are prone to swelling and dispersion when exposed to drilling fluids, leading to hole instability. By correlating mineralogical data with drilling performance, we develop a targeted approach to mitigate hole enlargement. The findings underscore the importance of tailoring drilling fluid compositions to the specific mineralogy of the formation, ultimately enhancing wellbore stability and reducing non-productive time. This case study demonstrates the effectiveness of XRD and CEC analysis in diagnosing and solving drilling problems in shale formations, providing a valuable reference for future drilling operations in similar geological settings.

Keywords: XRD, CEC, borehole instabililty, hole enlargement, shale, kaolinite

1. Introduction

Shale formations pose significant challenges in drilling operations due to their tendency to swell and enlarge the wellbore hole. This phenomenon, known as hole enlargement, can lead to severe operational issues, including increased costs, non-productive time, and potential wellbore instability. Understanding the mechanisms behind hole enlargement in shale formations is critical for developing effective mitigation strategies.

This study focuses on well HES-003, located in the North West Java region of Indonesia, where hole enlargement has been a recurrent issue. To address this, we employ X-ray Diffraction (XRD) and Cation Exchange Capacity (CEC) analysis, a powerful tool for characterizing the mineralogical composition of shale. By identifying the specific minerals and their interactions with drilling fluids, we aim to uncover the root causes of hole enlargement in this well.

XRD and CEC analysis approach provides detailed insights into the mineralogical properties of the shale, such as clay content and the presence of swelling clays like smectite. These properties are crucial for understanding how the shale reacts under different drilling conditions. This case study not only sheds light on the specific challenges encountered in well HES-003 but also contributes to the broader knowledge base of shale behavior in the North West Java region.

In this paper, we present the findings from XRD and CEC analysis, discuss the implications for drilling operations, and propose recommendations for minimizing hole enlargement. By leveraging the mineralogical data obtained through XRD and CEC analysis, we aim to enhance the efficiency and safety of drilling operations in shale formations.

2. Study Area

The well HES-003 is located in the North West Java Basin of Indonesia, where the well HES-001 is a development well targeting the Jatibarang Formation as the oil reservoir (**Figure 1**). This well was drilled on August 25 2019, reaching a final depth of 3812 mD on October 10 2019. The following formations were penetrated in the drilling of the well HES-003 based on mudlog data from youngest to oldest, as follows:

- Cisubuh Formation (0 – 820 mD). The Cisubuh Formation with lithology is dominated by claystone at the top (0 – 530 mD), and shale at the bottom (530 – 825 mD).
- Cibulakan Formation (820 - 1610 mD). The Cibulakan Formation with lithology is dominated by shale in the upper part (820 - 1125 mD), in the middle part (1125 - 1275 mD) it is dominated by siltstone, and in the lower part (1275 - 1610 mD) it is dominated by siltstone with sandstone and carbonate inserts.
- Parigi Formation (1610 - 2081 mD). The Parigi Formation with lithology is dominated by limestone.
- Talang Akar Formation (2081 - 2475 mD). The Talang Akar Formation with lithology is dominated by shale with sandstone and carbonate inserts.
- Jatibarang Formation (2475 – 3812 mD). The Jatibarang Formation has lithology dominated by tuff and conglomerate.

The lithology penetrated by drilling the well HES-003 is dominated by shale, with several formations containing sandstone and carbonate rock.

