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Provenance and Petrographic Analysis of Paleogene Sandstones in the Bukit Tigapuluh Area, Jambi Subbasin, Indonesia

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Abstract
The study investigates the provenance of Paleogene sandstone deposits from the Lemat Formation in the Lubuk Lawas and Lubuk Bernai sections of the Bukit Tigapuluh area, Jambi Subbasin, South Sumatra Basin, Indonesia. The research aims to elucidate the formation history and stratigraphic evolution of these sedimentary rocks through detailed petrographic analysis. Twenty-two rock samples were analyzed to classify the sandstones and determine their source rock types and tectonic settings. The results indicate that the sandstones are primarily classified as Lithic Arkose, Arkosic Subarkose, Feldspathic Litharenite, Silty Claystone, Sublitharenite, and Subarkosic Wacke. The provenance analysis suggests that these sandstones originated from a tectonic setting of a recycled orogenic zone, comprising quartzose recycled, transitional recycled, and mixed sources, indicating a combination of primary and recycled orogenic materials. Paleocurrent analysis from sedimentary structures in the Lubuk Bernai area suggests deposition directions from the southwest and southeast. This study provides significant insights into the paleogeography and tectonic evolution of the Lemat Formation within the Jambi Subbasin. Further research should focus on integrating geochemical data to refine the understanding of sedimentary provenance and tectonic implications.

1. Introduction

The study of sedimentary rock provenance is crucial for understanding the geological history and tectonic evolution of sedimentary basins. The Lemat Formation, located in the Bukit Tigapuluh area within the Jambi Subbasin of the South Sumatra Basin, represents a significant geological feature that has yet to be fully explored in terms of its sedimentary origin and stratigraphic evolution. The South Sumatra Basin, particularly the Jambi Subbasin, is characterized by complex stratigraphy and tectonic settings, which have been the subjects of numerous geological studies [1-2].

Previous research on the South Sumatra Basin has highlighted the intricate relationship between sedimentary processes and tectonic activity, which have collectively shaped the stratigraphic framework of the region [3-4]. The Lemat Formation, primarily composed of clastic sedimentary rocks ranging from mudstone to tuffaceous sandstone, presents an excellent case for provenance analysis to unravel the sedimentary processes and tectonic influences that contributed to its formation.

This study focuses on the Lubuk Lawas and Lubuk Bernai sections of the Bukit Tigapuluh area, aiming to provide a comprehensive petrographic analysis of the sandstones to determine their source rock types and tectonic settings. The provenance analysis employs petrographic methods to classify the sandstones and analyze their mineralogical compositions, which are essential for understanding the paleogeography and tectonic history of the region [5-6]. The primary objective of this research is to clarify the origin and depositional history of the Lemat Formation's sandstones by examining their petrographic characteristics and paleocurrent directions. This study will contribute to a better understanding of the stratigraphic relationships within the South Sumatra Basin and provide insights into the regional tectonic evolution. By integrating petrographic data with sedimentary structure analysis, we aim to elucidate the sedimentary processes and tectonic settings that have shaped the Bukit Tigapuluh area, offering new perspectives on the geological history of the Jambi Subbasin.

