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GEOLOGY AND TECHNICAL SCIENCES**

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**THE JOURNAL WAS FOUNDED IN 1940**

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*The scientific journal News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences has been indexed in the international abstract and citation database Scopus since 2016 and demonstrates stable bibliometric performance.*

*The journal is also included in the Emerging Sources Citation Index (ESCI) of the Web of Science platform (Clarivate Analytics, since 2018).*

*Indexing in ESCI confirms the journal's compliance with international standards of scientific peer review and editorial ethics and is considered by Clarivate Analytics as part of the evaluation process for potential inclusion in the Science Citation Index Expanded (SCIE), Social Sciences Citation Index (SSCI), and Arts & Humanities Citation Index (AHCI).*

*Indexing in Scopus and Web of Science ensures high international visibility of publications, promotes citation growth, and reflects the editorial board's commitment to publishing relevant, original, and scientifically significant research in the fields of geology and technical sciences.*

*«Қазақстан Республикасы Ұлттық ғылым академиясының Хабарлары. Геология және техникалық ғылымдар сериясы» ғылыми журналы 2016 жылдан бастап халықаралық реферативтік және ғылымиметриялық Scopus дерекқорында индекстеледі және тұрақты библиометриялық көрсеткіштерді көрсетіп келеді.*

*Сонымен қатар журнал Web of Science платформасының (Clarivate Analytics, 2018) халықаралық реферативтік және наукометриялық дерекқоры Emerging Sources Citation Index (ESCI) тізіміне енгізілген.*

*ESCI дерекқорында индекстелуі журналдың халықаралық ғылыми рецензиялау талаптары мен редакциялық этика стандарттарына сәйкестігін растайды, сондай-ақ Clarivate Analytics компаниясы тарапынан басылмды Science Citation Index Expanded (SCIE), Social Sciences Citation Index (SSCI) және Arts & Humanities Citation Index (AHCI) дерекқорларына енгізу қарастырылуда.*

*Scopus және Web of Science дерекқорларында индекстелуі жарияланымдардың халықаралық деңгейде жоғары сұранысқа ие болуын қамтамасыз етеді, олардың дәйексөз алу көрсеткіштерінің артуына ықпал етеді және редакциялық алқаның геология мен техникалық ғылымдар саласындағы өзекті, бірегей және ғылыми тұрғыдан маңызды зерттеулерді жариялауға ұмтылысын айқындайды.*

*Научный журнал «News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences» с 2016 года индексируется в международной реферативной и наукометрической базе данных Scopus и демонстрирует стабильные библиометрические показатели.*

*Журнал также включён в международную реферативную и наукометрическую базу данных Emerging Sources Citation Index (ESCI) платформы Web of Science (Clarivate Analytics, 2018).*

*Индексирование в ESCI подтверждает соответствие журнала международным стандартам научного рецензирования и редакционной этики, а также рассматривается компанией Clarivate Analytics в рамках дальнейшего включения издания в Science Citation Index Expanded (SCIE), Social Sciences Citation Index (SSCI) и Arts & Humanities Citation Index (AHCI).*

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## PETROGRAPHIC, PROVENANCE AND TECTONIC SETTING OF DOLOKAPA FORMATION SANDSTONE, NORTH GORONTALO

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**Abstract.** Sandstone is one of the most abundant clastic sedimentary rocks, comprising nearly a quarter of the sedimentary rock record, and is primarily composed of quartz, feldspar, lithic fragments, and matrix. Sandstone provenance analysis is crucial for interpreting source areas, tectonic settings, and sedimentary history. The Dolokapa Formation in North Gorontalo Regency, located within the tectonically complex Tomini Bay region, is dominated by sandstones interbedded with mudstone, conglomerate, and volcanoclastic deposits of Middle to Late Miocene age. This study aims to characterize the petrographic properties and provenance of Dolokapa Formation sandstones in order to reconstruct their tectonic and depositional evolution. Field surveys and representative sampling were conducted in Sumalata Timur District, yielding five sandstone samples (D1–D5). Petrographic thin-section analysis was performed using the point-counting method to determine modal composition, classified following Pettijohn, and

further assessed using Q-F-L, Qm-F-Lt, and Qp-Lv-Ls diagrams according to Dickinson and Suczek. The results show that the Dolokapa sandstones consist of two types: Lithic Arenite (D1–D4) and Feldspathic Wacke (D5). Their composition is dominated by monocrystalline quartz (25–40%), feldspars (21–34%), and volcanic lithic fragments (20–42%), with poorly to moderately sorted, angular to sub-angular grains and moderate porosity. Provenance analysis consistently places these sandstones within a magmatic arc setting, particularly in the Dissected Arc subzone, with one sample plotting into the Recycled Orogen field. The Qp-Lv-Ls diagram indicates an arc orogen source strongly influenced by volcanic detritus. These findings suggest that the Dolokapa Formation sandstones were derived from erosion of volcanic arc materials associated with subduction-related processes in the Tomini Bay magmatic arc. This study provides new insights into the sedimentary and tectonic history of North Gorontalo, highlighting the significant role of volcanism, magmatism, and orogenic deformation in shaping its geological framework.

