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Provenance Analysis from Lemat Formation in Lubuk Lawas and Lubuk Bernai Areas, Jambi Subbasin, Jambi Province

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Abstract
The study of the sedimentary rocks from the Lemat Formation in Bukit Tigapuluh, particularly in the Lubuk Lawas and Lubuk Bernai Areas, aims to clarify and provide an overview of the formation's history and the evolution of Paleogene stratigraphy within the Jambi Subbasin. Provenance analysis was concluded using petrographic analysis to determine the classification of sandstone types, source rock characteristics and tectonic order. Sandstones in the Lubuk Lawas and Lubuk Bernai areas are classified into Lithic arkose, arkosic, subarkose, felspathic litharenite, silty claystone, sublitharenite and subarkosic wacke. Petrographic data revealed that these sandstones originated from a tectonic setting within the recycled orogenic zone, with sub-zones varying between quartzose recycled, transitional recycled and mixed. This variation indicates a combination of primary source rocks and recycled orogens. Paleocurrent data derived from the sedimentary structures of sandstones in the Lubuk Bernai area suggest deposition directions from the southwest and southeast.

1. Introduction

Geographically, the study area located in West Tanjung Jabung Regency, Jambi Province, within the South Sumatra Basin, specifically in the Jambi Subbasin, which was formed as part of a back-arc basin (Figure 1). The stratigraphy of the South Sumatra basin generally consists of a single large sedimentation cycle, starting with a transgression phase and ending with a regression phase [1]–[3]. The geology and stratigraphy of the South Sumatra Basin have been extensively studied [4], [5]. According to Daryono [5], the Tertiary stratigraphic nomenclature of the South Sumatra Basin has been described in detail, but challenges remain in understanding the stratigraphic relationship of Paleogene rocks in this region. This difficulty arises because Paleogene rocks in the basin are predominantly terrestrial deposits, making it challenging to determine their age using fossil content, development, changes, distribution and origin or source of each lithological unit. The South Sumatra Basin exhibits a diverse range of rocks, geological structures, morphogenesis, and geological history, making it a fascinating area of study [6]. Among the notable formations exposed in this region is the Lemat Formation, which is the primary focus of this research.

The Lemat Formation features outcrops of clastic sedimentary rocks, ranging grom mudstone to tuffaceous sandstone [7], [8]. These clastic rocks comprise various compositions derived from source rocks, which may include igneous and metamorphic rocks or reworked sediments. To uncover the origin of these rocks and their paleogeographic implications, provenance analysis is essential. Provenance analysis involves examining petrographic parameters (Table 1) such as lithic composition, mineralogy, and texture to deduce the source area, tectonic setting, paleoclimate, paleocurrent and transportation history of siliciclastic sedimentary rocks [9]. Consequently, this study aims to conduct a provenance analysis of the Lemat Formation in Bukit Tigapuluh to address the unresolved questions surrounding Paleogene sediments in the South Sumatra Basin. Specifically, the research seeks to determine the paleogeography of the Lemat Formation deposits in West Tanjung Jabung Regency, Jambi Province, within the Jambi Subbasin.