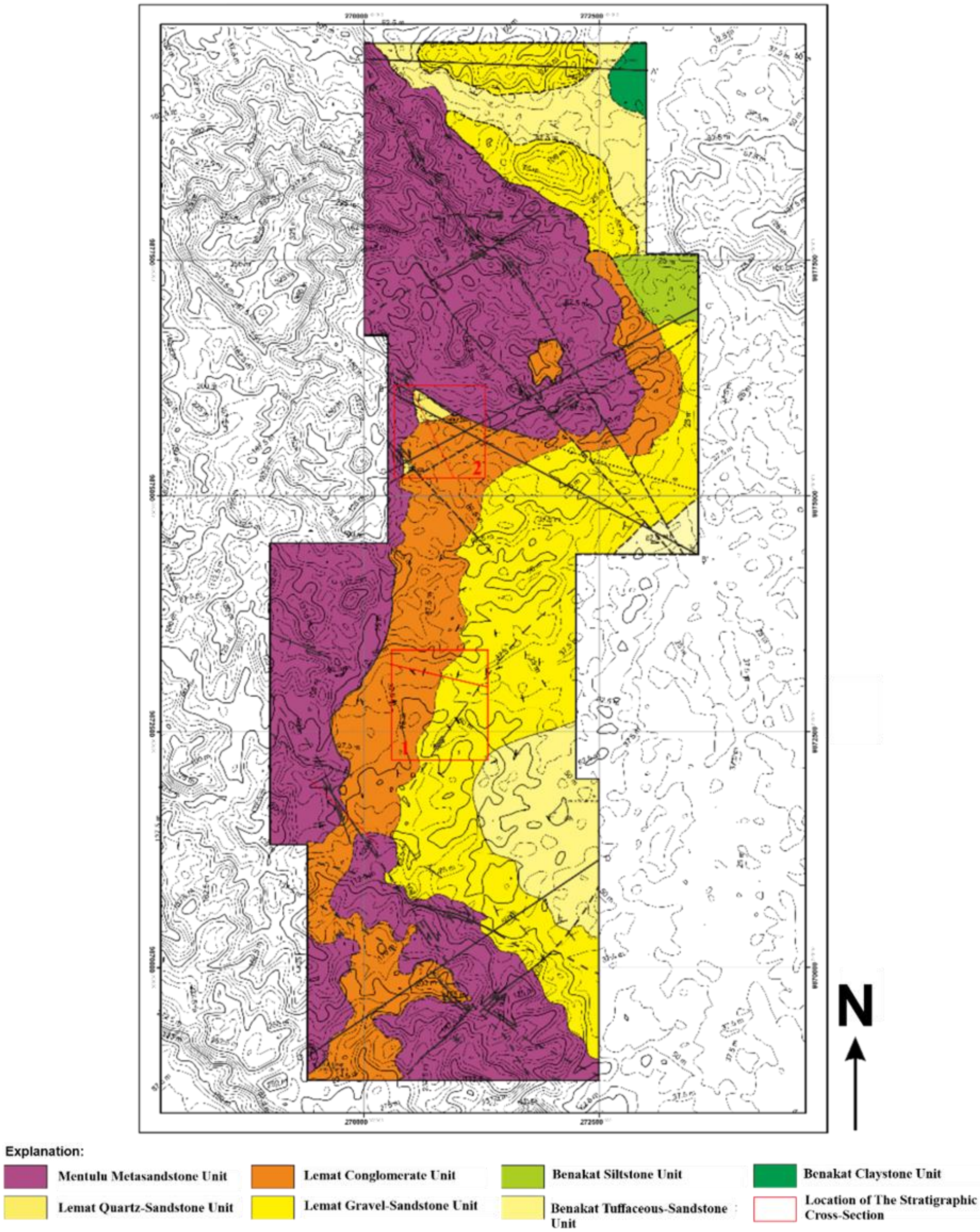

Figure 1. Geological map of the research area, Bukit Tigapuluh National Park, West Tanjung Jabung Regency, Jambi Province

2. Regional geology

The South Sumatra Basin, prominently located onshore in Sumatra, Indonesia, represents a significant geological entity characterized by its complex stratigraphy and tectonic history. The Jambi Subbasin, situated within the northern part of the South Sumatra Basin (see Figure 1), is bounded by notable geological features: the Tigapuluh Mountains to the north, the Twelve Mountains to the south, the Barisan Mountains to the west, and the Sunda Shelf to the east [7].

The stratigraphic framework of the South Sumatra Basin comprises a sequence of sedimentary units that reflect a comprehensive sedimentation cycle. This cycle begins with a transgressive phase followed by a regressive phase. The detailed stratigraphy includes the Pre-Tertiary rocks at the base, followed by the Kikim Formation, Lahat Group (including the Lemat and Benakat Formations), Telisa Group, Tanjung Baru Formation, Talangakar Formation, Gumai Formation, and Baturaja Formation. The Palembang Group, comprising the Air Benakat Formation, Muara Enim Formation, and Kasai Formation, overlays these units, culminating in Quaternary deposits [6,8].

The Lemat Formation, central to this study, is interpreted as an Early Oligocene syn-rift sequence deposited in paleo-lows or grabens. This formation, predominantly composed of non-marine sandstone, siltstone, and shale, transitions into shale towards deeper basins and contains tuffaceous materials in certain areas [1].

The South Sumatra Basin's tectonic evolution is marked by its position as a back-arc basin, influenced by the subduction of the Indo-Australian Plate beneath the Eurasian Plate. This tectonic interaction has led to the development of various structural patterns, including the Sunda Pattern (North-South trend), Lematang Pattern (West-Northwest to East-Southeast trend), Jambi Pattern (Northeast-Southwest trend), and Sumatra Pattern (Southeast-Northwest trend) [3]. The island of Sumatra itself is a product of the accretion and suturing of microcontinents during the late Pre-Tertiary period, leading to the formation of its present-day geological structure [1,3]

The provenance analysis of the Lemat Formation sandstones in the Lubuk Lawas and Lubuk Bernai areas indicates a complex depositional environment influenced by a combination of primary source rocks and recycled orogens. The presence of quartz, feldspar, and lithic fragments points to a tectonic setting of a recycled orogenic zone, with contributions from volcanic, sedimentary, and metamorphic sources [5].

Paleocurrent analysis from sedimentary structures in these areas suggests that the sandstones were deposited from directions ranging from the southwest to the northeast and the southeast to the northwest, indicating a dynamic depositional environment influenced by fluvial processes.

3. Methodology

Field mapping was carried out in the Bukit Tigapuluh area, West Tanjung Jabung Regency, and Jambi (Figure 1), especially in the Lubuk Lawas and Lubuk Bernai areas. Twenty-two rock samples consisting of black limestone, carbonaceous siltstone, tuffaceous siltstone, carbonaceous sandstone, and tuffaceous sandstone were selected for provenance, and petrographic analysis. The samples were collected using a purposive sampling method (a determination samples technique with specific considerations that are considered representative of the existing population) in measured stratigraphic sections. There are two measured stratigraphic sections, namely the stratigraphic section of the Lubuk Lawas area containing 12 samples (Figure 2) and the stratigraphic section of the Lubuk Bernai area containing ten rock samples (Figures 2 and 3).

Table 1. Parameters used

Q	Quartz
Qm	Monocrystalline quartz
Qp	Polycrystalline quartz
F	Total feldspar grains (Plagioclas + Kfeldspar)
L	Lithic fragments (Lv + Ls + Lsm)
Lt	L + Polycrystalline quartz

Detailed lithology analysis was conducted using the petrographic thin section method, which was observed based on cross Nicol and parallel Nicol. Provenance analysis of sandstone was carried out by counting grain compositions of quartz (Q), feldspar (F), and rock fragments (L), with a grain size of >0.03 mm and a total of grains >300 [5]. Plotting the percentage composition of QFL referred to the ternary classification diagram of [5].

The QFL plot technique used to classify sandstones has been carried out based on Folk (1980). The main detrital components of the rock samples were quantified and normalized to 100% (Tables 2 and 3). Quartz, feldspar, and lithic fragment (QFL) diagrams were plotted as in [5] (Figures 7 and 8). Quartz grains identified in rock fragments were monocrystalline and polycrystalline quartz. Feldspars were subdivided into alkali feldspars (orthoclase and microcline) and plagioclase, with the latter being the most common type. The identified lithics were divided into sedimentary, volcanic, and metamorphic lithics.

This study employs a comprehensive methodology to investigate the provenance and depositional history of Paleogene sandstone deposits from the Lemat Formation in the Lubuk Lawas and Lubuk Bernai sections of the Bukit Tigapuluh area, Jambi Subbasin, South Sumatra Basin. The following steps outline the research methodology:

Field Mapping and Sample Collection
Fieldwork was conducted in the Bukit Tigapuluh area, focusing on the Lubuk Lawas and Lubuk Bernai sections. Detailed field mapping was performed to document the geological features and stratigraphy of the area. A total of twenty-two rock samples, including black limestone, carbonaceous siltstone, tuffaceous siltstone, carbonaceous sandstone, and tuffaceous sandstone, were collected using purposive sampling. This method ensures that the samples are representative of the existing population and stratigraphic sections.