**Keywords:** Dolokapa Formation, Magmatic Arc, North Gorontalo, Petrography, Provenance, Sandstone

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## СОЛТҮСТІК ГОРОНТАЛОДАҒЫ ДОЛОКАПА ҚҰМТАСТАРЫНЫҢ ПЕТРОГРАФИЯЛЫҚ, ШЫҒУ ТЕГІ ЖӘНЕ ТЕКТОНИКАЛЫҚ ОРНАЛАСУЫ

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**Аннотация.** Құмтас – ең көп таралған кластикалық шөгінді жыныстардың бірі, барлық шөгінді жыныстардың шамамен төрттен бірін құрайды және негізінен кварцтан, дала шпатынан, литикалық фрагменттерден және матрикстен тұрады. Құмтастың шығу тегін (provenance) талдау оның бастапқы көзі, тектоникалық орталары және шөгінді тарихын түсіндіру үшін аса маңызды. Томини шығанағының тектоникалық тұрғыдан күрделі аймағында орналасқан Солтүстік Горонтало ауданындағы Долокапа формациясы орта-кеш миоцен жасындағы сазды тақтатастармен, конгломераттармен және вулканогенді шөгінділермен қабаттасқан құмтастардан тұрады. Бұл зерттеу Долокапа формациясының құмтастарының петрографиялық қасиеттері мен шығу тегін сипаттап, олардың тектоникалық және шөгінділік эволюциясын қайта құруды мақсат етеді. Далалық жұмыстар мен репрезентативті үлгілерді жинау Сумалата Тимир ауданында жүргізіліп, бес құмтас үлгісі (D1–D5) алынды. Петрографиялық талдау үлгілердің модальды құрамын анықтау үшін point-counting әдісімен жүргізілді, Петтиджон бойынша классификацияланды және Дикинсон мен Сучек диаграммаларына (Q–F–L, Qm–F–Lt, Qp–Lv–Ls) сәйкес тектоникалық тұрғыдан бағаланды. Нәтижелер Долокапа құмтастары екі түрден тұратынын көрсетті: Литикалық арениит (D1–D4) және Далашпаттық вакке (D5). Құрамы негізінен монокристалды кварцтан (25–40%), дала шпаттарынан (21–34%) және жанартаулық литикалық фрагменттерден (20–42%) тұрады, нашардан орташаға дейін сортталған, бұрышты–жартылай бұрышты түйірлер мен орташа кеуектілігі бар. Шығу тегін талдау бұл құмтастардың магмалық доға орталарына, әсіресе Dissected Arc ішкі аймағына жататынын тұрақты түрде көрсетеді, бір үлгісі Recycled Orogen аймағына түсті. Qp–Lv–Ls диаграммасы жанартаулық детритке қатты тәуелді доғалық орогендік көзді көрсетеді. Бұл нәтижелер Долокапа құмтастары Томини шығанағының магмалық доғасында субдукция процестерімен байланысты жанартаулық доғалық материалдардың эрозиясынан пайда болғанын дәлелдейді. Зерттеу Солтүстік Горонталонң шөгінділік және тектоникалық тарихына жаңа көзқарас береді және аймақ геологиялық құрылымының қалыптасуына вулканизм, магматизм және орогендік деформацияның маңызды рөлін көрсетеді.

**Түйін сөздер:** Долокапа формациясы, магмалық доға, Солтүстік Горонтало, петрография, шығу тегі, құмтас

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## ПЕТРОГРАФИЧЕСКИЕ ХАРАКТЕРИСТИКИ, ПРОИСХОЖДЕНИЕ И ТЕКТОНИЧЕСКАЯ ОБСТАНОВКА ПЕСЧАНИКА ФОРМАЦИИ ДОЛОКАПА, СЕВЕРНЫЙ ГОРОНТАЛО

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**Аннотация.** *Актуальность.* Песчаник является одной из наиболее распространённых обломочных осадочных пород, составляя почти четверть общего объёма осадочных толщ, и представлен преимущественно кварцем, полевыми шпатами, литическими фрагментами и матриксом. Анализ происхождения (provenance) песчаников имеет ключевое значение для реконструкции областей источников, тектонической обстановки и истории осадконакопления. Формация Долокапа в районе Северный Горонтало, расположенная в тектонически сложной зоне залива Томини, представлена песчаниками, переслаивающимися с аргиллитами, конгломератами и вулканогенными отложениями среднего–позднего миоцена. *Цель исследования* - охарактеризовать петрографические особенности и установить происхождение песчаников формации Долокапа для реконструкции их тектонической и седиментационной эволюции. *Методы.* Полевые исследования и отбор репрезентативных образцов проведены в районе Сумалата Тимур, где было собрано пять образцов песчаников (D1–D5). Петрографический анализ тонких шлифов выполнен методом количественного точечного подсчёта (point-counting), что позволило определить минеральный состав, провести классификацию по Петтиджону и осуществить интерпретацию по диаграммам Дикинсона и Сучека (Q–F–L, Qm–F–Lt, Qp–Lv–Ls). *Результаты и выводы.* Установлено, что песчаники формации Долокапа подразделяются на два типа: литические арениты (D1–D4) и полевошпатовые вакке (D5). Их состав характеризуется преобладанием