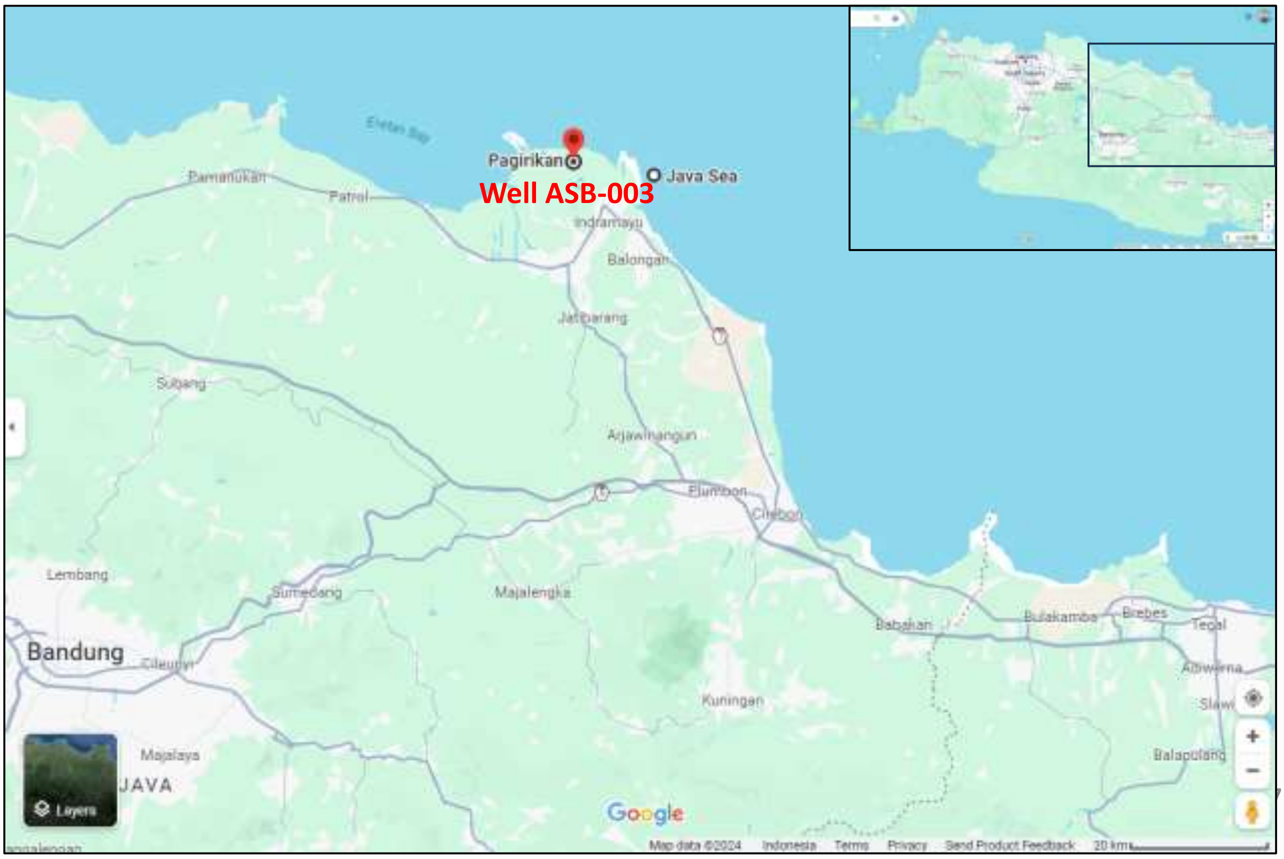

Figure 1. Location of well HES-003 (Modified from Google Map)

3. Literature Review

Hole enlargement in shale formations poses significant challenges in drilling operations, leading to increased non-productive time, higher costs, and potential wellbore instability. In the context of well HES-003 in the North West Java region of Indonesia, applying X-ray Diffraction (XRD) Cation Exchange Capacity (CEC) analysis provides a valuable approach to understanding and mitigating these issues. This literature review explores the use of XRD and CEC analysis to address hole enlargement in shale formations, focusing on identifying causative factors, evaluating mitigation strategies, and applying findings to improve drilling outcomes.

Shale instability is a well-documented problem in drilling, primarily due to the swelling and weakening of shale when exposed to drilling fluids (Wilson et al 1999). Factors contributing to shale instability include the mineralogical composition, pore pressure, and the mechanical properties of the shale. Studies indicate that the presence of clay minerals, such as smectite, significantly impacts the swelling behavior and mechanical integrity of shale formations (Santarelli et al 1992; Van Oort 1997; Kwon 2004).

XRD analysis is a powerful tool in geological studies, offering insights into the mineralogical composition of rock samples. This technique is particularly useful in identifying the types and proportions of clay minerals present in shale, which are critical for understanding swelling behavior and mechanical properties (Moore & Reynold 1997). XRD analysis has been widely used to characterize shale formations and develop appropriate drilling fluid formulations to mitigate instability (O'Brien & Chenevert 1973).

