Deformation mechanism of boudin structures at the Bulukuning area, Banjarnegara

E Puswanto1*, M Al Afif1, A Farisan1, D Hastria1, P D Raharjo1, D Arisa1, M Z Tuakia2

1Research Center for Geotechnology, Indonesian Institute of Sciences
2Geological Engineering Study Program, Universitas Pattimura, Kampus Poka, Ambon

*Corresponding author: epuswanto@gmail.com

Abstract. The greywacke sandstone in the Bulukuning area, Banjarnegara where was previously proposed as the Bulukuning Formation is part of the Luk Ulo Mélange Complex. In general, these molassic deposits show alternation between siltstone and siltstone with thin bedding deposited in the foreland basin. The Eocene sandstones are in some parts associated with the boudin structure, folded and cut by faults in the contractional regime. This study aims to determination of boudin type, structural orientation is highly correlated with deformation mechanism. This mechanism of deformation can be formed in different deformation periods. The correlation between the orientation of the systematic fault P-foliation, Y-shear, and R shows that the formation of boudinage is thought to be affected by the presence of a right movement (dextral), which follows the principle of the riedel shear. The deformation mechanism in the formation of sandstone boudin structures embedded in the scaly clay matrix is thought to be affected by plastic (ductile) by following the simple shear principle.

Keyword: Boudin, Structure, Deformation, Sandstone, Fault

1. Introduction

The research area is in Bulukuning Village, Purwanegara District, Banjarnegara Regency, Central Java. Geological conditions in the study area have been studied by previous researchers [1], [2], [3], [4], [5]. Sedimentary lithologies in the study area had previously been mapped as Pre-Eocene sedimentary sequence of Upper Cretaceous – Paleocene [6] (Figure 1). The sedimentary rock sequence, all of which are relatively deformed and slightly metamorphic, was proposed as the metasediment Bulukuning Formation [4]. The proposed new formation is based on different lithological and age characteristics from the around Luk Ulo Melange Complex.

Sedimentary rock units in the study area generally show an alternation between siltstone and claystone. The process of boudinage in several parts is found in sandstone blocks which are embedded in the eroded claystone matrix, and sandstones that are inserted inside the claystone. Boudinage is a process of forming boudin structure. The term boudin was first introduced by Lohest (1909) to explain the appearance of sandstone structures that resemble the shape of sausages [7]. The mechanism of the process of boudinage
formation in the study area has never been specifically discussed. Boudin mechanism processes in the progress of science can present as indicators of the deformation kinematic [8]. The existence of boudin structure is one of the parameters of interpretation of the deformation period. Determination of boudin type, structural orientation is highly correlated with deformation mechanism. This mechanism of deformation can be formed in different deformation periods, associated with plastic or brittle deformation. The period of deformation is closely related to tectonic evolution.

Figure 1. Distribution unit Pre-Eocene sedimentary rocks (Ketner et al., 1976) [6] proposed Prasetyadi (2007) [4] as metasediment Bulukuning Formation (index of box line blue color) (data from Condon et al., 1996 [9] and Asikin et al., 1992 [10]).

2. Regional Geology
Physiographically, the Bulukuning area, Kaliajir Village, Purwanegara District is part of the South Serayu Mountain range that overlaps unconformably over the Pre-Tertiary bedrock. This Pre-Tertiary bedrock is known as the Luk Ulo Melange Complex which is the result of the process subduction of the Hindia-Australian Plate and Eurasian plate Upper Cretaceous – Paleocene [1], [2], [3]. The Luk Ulo Melange Complex is composed of a mixture of blocks metamorphic rocks, mafic-ultramafic igneous rocks
(ophiolite), pelagic and hemipelagic sedimentary rocks. These various blocks are embedded in the claystone matrix and eroded tectonically \cite{1}, \cite{2}.

This subduction tectonic process is then followed by a collision between the microcontinent of East Java and the eastern part of the Sunda mainland in the Early Eocene - Early Oligocene \cite{11}, \cite{12}. This post-collision produced the Karangsambung Formation and Totogan Formation deposited unconformably over the Luk Ulo Melange Complex. Paleogene lithology's Karangsambung Formation and Totogan Formation which is olistostrome deposits due to deep-sea gravitational avalanches composed of fragments of various materials mixed in the clay matrix \cite{1}. The Paleogene metasediment was proposed as the Bulukuning Formation fills shallow marine basins in the north Karangsambung \cite{4}. This bottom-up metasediment rock sequence consists of layered sandstones, shales with conglomerate lenses and limestone inserts. Stratigraphically, the Bulukuning Formation separates from the around Luk Ulo Mélange Complex based age differences and lithological characteristics \cite{5}.

3. Research Methods

The research methodology is related to identifying boudin structures that develop in the study area using the classification approach Goscombe et al. (2004) \cite{8}. The intensity of boudin formation is known by making an aspect ratio (AR) comparison chart between the elongated direction of the surface of the boudin (Bbs) and the blunt edge of the boudin (B-t).

Identifying the types of primary and accompanying structures mainly focuses on the geometry and correlation between structures that intersect each other. The boudin structure that develops in the claystone matrix shows the geometry of area cleavages that are connected. This correlation forms a geometry that can support the interpretation of kinematics and deformation mechanism.