монокристаллического кварца (25–40%), полевых шпатов (21–34%) и вулканогенных литических фрагментов (20–42%). Породы обладают плохой–средней сортировкой, угловатыми–субугловатыми зёрнами и умеренной пористостью. Анализ происхождения устойчиво указывает на формирование в условиях магматической дуги, преимущественно в подзоне Dissected Arc, при этом один из образцов демонстрирует признаки зоны Recycled Orogen. Диаграмма Qp–Lv–Ls подтверждает источник дугового орогена с существенным вкладом вулканогенного детрита. Полученные результаты свидетельствуют о том, что песчаники формации Долокапа сформировались в результате эрозии вулканодуговых пород, связанных с субдукционными процессами в пределах магматической дуги залива Томини. Данное исследование расширяет представления о седиментационной и тектонической эволюции региона Северного Горонтало, подчёркивая ключевую роль вулканизма, магматизма и орогенных деформаций в формировании его геологической структуры.

**Ключевые слова:** формация Долокапа, магматическая дуга, Северный Горонтало, петрография, происхождение, песчаник

**Introduction.** Sandstone is a clastic sedimentary rock that constitutes approximately one-quarter of all sedimentary rocks, excluding volcanic sand and carbonate sand. It belongs to the coarse clastic sediment group, characterized by grain sizes ranging from 0.125 to 2 mm. Sandstone is commonly composed of quartz, feldspar, cement, matrix, and lithic fragments (Pettijohn, 1975; Zou et al., 2023; Raya and Hastuti, 2023; Han et al., 2023; Wu et al., 2024). The mineralogical and textural characteristics of sandstone preserve important information about the source rocks, transport history, and depositional environment, making sandstone a key archive for reconstructing sedimentary basin evolution.

The term *provenance* originates from the French word *provenir*, meaning “to come from” or “to originate.” In geology, provenance refers not only to the source area of sediment but also encompasses broader aspects such as transport distance, transport direction, sediment volume, grain size, lithology of the source rocks, tectonic setting, climate, and relief of the source region (Pettijohn, 1975). Provenance studies are closely related to plate tectonics theory, which provides insights into whether sediments are derived from continental blocks, magmatic arcs, recycled orogens, or collisional belts (Aini et al., 2019; Atmajaya et al., 2019; Prabowo et al., 2022; Rochmana et al., 2023; González-Acebrón et al., 2025). Consequently, sandstone provenance analysis has become an essential tool for understanding regional tectonic evolution and basin development.

The geology of the Tomini Bay region is particularly distinctive and complex due to the interaction of several tectonic domains, including the Eurasian, Pacific, and Australian plates. This tectonic convergence has produced a mosaic of volcanic arcs, ophiolitic complexes, plutonic intrusions, and sedimentary basins. The region is dominated by volcanic andesites, plutonic rocks, limestones, sandstones, coal-

bearing units, and alluvial deposits that are structurally controlled by active fault systems, particularly the Gorontalo Fault, which reflects ongoing deformation and seismicity (Permana et al., 2025a). Such a complex tectonic and lithological setting provides a highly variable sediment supply, making Tomini Bay an ideal natural laboratory for provenance analysis.

Three major formations in the study area are dominated by sandstone, namely the Dolokapa, Randangan, and Lokodidi Formations. Among these, the Dolokapa Formation (Tmd) consists of wacke sandstone, siltstone, mudstone, conglomerate, tuff, agglomerate, volcanic breccia, and andesitic–basaltic lava flows, and is interpreted to be of Middle to Late Miocene age. Sandstone outcrops of this formation are widely distributed in North Gorontalo Regency (Salama et al., 2021; Sandi et al., 2024).

Although previous studies have described the regional geology and stratigraphy of the Dolokapa Formation, detailed and integrated investigations of sandstone characteristics and provenance remain limited. Most existing works emphasize lithostratigraphic descriptions and regional tectonics, while quantitative petrographic and geochemical approaches for determining sediment sources, tectonic setting, and sediment recycling in the Dolokapa sandstones are still scarce. Furthermore, no comprehensive study has yet combined petrographic data with provenance discrimination diagrams specifically for the Dolokapa Formation within the complex tectonic framework of Tomini Bay.