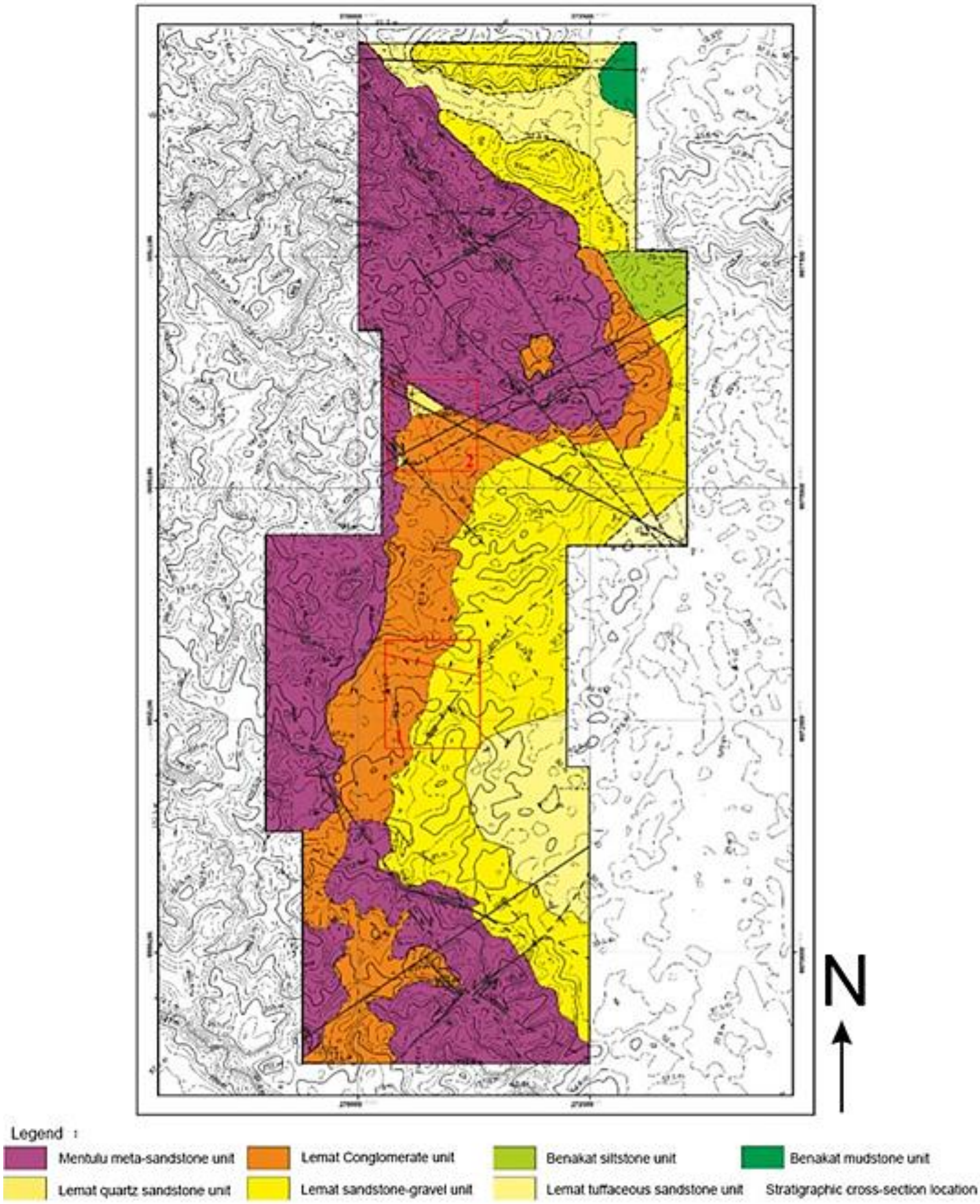

Figure 1. Geological map of the research area, Bukit Tigapuluh National Park, West Tanjung Jabung Regency, Jambi Province [16].

The South Sumatra Basin is primarily located onshore in Sumatra, Indonesia. The study area is situated in the northern part of the Jambi Subbasin. The Jambi Subbasin is bordered by the Tigapuluh Mountains to the north, the Duabelas Mountains to the south, the Barisan Mountains to the west and the Sunda Shelf to the east [7].

The lithostratigraphic nomenclature of the South Sumatra Basin, particularly for Paleogene deposits, varies among researchers. These differences are related to the characterization of pre-rift, syn-rift, and post-rift Paleogene sequences [10], [11]. According to Daryono [5], the stratigraphy of the South

Sumatra Basin consists of the following units, listed from the oldest to youngest: Pre-Tertiary Rocks, Kikim Formation, Lahat Group (the Lemat Formation and Benakat Formation), Telisa Group (Tanjung Baru Formation, Talangakar Formation, Gumai Formation, and Baturaja Formation), Palembang Group (the Air Benakat Formation, Muara Enim Formation, and Kasai Formation) and Quaternary sediments.

