

RESEARCH ARTICLE

Characteristic of Mineral Alteration of Geothermal in Endut Mount Based on petrography, Spectra, XRD, and MeB methods

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Received: Apr 7, 2025; Accepted: Mar 12, 2026.

DOI: 10.25299/jgeet.2026.11.1.21933

Abstract

Endut Mount is one of the geothermal prospect locations in Indonesia. In order to optimize the geothermal potential of the research area, it is necessary to conduct research on geothermal characteristics. One such study is the examination of altered minerals in geothermal manifestations. The primary objective of this research is to conduct alteration investigations utilizing coring data obtained from the drilling of Well 1 by petrography, MeB, Spectra, and XRD method approaches. The result of the research shows that the lithology of this Well is a product of Endut Mount activity, with an intensity ranging from medium to strong. The lithology is composed of altered tuff and altered andesite breccia, which are a product of the Pleistocene period, and altered volcanic breccia and altered tuff breccia, which are a product of the Miocene period. This lithology is based on the oldest to the youngest succession. The alteration assemblages in Well 1 are classified into two zones based on the assemblage of alteration minerals: the illite-chlorite±epidote zone, which is located at a depth of 9.7– 40.9 MD, and the smectite-sericite-chlorite-epidote zone, which is located at a depth of 40.9 – 111.15 MD. The type of alteration in Well 1 is propylitic, with a neutral pH and a temperature range of 200°C to 300°C, as indicated by the mineral composition and alteration zone. This alteration zone has the potential to function as a reservoir zone.

Keywords: Mineral Alteration, Geothermal Prospect, Endut Mount, Propylitic Type, Reservoir Zone.

1. Introduction

1.1 Background

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In Indonesia, geothermal energy is a naturally occurring energy resource that is extensively distributed (Augusty et al., 2022; Khasmadin and Harmoko, 2021; Marry et al., 2017). This geothermal potential could serve as a sustainable source of renewable energy, thereby reducing reliance on fossil fuels.

In active geothermal systems, hydrothermal alteration is a frequent occurrence that can substantially alter the physiochemical properties of (Fulignati, 2020; Heap et al., 2020; Maza et al., 2021; Schaefer et al., 2021; Weydt et al., 2022). The development of secondary minerals as one of the manifestations of geothermal systems through hydrothermal alteration can interpret subsurface condition (Kraal et al., 2024), indicate the formation temperature, because hydrothermal alteration minerals show temperature sensitivity and are stable at certain temperatures (Beaufort et al., 1996a; Lagat, 2017; Padriue et al., 2025; Reyes, 1990; Waweru, 2019) and development of the thermal source and fluid composition related to geothermal systems (Milicich et al., 2018; Waweru, et al., 2019). The rocks are generally modified due to the circulation of hydrothermal fluids (in geothermal system) and can be categorized into several zones; argillic, transition, and propylitic (e.g. (Stimac et al., 2015), and advanced argillic (Hedenquist and Arribas, 2022). These fluids are typically in the form of hot steam or bicarbonate

water. Detailed comprehension of the reservoir is necessary to enhance the appraisal and modelling of high-temperature geothermal resources associated with active volcanic environments, including through the approach of hydrothermal alteration and mineral assemblages, as minerals formed in geothermal systems provide information about present and past geothermal reservoir conditions (Waweru, 2019).

The Gunung Endut region is composed of Quaternary volcanic igneous rocks and Tertiary plutonic igneous rocks, which are believed to have been formed as a result of tectonic subduction in southern Java, is evidenced by the fact that the magma series that formed the igneous rocks of Gunung Endut is a calc-alkaline (Adikusuma et al., 2019). Mount Endut is one of the areas included in the geothermal prospect area. It is believed that the geothermal system in the Mount Endut area consists of two systems: the geothermal system in the Cikawah area and the geothermal system on the western slopes of Mount Endut (Permana et al., 2021). The geothermal resource in this area is around 38 MWe in the Probable Reserve group (Permana et al., 2021). The results of research conducted by (Nurdin et al., 2023) based on the results of the temperature slope found that the formation temperature in well 1 was 44°C at a depth of 77-meters with a thermal gradient value of 23.74°C/100 meters, and in well 2 the formation temperature was 81.39°C at a depth of 500-meters with a temperature slope value of 11.1°C/meters. Based on this, it has not been discussed in detail regarding the alteration that developed in the research area. Therefore, the main objective of this study is to confirm the host rock, the

characteristics of alteration minerals in the subsurface, and the determination of the alteration assemblage and alteration type in the study area and estimate the formation temperature in the geothermal system in the research area (Fig.1).