Stratigraphic Section Measurement
Two stratigraphic sections were measured to detail the vertical distribution of rock units. The Lubuk Lawas section contained twelve samples, while the Lubuk Bernai section contained ten samples. The sampling points were marked on the stratigraphic columns to provide a clear reference for the analysis.

Petrographic Analysis
Petrographic thin sections of the collected samples were prepared and observed under a microscope using both cross-polarized (cross Nicol) and plane-polarized (parallel Nicol) light. The petrographic analysis aimed to identify and quantify the mineralogical composition and texture of the sandstones. Key parameters analyzed include quartz (Q), feldspar (F), and lithic fragments (L). The quartz was further categorized into monocrystalline quartz (Qm) and polycrystalline quartz (Qp), while lithic fragments were divided into volcanic, sedimentary, and metamorphic lithics (see Table 1).

Provenance Analysis
The provenance of the sandstones was determined using the [5] QFL (quartz, feldspar, lithic fragments) ternary diagrams. The composition of the samples was plotted on QFL and QmFLt (monocrystalline quartz, feldspar, total lithic fragments) diagrams to classify the sandstones and infer their tectonic settings. The classification followed [9] sandstone classification system, and the results were normalized to 100% for comparison.

Paleocurrent Analysis
Sedimentary structures, such as cross-bedding, were analyzed to infer paleocurrent directions. The orientation of these structures provided insights into the ancient depositional environment and current directions during the time of sedimentation. Measurements were taken at various angles, and the data were plotted to identify predominant paleocurrent directions.

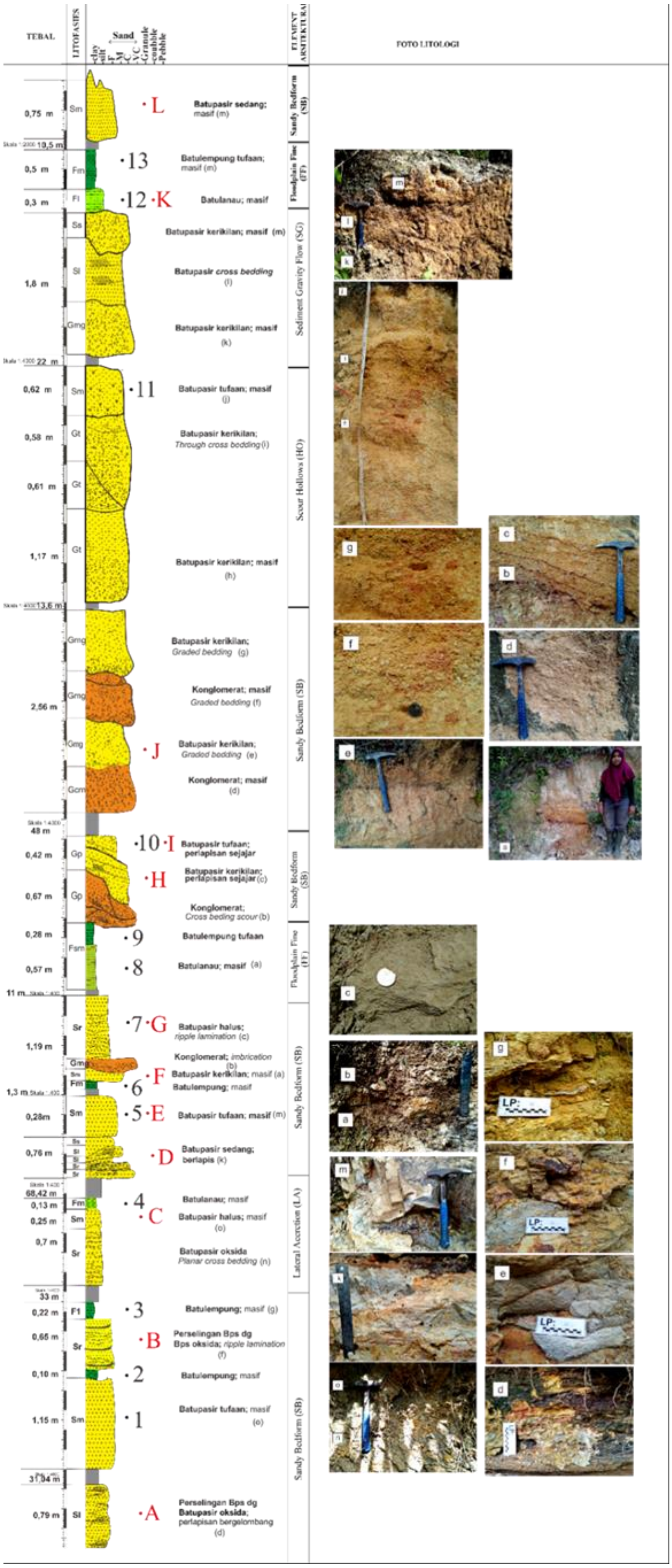

Figure 2. Stratigraphic section 1 of conglomerate and sandstone deposits in the Lubuk Lawas. Red letter on the stratigraphic section showed a sampling point.