The Lemat Formation is interpreted as an Early Oligocene syn-rift sequence deposited in paleo-lows or grabens and is absent in paleo-highs, particularly in horst-type structures. This formation consists of alternating non-marine sandstone, siltstone and shale, which transition into shale in deeper basin areas [12]–[14]. In some regions, the Lemat Formation contains tuffaceous materials. The Sumatra Island is believed to have formed through the collision and suturing of microcontinents during the Late Pre-Tertiary period [1], [15]. Four main geological structural patterns are observed in the study area, namely: The Sunda Pattern, trending north-south, The Lematang Pattern, trending west-northwest to east-southeast (WNW-ESE), the Jambi Pattern, trending northeast-southwest (NE-SW), and the Sumatra Pattern, trending southeast-northwest (SE-NW).

2. Methodology

Field mapping was conducted in the Bukit Tigapuluh area, West Tanjung Jabung Regency, Jambi Province (Figure 1), focusing on the Lubuk Lawas and Lubuk Bernai areas. A total of 22 rock samples were collected for petrographic analysis to study provenance. These samples included black shale, carbonaceous siltstone, tuffaceous siltstone, carbonaceous sandstone, and tuffaceous sandstone. The samples were collected using a purposive sampling method, a technique that selects samples based on specific criteria considered representative of the population, along a measured stratigraphic cross-section.

Detailed analysis of lithology was carried out using the petrographic thin section method which was observed based on cross nicol and parallel nicol using a Brunel SP75P type microscope with a magnification of 4 to 25 times. Provenance analysis of the sandstone samples was performed by calculating the composition of quartz grains (Q), feldspar (F) and lithic fragments (L) greater than 0.03 mm in size. A minimum of 300 grains were analyzed per sample, following the methodology outlined by Dickinson [9]. The percentages of Q, F, and L were plotted on a ternary diagram based on the classification scheme developed by Dickinson and Suczek [9], [17] to interpret the provenance of the sandstone samples.

The classification of sandstones was performed using the QFL plot technique. The major detrital components of the rock samples were calculated and normalized to 100% (Tables S2 and S3). The QFL diagram, illustrating the proportions of quartz, feldspar, and lithic fragments, was plotted following the methodology of Dickinson and Suezek [17] (Figures 4 and 5).Quartz grains identified in the samples included both monocrystalline and polycrystalline varieties. Feldspar grains were further categorized into alkali feldspars (orthoclase and microcline) and plagioclase, with plagioclase being the predominant type. Lithic fragments were classified into three groups: sedimentary lithics, volcanic lithics, and metamorphic lithics.