The results of this study are expected to provide insights into the geothermal system's status in the study region, specifically about the existing hydrothermal alteration, which may later inform the assessment of geothermal field growth in Mount Endut.

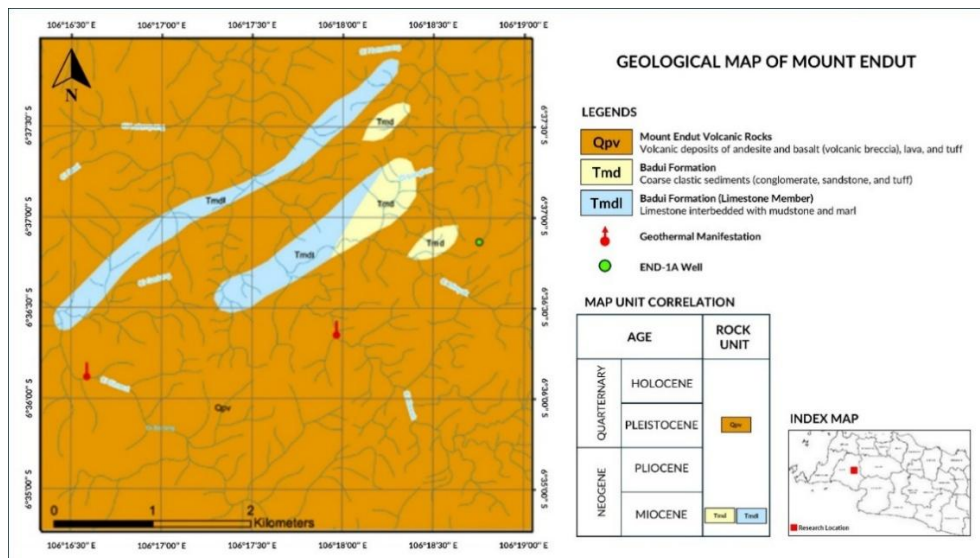


Fig. 1 Geological map of the region in the study area from the Leuwidamar sheet (Modified from Sudjatmiko and Santosa, 1992).

1.2 Regional geology of the research area

Based on regional stratigraphy (Sudjatmiko and Santosa, 1992), the study area, from old to young, is composed of Cimapag Formation (Tmc), Baduy Formation (Tmd), and Limestone member Baduy Formation (Tmdl) (Fig.1). Cimapag Formation is estimated to have early to Late Miocene age, deposited in marine to terrestrial environments and partly in turbidite currents, consisting of breccia bedding or marine to terrestrial environments and partly in turbidite currents, consisting of a base of breccia or conglomerate with components of older rock fragments, lava, quartz veins and altered rocks. Breccia or conglomerate of various material, bluish-green cloudy white color, coarse-grained, pelitic to pseudophytic. Tuff, composed of andesite or dacite; Lava, andesite-composed, horizontally emplaced and is an insertion between tuffs. Baduy Formation consists of coarse clastic sediments (conglomerate, sandstone, and tuff). Limestone member Baduy Formation consists of limestone, mudstone, marl and tuff. Limestone, yellow-color pale grey turbid, friable; contains foram fossils. Limestone, color grey to black, locally lumpy with flow structure, several tens of centimeters in thickness, as an insertion in limestone. Napal, grey to greenish white-color, moderately hard and compact, interbedded with limestone, only a few meters in thickness.

2. Material and Methods

The object of study is core samples from the drilling of END-1A Well to a depth of 111.15 m, which was carried out in August - September 2023. 10 (ten) petrographic samples were analyzed at the Petrology and Mineralogy Laboratory, FTG, Unpad, in 2023. Petrographic analysis was conducted to identify the rock characteristics of core samples, such as texture, structure, the composition of minerals, and the name of the rocks (Maitre, 2002; Schmid, 1981; Streckeisen, 1979).