4. Results and Discussion

The existence and distribution of sandstone units in the scaly clay matrix can be found from the Kali Sat route in the western part to the Lebak Menak River route in the eastern part of the study area (Figure 2). The flake clay matrix in the study area generally shows the position of the cleavage in the west-southwest to east-northeast direction with a slope to the south about 40° and north 35°.

4.1. Boudin Structure Geometry Analysis

The clay matrix in the study area generally has black, scaly, and flake characteristics, with sandstone insertions. The sandstone inserts in mudstone relatively less competent in some parts indicated experiencing boudinage and produce boudin structure. Appearance boudin geometry of the structure generally a sandstone lenses, asymmetrical, and rounded at the tip (Figure 3). Based on the classification of boudin structure indicates that the structure of sandstone boudin in the study area is a type of boudin shearband \cite{8}.

In general, the longest axis boudin directed N280°E, cut by systematic fractures. The aspect ratio (AR) calculation is performed to determine the intensity of boudinage that has been formed during the formation of boudin. Calculation of the aspect ratio involves comparing the direction of extending the boudin’s surface (Bbs) and the thickness of the boudin presented in the chart (Figure 4). Boudin's longest axis aspect ratio (AR) comparison chart shows that the AR value is quite large. The comparison shows a significant level of boudinage development.
Figure 2. Distribution of sandstones in the scaly clay matrix (index of box line red color), Ketner et al., 1976 [6]

Figure 3. (a and b) The structure of sandstone boudin within the scaly clay matrix in the Kali Sat indicates the type of boudin shear band. (c) Illustration of shear band boudin type Goscombe et al., 2004 [8]

The longest axis value of boudin between 10-20 cm shows the aspect ratio increasing to 15. The frequency comparison chart and aspect ratio analysis presented (Figure 5) shows a range of 2-5. The high aspect ratio indicates that the boudinage is well developed [13].
4.2. Deformation Mechanism

The sandstone boudin structure embedded in a relatively less competent clay matrix shows a structural correlation that follows the Riedel shear principle, which shows the correlation between R1 and R2. R1 and R2 are synthetic and antithetic fault sets. This principle is identical to the development of the formation of microstructures in the gouge zone bounded by a parallel fault plane. The fault area can develop locally on relatively competent rock bodies within the gouge zone [14]. The parallel fault plane is known as Y-shear. This field is specifically interpreted as the main fault that develops locally [15].

The microstructure in the gouge zone is interpreted to control the formation of boudin structures in the study area are generally asymmetrical and separated along with the riedel shear. As shown in Figure 6, the P-foliation plane is formed parallel to the direction of the boudin’s longest axis. This P-foliation is a cleavage that develops on the clay matrix, which is relatively tilted to the north. Riedel shear (R1) is formed at an oblique angle in the opposite direction to P-foliation. Conjugate riedel shear (R2) is formed at a larger angle in the gouge zone in the opposite direction with R1. The correlation between orientation systematic fault P-foliation, Y-shear, and R shows that the formation of boudinage is thought to be affected by the presence of right movement (dextral).

The deformation mechanism within the becoming of sandstone boudin structures embedded in the scaly clay matrix is estimated to be affected by plastic deformation (ductile) by following the simple shear principle. This deformation mechanism causes the pull out of sandstones around the clay matrix which is relatively less competent in line with the increase in pressure and viscosity difference.

**Figure 4.** Comparison aspect ratio (AR) chart ratio (AR) boudin.

**Figure 5.** Chart of comparison of frequency and aspect with boudin's longest axis
Figure 6. Correlation of systematic fault orientation of P-foliation, Y-shear, and R which affect the formation of boudin structures in the Kali Sat.

A specific description of the pressure and temperature conditions associated with the formation of deformations in rocks faulted, especially incompetent rocks along the gouge zone, can be known by measuring the value of Illite Crystallinity (IC) on the clay matrix. The value of Illite Crystallinity (IC) on a clay matrix in the study area is about 0.632 - 0.714 [15]. This shows that the deformation mechanism is formed at temperatures around 205,916 - 223,014°C (± 30°C) at depths of approximately 4-5 kilometers. The temperature measurement is based on the equation $T (°C) = 353 - 206 \text{ IC} (°C)$ proposed by Hara and Kurihara 2010 with a correlation coefficient of 0.92 and error of ± 30°C [16].

The molasses deposition in the study area dominated by sandstone and claystone units was deposited in the wedge-top portion of the foreland basin [15]. Molasses deposited is interpreted as the result of erosion of the Karangsambung accretion complex formed previously and mixed with volcanic rocks and Sunda land blocks lifted up. This lifting mechanism is related to the collision of the East Java microcontinent with the eastern part of the Sunda land in the Early Eocene - Early Oligocene [11],[12].

5. Conclusions
1. Sandstone boudin structure, which is embedded in the relatively less competent clay matrix, shows the structure’s relationship, which follows the principle of the Riedel shear.
2. The correlation between the orientation of the systematic fault P-foliation, Y-shear, and R shows that the formation of boudinage is thought to be affected by the presence of a right movement (dextral).
3. The deformation mechanism in the formation of sandstone boudin structures embedded in the scaly clay matrix is thought to be affected by plastic (ductile) by following the simple shear principle.
4. This deformation mechanism causes the pull out of sandstone bodies around the clay matrix which is relatively less competent.

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