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RESEARCH ARTICLE

A geological overview of the limestone members of the Woyla Group of Sumatra, Indonesia

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Abstract

Mesozoic limestone units of the Woyla group were identified in many places across the northern part of Sumatra, Indonesia. Even though these sedimentary rocks may play an important role as an element of the potential Pre-Tertiary hydrocarbon play of Sumatra, their characteristics are still not well understood. This study tries to fill this research gap and aims to better understand the characteristics of the limestone members of the Woyla group. There are three objectives of this study: (1) to characterise structural features, and deformation of the Woyla Group; (2) to provide sedimentary characteristics of the limestone members of the Woyla Group; and (3) to understand the main influences on the development of the limestone members of the Woyla Group. An integrated geological analyses, including structural scanline analysis, petrographic analysis, and acid digestion analysis, was conducted to achieve the objectives of this study.

Findings from this research show that the limestone members of the Woyla group were strongly deformed, and structural features such as bedded strata, faults, folds, and joints were identified within these rocks. The limestone units of the Woyla group consist of at least six microfacies. These are wackestone, packstone, wackestone-packstone, packstone-rudstone, fossiliferous sandstone, and fossiliferous shale. Depositional processes, sea level fluctuations, tectonisms, and climatic variations are interpreted as the main factors influencing the development and evolution of these limestone units. It is expected that the results of this study could advance our understanding of the Pre-Tertiary carbonate rocks in general, and the Woyla group of Sumatra in particular.

Keywords: limestone members of the Woyla group, Pre-Tertiary carbonate rocks, Sumatra

1. Introduction

Pre-Tertiary carbonate rocks were identified in many locations worldwide such as in southeast asia, middle east, america, europe, and australia. These sedimentary units are important element of petroleum system, and acted as a proven hydrocarbon reservoir in many oil and gas fields. Carbonate rock plays an important role in the petroleum industry because more than 40% of the world's oil and gas resources are in the carbonate reservoirs (Lamarche et al., 2012). Carbonate rocks are well known for their highly heterogeneous nature. This is mainly due to the presence of greatly varied biotas/grain types and various diagenetic processes that can increase, maintain, or reduce the quality of a reservoir (Chiarella et al., 2017; Zecchin and Catuneanu, 2017). The generation of fracture systems by tectonic activities also increases the complexity of the carbonate rocks. Therefore, a better understanding of carbonate rocks is necessary and compulsory in order to have better insights into the quality of this particular type of rock.

In Indonesia, Pre-Tertiary carbonate rocks are scattered across the nation, however, it is suggested that the most extensive outcrops of Paleozoic and Mesozoic carbonate rocks of Indonesia are located in Sumatra (Hall, 2009). This study focus on the limestone members of the Woyla group, which are located in the Province of Aceh, northern part of Sumatra, Indonesia (Fig.1). These Pre-Tertiary carbonate rocks were selected for this study due to the potential of these rocks as good quality reservoir, due to the presence of extensive fracture systems (Rusydy et al., 2019; Rusydy and Al-Huda, 2021), and also due to the report of the possibility of Pre-Tertiary hydrocarbon play in Sumatra (Bahesti et al., 2015; Bahesti, 2017). These limestone members of the Woyla group were found in many locations across northern Sumatra, however, characteristics of these sedimentary units and the main factors influencing their development are not well understood.

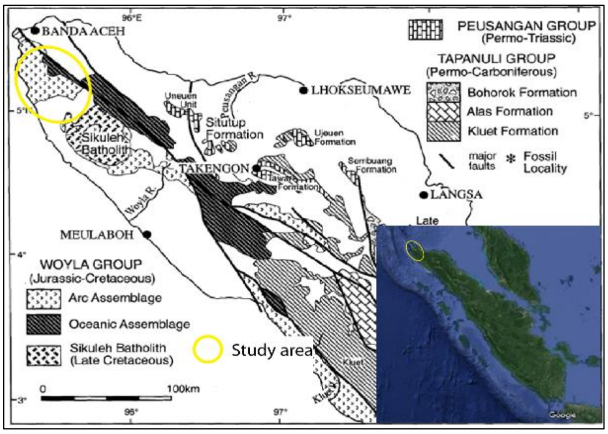

Fig 1. Simplified geological map of northern Sumatra, showing the distribution of Pre-Tertiary stratigraphic units, including the Woyla group (modified from Barber et al., 2005).

