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GEOMECHANIC PROPERTIES AND PROVENANCE ANALYSIS OF QUARTZ SANDSTONE FROM THE WARUKIN FORMATION

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ABSTRACT: Quartz sandstone is the main constituent material of the Warukin Formation in the Kusan Block, Tanah Bumbu regency, South Kalimantan. This study aims to determine provenance of the Warukin quartz sandstone by using petrographic analysis method. The method is carried out by an approach based on the percentage of feldspar, quartz, and rock fragments composition plotted on the Q-F-L ternary diagram. For provenance determination, it is done by plotting the composition on the Qm-F-L ternary diagram. The analysis was carried out on 7 sandstone samples taken from the surface of mine slopes at the Warukin Formation. Based on microscopic observation on thin sections of the samples, quartz minerals of the samples are monocrystalline. Sandstones in the Kusan Block have homogeneous property in terms of constituent mineral content. According to the Pettijohn classification in 1975, sandstones and claystones of the Warukin Formation are both classified as greywacke. The result of provenance analysis according to the classification by Dickinson and Suczek in 1979 shows that the sandstones provenance is recycled orogen with subclassification of quartzose recycled. Provenance of sandstones at the Warukin Formation is from the older formation.

Keywords: Warukin, Sandstone, Provenance, Geomechanics, Petrography

1. INTRODUCTION

Each tectonic setting has its own rock characteristic [1]. When rocks go through erosion and deposition, they will form into sandstones that have typical characteristic of the composition [2-4]. This is the basis behind the study of sandstone provenance.

Provenance analysis aims to reconstruct the pre-deposition history of sediments or sedimentary rocks [5], including distance, direction, tectonic setting, climate, and relief of the origin area of sedimentary materials [6]. Determining sandstone tectonic setting by framework of the mineral composition (detrital) was first introduced by [7] and then subsequently perfected [2,3,8,9]. Combination of petrographic and geochemical data of sedimentary rocks can reveal the area where the sediments originated, the basin tectonic settings, and the paleoclimate conditions [2,10-15].

Although geochemical composition can change during weathering through oxidation [16] and/or diagenesis [17,18], as long as the bulk composition is not completely changed, geochemical analysis is still useful for sandstone provenance study[12].

An important clue among other parameters to determine the tectonic setting of a basin is the relative depletion of oxides such as CaO and Na2O (most mobile elements), and enrichment of SiO_2 and TiO_2 (most immobile elements). These oxides indicate enrichment or depletion in the composition of quartz, K-feldspar, mica, and plagioclase. The ratio of most mobile elements to most immobile elements will increase in line with more passive tectonic margins due to relatively more stable tectonics [13,19-22]. Thus, the weathering that occurs is getting longer. This is recorded in the paleoclimate index [17,23,24] and the sediment recycling.

Sandstones in the Kusan Block have homogeneous property based on the content of quartz mineral. Sandstones will degrade when they are exposed with the result that it affects the mechanical properties [25]. For claystone, the mechanical properties also depend on the type of clay mineral [26].

1.1 Regional Geology

The Barito Basin is one of the main geological basins in South Kalimantan. The Barito Basin is divided into the Barito Basin and the Asam-Asam Basin as a sub-basin. This basin stores abundant coal resources and reserves. One of the formations that hold coal seams is the Warukin Formation which extends from the southwest to the northeast. The rocks of the Warukin Formation are dominated by sandstones and claystones with coal inserts. Mining activities at the Warukin Formation have been carried out, causing exposure of the rocks.

Structural patterns in the Asam-Asam Basin are not often found in the field due to soft material so that tectonic behavior is not well recorded in rocks. The continuity of rock layers in the Asam-Asam

Basin is relatively continuous at the western part as well as the eastern part of the fold limbs [27].

The Barito Basin and the Asam-Asam Basin are separated by the Meratus Mountains (Fig. 1). Although there is no certain research, many experts estimate that the two basins are originally the same basin. This is indicated by the characteristics of rocks that are almost the same.