Therefore, the research gap of this study lies in the lack of a systematic, provenance-based evaluation of Dolokapa Formation sandstones that links mineralogical composition, textural maturity, and tectonic setting. Addressing this gap is crucial for improving the understanding of sediment supply and basin evolution in northern Gorontalo and the broader Tomini Bay region.

The novelty of this research is the application of an integrated sandstone characterization and provenance analysis specifically focused on the Dolokapa Formation in North Gorontalo Regency. By combining petrographic characteristics, compositional maturity, and provenance discrimination, this study provides new insights into sediment sources and tectonic controls that have not been previously reported for this formation. This approach allows a more refined reconstruction of Miocene sedimentary processes in Tomini Bay and contributes to the regional geological model of eastern Indonesia.

Based on this framework, the objective of this study is to analyze the characteristics and provenance of sandstones from the Dolokapa Formation in North Gorontalo Regency to better constrain their sedimentary sources and tectonic setting.

**Materials and methods.** Location: The study area is geographically located in Sumalata Timur District, North Gorontalo Regency, Gorontalo Province, Indonesia, approximately between 122°28'0"–122°36'0" E and 0°52'0"–1°2'0" N with a total area of about 157 km<sup>2</sup> (Figure 1). It lies within a topographic range

from near sea level along coastal plains to hilly uplands generally less than ~200 m above mean sea level, with some interior hills rising above this (typical of northern Gorontalo terrain). The district is situated on the northern coast of Sulawesi, immediately north of Tomini Bay. This coastal position places parts of the study area in proximity to marine depositional environments, whereas inland areas transition into more elevated volcanic and sedimentary terrain that is structurally influenced by regional tectonics. The broader region is also affected by structural features such as the active Gorontalo Fault system, which plays a significant role in local deformation and sediment sourcing across the Tomini Bay margin.

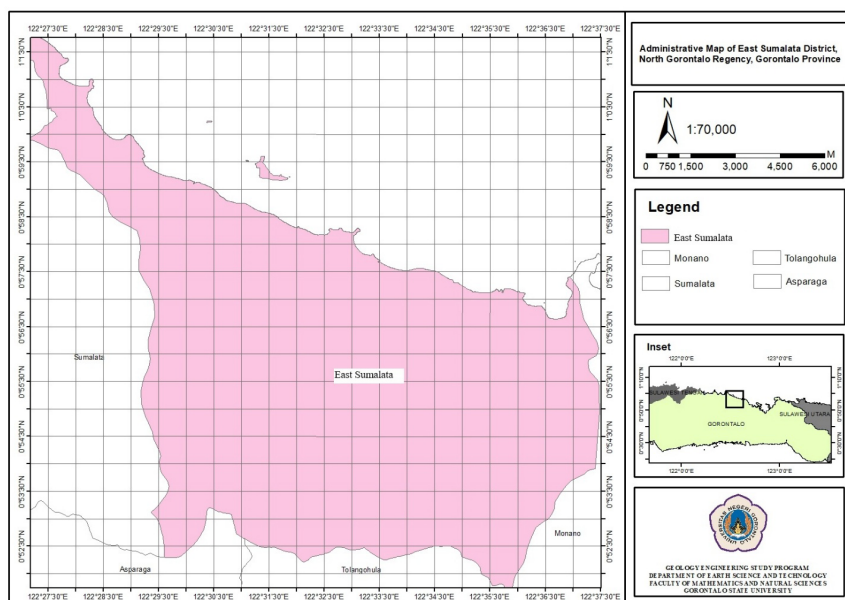


Figure 1. Administrative map of East Sumalata District, North Gorontalo Regency.

**Materials:** Representative sampling was carried out at selected sites with a focus on sandstone units of the Dolokapa Formation. Samples were chosen based on their fresh condition (unaltered and unweathered) and lithological variations. A total of five sandstone samples (D1, D2, D3, D4, and D5) were collected for petrographic analysis. These samples were deliberately selected to represent the main lithological units and facies of sandstone exposed in the study area, so that they adequately capture both lateral variations (along the strike and across different outcrops) and vertical variations (between stratigraphic levels) within the Dolokapa Formation. Sampling was conducted using a field-based geological survey approach to ensure that the collected materials accurately represent the overall characteristics of the sandstone units in the study area.

**Methods:** This study employed two main approaches: field geological survey and laboratory analysis. Field survey consisted of in situ observations

and macroscopic identification of rock characteristics, as well as the systematic collection of sandstone samples for laboratory analysis. Laboratory analysis involved petrographic examination of the five sandstone samples using a polarizing microscope to identify rock types, mineral composition, and textural features. Each sample was prepared as a thin section and analyzed in the Petrography Laboratory, Geological Engineering Study Program, Department of Earth Science and Technology, Universitas Negeri Gorontalo. The petrographic analysis aimed to identify the constituent minerals based on their optical properties, describe sandstone textures, and quantify the relative proportions of major minerals using the point-counting method (Martínez et al., 2007; Dabek et al., 2023; Azzam et al., 2024; Permana et al., 2022; 2025b; 2025c). Sandstone classification followed Pettijohn's scheme, using normalized percentages of quartz, feldspar, and lithic fragments.