X-Ray Diffraction (XRD) is used to determine the crystal structure and composition of minerals by determining the angle at which the X-Ray rays are diffracted. X-rays are electromagnetic waves with a wavelength between 0.5 – 2.5 Å. X-rays are produced by the collision of high-speed electrons with a metal

target. Therefore, an X-ray tube must have an electron source, a high voltage, and a metal target. Next, the colliding electrons experience a rapid reduction in speed and their energy is converted into photons.
The wavelength for X-Ray is in the range of 0.1 to 100 Å or 0.01 to 10 nm. Since the spacing of the atomic planes in crystalline materials is on the order of about 1 Å, this makes X-Ray a useful tool in analyzing crystal structure and mineral composition. However, the wavelength produced depends on the element used as the target. The target elements commonly used are Cu, Fe, Mo, and Cr. In general, the element commonly used is Cu.
X-rays are obtained from energy originating from a high electric voltage and then hit the target element, as shown in **Figure 2**. In the picture shown a mineral with a thickness d, the X-rays (n: 1, 2, 3) which come to the surface of the mineral form an angle ϴ.

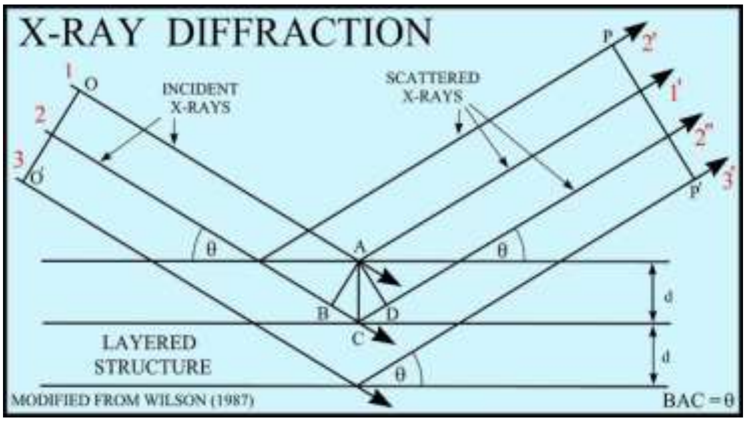

Figure 2. X-Ray Diffraction Working Scheme (Wilson 1987)

CEC (Cation Exchange Capacity) is used to determine the ability of clay to bind cations from a solution, namely by using methylene blue to measure the total cation exchange capacity of the clay, where the cation exchange depends on the type and crystallinity of the mineral, the pH of the solution, the type of cation exchanged, and the concentration of mineral content in clay. Cation exchange capability is based on the order of bond strength of ions as follows:

$$\mathbf{Li^+ < Na^+ < H^+ < K^+ < NH^{4+} < Mg^{3+} < Ca^{2+} < Al^{3+}}$$

The largest cation exchange value is owned by allogenic minerals (fragments of parent rock), while the smallest is owned by authogenic (chemical processes). The cation exchange capacity of several types of clay minerals is shown in **Table 1**.
According to O'Brien & Chenevert (1973) that shale problems can be classified according to the characteristics and clay mineral content, which are shown in **Table 2**.

Table 1. Typical CEC values for various Clay and Sand (Babajide 2016)

CLAY MINERAL	CEC RANGE OF VALUES
Smectite	80 to 120 meq/100g
Illite	10 to 40 meq/100g
Kaolinite	3 to 15 meq/100g
Chlorite	10 to 40 meq/100g
Sand	< 0.5 meq/100g

Table 2. Classification of Problem Shale (O'Brien & Chenevert 1973)

Class	Characteristics	Clay minerals
1	Soft, highly dispersive (Gumbo). Mud making	High smectite, some illite
2	Soft, fairly dispersive. Mud making	High illite, fairly high smectite
3	Medium hard, moderately dispersive, sloughing	High in mixed-layer, illite, chlorite
4	Hard, little dispersion, sloughing	Moderate illite, moderate chlorite
5	Very hard, brittle, no dispersion, caving	High illite, moderate chlorite

Mondshine (1966) in his paper presented the classification of clay from the results of X-ray defraction (XRD) and CEC analysis, both non-reactive shale and reactive clay (**Table 3**). CEC values are expressed in pounds per barrel of bentonite-equivalent clay/100 lb shale. Meanwhile, O'Brien & Chenevert (1973) also made another version of the classification, based on the shale problems that may occurred (**Table 2**).