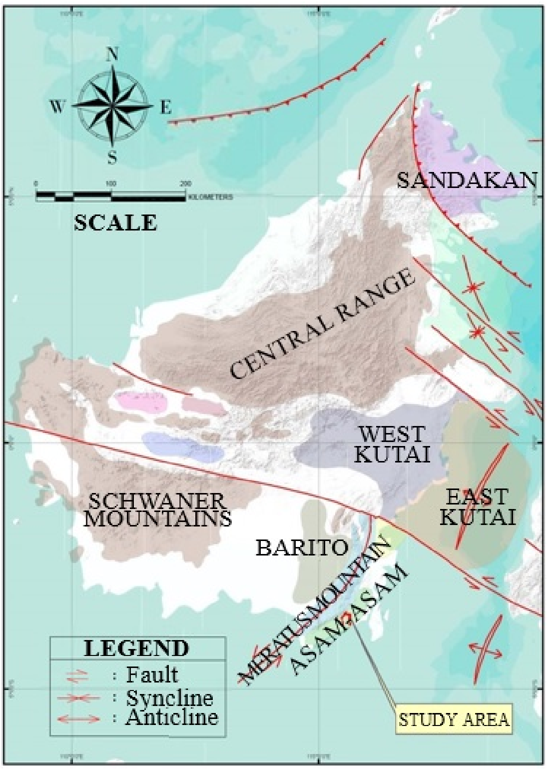


Fig.1 Map of basins and regional tectonic in Kalimantan

The formation of the Barito Basin and the Asam-Asam Basin began in the Late Cretaceous period where the Paternoster plate collided with Kalimantan microcontinent. The impact of this collision caused uplift in the southeastern part of Kalimantan, where alluvial fan and lacustrine deposit from the lower part of the Tanjung Formation in the Early Tertiary were developed. In the beginning of the Middle Eocene, as the result of marine transgression, fluvio-deltaic sediments became more dominant and were eventually dominated by sea sediments to form the center of the Tanjung Formation. In the Late Eocene until the Early Oligocene, marine transgression slowly submerged the uplifted area to form the upper part of the Tanjung Formation which was followed by forming of the Berai Formation. In the Miocene epoch, sea level declined due to the uplift of the Schwaner Mountains in the west and the Meratus Mountains in the middle, resulting in the deposits of the Warukin Formation. The uplift of the Meratus Mountains continued until the Pleistocene epoch and produced rock deposits of the Dahor Formation.

Tectonic activity in South Kalimantan is thought to have occurred since the Jurassic period, which resulted in the mixing of ultramafic rocks, mélange, amphibolite garnet schist, and silicified sandstones. Transgression and volcanic activity occurred in the beginning of the Late Cretaceous which produced the Pitap Formation (Ksp), the Manunggul Formation (Km), the Haruyan Formation (Kvh) and the Paau Formation (Kvp).

At the end of the Late Cretaceous, magma activity occurred which resulted in diorite intrusion (Kdi). The diorite intruded the bedrock of the Pitap Formation and the older rocks. Uplift and subsidence occurred at the beginning of the Paleocene - Eocene followed by deposition of the lower Tanjung Formation (Tet), while the upper part of this formation was formed during transgression. Carbonate shelf of the Berai Formation (Tomb) was formed during transgression in the early Oligocene - Miocene together with clastic sedimentation of the Pamaluan Formation (Tomp). At the time of the Middle Miocene, regression occurred together with deposition of the Warukin Formation (Tmw) in transition zones.

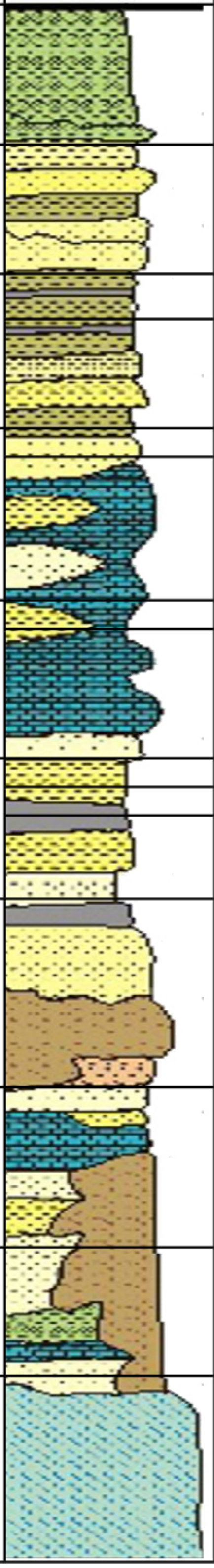
Tectonic activity occurred again in the Late Miocene causing almost all the Mesozoic-aged rocks forming the Meratus High in the western part separating the Barito Basin and the Pasir Basin. At the end of the Late Miocene, the Pre-Tertiary rocks were strongly folded and faulted. During the Plio-Pleistocene, subsidence and deposition of rocks that form the Dahor Formation (TQd) in the Pliocene occurred again, followed by deposition of alluvium (Qa).