Tectonic settings were interpreted using compositional data plotted on ternary diagrams: Q-F-L (Quartz–Feldspar–Lithic), Qm-F-Lt (Monocrystalline quartz–Feldspar–Total lithic), and Qp-Lv-Ls (Polycrystalline quartz–Volcanic lithic fragments–Sedimentary lithic fragments), following the classification proposed by Dickinson and Suczek (Bela et al., 2022; Sujatono, 2022; Kong et al., 2022; Borgohain and Pandey, 2023).

**Results and discussion.** Results: Geomorphology: the geomorphology of the study area can be divided into four units based on topographic and lithological characteristics: lava flow ridges, denudational hills, alluvial plains, and coastal plains (Figure 2).



Figure 2. Geomorphology of the denudational hill unit

**Stratigraphy:** Based on surface geological mapping, three lithological units were identified in the study area, consisting of layered sandstone, massive sandstone, and pyroclastic breccia. Massive sandstone is widespread in the study area (Figure 3). These units are named based on their lithological characteristics, including sedimentary structure, texture, and mineral composition.



Figure 3. Distribution of massive sandstone unit.

**Petrographic characteristics:** petrographic analysis was conducted on five sandstone samples (D1, D2, D3, D4, and D5). Results indicate two sandstone types: Lithic Arenite (samples D1–D4) and Feldspathic Wacke (sample D5), following the classification of Pettijohn (1975)(Figure 4).

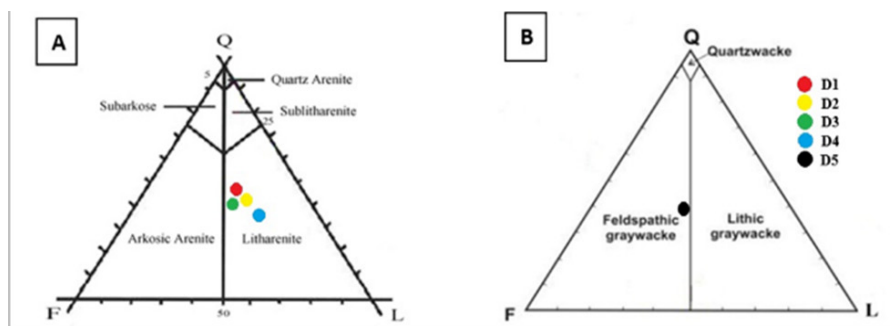


Figure 4. Determination of the type of sandstone name using the Pettijohn (1975) classification based on the results of petrographic analysis.

**Lithic Arenite (D1–D4):** Thin-section analysis shows weak oxidation (2%), with iron oxide likely acting as cement. Grain sizes range from 0.15–8 mm, with an average of 0.5 mm (coarse sand). The rock fabric is relatively compact, with poor sorting and predominantly sub-angular to angular grain shapes. Grain contacts include point contact, sutured, concavo–convex, and long contact types. Porosity is represented by intercrystalline pores and secondary pores (6%) of vuggy and moldic types. Mineral composition consists of monocrystalline quartz (25%), polycrystalline quartz (5%), small foraminifera (2%), lithic fragments (20%),

plagioclase (5%), orthoclase (11%), opaque minerals (3%), and calcite (7%). Fine-grained matrix accounts for 12%, with alteration minerals such as clay (1%) and chlorite (1%) also present (Figure 5).

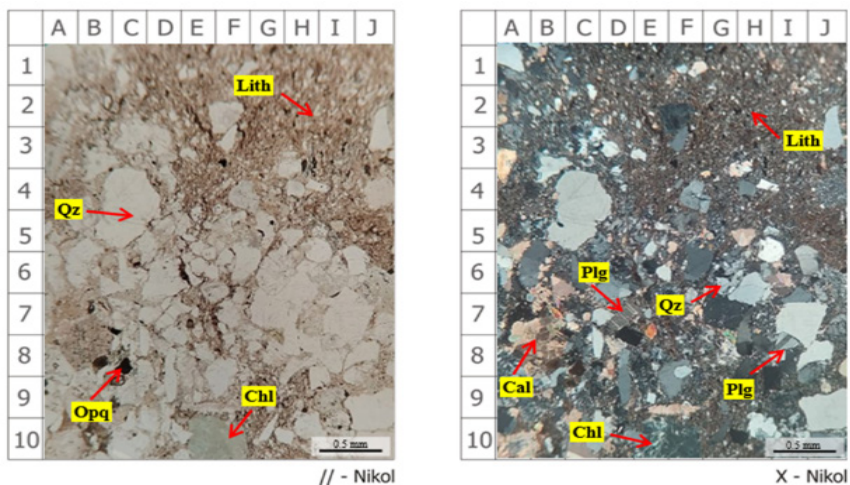


Figure 5. Petrographic analysis of sample section (D1) of lithic arenite.