This study aims to better understand the characteristics of the limestone members of the Woyla Group, Sumatra, South East Asia. There are three objectives of this study: (1) to characterise structural features, and deformation of the Woyla Group; (2) to provide sedimentary characteristics of the limestone members of the Woyla Group; and (3) to understand the main influences on the development of the Woyla Group.

2. Geological context

Complex structural deformations have strongly influenced the evolution of Sumatra, Indonesia. These include collision during Triassic, numerous strike-slip faulting during Jurassic-Cretaceous, several episodes of granite magmatism during Mesozoic-Cenozoic, and subduction during Cenozoic, among other geological events (Hall, 2009). Numerous fold systems and various types of faultings seen on many outcrops across Sumatra provide evidences of the deformations that occurred during the development of Sumatra (Barber et al., 2005; Cahyaningsih et al., 2017; Idarwati et al., 2021). Seismic interpretation of the subsurface of Sumatra also show many regional deformations that occurred in Sumatra (Hennings et al., 2012; Wils et al., 2021). Tectonic evolution of Sumatra and adjacent areas from the Jurassic to the Pliocene can bee seen in Hall (2012).

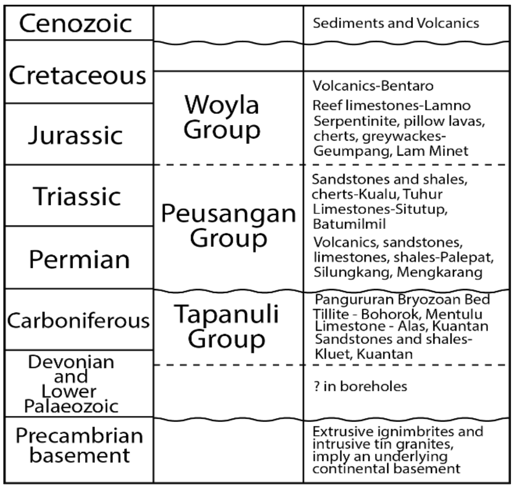

Fig 2. Pre-tertiary stratigraphy of Sumatra showing the main sedimentary units (Woyla group, Peusangan group, and Tapanuli group) of this geological period (modified from Barber and Crow, 2003) .

Basin filling, and deposition of various sedimentary formations have also contributed to the geological history of Sumatra. Palaeozoic, Mesozoic, and Cenozoic rock formations were discovered across Sumatra (Barber et al., 2005), and it is suggested that Sumatra contains the most extensive outcrops of Paleozoic and Mesozoic rocks of Indonesia (Hall, 2009). Outcrops of Pre-Tertiary rocks in Sumatra were found mainly in the northern Sumatra, and in this region the Pre-Tertiary rocks were classified into three major geological units: the Carboniferous-Early Permian Tapanuli Group, the PermoTriassic Peusangan Group and the Jurassic-Cretaceous Woyla Group (Fig.2) (Barber and Crow, 2003).

The Woyla group consists mainly of volcanic rocks, limestones, and serpentinite (Fig.2). This study, however, focus only on the limestone members of the Woyla group. Bennett et al. (1981) divided carbonate units from the Woyla Group, Sumatra into three limestone formations, namely the Lhoknga Formation, the Raba Formation and the Lamno Formation. These sedimentary units are defined as Late Jurassic to Early Cretaceous in age (Bennett et al., 1981; Barber and Crow, 2003; Advokaat et al., 2018). The limestone members of the Woyla group consist of massive calcarenite and calcilutite and dark thin-bedded cherty limestone and shale, consisting of coral (*Actiastraea minima, Slvlosmilia corallina)*, algae (*Clypeina* sp., *Permocalculus ampullacea, Lithocodium, Bacinella* sp., *Boueina* sp., *Thaumatoporella porvosiculifera*), and foraminifera (*seudocyclammina lituus*) (Bennett et al., 1981).