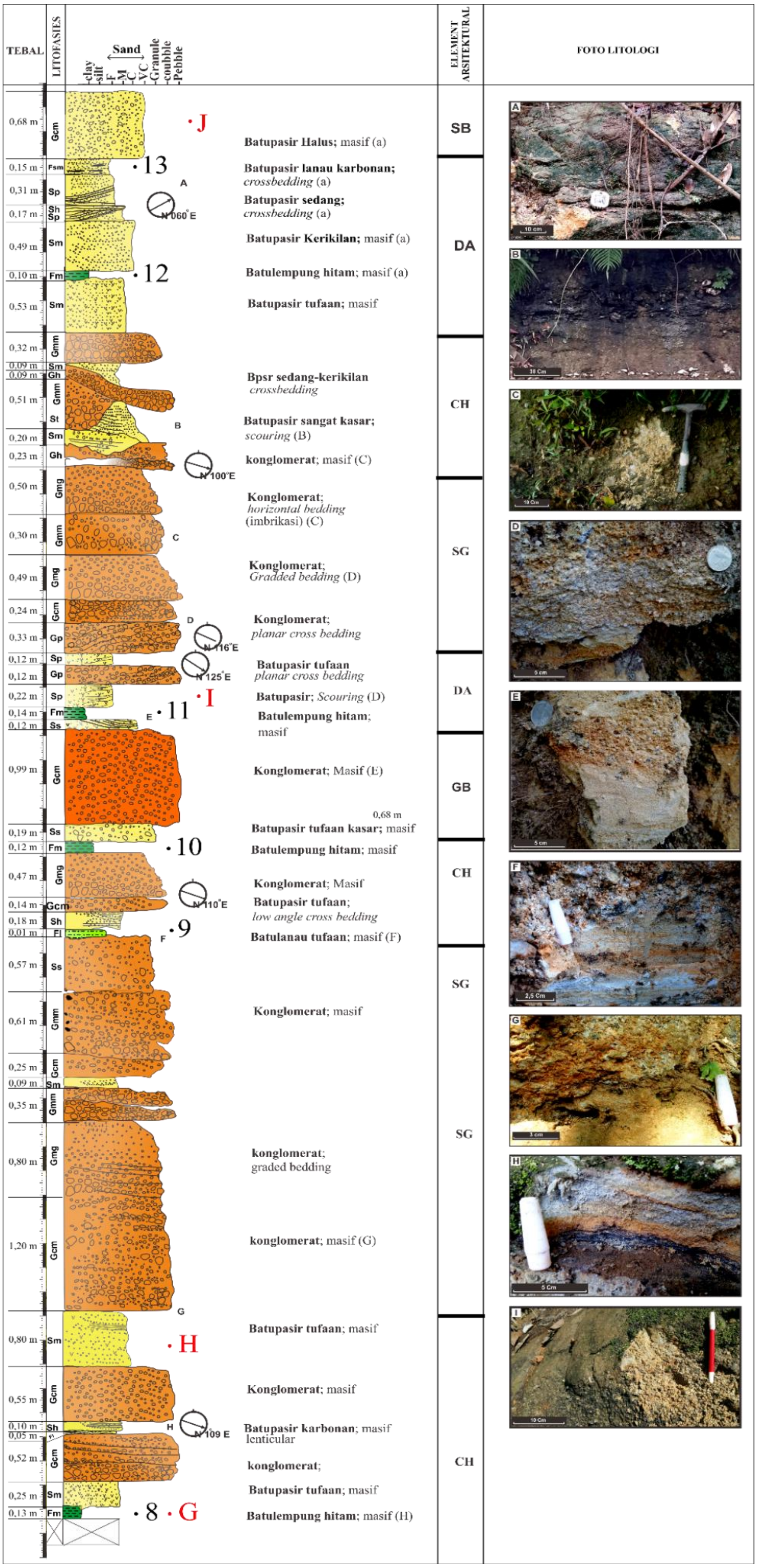

Figure 3. Stratigraphic section 2 of conglomerate and sandstone deposits in the Lubuk Bernai. Red letter on the stratigraphic section showed a sampling point.