1.2 Asam-Asam Basin

The study area belongs to the Asam-Asam Basin. This basin is located east of the Meratus Mountains. There are two types of coal in this basin, namely Eocene-aged coal and Miocene-aged coal. Characteristic of Eocene-aged coal is generally very massive, black, glass luster, bituminous - subbituminous coal type, and high calorie content. Eocene-aged coal is often well exposed, in the form of layers, and forms coal seams. On the other hand, Miocene-aged coal is mostly lignite, very soft, high moisture content, low dust content, and low calorie content. In general, Miocene-aged coal shows poorly shape of the layer in outcrops. This happens because the moisture content in coal is high, compaction pressure is low, and the clay layer is often present in the coal seam.

In terms of regional position, the study area is geologically included in the Regional Geological Map of Kotabaru Sheet [27]. Lithology in this area is Jura-aged bedrock, sedimentary rocks of Miocene

Table 1 Regional stratigraphic column [27]

AGES: ERA	AGES: PERIOD		FORMATION	MEMBER	THICKNESS (m)	LITHOLOGY	DESCRIPTION	DEPOSITIONAL SETTING
KUARTER			ALUVIUM		?		Claystone, Mudstone, Siltstone, Sandstone gravel	River Delta Swampy
TERSIER	PLOSEN		DAHOR		750 m		Quartz sandstone with low strength and intersection with claystone and siltstone	Parais
TERSIER	MIOSEN	A	WARUKIN		250 – 750 m		Sandstone with high strength and intersection with claystone and coal	Litoral - Parais
TERSIER	MIOSEN	T	WARUKIN		250 – 750 m			
TERSIER	MIOSEN	B	PAMALUAN		500 – 750 m		Sandstone intersection with claystone and limestone.	Neritic
TERSIER	OLIGOSEN	A	PAMALUAN		500 – 750 m			Neritic
TERSIER	OLIGOSEN	T	BERAU		500 – 1500 m		Limestone intersection with sandstone and napal.	Neritic
TERSIER	OLIGOSEN	B	BERAU		500 – 1500 m			Neritic
TERSIER	EOSEN	A	TANJUNG		1500 m		Intersection sandstone and claystone, limestone and konglomerat.	Delta Paralis Neritic
TERSIER	EOSEN	T	TANJUNG		1500 m			
TERSIER	EOSEN	B	TANJUNG		1500 m			
PRA TERSIER	KAPUR	ATAS	MANUNGGUL	PAA U	1500 m		Member PAA U : Breksi volcanic basal anglomeral, lufa & basal porfir Manunggul : konglomerat sandstone and claystone	
PRA TERSIER	KAPUR	TENGAH	PITAP	Batununggal	500 m		Ang. Batununggal: orbituna limestone Ang. Haruyan : Lava basal dan brecia	Litoral
PRA TERSIER	KAPUR	BAWAH	PITAP	Haruyan	1250 m		Intersection sandstone and siltstone with limestone, basal, brecia.	Rumpang Par it Busur
PRA TERSIER	JURA	KOMPLEX ULTRAMAFIX					Hazburgit, dunit, serpentinit gabro, basalt, dan piroksena	

and Pleistocene, to Quaternary-aged alluvium. Broadly speaking**,** there are several main formations in this area (Table 1). These formations are young alluvial deposits, Dahor Formation, Warukin Formation, Berai Formation, Tanjung Formation, and bedrock in the form of Pre-Tertiary sedimentary and volcanic rocks.

Young alluvial deposits is mainly found south of the Kusan River. Almost all tributaries that flow in this area are in thick alluvial deposits in the form of a mixture of various grain sizes of fine sand to gravel. Likewise in the upstream of the Batulaki River, alluvial deposits are exposed, covering most of the Warukin Formation and the Berai Formation. The constituent material consists of disintegration product of older rock unit specifically mafic igneous rock material, granitic material, to coal fragment as disintegration product of the Tanjung Formation and the Warukin Formation. In these alluvial deposits, there are some artisanal mining activities that attempt to mine gold traditionally.

The Dahor Formation consists of siltstone, sandstone, and claystone, is not compact and deposited in a paralic environment in the Plio-Pleistocene epoch [27]. This formation is exposed unclear because it is physically almost similar to the formation below that is the Warukin Formation. The depositional environment between lacustrine and marsh/swamp as well as land cannot be clearly distinguished. In addition, this young and not compact Dahor Formation is very susceptible to weathering. It is likely that weathered rock exposed in the palm oil plantation area east of the artisanal mining area to the Sekapuk Utara village is part of the Dahor Formation.