The development of limestone units of the Woyla Group is influenced by a highly oblique subduction system and the great Sumatran fault system (Barber, 2000; Dorobek, 2007; Berglar et al., 2008). The forearc carbonate system of Sumatra is not only influenced by tectonism, but also by volcanism (Bennett et al., 1981; Dorobek, 2007). Highly deformed sedimentary rocks, therefore, crop-out extensively as the Woyla Group, forearc Sumatra. Folded strata, bedded carbonates, fracture systems, and tilted-platform deposits are common in the Sumatra forearc basin. Advokaat et al. (2018), based on paleomagnetic data, suggested that the limestone units of the Woyla Group developed near equatorial latitudes during the middle Jurassic-Cretaceous. This is consistent with the hypothesis of Hall (2012). Moreover, Advokaat et al. (2018) also considered the Woyla Arc as part of the Australian Plate.

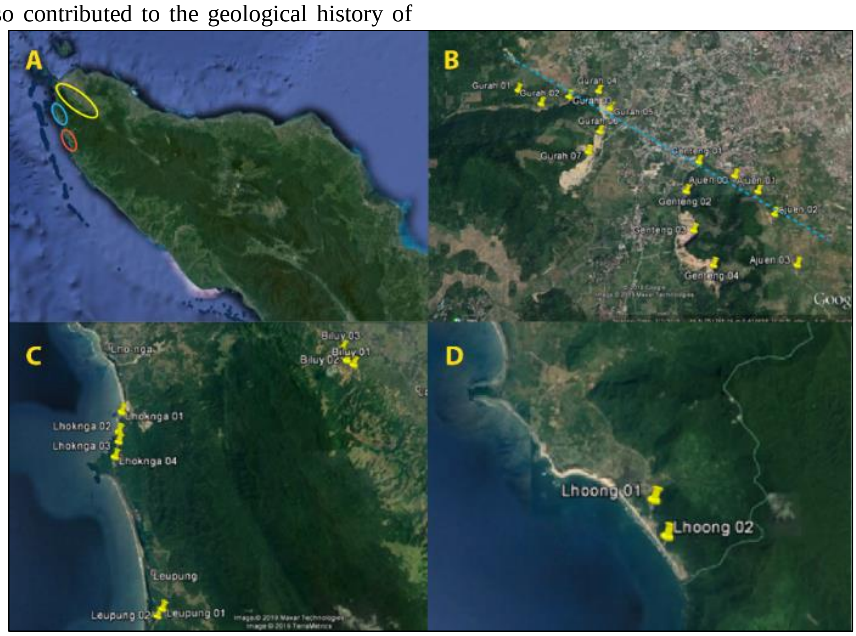

Fig.3. A. The study area is located in the province of Aceh, Sumatra, Indonesia, and this area is divided into three groups of data collection locations (Yellow circle = Fig.3.B, Blue circle = Fig.3.C, Red circle = Fig.3.D). B. 15 datasets were collected from 15 locations in the yellow circled area. C. Nine datasets were collected from nine locations in the blue circled area. D. Two datasets were collected from two locations in the red circled area.

3. Data and methods

Geological surface data collected from 26 locations across the Province of Aceh, northern part of Sumatra, Indonesia (Fig.3, table 1) were collected, analysed, and interpreted to achieve the aim and objectives of this study. These locations were selected due to the presence of the limestone members of the Woyla Group within these locations, and due to its accessible locations. Three types of analyses (scan-line, petrography, and acid digestion) were conducted to achieve the objectives of this study (summarized in Fig.4).

Table 1. Data used for this study were collected from 26 locations across the study area.

No	Location	Code	Northing	Easting
1	Gurah-01	GRH-01	611600	750294
2	Gurah-02	GRH-02	611426	750569
3	Gurah-03	GRH-03	611503	750882
4	Gurah-04	GRH-04	611575	751210
5	Gurah-05	GRH-05	611379	751341
6	Gurah-06	GRH-06	611100	751231
7	Gurah-07	GRH-07	610865	751112
8	Peukan Biluy-01	BLY-01	758277	604733
9	Peukan Biluy-02	BLY-01	757996	604918
10	Peukan Biluy-03	BLY-01	757822	605405
11	Ajuen-00	AJN-00	752701	610595
12	Ajuen-01	AJN-01	752946	610426
13	Ajuen-02	AJN-02	753107	610182
14	Ajuen-03	AJN-03	753305	609656
15	Glee Genteng-01	GTG-01	752317	610759
16	Glee Genteng-02	GTG-02	752175	610430
17	Glee Genteng-03	GTG-03	752238	610012
18	Glee Genteng-04	GTG-04	752429	609657
19	Lhoknga-01	LHG-01	748478	602784
20	Lhoknga-02	LHG-02	748350	601975
21	Lhoknga-03	LHG-03	748348	601571
22	Lhoknga-04	LHG-04	748199	600946
23	Leupung-01	LPG-01	750211	594714
24	Leupung-02	LPG-02	750010	594416
25	Lhoong-01	LHO-01	754734	573974
26	Lhoong-02	LHO-02	755172	572755