Table 3. General Classification of Clay Based on XRD and CEC Results (Mondshine 1966)

Shale Type	Typical hole problems	CEC* (meq/100g)	Water Content (Wt%)	Clay Types
Soft	Tight hole due to swelling Hole enalargement due to washout (dispersion) Ledges if interbeded with sandstone Bit balling, mud rings, blocked flowlines	20 - 40	25 - 70	smectite illite
Firm	Tigh hole due to swelling Possible wash out (poorly inhibited mud) Particularly prone to bit balling Occasional cavings	10 - 20	15 - 25	illite mixed layer
Hard	Cavings Cuttings beds leading to packing off Tight hole stressed formations	3 - 10	5 - 15	illite possibly smectite
Brittle	Cavings Hole Collapse Time delayed failure	0 - 3	2 - 5	illite kaolinite chlorite

4. Results and Disccussion

4.1. Data Collecting

The data used in the study include drill cuttings from the well HES-003 (depth 100 - 2444 mD) and mud log. Based on the correlation between mud log data and drill cuttings, all samples were subjected to XRD analysis. Representative drill cuttings from each formation penetrated by drilling the well HES-003, as follows:

- Drill cuttings (100–770 mD) represent the Cisubuh Formation,
- Drill cuttings (775 – 820 mD) represent the Parigi Formation,
- Drill cuttings (825 – 1584 mD) represent the Cibulakan Formation, and
- Drill cuttings (2100 – 2444 mD) represent the Talang Akar Formation.

Selection of drill cuttings from the well HES-003 for parallel clay-oriented analysis by considering the identified total clay mineral results, those with dominant total clay minerals were selected. Caliper Log data is also used in selecting drill cuttings as a basis for XRD-parallel clay-oriented analysis (**Figure 3**).

From **Figure 3**, drill cuttings were selected that represent the Cisubuh Formation taken at a depth of 100 to 770 mD, because they contain high total Clay minerals (above 30%) and the caliper log data also shows the presence of an overgauge hole marked in red. The same procedures and considerations were carried out in selecting parallel clay oriented XRD analysis for drill cuttings representing the Parigi and Cibulakan Formations.

4.2. Correlation of XRD and CEC Analysis Results with Hole Enlargement (Caliper Log Data)

The results of the XRD analysis with parallel clay oriented from selected drill cuttings representing the Cisubuh Formation, Parigi Formation, Cibulakan Formation, and correlated with the CEC are shown in **Figure 4**. Figure 4 shows the percentage of Kaolinite (13% avg), Illite (12% Avg), Smectite (5% avg), Interlayer Illite-Smectite regular (5% Avg), and Interlayer Illite-Smectite irregular (5% Avg) based on the total Clay minerals in each formation.

Figure 4 shows that the high percentage of Clay minerals in the Cisubuh Formation contains high Kaolinite. From the correlation trend of the clay mineral plot with the CEC, it can be seen that in general the CEC value from the top to bottom depth interval decreases, which indicates that with increasing depth the rock becomes increasingly brittle.

Figure 5 shows the correlation of the results of the XRD analysis with parallel clay oriented, CEC and caliper log of well HES-003, related to hole enlargement (caliper log data) in the depth interval starting from the Cisubuh Formation to the Cibulakan Formation.

The Kaolinite mineral has unique characteristics regarding changes in pH, where at $pH < 7$ flocculation will occur, and at $pH > 7$ it will disperse (Nurcholis 2007). This cannot be avoided because drilling mud additives work in the pH range of 8.5 - 10. Therefore, the presence of Kaolinite minerals in shale may have the effect of dispersing the surface of the hole walls from the time of the drilling operation until the time the drill string is removed and logging. This dispersion causes a reduction in the clay's function as a cement for other minerals (which in this case is quartz), so that it can trigger sloughing and cause borehole enlargement.

According to Ramirez et al. (2005) that shale which is dominated by Kaolinite is consistently exposed to KCl, it will cause a decrease in rock strength. From geochemical studies on the thermodynamic stability of the Kaolinite mineral contained in shale when it comes into contact with KCl, it shows that potassium ions disrupt the stability of kaolinite which has the implication that the shale becomes unstable and causes borehole enlargement.