Unlike the Dahor Formation which is not clearly exposed, the Warukin Formation is a major part of the rock unit exposed in the study area. This formation is characterized by thick coal with high moisture content. This formation is dominated by siltstone, sandstone (fine to medium sized and less compact), and few of greenish gray claystone which is widely exposed as the roof or floor of the main coal seams. The Warukin Formation was deposited in the littoral to marsh/swap environment in the Middle Miocene - Late Miocene. Coal in general has varied sulfur content due to the depositional environment. The litoral environment which is still affected by sea water causes relatively high sulfur content compared to the other parts in the same formation.

The Berai Formation was deposited in the marine environment at the time of the Oligocene - Miocene, so the rocks were dominated by marine facies. In the study area, limestone, marl, and marly claystone are exposed. In the north of the study area, limestone is exposed. This formation forms high and steep ridges. Marly claystone in the upper Berai Formation develops in the southeast, forming a vast plain.

The Tanjung Formation begins with conglomerate deposit the fragments of which consist of quartz cluster and some igneous rock. The main part of the fragments show a tendency to smooth upwards. Coal in this formation is at the bottom. The Tanjung Formation was deposited in the terrestrial to deltaic environment in the Eocene epoch.

The bedrock (Pre-Tertiary age) is exposed in the northwest of the study area. The bedrock consists of old formations of Cretaceous-aged or older. The constituent rocks consist of sediment, volcanic, and igneous rock unit composed of felsic to ultramafic. The relationship between units is tectonic contact.

The Asam-Asam Basin is composed of sandstone and claystone with low hardness and tends to have low physical and mechanical properties as well as tends to go through degradation when they are exposed. This is a challenge in designing mine slopes [28].

2. RESEARCH METHODS

The study was conducted on sandstone of the Warukin Formation which is the main constituent of the Warukin Formation. The parameter reviewed is mineralogy of sandstone composition. Equipment used in field identification includes geological compass, geological hammer, loupe, tape measure, camera, stationery, and sample bags for rock sampling.

Purposive sampling method was used for sampling. It is a method of determining samples selectively by certain considerations so that they can represent the existing population. The obtained samples are then tested at laboratory as part of the primary data plus field survey data. As a supporting data, secondary data is collected by literature study.

To achieve research objectives, direct observation in the field and laboratory analysis as well as the step of studio work were conducted. Direct observation in the field is carried out by means of lithology description in the study area, while laboratory analysis includes petrographic analysis.

The characteristics of the Warukin sandstones in this study are based on three aspects that are geological, geochemical, and geomechanical aspects (3G). Geological aspect includes rock type and provenance obtained by petrographic analysis and provenance analysis. Geochemical aspect is obtained by conducting XRD (X-Ray Diffraction) test, while geomechanical aspect is by geomechanical tests to determine the physical and mechanical characteristics of rocks.

Petrographic analysis is conducted on samples to study the texture and mineralogy of rocks