Geological scan-line method was applied to measure fracture system characteristics, and this includes fracture's orientation, abundance, type, pattern, density, size, aperture, morphology, and multi-episode development. The scanline survey involves sampling and measuring of the trace length of the discontinuities intersected by the line set on the exposed surface of rock (Ali et al., 2019). A total of 626 fractures from 21 locations across the study area were measured for the purposes of this study.

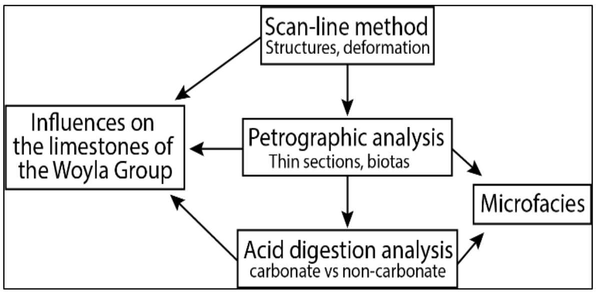

Fig 4. Flowchart showing the relationship of the analyses conducted (scan-line, petrographic, and acid digestion) and the objectives of this study. Microfacies and sedimentary characteristics were interpreted from thin sections and acid digestion data. The main influences on the limestones of the Woyla group were interpreted from all the analyses conducted in this study.

A total of 10 thin sections (AJN-01, AJN-03, BLY-02, GRH-03, GRH-05, GTG-01, GTG-02, GTG-04, LHG-01, LPG-02), all half stained with alizarin red and potassium ferricyanide for differentiation of calcite and dolomite (ferroan and non-ferroan) (Dickson, 1965; Dickson, 1966) were examined using Nikon Eclipse polarised microscope. The main biotas and diagenetic events were identified following Flugel (2010). Naming of the carbonate facies follows classification by Embry and Klovan (1971). Classification of the porosity of the microfacies follow examples of visual estimate of Flugel (2010).

Acid digestion was conducted on 8x~1 cm^3 samples (AJN-01, BLY-02, GRH-03, GTG-01, GTG-02, GTG-04, LHG-01, LPG-02) to determine the percentage of carbonate and non-carbonate material. Each sample was placed in a beaker with 10% hydrochloric acid (HCL), and chemical reaction of the sample and HCL within the beaker was monitored. The residue from the beaker was filtered using a filter paper, and dried at the temperature of 40 ^{0}C. The dried sample was weighted and the weight percentage (wt.%) was calculated quantitatively.

4. Results

Results from geological fieldwork show that the limestone members of the Woyla group is highly deformed, and strongly influenced by tectonisms. This is evidenced by the presence of numerous fault systems, bedded strata, folds, joints, and veins within the limestone members of the Woyla group in the study area (Fig.**5**). Folds are of various size and ranging from small size (<1 m), moderate size (1-10 m), and large size (>10 m). Angle of the fold's limb is ranging between 3-50^0. Bedded strata is also common within the limestones members of the Woyla group, and thickness of the individual bed varies from <20 cm up to 50 cm.

Structural measurement of the fracture systems of the limestone members of the woyla group show the presence of multi-phase and multi-episode fracture systems in the study area (Fig.5). Size (aperture) of these fracture systems varies from <1 cm, up to 15 cm. These fractures are partially and/or fully infilled with calcite minerals (Fig.5). Density of these fractures is ranging between 10-100 fractures/m. Morphology of these fracture systems include straight, arched, branching, and cross cutting, with majority of the fracture systems showing the straight and cross cutting morphology.

Orientation (strike, dip, trend, and plunge) of the fracture systems of the limestone members of the Woyla group varies significantly between the studied data (Fig.6). Strike and trend of the studied fracture systems are not consistent, and were identified pointing to multi-direction (shown in Fig.6). Dip and plunge of these fractures varies between 10-90^0.