Table 1. Parameter 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

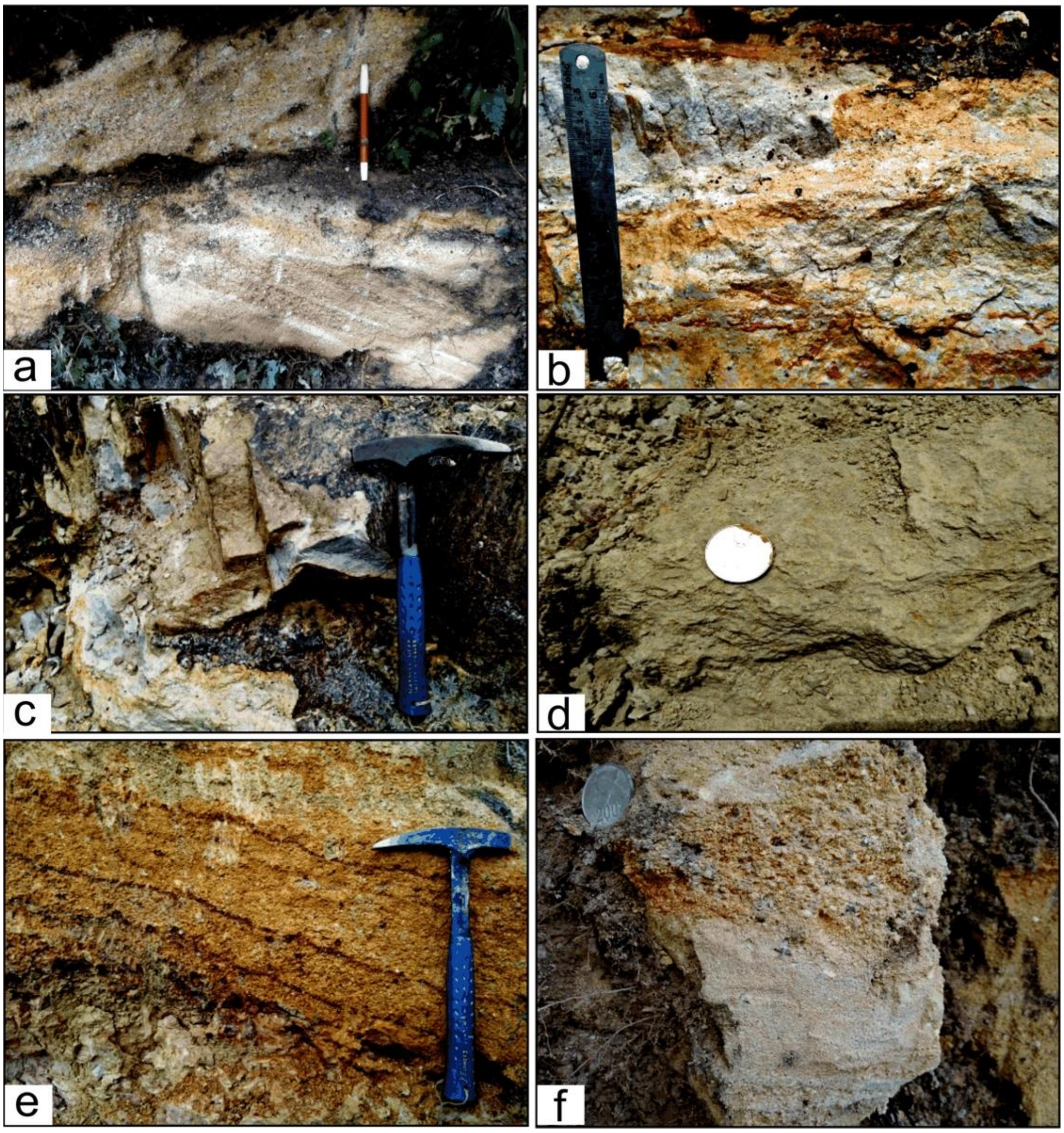

Figure 2. Photos: (a) Quarzt sandstone with planar cross-bedding structure, (b) Medium-grained quarzt sandstone with bedding structure, (c) Tuffaceous quarzt sandstone with massive structure, (d) Fine-grained quarzt sandstone with ripple lamination structure, (e) Pebbly quarzt sandstone with parallel bedding structure, (f) (upper part) Conglomerate with massive structure, and (lower part) Coarse tuffaceous quarzt sandstone with massive structure.

3. Results & Discussions

3.1. Petrography

The sandstones from the Lubuk Lawas and Lubuk Bernai areas were predominantly composed of quartz and lithic fragments (Figure 2a-f). Quartz grains were primarily monocrystalline, with smaller amounts of polycrystalline quartz. These grains varied from angular to rounded in shape and display point contacts. The lithic fragments were mainly derived from sedimentary and volcanic sources. Chert, granitic fragments, and metaquartzite were commonly observed in almost all samples, while calcite cement was present in some samples (Figure 3a-f). The sandstones in the Lubuk Lawas and Lubuk Bernai areas were classified as lithic arkose, arkosic, subarkose, feldspathic litharenite, silty claystone, sublitharenite, and subarkosic wacke.

3.2. Mineral Composition

The petrographic analysis data for all samples were summarized in Table 2 (in the appendix part) for Lubuk Lawas area and in Table 3 for Lubur Bernai area. Quartz, observed in both monocrystalline and polycrystalline forms, was the most abundant mineral, with total quartz composition ranging from 32.71% to 85%. Quartz grains were angular to subrounded. Monocrystalline quartz dominated and was likely derived from plutonic and volcanic igneous rocks. In contrast, polycrystalline quartz, which represented recrystallized quartz, was predominantly sourced from metamorphic rocks.