The mud log data shows that in the depth interval 100 – 1584 mD a KCl-Polymer mud system with a pH of 10 was used. Meanwhile, the results of the XRD analysis show that the relatively high presence of Kaolinite minerals in the Cisubuh Formation and Upper Cibulakan Formation, namely at a depth interval of 595 – 1170 mD, will have an impact in the form of dispersion of Kaolinite minerals, because during drilling operations the environment is pH 10. This condition has the potential causes types of hole collapse and time delayed failure in drilling problems (Mondshine, 1966; Ramirez et al., 2005).

Thus, the use of the KCl mud system in the well HES-033 when drilling penetrates the Cisubuh Formation and the Upper Cibulakan Formation which has a significant dominant Kaolinite mineral content, causes the shale to become brittle (delayed failure time), and may cause wash out (Mondshine, 1966; Ramírez, 2005). Meanwhile, the use of mud with a $pH > 9$ (alkaline) when drilling through shale intervals with a fairly dominant Kaolinite mineral content, will cause the shale to disperse and become brittle (time-delayed failure), and may cause wash out/hole collapse (Nurcholis 2007).

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The results of the XRD and CEC analysis can be identified that the hole enlargement problem in the well HES-003 when penetrating the Cisubuh Formation and Upper Cibulakan Formation, which are dominated by shale with quite significant kaolinite content, is caused by the use of KCl-Polymer mud system and a pH of more than 9.