Six types of sedimentary microfacies were identified from the studied thin sections and these are grouped into carbonate-dominated group (insoluble materials <30%), and siliciclastic-dominated group (insoluble material >70%. The carbonate-dominated group includes wackestone, packstone, wackstone-packstone, and packstone-rudstone, while the siliciclastic dominated group consists of fossiliferous sandstone, and fossiliferous shale (Fig.7).

Wackstone contains 21.71-26.86% insoluble non-carbonate materials, mud-supported with minor <2 mm size biotas (Ammobaculites sp, Textulariida sp, Miliolid sp, Orbitolina sp, Planktonic foraminifera), and was identified in AJN-01, AJN-03, GRH-03, and GRH-05. Packstone contains 25-26.46% insoluble non-carbonate materials, grain-supported with moderate < 2mm size biotas (Planktonic foraminifera, fragments of bivalve), and was identified in GTG-02, and LPG-02.

Wackestone-packstone contains ~11.01% non-carbonate materials, transition from mud-supported to grain-supported with minor to moderate <2 mm size biotas (Lituolinids sp, Miliolid sp, Textulariida sp), and was identified in LHG-01. Packstone-rudstone contains ~15.09% non-carbonate materials, grain-supported with moderate <2 mm to >2 mm size biotas (fragments of bivalve), and was identified in GTG-04.

Fossiliferous sandstone contain~71.14% non-carbonate materials (fragment of bioclasts, quartz), moderate subrounded to rounded quartz, rare-minor foraminifera, and was identified in BLY-02. Fossiliferous shale contains ~98.57% insoluble non-carbonate material (Planktonic foraminifera, clay minerals), and was identified in GTG-01. Some of the main biotas, and some examples of the fracture systems identified in the thin sections are shown in Fig.8. Percentage of the insoluble non-carbonate materials of each studied sample is shown in table 2.

Table 2. Results from acid digestion analysis. GRH=Gurah, LPG=Leupung, GTG=Glee Genteng, BLY=Biluy, AJN=Ajun, LHG=Lhoknga. C = Carbonate, NC = Non-carbonate.

No	Code	Initial sample Weight (Gr)	Filter paper (Gr)	Dried Weight (Insoluble+ paper) (Gr)	Insoluble Weight (Gr) (E-D)	Insoluble percentage (fraction) (F/C)	Insoluble percentage (%) (Gx100)	Remarks
A	B	C	D	E	F	G	H	
1	GRH-03	1.07	0.86	1.15	0.28	0.26	26.86	C
2	LPG-02	0.64	0.86	1.02	0.16	0.25	25.00	C
3	GTG-01	0.55	0.88	1.43	0.55	0.98	98.57	NC
4	GTG-02	0.89	0.89	1.13	0.23	0.26	26.46	C
5	GTG-04	0.72	0.89	1.00	0.11	0.15	15.09	C
6	BLY-02	0.94	0.88	1.55	0.67	0.71	71.14	NC
7	AJN-01	0.84	0.87	1.05	0.18	0.21	21.71	C
8	LHO-01	0.87	0.86	0.95	0.09	0.11	11.21	C