There are 14 core samples selected for spectra analysis for clay mineral identification by firing the Light spectrum on the sample so as to produce a graph of reflectance against wavelength that can be processed through the DARWin SP application, and 2 sample XRD has been done. It was conducted at PSDMBP in 2023. This method is used to identify clay mineral compositions.

Powder samples were tested using the Methylane Blue (MeB) test. Methylane Blue analysis was carried out at every 3 m depth of the well, with the aim of estimating the clay mineral content by looking at the rate of increase in MeB concentration. The test was carried out by heating 0.2 g of powder sample with 15 ml of H₂SO₄ concentrate 2N as solvent on a magnetic stirrer.

The stirred and heated sample was 0.2 ml of MeB solution was added periodically until it produced a blue stain on the test paper produced a blue stain on the clay mineral content test paper on the powder sample using MeB dye. The higher the level of MeB required to produce a blue stain, the higher the percentage of clay minerals. The test results were calculated to produce MeB index with the following formula.

$$\text{MeB Index: } \frac{\text{MeB (ml)}}{\text{Massa (g)}} \times 3$$

3. Results and Discussion

3.1 Stratigraphy of End-1A Well

The well is located at coordinates 06°18'45.043' East and 60.36°8.150' LS and has a depth of up to 111.15 MD (meter depth). Based on the composite log results, the lithology of Well 1, from old to young are as follows; (1) altered volcanic breccia, (2) altered tuff, (3) andesite breccia, and (4) volcanic breccia (Table 1).

(1) Altered Volcanic breccia (86.6 - 111.15 m)

The rock exhibits a reddish to greenish grey colors. The breccia is angular-subangular in shape, weakly sorted, open-packed, and has fractured and filled by quartz. It is

weak - intermediate (Morrison, 1996). The andesite fragments in the volcanic breccia are between 9.7 and 31.5 m, brownish grey to blackish grey in color, with a porphyritic-aphanitic texture, soft-brittle hardness, and phenocrysts composed of plagioclase partially altered to chlorite, clay minerals, and calcite. They are embedded in a groundmass of plagioclase microlites partially altered to clay minerals (Fig. 4). The tuff matrix is characterized by an

angular grain in shape, fine-medium in size, poor sorting, open packing. Chlorite and a small amount of epidote have been resulted from the majority of lithic fragments and crystals, which are plagioclase and amphibole. There are opaque minerals as accessory minerals. The degree of alteration in this rock is intermediate to weak (Morrison, 1996).

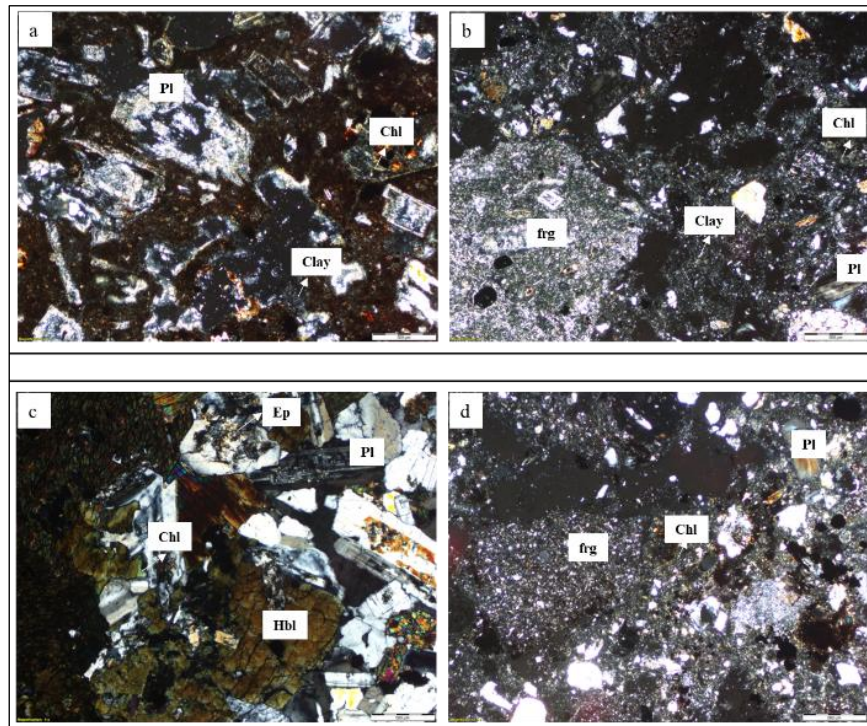


Fig. 3 Photomicrograph volcanic breccia with the fragment of the andesite (a) and the diorite (c) and the matrix of the lithic tuff (c,d), have alteration with low to intermediate intensity. (Pl=plagioclase; Hbl=Hornblende; frg=rock Fragment; Chl=Chlorite; Ep=epidote).