Feldspar was present in smaller amounts, ranging from 5.9% to 30.51%, making it the least abundant mineral compared to quartz and lithic fragments. K-feldspar was more dominant than plagioclase in all samples. The relatively low feldspar content compared to quartz and lithics suggested significant transport distance, during which feldspar minerals underwent extensive weathering. Rock fragments (lithics) accounted for 0.00% to 49.53%, making them the second most abundant detrital component after quartz. The identified lithics included volcanic, sedimentary, and metamorphic types. Sedimentary lithics consisted of chert, sandstone, and mudstone. Volcanic lithics included fragments of volcanic rocks and granite, while metamorphic lithics comprised metaquartzite and schist. The distribution of lithic fragments was relatively uniform across all samples.

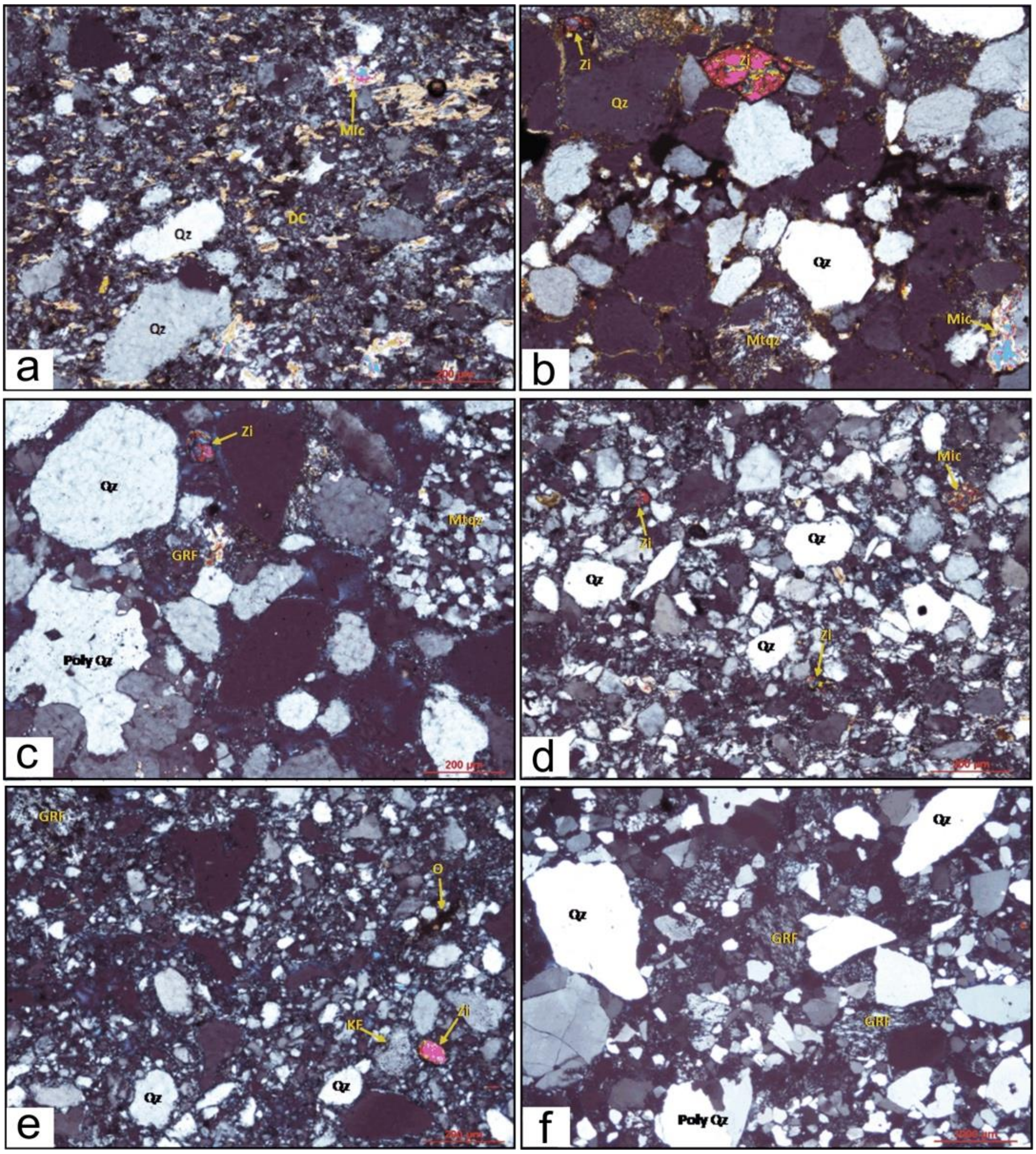

Figure 3. Selected petrographic photographs of quarzt sandstones: (a) Arkose. Various lithic were observed, such as limestone fragments (LI), metamorphic fragments (Lm), volcanic fragments (Lv) with plagioclase (Pl) and monocrystalline quartz (Qz). (b) Lithic arkose, (c) Sublitharenite, (d) Subarkosic wacke, (e) Arkose, (f) Subarkosic.