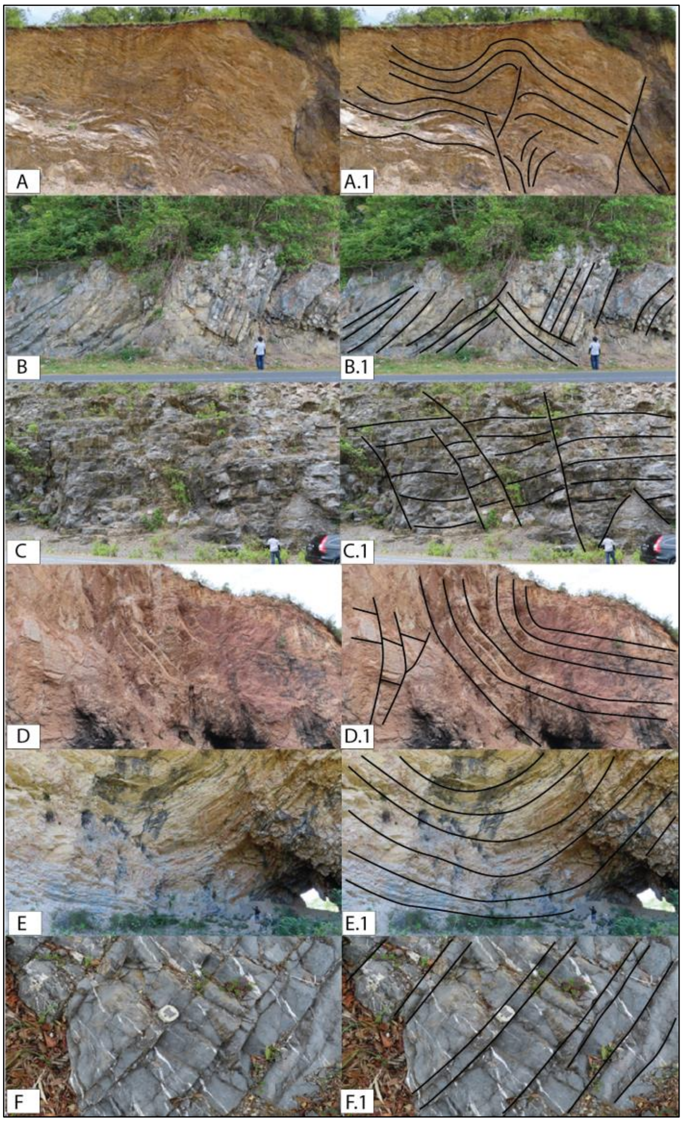

Fig 5. Showing un-interpreted (left, A-F) versus interpreted (right, A.1-F.1) field photographs of the limestone members of the Woyla group. Gradual erosion and dissolution of the limestones are common in the study area. A. Photograph from Gurah-06 showing numerous folds, normal and reverse faults. B. Photograph from Lhoknga-01 showing bedded limestone with extensive fracture systems. C. Photograph from Lhoong-02 showing normal faults systems, and bedded limestones with chaotic and irregular structures. D. Photograph from Glee genteng-02 showing bedded limestone, folds, normal and reverse faults. E. Photograph from Gurah-05 showing fold systems, and bedded limestones with extensive fracture systems. F. Photograph from Lhoknga-02 showing partially and fully infilled fracture systems within the limestone members of the Woyla group. These fractures are abundant in the study area, and were mainly infilled with calcite minerals.

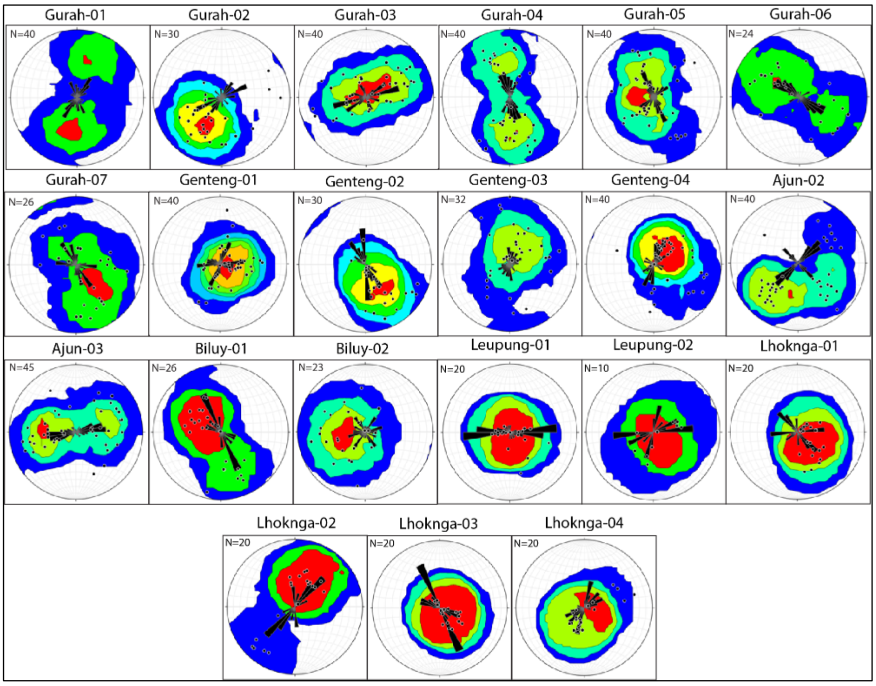

Fig 6. Results from structural measurements of the fracture systems of the limestone members of the Woyla group from several locations across the study area, showing multi-directional orientation of the fracture systems. N = number of data.