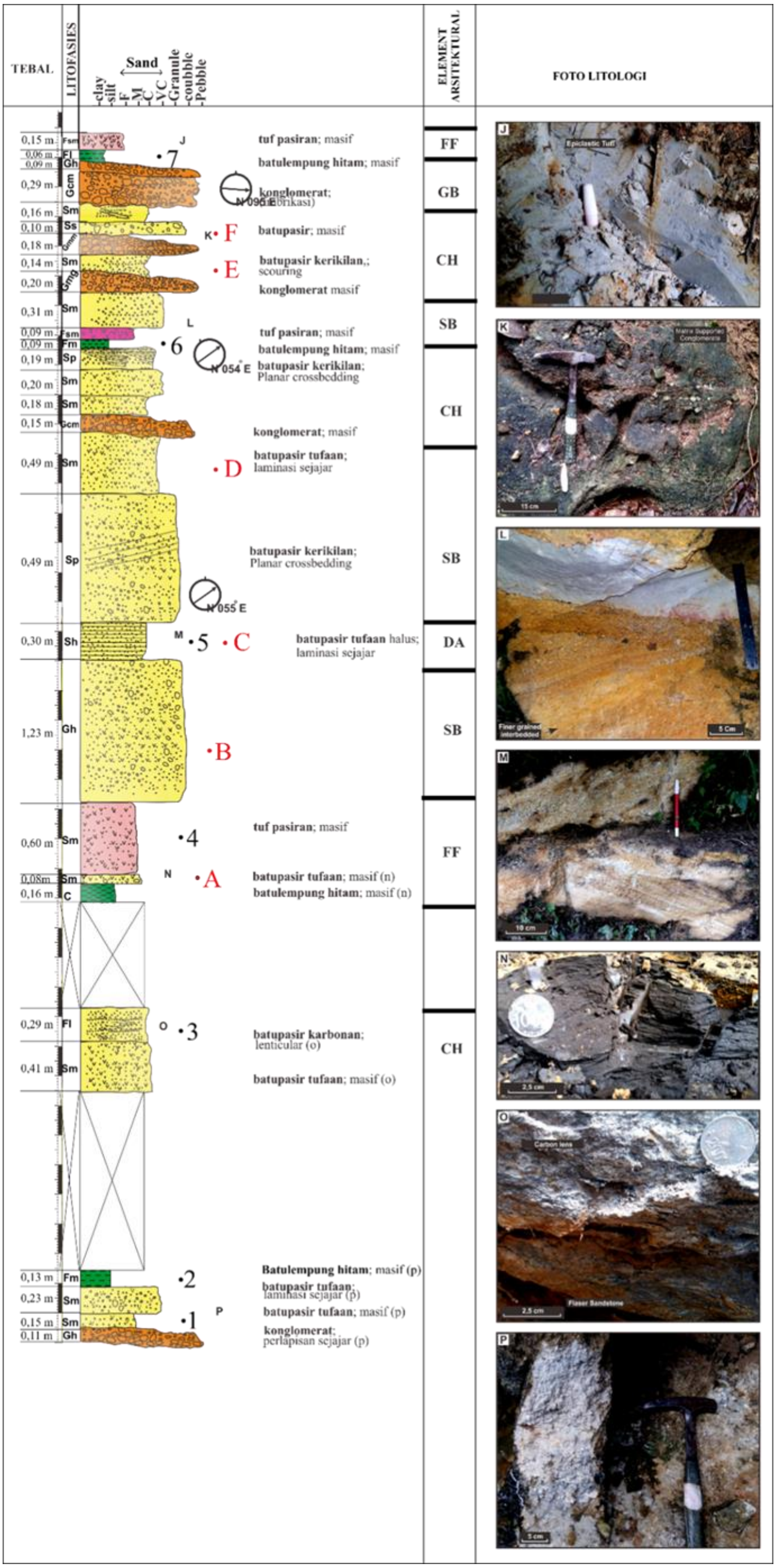

Figure 4. Continued stratigraphic section 2 of conglomerate and sandstone deposits in the Lubuk Bernai. Red letter on the stratigraphic section showed a sampling point

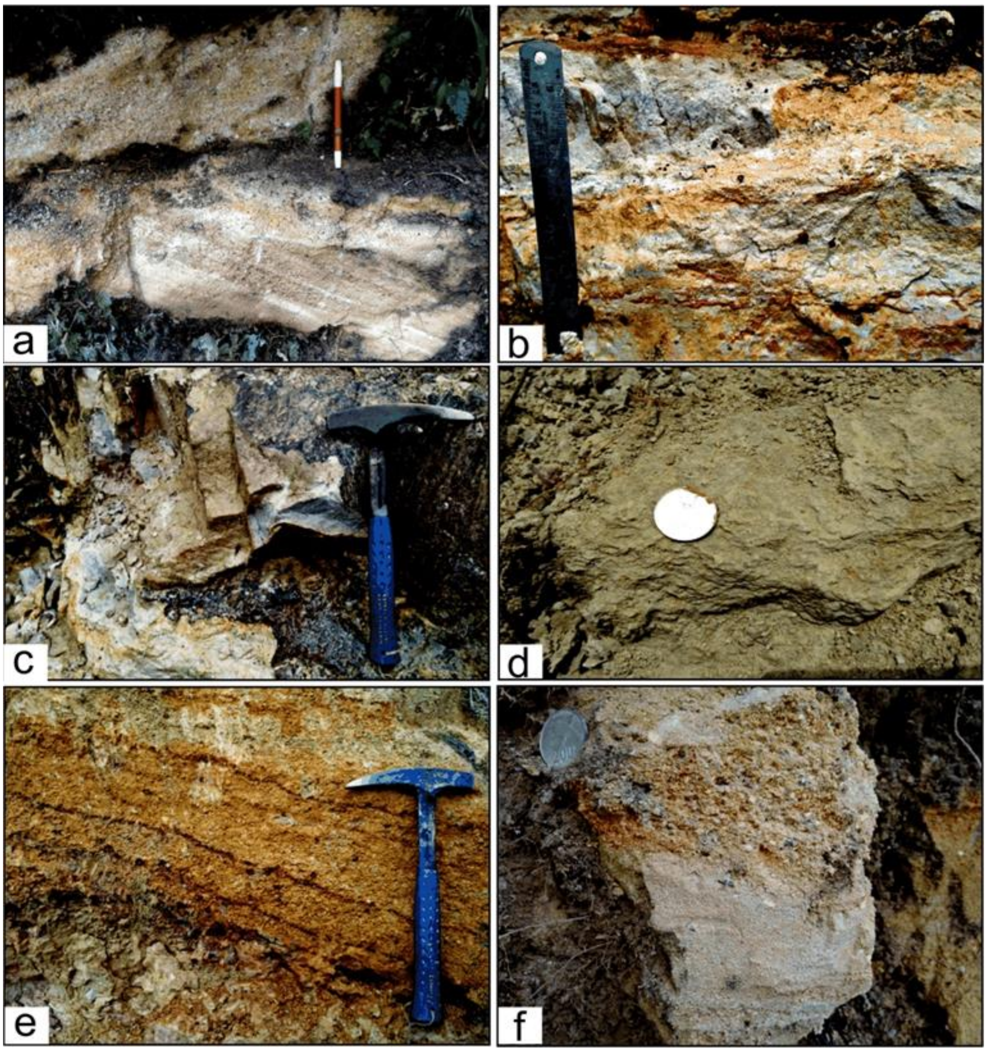

Figure 5. (a) Sandstone with planar crossbedding structure; (b) medium sandstone with a layered structure; (c) Tuff sandstone with a massive structure, (d) Fine sandstone with a ripple laminated structure, (e) Pebble sandstone with a parallel bedding structure, (f) conglomerate of massive structure (top part) and coarse tuffaceous sandstone with massive structure (lower part).

Data Analysis and Interpretation

The collected petrographic and sedimentological data were analyzed to interpret the depositional environment and provenance of the sandstones. The results were compared with existing literature to contextualize the findings within the broader geological framework of the South Sumatra Basin. The tectonic implications of the provenance data were discussed in relation to the recycled orogenic zone identified in the study area.

4. Results and discussions

Petrographic Analysis

The sandstones studied in the Lubuk Lawas and Lubuk Bernai areas mainly consisted of Quartz and lithic fragments (Figure 4). Quartz was mostly monocrystalline grains with a smaller amount of polycrystalline Quartz and was angular to a rounded shape and showed point contact. Lithic fragments mostly came from sedimentary and volcanic lithics. Chert fragment, granitic type, and metaquartzite were observed in almost all rock samples, and calcite cement was present in some samples (Figure 6). The classification of sandstone in the Lubuk Lawas and Lubuk Bernai areas was Lithic arkose, Arkosic, Subarkose, Feldspathic litharenite, Silty claystone, Sublitharenite, and Subarkosic wacke [9].