3.2 Alteration Minerals

Based on the results of microscopic analysis and spectra analysis, the alteration minerals found in well 1 are clay minerals, quartz, chlorite, calcite, epidote, opaque minerals, and oxide minerals. The following is a more detailed explanation of the characteristics of each alteration mineral.

Clay mineral

The presence of clay minerals in END - 1A Well is scattered almost at every depth, with fluctuating abundance. The presence of clay minerals in geothermal systems is crucial to determine the boundary between reservoir and cap rock. Analysis of the clay mineral intensity was supported through the Methylane Blue Test (MBT) by calculating the MeB index per 3 MD. Based on the analysis, the kind of clay minerals which are dominantly smectite, illite, and kaolin (Table 2). In addition, it also has been seen in Fig. 4. Smectite is a group of clay minerals with a sheeted morphology that is stable in low temperature neutral to acidic environments, especially at temperatures >140°C (Deer et al., 2013; Reyes, 1990). Illite is a mica-clay mineral that stabilizes in the temperature range of 200°C - 300°C in a weakly acidic environment with high CO₂ content. It can be used as an index mineral in geothermometers (Reyes, 1990). Kaolin is stable in acidic environments at temperatures < 150°C - 200°C, commonly found close to the surface, in zones heated by steam, above the water table (Kraal et al., 2024; Reyes, 1990).

Table 2. Clay mineral content and MeB index at each depth

Depth (MD)	MeB Index						The average of MeB Index	Kind of clay mineral
	5	10	15	20	25	30		
5	[Line graph showing MeB index values]						10,2	Smectite, illite - smectite
10	[Line graph showing MeB index values]							Smectite, illite
15	[Line graph showing MeB index values]							Illite-Smectite
20	[Line graph showing MeB index values]						19	Smectite, illite - smectite
25	[Line graph showing MeB index values]							Smectite, illite - smectite
30	[Line graph showing MeB index values]							Smectite, illite - smectite
35	[Line graph showing MeB index values]						28,5	Smectite
40	[Line graph showing MeB index values]							Smectite
45	[Line graph showing MeB index values]							Smectite, illite, kaolin - illite
50	[Line graph showing MeB index values]						28,5	Smectite, illite, kaolin - illite
55	[Line graph showing MeB index values]							Smectite
60	[Line graph showing MeB index values]							Smectite
65	[Line graph showing MeB index values]						28,5	Smectite
70	[Line graph showing MeB index values]							Smectite
75	[Line graph showing MeB index values]							Smectite
80	[Line graph showing MeB index values]						28,5	Smectite
85	[Line graph showing MeB index values]							Illite Smectite
90	[Line graph showing MeB index values]							Smectite - kaolin
95	[Line graph showing MeB index values]						28,5	Smectite - kaolin
100	[Line graph showing MeB index values]							Smectite
105	[Line graph showing MeB index values]							Smectite
110	[Line graph showing MeB index values]						Smectite	

Quartz

The presence of quartz in Well 1 is found at every depth as a secondary mineral in the rock. Based on petrographic observations, quartz (Fig.2a) is generally colorless, low relief, no cleavage, often found in microcrystalline form replacing groundmass. The presence of quartz is also found in the form of amygdaloids and veinlets. Temperature range of quartz is between 90°C - 180°C and predominant above 180°C dan wide pH range (Corbett and Leach, 1998; Fournier, 1985).