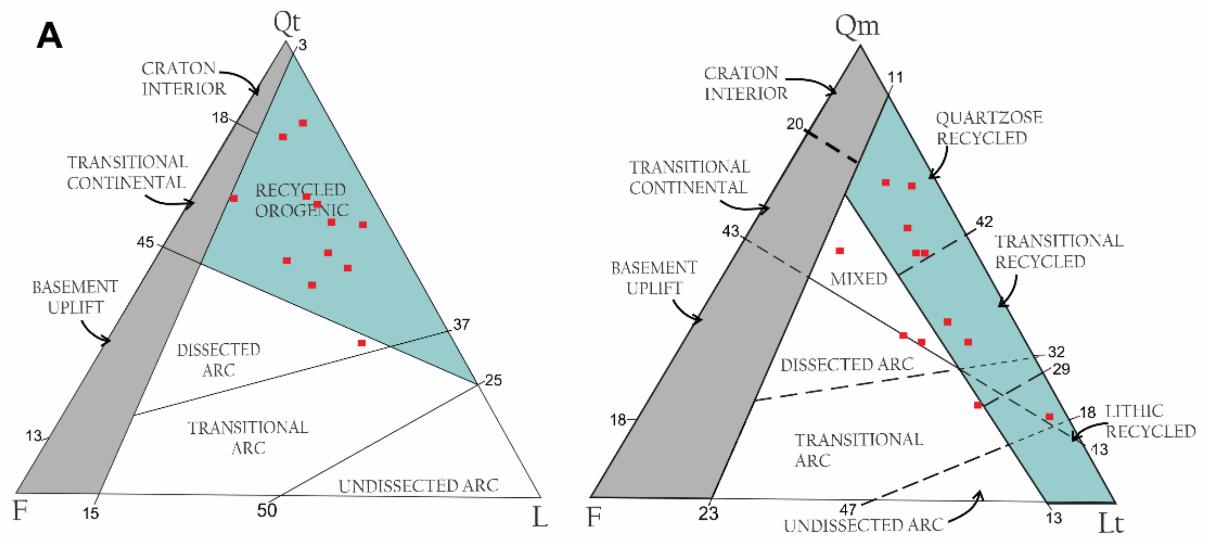

Figure 4. QFL triangle diagram and QmFLt diagram showing the average tectonic origin of studied sandstones in the Lubuk Lawas area [17].

3.3. Provenance

The abundance of quartz grains with straight extinction suggested that granite rocks were a major component in the source area for Lubuk Lawas area (Figure 4). Quartz grains exhibiting undulose extinction and/or inclusions indicated their origin from metamorphic source areas. The presence of K-feldspar and plagioclase fragments further suggested that the source area was derived from igneous rocks. Additionally, sedimentary and metamorphic fragments pointed to the presence of metasediments and metamorphic processes in the source area. Dickinson and Suczek [17] proposed that the average composition of sandstone grains from various source areas, influenced by plate tectonic processes, can be analysed using QFL (quartz, feldspar, lithic fragments) and QmFLt (monocrystalline quartz, feldspar, total lithic fragments) diagrams. Sample data from the Lubuk Lawas and Lubuk Bernai areas were presented in Tables S2 and S3. The QFL and QmFLt diagram plots revealed that the 22 analysed samples indicated a provenance from the tectonic setting of the orogenic recycled zone, for Lubuk Bernai area (Figure 5). The QmFLt plot showed that the samples were distributed across sub-zones, reflecting variations from quartzose recycled, transitional recycled, and mixed. This suggested a mixture of primary source rocks and recycled orogens.