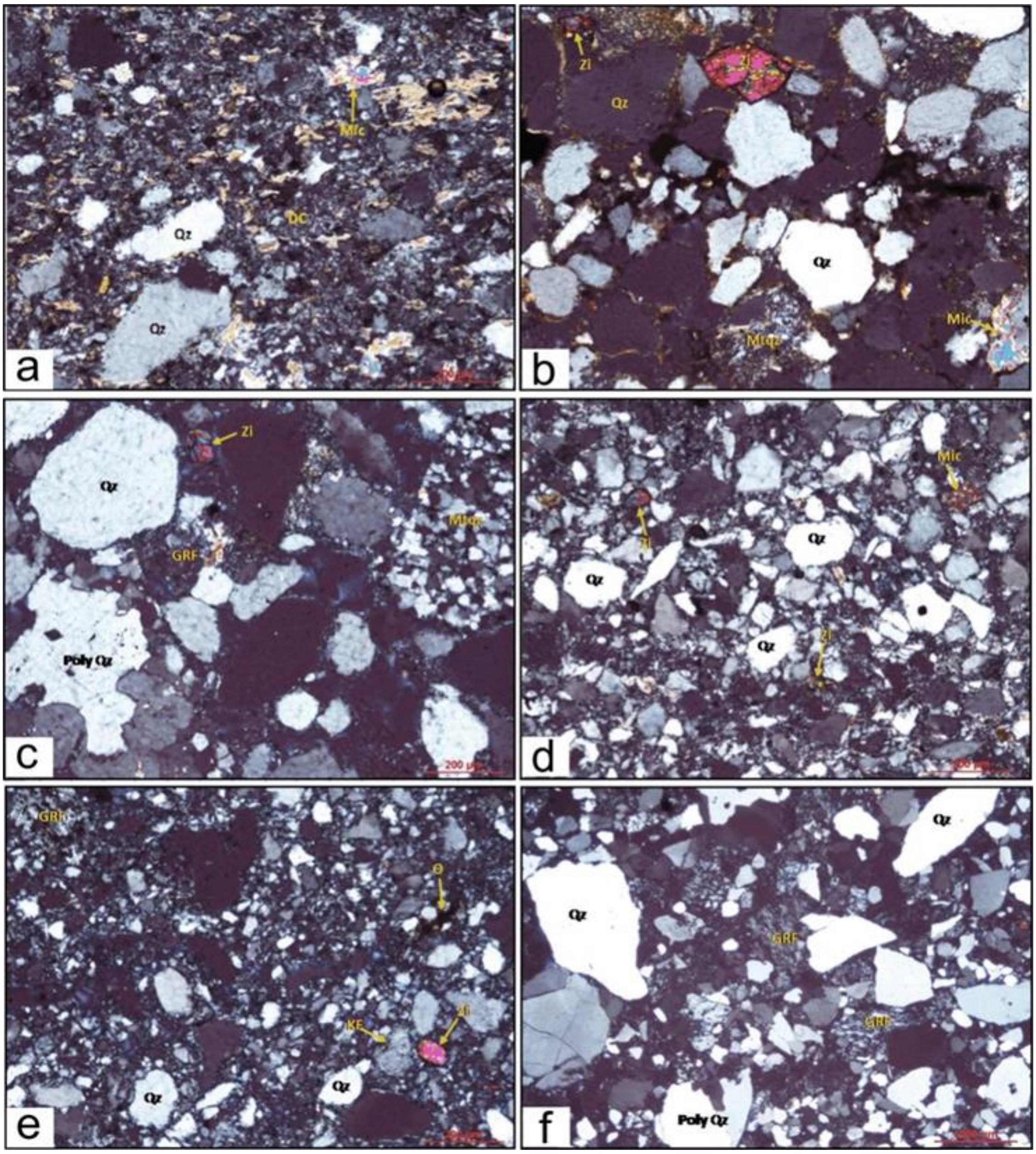

Figure 6. Petrography picture of selected sandstone: (a) Arkose. Various lithics could be observed: limestone rock fragments (LI), metamorphic rock fragments (Lm), volcanic rock fragments (Lv) with plagioclase (PI) and monocrystalline quartz (Qz). (b) Lithic arkose (c) Sublitharenite. (d) Subarcosic wacke (e) Arkose (f) Subarcosic.

Data from petrographic analysis of all samples are presented. The observed quartz composition showed monocrystalline and polycrystalline types. The percentage of total quartz mineral composition varied by 32.71% - 85%. This percentage was the most significant mineral present in the rock sample. Quartz grains were angular–subrounded. Monocrystalline quartz was the dominant type of quartz, which probably came from plutonic and volcanic igneous rocks. Polycrystalline quartz was recrystallized quartz, most likely originating from metamorphic rocks.

Feldspar had a percentage of 5.9% - 30.51%; this percentage was the lowest compared to quartz and lithic. K-feldspar was a feldspar that was more dominant than plagioclase in all rock samples. The percentage of feldspar that was less than quartz and lithic indicated that the rock had been transported, so the feldspar group minerals had experienced a lot of weathering.