Results from the petrographic study show that the limestone units of the Woyla group have poor quality primary porosity and permeability (on the basis of visual estimate) (Fig.7-8). These sedimentary units, however, have moderate-good quality secondary fracture porosity (Fig.5). Open fractures are common within the limestone members of the Woyla group in the study area and these fractures provide good quality porosity, and high quality migration pathways for fluid. In some locations, these open fractures porosity were occluded with calcite minerals and this has reduced the quality of the porosity of this rock (Fig.5, 7-8).

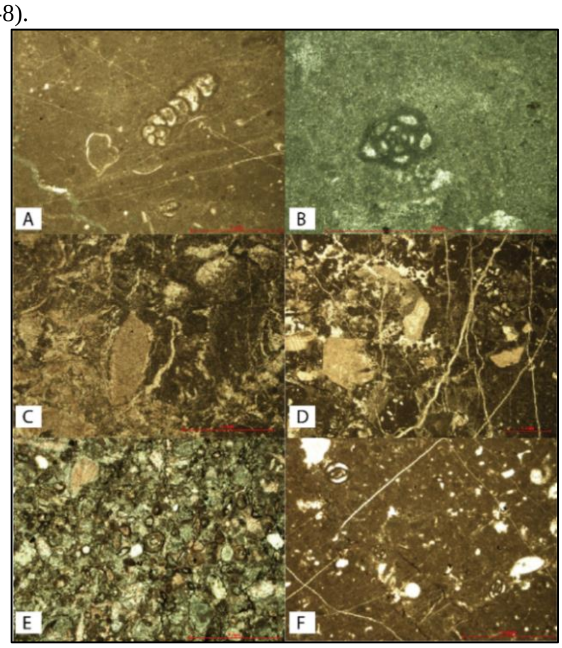

Fig 7. Thin sections photomicrographs showing six main microfacies of the limestone members of the Woyla group. A. Wackestone, with multichambered uniserial Ammobaculites sp, (middle of the picture) B. Packstone, with Miliolid sp. (middle of the picture) C. Wackestone-Packstone. D. Packstone-Rudstone. E. Fossiliferous sandstone. F. Fossiliferous shale. Scale bar is 1 mm.

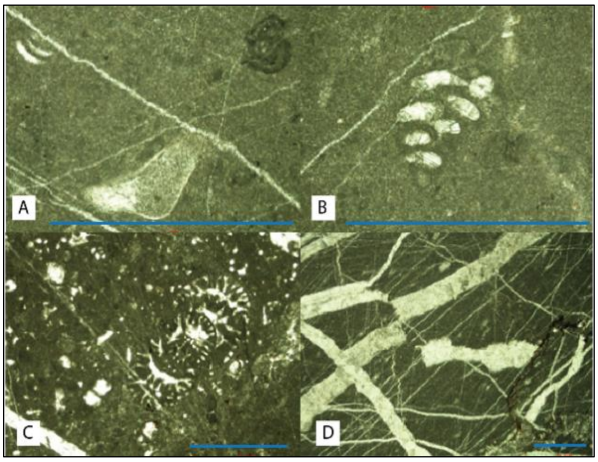

Fig 8. Thin section photomicrographs of the limestone members of the Woyla group showing the main biotas and fractures. A. Orbitolina sp. B. Textulariida sp. C. Lituolinids sp. D. Multi-size and multi-episode fracture systems. Scale bar 1 mm.

5. Interpretation and Discussion

Structural study of the limestone members of the Woyla group shows the presence of extensive folds, and fracture systems within these sedimentary rocks (evidences shown in Fig.5-8). These evidences suggest the influences of strong tectonic activities during the evolution of the limestone members of the Woyla group. The presence of multi size and multi episodes fracture systems is suggestive of the episodic development of the limestone members of the Woyla group, interpreted to be associated with multi-stage evolution of Sumatra. Furthermore, outcrops of Woyla group located in the southern part of Sumatra, also show the presence of various structural features (Idarwati et al., 2021) and this is suggestive of similar processes affecting the Woyla group across Sumatra.