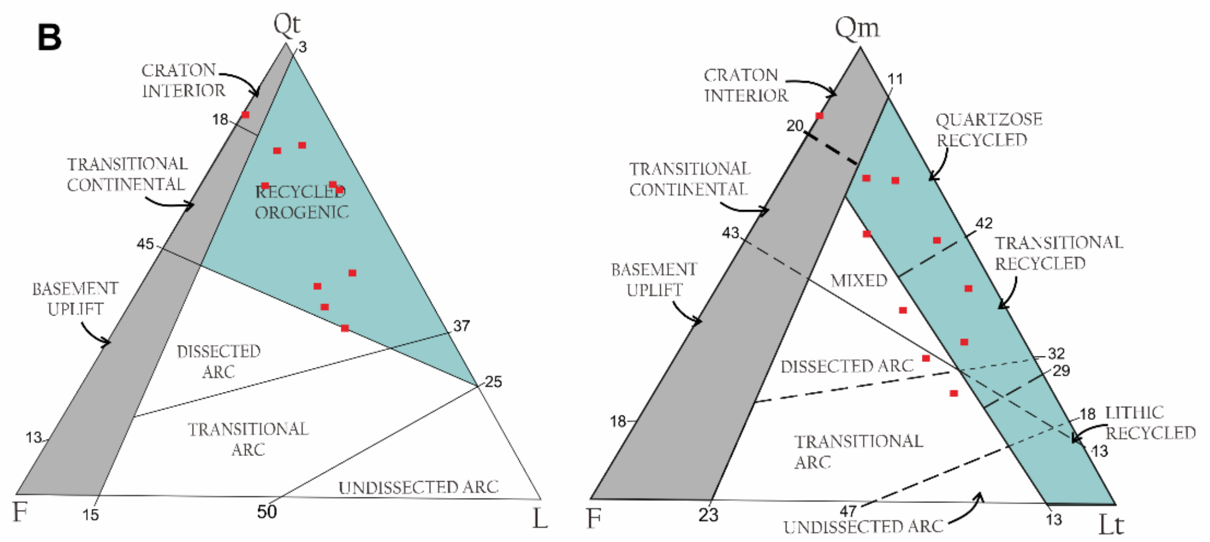

Figure 5. QFL triangle diagram and QmFLt diagram showing the average tectonic origin of studied sandstones in the Lubuk Bernai area [17].

Figure 6. (a) Cross bedding sedimentary structure with direction N55°E, (b) Low angle cross bedding sedimentary structure with direction N110°E, (c) Plannar crossbedding sedimentary structure with direction N125°E.

3.4. Paleocurrent

The observed sedimentary structures provided valuable insights into the paleocurrents during deposition. In the Lubuk Bernai sandstone, sedimentary structures such as crossbedding with a direction of N 55°E, low angle crossbedding with a direction of N 110°E, and planar crossbedding with a direction of N125°E indicated paleocurrent directions. These structures suggested deposition occurred from the Southwest to the Northeast (Figure 6a) and from the Southeast to the Northwest (Figures 6b and 6c). The deposits were interpreted to have been transported and deposited predominantly by water.

4. Conclusion

The quarzt sandstone of the Lemat Formation in the Lubuk Lawas and Lubuk Bernai areas has been classified into several types, including lithic arkose, arkosic, subarkose, feldspathic litharenite, silty claystone, sublitharenite, and subarkosic-wacke. All sandstones were composed of mixed detritus derived from igneous, sedimentary, and metamorphic sources. The provenance of these sandstones indicated a tectonic setting from the recycled orogenic zone, with sub-zones that varied from quartzose recycled, transitional recycled, to mixed, suggesting a mixture of primary source rocks and recycled orogens, subprovenance foreland uplift. Additionally, paleocurrent analysis based on sedimentary structures in the Lubuk Bernai area showed deposition directions from the Southwest and Southeast in fluvial environments. The composition of the sandstone is thought to come from pre-Tertiary rocks in the Bukit Tigapuluh Mountains itself. The abundance of sandstone from the Lemat Formation acts as a reservoir rock which is the main target for oil and gas exploration in subsequent research.

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Appendix

Table 1. Quartz, Feldspar, and Lithics sandstone calculation data in the Lubuk Lawas Area.