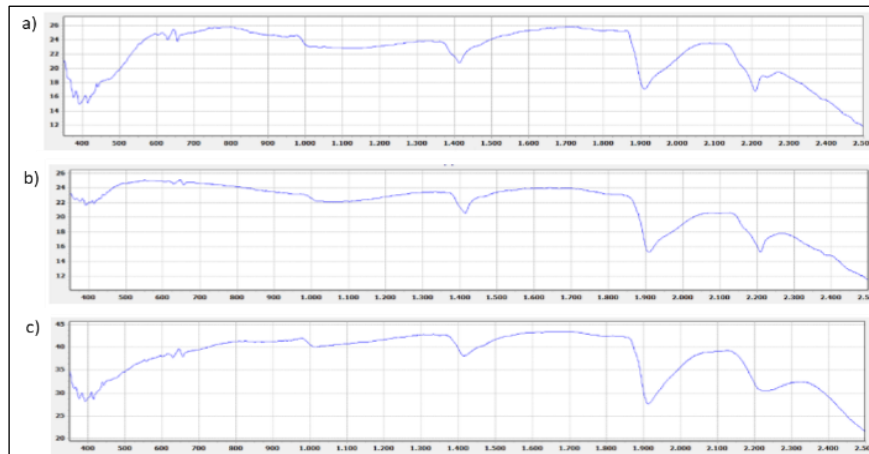


Fig. 4 Spectral graphics of (a) kaolin in 38 MD; (b) halloysite in 91 MD, and (c) Illite characters in 40 MD.

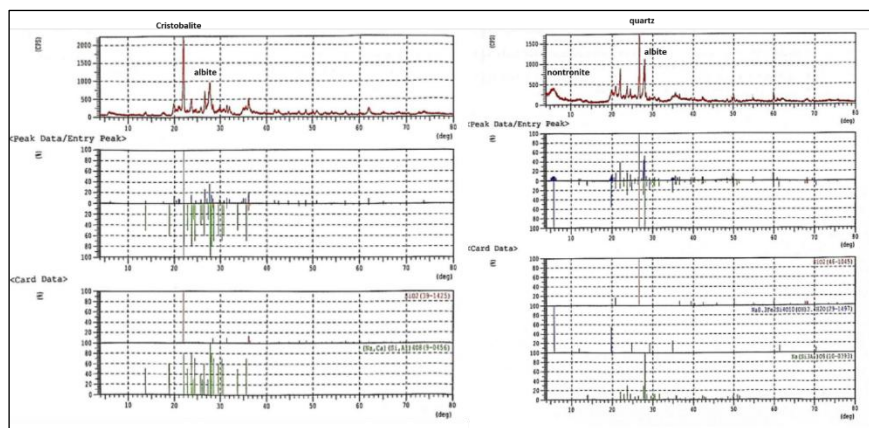


Fig. 5. The XRD patterns for volcanic breccia at a depth of 30.90 meters (left) and altered tuff at a depth of 71.10 meters (right).

Sericite

Sericite in well 1 was found at a depth of 42.1 m (Fig.2a). In thin section, it is colorless, has second – third order interference color, low relief, fibrous texture. This mineral is identified as altered plagioclase.

Chlorite

Based on microscopic analysis, mineral chlorite was found in abundance with increasing depth (Fig.2). it exhibits green color and fibrous – aggregate texture. The presence of chlorite is the result of alteration of plagioclase, amphibole, and groundmass. Chlorite minerals are minerals that have a fairly long temperature range of >120°C (Reyes, 1990) and above 220°C (Fulignati, 2020).

Carbonate

In under microscope, carbonate minerals are characteristically colorless or brownish in color, granular texture, high relief, high interference color, and some are found two cleavages. Calcite is present alteration from Ca-plagioclase. It is widely dispersed and frequent in a broad range of temperatures (Calvin and Pace, 2016), therefore it cannot be utilised as a mineral indicator.

Epidote

Epidotes in Well 1 were found at 27.5 m, 35.7 m, and at 42.1 m in depth. In thin section, the epidote is brownish in color, high relief, high birefringence, and second - third order interference color (Fig.2a). It is the result of alteration plagioclase. Epidote is a mineral that is commonly present in hydrothermal systems with a temperature > 230°C at medium - high pH (Morrison, 1996). Epidote being one of the index minerals related to geothermometer,

permeability and fluid composition in geothermal systems (Reyes, 1990).

3.3 Alteration of mineral assemblages and geothermal system

Based on the assemblages of minerals are divided into two, which can later become a reference for estimating paleotemperatures.