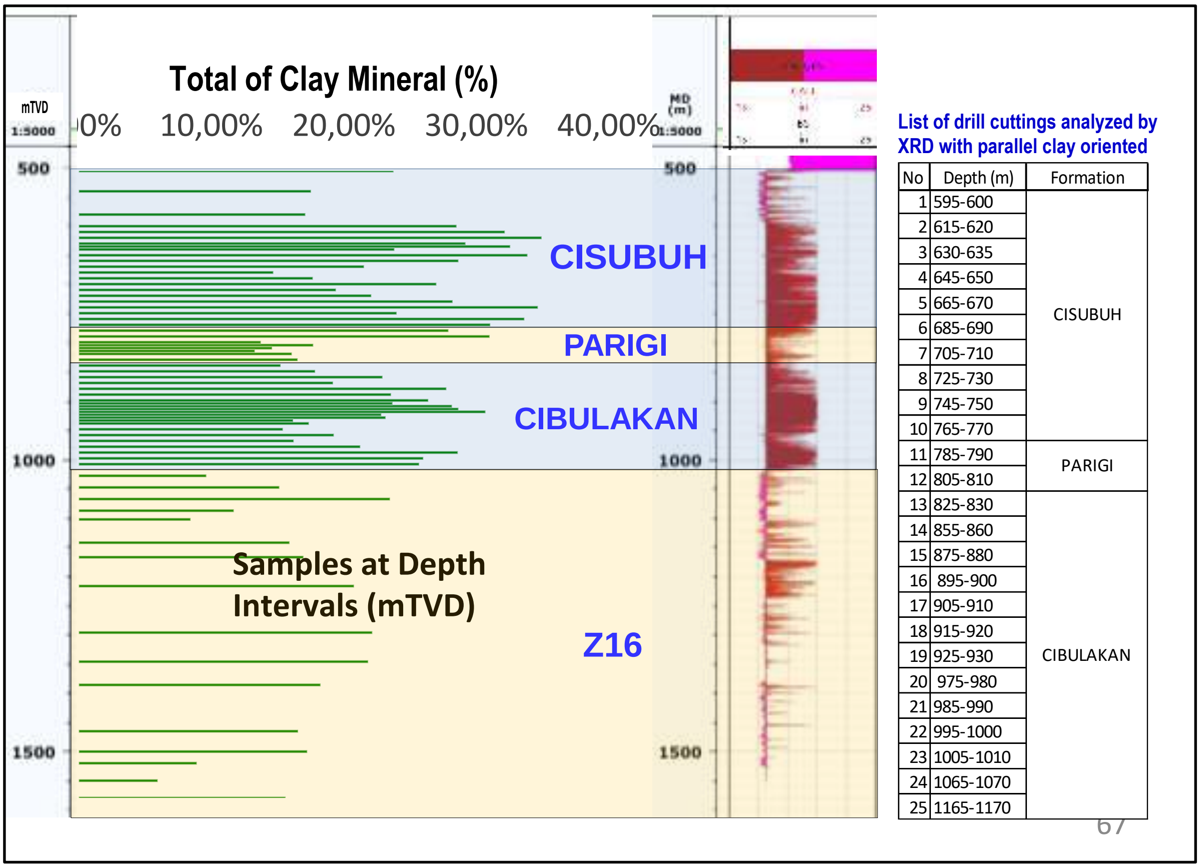

Figure 3. Selection of drill cuttings for parallel clay oriented XRD analysis

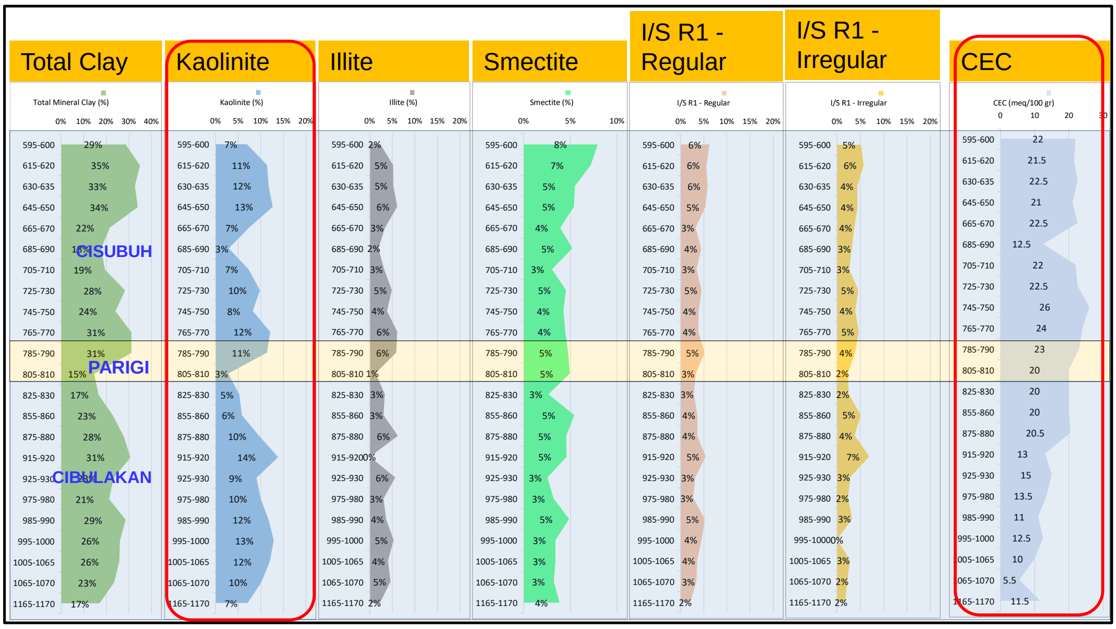

Figure 4. Correlation of Clay Mineral Percentage with CEC Results

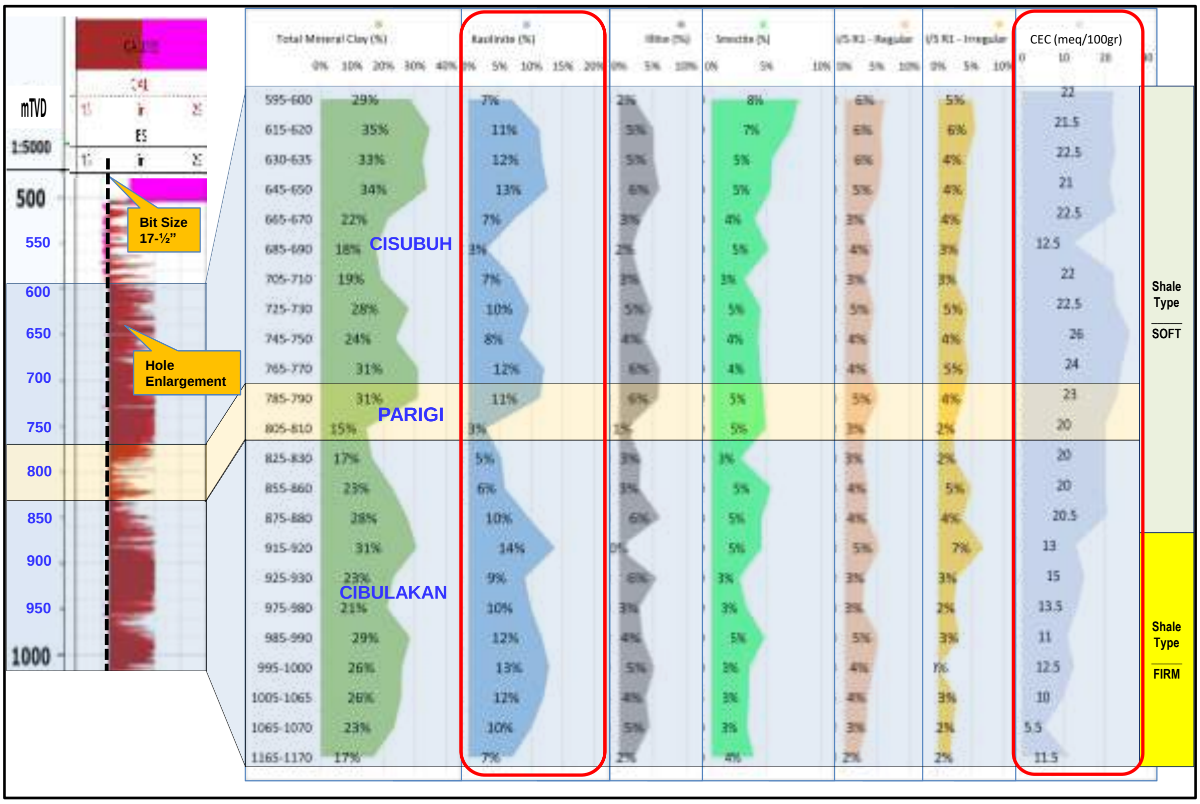

Figure 5. Correlation of Caliper Log with Total Percentage of Clay Minerals, and CEC from Well HES-003

4.3. Drilling Mud Planning Recommendations

Based on the results of the plot of clay mineral percentage vs depth interval and the correlation of XRD and CEC analysis results with hole enlargement (caliper log data), it can be recommended to plan drilling mud in general for each formation according to the formation character, especially those related to the issue of hole enlargement that occurs in the well HES-003, as follows:

- The relatively high presence of Kaolinite minerals in both Cisubuh and Upper Cibulakan Formations has an impact in the form of dispersion of Kaolinite minerals, because during drilling operations the pH environment is 10. This cannot be avoided because drilling mud additives work in the pH range of 8.5 - 10, so that it can trigger sloughing and cause borehole enlargement.
- To anticipate hole enlargement, it is not recommended to use KCl mud system, but replaced with a Polyamine mud system or other mud system, and also control the pH.

5. Conclusion

XRD and CEC analysis provides a robust framework for addressing hole enlargement in shale formations. By identifying the mineralogical composition of shale, drilling engineers can tailor fluid formulations to mitigate swelling and borehole instability, leading to more efficient and cost-effective drilling operations. The case study of well HES-003 in the North West Java region underscores the practical benefits of this approach, highlighting the potential for broader applications in similar geological settings.

Author Contributions

Prof. Aris Buntoro, Ph.D. as the Lead researcher (Drilling Engineer) who summarizes the research results for writing this paper; **Basuki Rahmad, Ph.D.** as a member of the researcher (Geologist) who makes subsurface analysis in this research; **Prof. Muhammad Nurcholis, Ph.D.** as a member of the researcher (Mineralogist) who makes XRD and CEC analysis in this research; **Allen Haryanto Lukmana** (Drilling Engineer) as research members who conducted laboratory work; **Edo Anuraga** (Drilling Expert - Pertamina EP) who has provided data and gave permission for research and publication; all authors had approved the final version.

Conflict of Interest

The authors declare no conflict of interest regarding the publication of this paper.

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