Feldspathic Wacke (D5): Thin-section analysis reveals grain sizes of 0.1–0.3 mm, with an average of 0.2 mm (fine sand). The fabric is compact with relatively good sorting, angular grain shapes, and porosity dominated by intercrystalline pores and secondary vuggy pores (5%). Grain contacts include point contact, concavo–convex, and long contact types. The mineral composition includes monocrystalline quartz (25%), polycrystalline quartz (2%), orthoclase (17%), plagioclase (6%), opaque minerals (5%), and lithic fragments (20%), with fine-grained matrix comprising 20% (Figure 6).

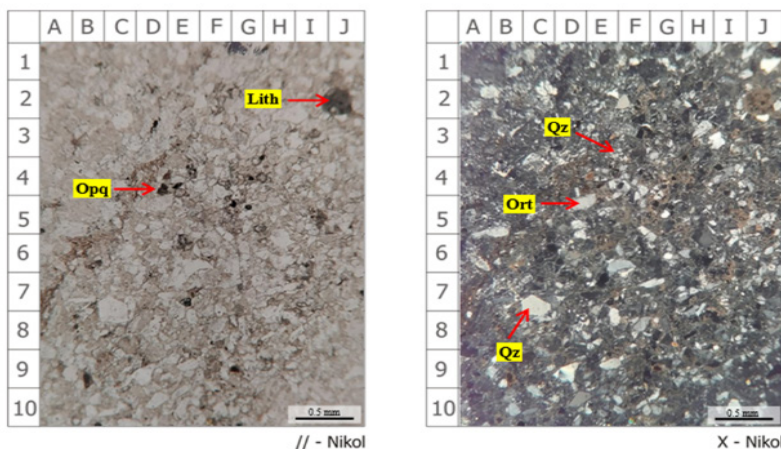


Figure 6. Petrographic analysis of sample section (D1) of feldspathic wacke.

Provenance and tectonic setting analysis: provenance and tectonic setting were interpreted using sandstone modal compositions obtained from thin-section petrography, following Dickinson and Suczek (1979). The compositional parameters include:

1. Quartz: subdivided into total quartz (Q), polycrystalline quartz (Qp), and monocrystalline quartz (Qm).

2. Feldspar (F): subdivided into total feldspar (F), plagioclase (P), and K-feldspar (KF).

3. Lithic fragments (L): subdivided into total lithic (L), volcanic lithic (Lv), and sedimentary lithic (Ls).

These data were plotted on ternary diagrams (Q–F–L, Qm–F–Lt, and Qp–Lv–Ls) to determine provenance and tectonic settings.

Q–F–L diagram: the Q–F–L diagram (Table 1) shows that the Dolokapa Formation sandstones are generally associated with a magmatic arc setting, primarily within the Dissected Arc subzone, while one sample (D1) plots into the Recycled Orogen subzone (Figure 7A). The Dissected Arc represents island arcs that have undergone significant erosion, fragmenting the arc into smaller islands. In contrast, the Recycled Orogen subzone represents sediment recycled from ancient orogenic belts.

Table 1. Model composition (Q–F–L) of Dolokapa Formation sandstones.

Observation Station	Sandstone Name (Pettijohn, 1975)	Mineral Composition Amount (%)			Total (%)
		Q	F	L	
D1	Lithic Arenite	45.4	24.2	30.4	100
D2	Lithic Arenite	40.5	24.3	35.2	100
D3	Lithic Arenite	40	27.1	32.9	100
D4	Lithic Arenite	36.6	21.1	42.3	100
D5	Feldspathic Wacke	38.5 %	32.8	28.7	100

Qm–F–Lt diagram: results from the Qm–F–Lt diagram (Table 2) further confirm that all sandstone samples plot within the Dissected Arc subzone of magmatic arc settings (Figure 7B). Together, the Q–F–L and Qm–F–Lt diagrams consistently indicate a magmatic arc provenance.

Table 2. Model composition (Qm–F–Lt) of Dolokapa Formation sandstones.