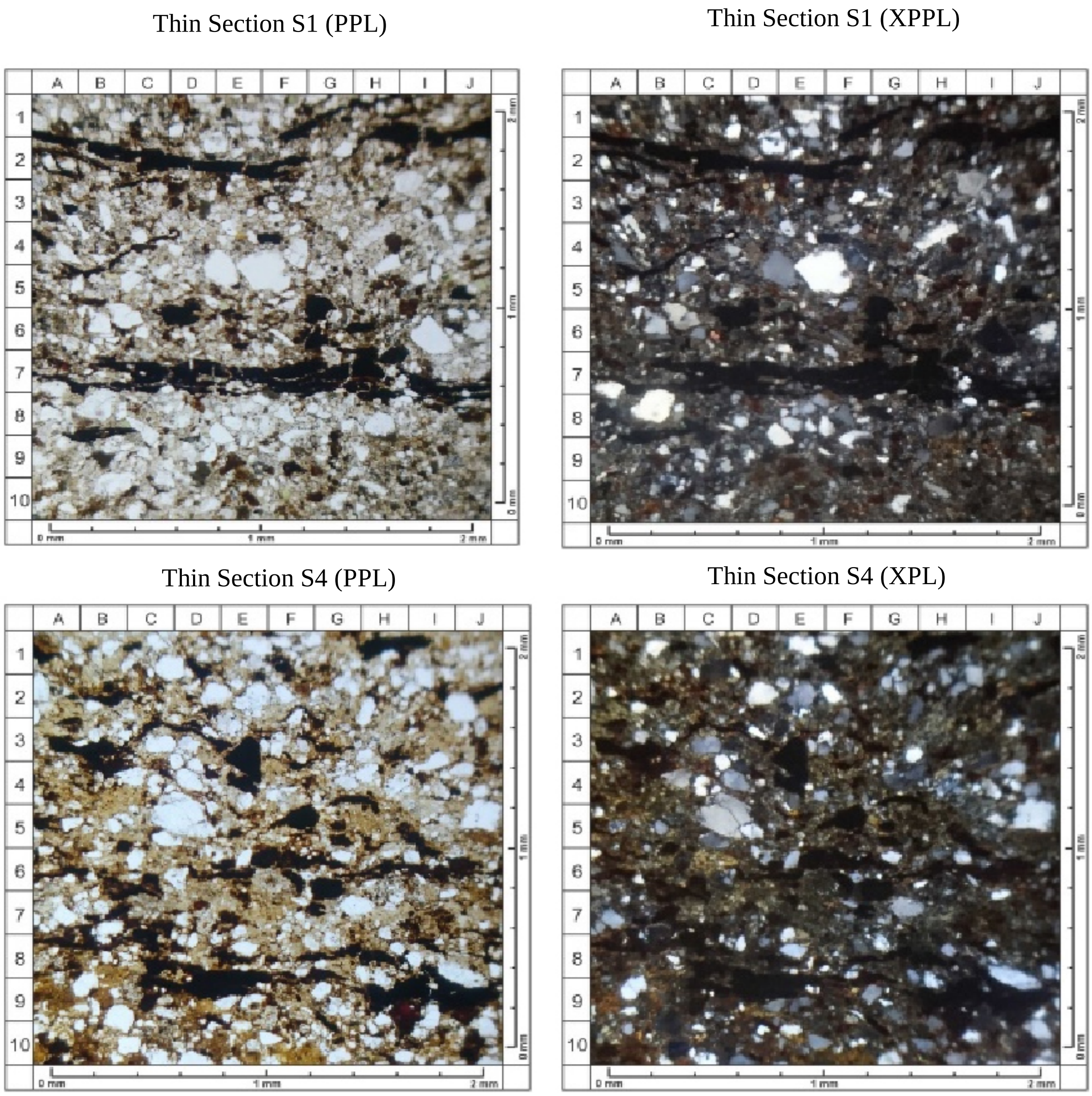


Fig 2. Appearance of sandstone thin sections

microscopically, including index mineral, texture and description of primary and secondary mineral assemblages, as well as other secondary processes such as alteration, change in texture and distribution of certain composition contained in rocks. Thus, the rock type can be determined more specifically based on the specified classification. Percentage calculation of fragment and mineral content in the thin section was carried out visually. Furthermore, provenance analysis was performed to obtain information about the provenance of the Warukin sandstone.

Geochemical parameter of sandstone was obtained by conducting XRD (X-Ray Diffraction) test by utilizing the X-ray wave bias. In XRD test, mineral content chemically was analyzed by estimating the wave phase and interpretation of mineral was obtained by using the Reference Intensity Ratio (RIR) which refers to the intensity ratio of the X-ray waves.

3. RESULT AND DISCUSSION

3.1 Petrographic Analysis

According to the Pettijohn classification of sandstones in 1975 [29], sandstones are petrographically classified based on the percentage of three components in the form of a triangle combined with the percentage of the matrix content. The three components are quartz (Q), feldspar (F), and rock/lithic fragment (L).

Petrographic analysis was performed on the Warukin sandstone using 7 samples that were considered to represent the study area. By petrographic analysis, the composition of rocks can be seen microscopically in more detail. The composition or mineral content of the observed thin sections is composed of mostly quartz mineral, organic carbon, feldspar in very limited quantity, and matrix of clay mineral. The appearance of the sandstone thin sections is in the figure below (Figure 2).

Abundance of quartz observed in the thin sections is on average of 40%, minimum of 25%, and maximum of 50% monocrystalline quartz, low relief anhedral without cleavage, low pleochroism with white color in plane polarized light (PPL), and white to gray in crossed polarized light (XPL).

In the thin sections, abundance of organic carbon material was also observed with the result of minimum of 4%, maximum of 14%, and average of 7.7%. Lithic fragment and shale or coal disintegration product were shown by subrounded – subangular grained texture, shale following depositional pattern in plane polarized light (PPL), and brownish black in crossed polarized light (XPL).