1. Illite – smectite – chlorite ± epidote ± carbonate

It has been found at a depth of 9.7 - 42.1 m. The alteration minerals found are dominantly illite, smectite, chlorite, and a little epidote, sericite, and oxide minerals (Table 3), so that this assemblage is included by a propylitic type (Corbett and Leach, 1998; Stimac et al., 2015). Based on the association of alteration minerals, the pH in this zone is relatively neutral because the dominating mineral is illite. The formation temperature of this zone ranges from 200 - 300°C (Reyes, 1990).

Table 3. Illite – kaolin – chlorite ± epidote zone formation temperature

Kind of minerals	Temperature (oC) (Reyes, 1990)							
	50	100	150	200	250	300	350	400
Illite				-----	-----	-----	-----	
Kaolin			-----	-----	-----	-----		
Chlorite			-----	-----	-----	-----	-----	
Epidote				-----	-----	-----	-----	

2. smectite – sericite – chlorite – epidote

It has been found at a depth of 42.1 - 111.15m. At depth, the alteration minerals are smectite, sericite, chlorite, and

epidote, some present calcite (Table 4). Based on the mineral content, this zone is propylitic type (Corbett and Leach, 1998; Stimac et al., 2015). Based on the alteration of mineral associations, it includes acidic-neutral pH, has range of temperature 100°C - 200°C.

Table 4. smectite –sericite – chlorite – epidote zone formation temperature

Kind of minerals	Temperature (oC) (Reyes, 1990)							
	50	100	150	200	250	300	350	400
smectite			-----	-----	-----	-----	-----	-----
Kaolin			-----	-----	-----	-----	-----	-----
Sericite			-----	-----	-----	-----	-----	-----
Chlorite			-----	-----	-----	-----	-----	-----
Epidote			-----	-----	-----	-----	-----	-----

The temperature of the Well 1 is obtained through paleotemperatures and measurements of temperature ramps taken during the drilling process. The temperature increase that occurs along with the increase in depth produces a temperature gradient that is crucial in analyzing the potential for geothermal utilization. The results of the paleotemperature estimation based on the assemblages of minerals depicts a decrease in temperature towards the bottom of the well, with the estimated temperature at a depth of 10 - 42.1 m is 200 - 300°C, and the temperature at a depth of 40 - 111.15 m is 200 - 300°C. The occurrence of this temperature drop caused by the presence of stilbite minerals that indicate cooling due to meteoric water. Meanwhile, based on the previous temperature slope measurement data for 1 point in the Well 1 using the Horner Plot method shows a temperature of temperature of 44.18°C at a depth of 77 m. Based on this data, it was obtained average temperature increase of 23.74°C/100 m (Nurdin et al., 2023). The presence of hydrothermal alteration and thermal gradient anomalies indicate the Well is located in the geothermal prospect area of the Mount.

The results of the comparison between paleotemperatures and temperature ramps showed significant difference, where the measurement results using the Horner plot method at 77 MD showed a temperature of 44.8°C or more. Horner plot at 77 MD shows a temperature of 44.8°C or 155.2°C lower than the average paleotemperature of 200°C at the depth. This indicates that there has been a decrease in temperature. Characteristics of the geothermal system in the Endut Mount Geothermal Field based on End - 1A Well is generated by linking all the data obtained from the lithology, mineral alterations, and the comparison of paleotemperatures with current temperatures, it is found that the alteration associations in the End - 1A Well is included by propylitic type (42.1 - 111.15 m). Based on the results of paleotemperature estimates, the temperature at depth of 9.7 - 42.1 m reaches > 280°C, indicating the presence of a reservoir zone in the geothermal system, characterized by the presence of epidote.

Conclusion

The examining alteration of minerals from END - WELL 1A in geothermal manifestations in the research study shows that lithology is influenced by the result of Endut Mount activity. The alteration assemblages in this Well are classified into two zones: the illite – chlorite ± epidote zone and the smectite – sericite – chlorite – epidote zone. The alteration zone is propylitic, with a

neutral pH and temperature range of 200°C to 300°C. The results of this mineral alteration study provide information that the area acts as a reservoir zone. To further confirm the distribution and thickness of the reservoir, further research is needed by adding drilling data around End - 1A Well.

Acknowledgement

I would like to thank PSDMBP (Geological Agency) whom involved us in field observation and facilitating the opportunity to conduct Spectra and XRD analysis.

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