Observation Station	Sandstone Name (Pettijohn, 1975)	Mineral Composition Amount (%)			Total (%)
		Qm	F	Lt	
D1	Lithic Arenite	40.9	26.2	32.9	100
D2	Lithic Arenite	34.3	26.8	38.9	100
D3	Lithic Arenite	37.3	28.3	34.4	100
D4	Lithic Arenite	35.7	21.4	42.9	100
D5	Feldspathic Wacke	36.7	33.8	29.5	100

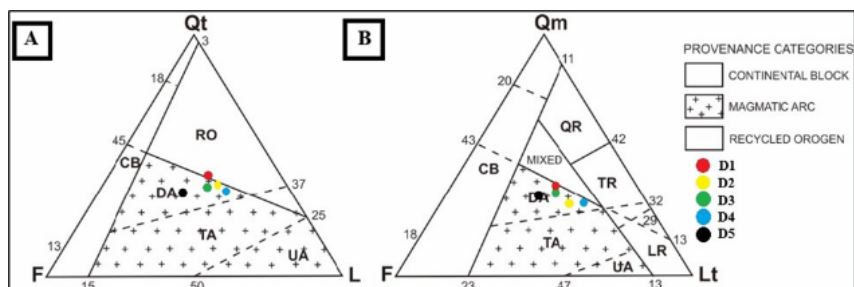


Figure 7. (A) Q–F–L diagram showing samples in the Dissected Arc and Recycled Orogen subzones. (B) Qm–F–Lt diagram confirming provenance within the Dissected Arc.

Qp–Lv–Ls diagram: the Qp–Lv–Ls diagram (Table 3) was used to further distinguish arc-related sources. All samples plot within the arc orogen field, dominated by volcanic lithic fragments (Lv), indicating a strong volcanic input (Figure 8). This pattern reflects a tectonic setting where sedimentation occurred in a volcanic arc environment associated with subduction, evolving toward a collisional orogen.

Table 3. Model composition (Qp–Lv–Ls) of Dolokapa Formation sandstones.

Observation Station	Sandstone Name (Pettijohn, 1975)	Mineral Composition Amount (%)			Total (%)
		Qp	Lv	Ls	
D1	Lithic Arenite	15	35	50	100
D2	Lithic Arenite	11.21	36.26	52.53	100
D3	Lithic Arenite	11.54	35.38	53.08	100
D4	Lithic Arenite	3.23	41.03	55.74	100
D5	Feldspathic Wacke	9.10	36.36	54.54	100

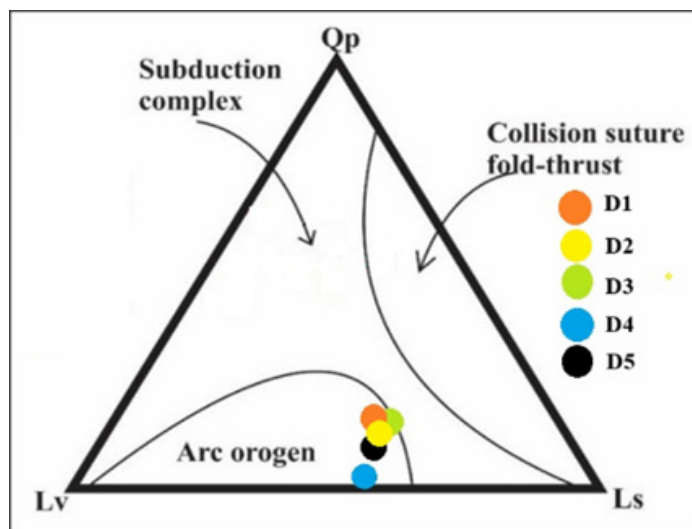


Figure 8. Qp–Lv–Ls diagram showing all samples clustered in the arc orogen field.

Tectonic model: the provenance and tectonic interpretation can be summarized in the magmatic arc model illustrated in Figure 9. In this setting, subduction of oceanic lithosphere beneath a continental or arc margin generated partial melting, producing magmas that built volcanic arcs. These volcanic edifices were subsequently eroded, supplying volcanic detritus to adjacent basins. The petrographic evidence from the Dolokapa Formation sandstones demonstrates that they were primarily derived from erosion of volcanic arc sources, confirming the influence of subduction-related processes in the Tomini Bay region.

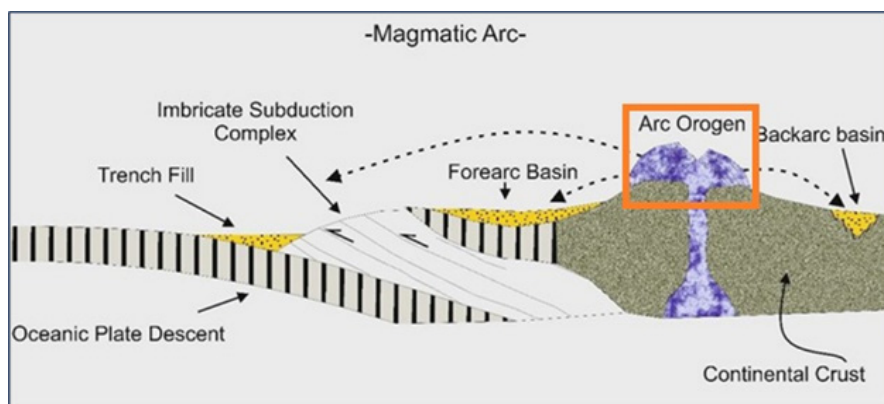


Figure 9. Tectonic model of sandstone provenance in a magmatic arc setting (after Dickinson and Suczek, 1979).