Abundance of feldspar mineral is very limited that is 1-2% and not seen in the 2 sections, with average of 1.3%. It is light brown in plane polarized light (PPL), white gray in crossed polarized light (XPL), carlsbad and carlsbad-albite twin, moderate pleochroism, and cleavage in one direction.

Matrix of clay mineral was indicated to be a mixture of illite and kaolinite minerals, light brown in plane polarized light (PPL) and grayish brown in crossed polarized light (XPL). Pleochroism is difficult to see because the mineral sizes are very small. Abundance of matrix composition was observed to be minimum of 37% and maximum of 68% with average of 51%. Data on the abundance of sandstone material is shown in Table 3.

Table 3 Data of petrographic observation

ID	Abundance (%)			
	Quartz	Feldspar	Organic carbon	Clay mineral (matrix)
S1	50	2	11	37
S2	35	2	4	59
S3	50	2	4	44
S4	48	1	14	37
S5	33	2	8	57
S7	39	-	6	55
S8	25	-	7	68

Next, calculation was made to determine the classification of sandstones. The components used as parameters are quartz (Q), feldspar (F), and rock/lithic fragment (L) associated with the percentage of matrix abundance (Table 4).

According to the Pettijohn classification of sandstones in 1975 [29] and based on petrographic analysis of the thin sections, the Warukin Formation

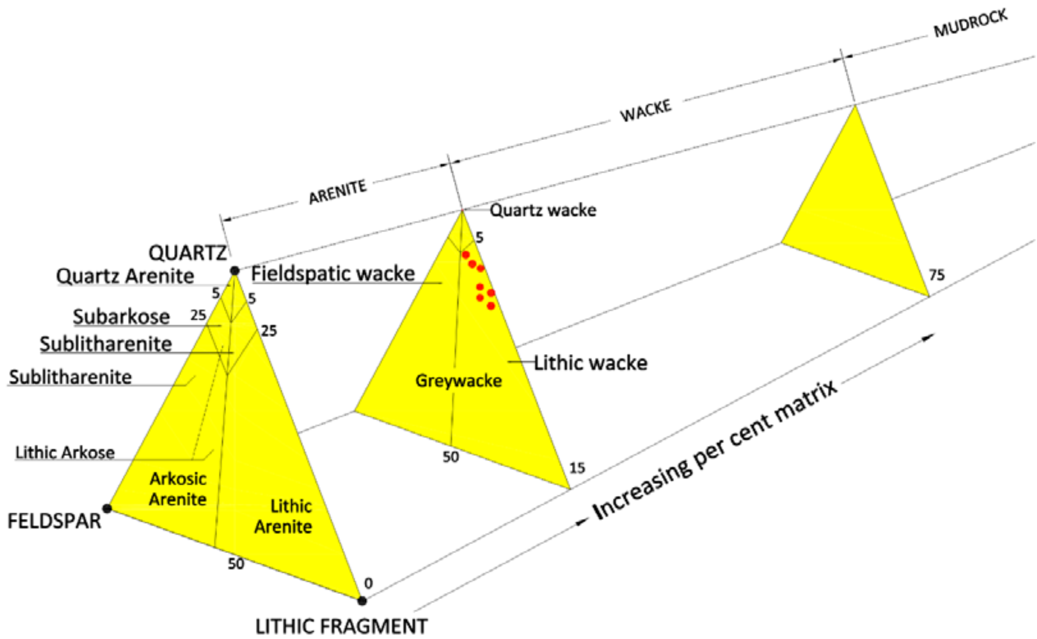


Fig.3 Classification of Warukin sandstones according to the classification by Pettijohn 1975.

sandstones are classified in the greywacke category as lithic wacke (Figure 3).

Table 4 Percentage of Q, F, and L from petrographic observation

ID	Abundance (%)		
	Quartz	Feldspar	Rock/lithic
S1	79.37	3.17	17.46
S2	85.37	4.88	9.76
S3	89.29	3.57	7.14
S4	76.19	1.59	22.22
S5	76.74	4.65	18.60
S7	86.67	0.00	13.33
S8	78.13	0.00	21.88

The presence of coal lithic fragment in the Warukin sandstones indicates that the constituent material of the Warukin sandstones comes from older sedimentary rocks.

3.2 Provenance Analysis

Provenance determination of sedimentary material from a sedimentary rock can be done by identifying the relationship of clastic sediment compositions to genesis and tectonic position. This is due to the fact that the genesis of sedimentary rock formation at certain tectonic position (provenance environment) can influence the composition of fragments and minerals in the rock. Thus, the determination of provenance environment can be done based on the result of mineral composition analysis.