ID Code	Rock Name (after Folk, 1980)	Quartz		Feldspar		Lithics			Total	Mineral composition (%)			Mineral composition (%)		
		Qm	Qp	K-feld	Plg	Ls	Lv	Lm		Qt	F	L	Qm	F	Lt
L	Feldspathic litharenite	30	2.8	3.6	2.4	11.2	2.4	3.2	55.6	58.99	10.79	30.22	53.96	10.79	35.25
K	Siltstone	39.2	2.8	4.8	2.8	11.2	2.4	3.2	66.4	63.25	11.45	25.30	59.04	11.45	29.52
J	Subarkose	45.2	7.6	2.8	0.8	3.6	3.2	2.4	65.6	80.49	5.49	14.02	68.90	5.49	25.61
I	Feldspathic litharenite	8.8	5.2	4.4	3.2	9.2	4.4	7.6	42.8	32.71	17.76	49.53	20.56	17.76	61.68
H	Arkosic	22.4	9.6	7.2	0.8	3.2	13.2	8.4	64.8	49.38	12.35	38.27	34.57	12.35	53.09
G	Subarkosic wacke	45.2	5.6	5.6	1.2	2.4	3.2	2	65.2	77.91	10.43	11.66	69.33	10.43	20.25
F	Arkosic	27.6	4.8	7.2	6.4	1.6	3.2	0	50.8	63.78	26.77	9.45	54.33	26.77	18.90
E	Lithic arkose	21.6	8	6	2	4.4	8.4	5.6	56	52.86	14.29	32.86	38.57	14.29	47.14
D	Arkosic	18.4	5.6	6.4	4.8	5.2	3.2	9.6	53.2	45.11	21.05	33.83	34.59	21.05	44.36
C	Subarkose	12.8	27.6	3.6	0	6.8	4.8	13.6	69.2	58.38	5.20	36.42	18.50	5.20	76.30
B	Lithic arkose	35.2	7.2	5.2	2.8	4.8	4	6	65.2	65.03	12.27	22.70	53.99	12.27	33.74
A	Lithic arkose	16	6.4	6.4	4	2	2.8	6.4	44	50.91	23.64	25.45	36.36	23.64	40.00

Table 2. Quartz, Feldspar, dan Lithics sandstone calculation data in the Lubuk Bernai Area.

ID Code	Rock Name (after Folk, 1980)	Quartz		Feldspar		Lithics			Total	Mineral composition (%)			Mineral composition (%)		
		Qm	Qp	K-feld	Plg	Ls	Lv	Lm		Qt	F	L	Qm	F	Lt
J	Arkosic	25.2	2.8	9.2	3.2	4	10.8	5.2	60.4	46.36	20.53	33.11	41.72	20.53	37.75
I	Subarkose	45.2	4.8	3.2	1.6	2.8	4	2.4	64	78.13	7.50	14.38	70.63	7.50	21.88
H	Feldspathic litharenite	8.8	5.2	4.4	3.2	9.2	4.4	2.8	38	36.84	20.00	43.16	23.16	20.00	56.84
G	Silty claystone	6.8	0	1.2	0	0	0	0	8	85.00	15.00	0.00	85.00	15.00	0.00
F	Sublitharenite	26.4	12.4	2.4	0.8	5.6	2	7.2	56.8	68.31	5.63	26.06	46.48	5.63	47.89
E	Subarkosic wacke	29.6	6	2.8	0.4	4.4	2	6.4	51.6	68.99	6.20	24.81	57.36	6.20	36.43
D	Arkosic	29.6	5.2	6.4	3.2	2.8	3.2	0	50.4	69.05	19.05	11.90	58.73	19.05	22.22
C	Subarkose	44.4	3.6	5.2	2.8	1.6	2.8	2	62.4	76.92	12.82	10.26	71.15	12.82	16.03
B	Arkosic	22.4	9.6	7.2	0.8	3.2	13.2	8.4	64.8	49.38	12.35	38.27	34.57	12.35	53.09
A	Arkosic	18.4	6.4	9.6	3.2	2.4	13.2	6.4	59.6	41.61	21.48	36.91	30.87	21.48	47.65