Discussion: The geomorphological framework of the study area, comprising lava flow ridges, denudational hills, alluvial plains, and coastal plains, reflects the combined influence of volcanism, tectonic uplift, and erosion. Lava flow ridges represent remnants of volcanic edifices that served as major sediment sources, whereas denudational hills expose eroded volcanic–sedimentary successions of the Dolokapa Formation. The alluvial and coastal plains indicate sediment reworking and redistribution toward the Tomini Bay margin, suggesting that sediments were transported from volcanic highlands into a proximal basin setting.

Stratigraphically, the association of massive and layered sandstones with pyroclastic breccia indicates deposition within a volcanoclastic-dominated basin. Massive sandstones likely record high-energy depositional processes such as channelized gravity flows or proximal deltaic input, whereas layered sandstones and breccias reflect episodic volcanic and sedimentary events.

Petrographically, the dominance of Lithic Arenite (D1–D4) and Feldspathic Wacke (D5) indicates low to moderate sediment maturity. High proportions of lithic fragments and feldspar, angular to sub-angular grain shapes, and poor sorting reflect short transport distances and rapid deposition, typical of tectonically active volcanic arc settings. The abundance of volcanic lithics, plagioclase, and matrix-rich textures supports derivation from unstable, rapidly eroding arc-related source

rocks. Secondary porosity suggests post-depositional diagenesis but does not obscure the primary provenance signal.

Provenance discrimination diagrams consistently place the Dolokapa sandstones within a magmatic arc, predominantly in the Dissected Arc field. This indicates derivation from an eroded volcanic arc, where volcanic edifices and associated plutonic rocks were uplifted and dissected. The minor Recycled Orogen signature observed in one sample (D1) suggests limited sediment recycling from uplifted older arc or accretionary complexes, likely related to tectonic activity along the Gorontalo Fault system. The Qp–Lv–Ls diagram further confirms an arc orogen source dominated by volcanic lithic fragments, indicating strong volcanic input in a subduction-related tectonic environment.

These results are consistent with previous geological interpretations of the Tomini Bay region, which describe the Dolokapa Formation as part of a Miocene volcanoclastic system associated with arc tectonics. However, earlier studies mainly emphasized stratigraphy and regional tectonics, whereas this study provides quantitative petrographic and provenance-based constraints on sediment sources. The identification of lithic arenite and feldspathic wacke, together with their systematic plotting in arc-related fields, refines earlier qualitative interpretations and demonstrates that the Dolokapa sandstones were derived primarily from a dissected volcanic arc.

Regionally, the dominance of arc-derived detritus indicates that during the Middle to Late Miocene, northern Gorontalo was located close to an actively eroding volcanic arc supplying large volumes of volcanoclastic material to adjacent basins. This supports tectonic models that interpret Tomini Bay as part of a convergent margin or arc–back-arc system influenced by subduction. The minor recycled component further implies episodic uplift and erosion of older arc or accretionary complexes, highlighting the dynamic tectonic evolution of the region.

This study is limited by the number of samples and by reliance on petrographic modal data alone. Although the five samples were selected to represent lateral and vertical lithological variations, additional geochemical and geochronological data (e.g., whole-rock geochemistry, heavy minerals, detrital zircon U–Pb dating) would allow more precise discrimination of sediment sources and tectonic evolution. Future integrated studies are therefore required to further refine the sedimentary and tectonic history of the Dolokapa Formation and the Tomini Bay region.

**Conclusion.** The sandstones of the Dolokapa Formation in North Gorontalo Regency are classified into two main types: Lithic Arenite (samples D1–D4) and Feldspathic Wacke (sample D5). Petrographic analysis reveals that these sandstones are dominated by quartz, feldspar, and lithic fragments, with angular to sub-angular grains, poor to moderate sorting, and both intergranular and secondary porosity. Provenance analysis using Q–F–L, Qm–F–Lt, and Qp–Lv–Ls

diagrams consistently indicates a magmatic arc tectonic setting, primarily within the Dissected Arc subzone, with one sample plotting into the Recycled Orogen subzone. The dominance of volcanic lithic fragments highlights a strong influence of volcanic sources. These results demonstrate that the Dolokapa Formation sandstones were derived from the erosion of volcanic arc materials associated with subduction-related processes in the Tomini Bay magmatic arc, reflecting a geologically complex system strongly controlled by volcanism, magmatism, and orogenic deformation in North Gorontalo. Scientifically, these findings provide quantitative petrographic evidence that constrains the Miocene tectono-sedimentary evolution of the Tomini Bay region, support models of arc-related basin development in northern Sulawesi, and offer a reference framework for future provenance, basin analysis, and resource-related studies in eastern Indonesia.

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