By using the results of petrographic observation, determination of sandstone provenance can be done. The classification that will be used to determine provenance is the classification by Dickinson and Suczek [2].There are several types of provenance that are continental block, magmatic arc, and recycled orogen [3].

Continental block is divided into three parts namely craton interior which tends to originate from granite and sometimes gneiss and have a high percentage of Qm/Qp composition, transitional continental, and basement uplift which most of the sandstones are arkose and quartzofeldspathic.

In magmatic arc, the sandstones consist of volcanic and plutonic material derived from stratovolcano in the form of arkose and siliceous mixture. Magmatic arc divided into dissected arc, transitional arc, and undissected arc. Rocks in the dissected arc have quartzofeldspathic composition that composes volcano-plutonic sandstone originating from batholith which is exposed due to erosion. Materials from the undissected arc have abundant amount of rock fragments in the form of volcanic sandstone, whereas the transitional arc contains a few rock fragments.

Recycled orogen includes subduction zone in the form of a folded isoclinal zone and a mélange zone along the tectonic area between ocean trench and fore-arc basin. Back-arc basin zone shows folded sedimentation zone and metasediment originating from continents. Collision zone of micro-crust shows the nature of oceanic and continental plates.

Parameters used for classification are quartz (Qt = Qm + Qp), feldspar (plagioclase + K-feldspar), and rock fragments (Lv, Ls, Lm). Based on petrographic observation, the only quartz found is

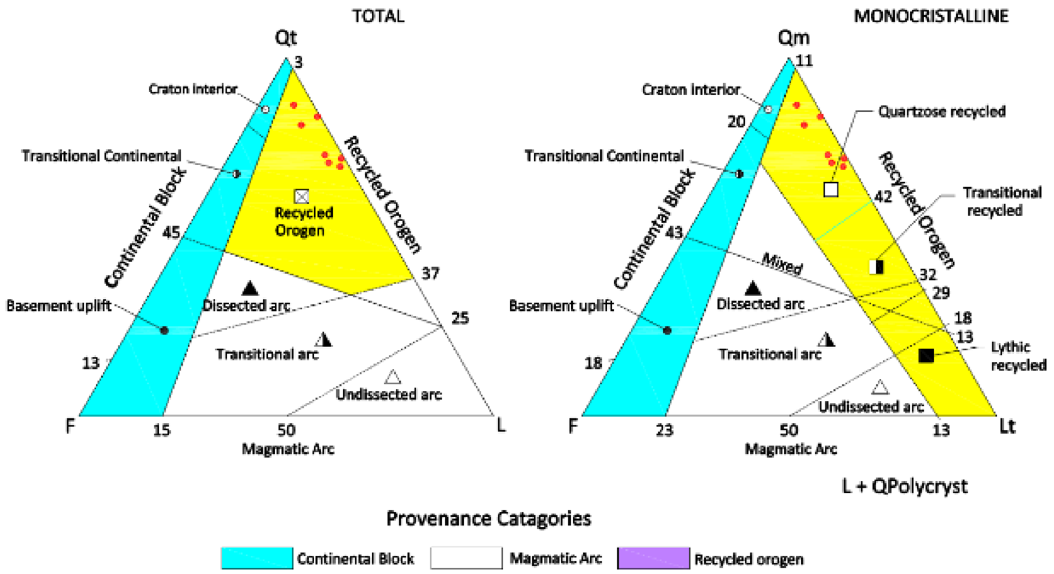


Fig.4 Provenance classification of Warukin sandstones

monocrystalline quartz (Qm), lithic is disintegration product of coal (Ls), and feldspar is in a very limited amount (F); it can refer to Table 4. The data then was plotted into Q-F-L ternary diagram of Dickinson and Suczek [2]. According to the classification, provenance of Warukin standstones is generally recycled orogen with subclassification of quartzose recycled (Figure 4).

3.3 Geomechanical Analysis

To define the geomechanical characteristics of the Warukin Formation, geomechanical testing was carried out on 23 sandstone samples in the in-situ condition from the result of rock core drilling by correlation and interpretation based on stratigraphic position of the rock layers. Geomechanical characteristics of rocks reflect how the physical and mechanical characteristics of rocks. The analysis focuses on the density, cohesion, and internal friction angle obtained from triaxial test as well as compressive strength and axial strain obtained from uniaxial test.