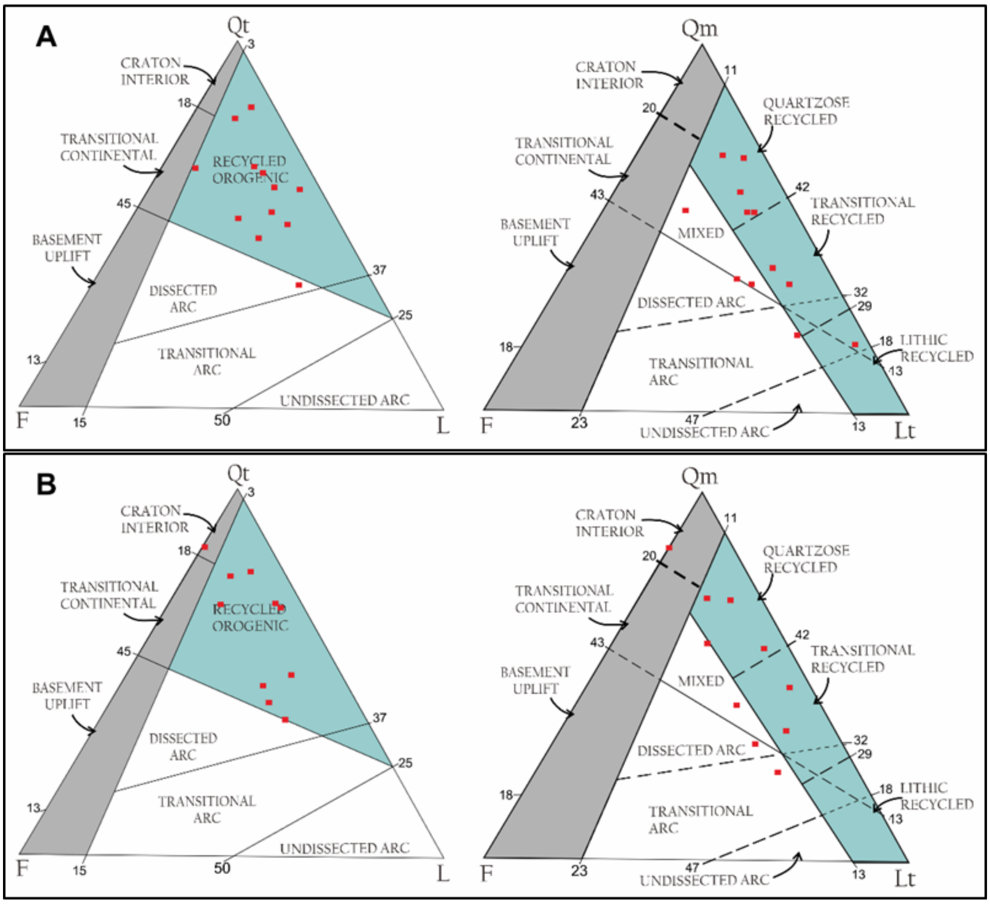

Figure 7 (top). QFL and QmFLt diagrams showed the average tectonic origin of sandstone in the Lubuk Lawas [5]. **Figure 8 (bottom).** QFL and QmFLt diagrams showed the average tectonic origin of sandstone in the Lubuk Bernai [5]

Rock Fragments (Lithic), with a percentage of 0.00% - 49.53%, were the second largest dendrites after quartz. The identified lithics were volcanic, sedimentary, and metamorphic lithics. The average number of lithics analyzed was almost even across all rock samples. Lithic sediments consisted of chert, sandstone, and mudstone. Volcanic lithics consisted of volcanic rock and granite. Metamorphic lithics consisted of Metaquartzite and Schist.

The petrographic analysis of sandstone samples from the Lubuk Lawas and Lubuk Bernai areas revealed that the sandstones are predominantly composed of quartz and lithic fragments, with varying amounts of feldspar. The quartz grains are primarily monocrystalline, with a minor proportion of polycrystalline quartz, indicating a significant contribution from igneous and metamorphic source rocks. The quartz grains are angular to sub-rounded, suggesting limited transport and reworking. Lithic fragments include volcanic, sedimentary, and metamorphic lithics, with a notable presence of chert, granitic fragments, and metaquartzite. The feldspar content, predominantly K-feldspar, indicates a relatively low degree of weathering and transport, supporting the inference of proximal source areas [5]. The sandstones are classified into several categories based on their composition: Lithic Arkose, Arkosic Subarkose, Feldspathic Litharenite, Silty Claystone, Sublitharenite, and Subarkosic Wacke. The classification aligns with the petrographic observations, confirming a diverse sedimentary environment influenced by multiple source rock types.

Figure 9. (a) Cross bedding sedimentary structure in the direction of N 55° E **(b)** low angel cross bedding sedimentary structure in the direction of N 110° E **(c)** planar crossbedding sedimentary structure in the direction of N 125° E.

Provenance Analysis

The presence of abundant quartz grains with indications of straight extinction indicated that granite was the constituent rock in the source area (Figure 6). Quartz grains with undulose extinction and inclusions were indicated to originate from metamorphic source areas. K-feldspar and plagioclase fragments showed that the source area originates from igneous rocks. Sedimentary and metamorphic fragments also indicated the presence of metasediments and metamorphs in the source area.

[5] proposed that the average composition of sandstone grains originating from different types of locality controlled by plate tectonic processes can be plotted in QFL (quartz, feldspar, lithic fragments) and QmFLt (monocrystalline quartz, feldspar, total fragments lytic). Analysis of samples from the Lubuk Lawas and Lubuk Bernai areas is presented in Table 2 and Table 3. QFL and QmFLt diagram plots showed that the results of the 22 plotted samples showed provenance originating from the tectonic setting of the recycled orogenic zone (Figure 7). The QmFLt plot showed that the samples appeared to be spread across sub-zones, from recycled quartzose, transitional recycled, and mixed, indicating a mixture of primary source rocks and recycled orogens.

The provenance analysis using QFL and QmFLt ternary diagrams [5] indicates that the sandstones were derived from a recycled orogenic zone. The samples plot within the fields of quartzose recycled, transitional recycled, and mixed provenance, suggesting a mixture of primary source rocks and recycled orogens. The presence of abundant monocrystalline quartz with straight extinction suggests a significant contribution from granitic rocks, while polycrystalline quartz with undulate extinction and inclusions points to a metamorphic origin.

The feldspar and lithic fragment compositions further support the mixed provenance, with contributions from igneous, sedimentary, and metamorphic rocks. The presence of volcanic lithics indicates active tectonic processes, such as volcanic arc activity, contributing to the sediment supply. The diverse provenance suggests a complex tectonic setting, with multiple orogenic cycles influencing sediment deposition [5-6].