Tectonic activities that influence the Woyla group are interpreted to be associated with plate tectonic subduction, and faultings that occurred during the evolution of Sumatra and Simeulu island (Aribowo et al., 2014; Craig and Copley, 2018;

Salman et al., 2020). The subduction zone southwest of Sumatra is part of a long convergent belt that accommodates the northward motion of the Australian plate into Eurasia (McCaffrey, 2009). The Woyla group was proposed to have formed above a west-dipping subduction zone in the Early Cretaceous, synchronous with east-dipping subduction below Sundaland (Advokaat et al., 2018).

The presence of various structural features within the limestone members of the Woyla group may also be associated with the formation of numerous sedimentary basins and sub-basins (Houqin et al., 2022), and the development of the great Sumatran Fault systems that took place during Cenozoic (Fernández-Blanco et al., 2016; Hady and Marliyani, 2021). Tectonic activity in Sumatra is a continuous process that occurred throughout the geological records, due to its active plate tectonic movement (Hall and Spakman, 2015; Muksin et al., 2023; Rafie et al., 2023).

This study has succesfully identified 6 microfacies of the limestone members of the Woyla group, and these are grouped into carbonate-dominated facies, and siliciclastic-dominated facies. The presence of both carbonate-dominated facies and siliciclastic-dominated facies is suggestive of the influence of various depositional processes, climatic variations and relative sea-level changes (Chiarella et al., 2017). Siliciclastic materials are interpreted to have been transported into the basin during the relative sea-level lowstand, while carbonate growth dominated during relative sea-level highstands (Garzanti, 1999; Bauer et al., 2003). Sea-level fluctuations clearly affected the development of the limestone units of the Woyla group, as evidenced by the presence of both carbonate and siliciclastic materials within these sedimentary units.

Limestones members of the Woyla group contain miliolids sp, and lituolinids sp, among other foraminiferas/biotas. The presence of miliolids sp, and lituolinids sp are indicative of deposition in an inner shallow platform, that may be influenced by local/regional climatic variations (Flugel, 2010). The presence of siliciclastic materials is also suggestive of the deposition in a location near to the source of the siliciclastic materials. This location is interpreted to be the inner shallow platform, probably associated with reefs.

Previous study of the limestone members of the Woyla group proposed that this sedimentary unit consists of the Lhoknga Formation, the Raba Formation and the Lamno Formation (Bennett et al., 1981). These limestones are massive, recrystallised, consist of calcarenite and calsilutite, with corals, algae, and foraminieras as the main biotas and are interpreted to be associated with the island arc assemblage, as fringing reefs to volcanic islands (Bennett et al., 1981; Barber et al., 2005). Finding of this study support the description, and interpretation of the depositional environment of the limestone members of the Woyla group by the aforementioned researchers. However, this study shows that the limestone members of the Woyla group composed of not only carbonate rocks/materials, but also siliciclastic materials. Earlier researchers (Bennett et al., 1981; Barber et al., 2005) didn’t explain the presence of moderate-major siliciclastic materials within the limestone members of the Woyla group. Findings of this study suggest that a comprehensive re-evaluation of the limestones members of the Woyla group, integrating various geological analyses, is needed in order to have a better understanding of the characteristics of these Mesozoic sedimentary units.

6. Conclusion

The limestone members of the Woyla group is highly deformed. Numerous folds, fault systems, joints, veins, and bedded structure were identified within these Mesozoic sedimentary units. Findings of this study show the presence of at least six microfacies within the limestone members of the Woyla group, and these facies are classified into carbonate-dominated facies (wackestone, packstone, wackstone-packstone, and packstone-rudstone), and siliciclastic facies (fossiliferous sandstone, and fossiliferous shale). The development of the limestone members of the Woyla group were strongly influenced by depositional processes, sea-level fluctuations, climatic variations, and tectonic activities. The episodic development of the limestone members of the Woyla group was associated with the multi-phase evolution of Sumatra, and the nearby Simeulu island. Findings of this study show the presence of moderate-major siliciclastic materials within the limestone members of the Woyla group, and this was not reported by any earlier researchers. We strongly believe that further geological studies are needed to complement this research, and to reveal many new insights/information of the limestone members of the Woyla group.

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