Based on the results of geomechanical test on the rock core samples of Warukin sandstones, it is known from the physical property test that the wet density (ρ_w) ranges from 1.99 g/cm^3 to 2.19 g/cm^3 with an average of 2.10 g/cm^3. The saturated density (ρ_s) ranges from 2.02 g/cm^3 to 2.19 g/cm^3 with an average of 2.12 g/cm^3. From the triaxial test results, the cohesion (C) value ranges from 81.91 kPa to 99.28 kPa with an average of 91.75 kPa. The internal friction angle (ϴ) ranges from 27.13° to 29.85° with an average of 28.39°. From the uniaxial test results, the compressive strength (σ) ranges from 556.12 kPa to 659.48 kPa with an average of 617.70 kPa. The axial strain ranges from 6.96% to 7.94% with an average of 7.59%. Tabulation of the geomechanical test results are shown in Table 5.

Table 5 The physical and mechanical properties of sandstones that have not been exposed

ID	C (kPa)	ϴ (°)	ρ_w (g/cm^3)	σ_u (kPa)	ε (%)
S1	81.91	27.54	2.12	605.71	7.67
S2	91.59	29.26	2.13	582.70	7.65
S3	92.69	27.13	2.05	623.91	7.64
S4	95.33	27.56	2.13	659.48	7.94
S5	89.45	27.93	2.19	556.12	6.96
S7	91.97	29.47	2.11	648.87	7.66
S8	99.28	29.85	1.99	647.07	7.60

Geomechanically, sandstone of the Warukin Formation is very soft with the rock strength of less than 1 MPa. The cohesion is less than 100 kPa and the internal friction angle is less than 30° with maximum difference in water content between saturated and wet (natural) condition of 0.03 g/cm^3. Technically, a relatively gently sloping slope condition (<30°) is required to maintain safety.

3.4 Geochemical Analysis

To chemically find out the mineral content, XRD (X-Ray Diffraction) test was carried out by utilizing the X-ray wave bias. In the XRD test, estimated wave phase and mineral interpretation were obtained by using the Reference Intensity Ratio (RIR).

The minerals in the chemical compound observed in the XRD test are as follows:
Quartz (SiO_2)
Orthoclase (K, Si_3 (AlO_8))
Muscovite (KAl_{22} ($AlSi_3O_{10}$) $(OH)_2$)
Kaolinite ($Al_3Si_2O_5$ $(OH)_4$)
Fayalite ((Fe, MG)$_2$, SiO_4)

Interpretation based on the XRD test shows that the sandstone of Warukin Formation is composed by quartz of 83-100%, feldspar (orthoclase) of 0-3%, mica (muscovite) of 0-4%, and clay minerals (kaolinite) of 0-11%. Some are seen as coal fragment or other material that is not observed, as the component value lost by ignition (Loss on Ignition or LOI) of 1.55-10.21%. The XRD test result is shown in Table 6.

Table 6 XRD test result

ID	XRD – Identified Mineral/Phase (%)						
	LOI %	Quartz	Orthoclas	Mucovit	Kaolinite	Fayalite	Total
S1	10.21	83	3	4	6	4	100
S2	0.50	100	-	-	-	-	100
S3	3.90	97	-	3	-	-	100
S4	6.49	92	-	-	8	-	100
S5	6.20	94	-	-	6	-	100
S7	7.84	82	3	4	11	4	100
S8	1.55	100	-	-	-	-	100

4. CONCLUSION

1. According to the Pettijohn classification of sandstones and based on petrographic analysis of the thin sections, the Warukin Formation sandstones are classified in the greywacke category as lithic wacke.
2. According to the classification by Dickinson and Suczek, provenance of Warukin standstones is generally recycled orogen with subclassification of quartzose recycled.

3. The constituent material of the Warukin sandstones comes from older sedimentary rocks. It is indicated by the presence of coal lithic fragment observed from petrographic observation.
4. Interpretation based on the XRD test shows that the dominant constituent material of sandstones is quartz (SiO_2), with other constituent minerals such as orthoclase (K, Si_3 (AlO_8)), muscovite (KAl_{22} ($AlSi_3O_{10}$) $(OH)_2$), kaolinite ($Al_3Si_2O_5$ $(OH)_4$), and fayalite ((Fe, MG)$_2$, SiO_4) are found only in one sample.
5. Geomechanically, sandstone of the Warukin Formation is very soft with the rock strength of less than 1 MPa. The cohesion is less than 100 kPa and the internal friction angle is less than 30° with maximum difference in water content between saturated and wet (natural) condition of 0.03 g/cm^3.

5. ACKNOWLEDGMENTS

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