Recent studies have highlighted similar provenance characteristics in other regions, such as the Rampong Formation in Aceh [10] and the Sinamar Formation in Jambi [11], where mixed provenance and complex tectonic settings have been identified. Additionally, the work by [12] on volcanic evidence in the Mengkarang area supports the presence of significant volcanic contributions to the sedimentary deposits in the region.

Paleocurrent Analysis

Observed sedimentary structures were used to infer ancient currents from deposition. From the sedimentary structure in the form of crossbedding in the direction of N 55^{O} E, low angel crossbedding in the direction of N 110^{O} E, plannar crossbedding in the direction of N 125^{O} E in the Lubuk Bernai sandstone, it was deposited from the southwest to the northeast (Figure 8a) and from the southeast to the northwest. (Figures 8b and 8c) which were probably deposited by water media.

The analysis of sedimentary structures, including cross-bedding, reveals predominant paleocurrent directions from the southwest and southeast. These directions suggest that the sandstones were deposited by fluvial processes, with sediment transported from elevated source areas to the depositional basin. The paleocurrent data align with the petrographic and provenance analysis, supporting the interpretation of a tectonically active region with significant sediment reworking and transport.

Tectonic Implications

The tectonic setting of the Lubuk Lawas and Lubuk Bernai areas, as inferred from the petrographic and provenance analysis, is indicative of a recycled orogenic zone. The presence of multiple lithic fragments, including chert, volcanic, and metamorphic lithics, suggests a tectonically complex region influenced by both active and passive margin processes. The sandstone compositions reflect a dynamic geological environment with contributions from different tectonic settings, including volcanic arcs and collisional orogens [1].

Comparative studies have shown similar tectonic influences in other regions, such as the basin modeling of the Jambi Subbasin by [13] and the petrogenesis of pre-Tertiary granitoids in Jambi, which highlights the region's complex tectonic history and its implications for sediment deposition [14]. Additionally, this study's findings align with previous research on the geological history and tectonic evolution of the South Sumatra Basin. For instance, [12] highlighted the significance of volcanic evidence in the Jambi Province, supporting the presence of volcanic lithics in the studied samples. Similarly, [10] emphasized the importance of provenance analysis in understanding sedimentary formations, which corroborates our approach and findings.

[13] conducted basin modeling in the Jambi Subbasin, underscoring the tectonic complexities that influence sediment deposition. Our study further elaborates on these complexities by providing detailed petrographic and provenance data. [14] discussed the petrogenesis of granitoids in the Jambi area, which aligns with our identification of granitic fragments in the sandstone samples, indicating a granitoid source. [15] and [16] provided insights into the provenance and paleoclimate analysis of sedimentary formations, which is crucial for interpreting the depositional history and tectonic settings of our study area. [17] and [18] emphasized the significance of detailed petrographic studies in understanding the provenance and basin origin, reinforcing the methodology and findings of our research.

The study's findings contribute to the understanding of the stratigraphic and tectonic evolution of the South Sumatra Basin, particularly the Jambi Subbasin. The integration of petrographic, provenance, and paleocurrent data provides a comprehensive picture of the depositional environment and tectonic history, highlighting the importance of multidisciplinary approaches in geological studies. Future research should focus on integrating geochemical data to further refine the understanding of sedimentary provenance and tectonic implications [19].

5. Conclusion

This study provides a comprehensive analysis of the provenance, petrography, and tectonic setting of Paleogene sandstones from the Lubuk Lawas and Lubuk Bernai sections of the Lemat Formation in the Bukit Tigapuluh area, Jambi Subbasin. The findings contribute significantly to the understanding of the sedimentary processes and geological history of the South Sumatra Basin.

The petrographic analysis reveals that the sandstones are predominantly composed of quartz and lithic fragments, with varying amounts of feldspar. The quartz grains are primarily monocrystalline, indicating significant contributions from igneous and metamorphic source rocks. The angular to sub-rounded nature of the quartz grains suggests limited transport and reworking, supporting a proximal source origin. The diverse lithic fragments, including volcanic, sedimentary, and metamorphic lithics, reflect a complex depositional environment influenced by multiple tectonic processes.

Provenance analysis using QFL and QmFLt ternary diagrams indicates that the sandstones were derived from a recycled orogenic zone, characterized by contributions from both primary and recycled orogens.

This complex provenance suggests a tectonically active setting with significant sediment reworking and transport. The presence of volcanic lithics supports the influence of volcanic arc activity in the sediment supply, corroborating findings from other regions such as the Rampong Formation in Aceh [10] and the Sinamar Formation in Jambi [11].

The paleocurrent analysis reveals predominant sediment transport directions from the southwest and southeast, indicative of fluvial depositional processes. This aligns with the petrographic and provenance data, reinforcing the interpretation of a dynamic depositional environment shaped by fluvial action and tectonic activity.

The tectonic implications of the study underscore the complexity of the South Sumatra Basin's geological history. The presence of various lithic fragments and the mixed provenance of the sandstones suggest a region influenced by both active and passive margin processes. This is consistent with the basin modeling of the Jambi Subbasin by [13] and the petrogenesis studies of pre-Tertiary granitoids in Jambi, which highlight the region's intricate tectonic evolution [14].

In conclusion, this study enhances the understanding of the provenance and tectonic setting of the Lemat Formation's sandstones, offering insights into the geological history and sedimentary processes of the South Sumatra Basin. The integration of petrographic, provenance, and paleocurrent analyses provides a holistic view of the depositional environment, emphasizing the importance of multidisciplinary approaches in geological research. Future studies should incorporate geochemical analyses and advanced modeling techniques to further refine the understanding of sedimentary provenance and tectonic implications. Additionally, comparative studies with similar formations in the region can provide broader insights into the geological evolution of Southeast Asia.

By expanding on these findings, researchers can better comprehend the geological complexities of the South Sumatra Basin and its significance in the broader context of regional geology. This study serves as a foundation for future research endeavors aimed at unraveling the intricate interplay between tectonics and sedimentation in one of Indonesia's most geologically intriguing regions.

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