



Structure Evolution and Palinspastic Analysis of The Gurami-Tamiang Area, North Sumatra Basin, Indonesia

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ABSTRACT - The Sumatran back-arc basins developed beginning in the Middle Eocene, characterized by a variety of graben alignment patterns, which serve as critical indicators in understanding their formation history. One such basin is the North Sumatra Basin, dominated by north-south-trending grabens. These grabens are best observed in the Gurami-Tamiang Area. This research focuses on the subsurface analysis of this area, specifically: (i) detailed seismic interpretation of four east-west cross-sections that span several grabens, and (ii) palinspastic reconstructions to investigate structural and strain evolution over time, and its tectonochronostratigraphic chart. Generally, the structural configuration of the Gurami-Tamiang Area is defined by half-grabens bounded by east-dipping faults originating from negative flower structures at depth. The results show three phases of evolution: (i) Extensional Phase (45 - 32 Ma) is characterized by growth strata and strain magnitudes of (+) 4.2% to (+) 11.64%, (ii) Transitional Phase (32 - 22 Ma) is displaying both positive and negative strains of (+) 2.3% to (-) 1.7%, with growth strata that are extending across grabens; and (iii) Contractional Phase (22 Ma – present) is characterized by negative strains of (-) 0.92% toward zero and mostly covered by post-extensional and syn-inversion deposits. The evolutionary phases indicate a novelty in the area, with the graben formation being part of a wrench fault system that includes the Khlong-Marui Fault, the Lokop-Kutacane Fault, and the Sumatra Fault.

Keywords: North Sumatra Basin, Gurami-Tamiang area, palinspastic, wrench, structure evolution.

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INTRODUCTION

The Sumatran back-arc basins are a Tertiary-age basin, a productive oil and gas-producing basin in Indonesia (Doust & Noble, 2008). The back-arc basins are divided by the Asahan and Tigapuluh arches into the North, Central, and South Sumatra Basins (Barber et al., 2005; Darman and Sidi 2000; Koesoemadinata 2020). These basins (Figure 1) formed at the beginning of the Early Paleogene, mostly in the Late Eocene, and are notable for their distinct graben lineament patterns. The dominant pattern in the North Sumatra Basin (NSB) area consists of north-south-trending grabens. The Gurami-Tamiang Area is one of the best places to determine the north-south trending graben in the

NSB. It is believed that the north-south structural grain from the pre-Tertiary period influences the NSB, which seems to control sedimentation processes during the Tertiary evolution (Davies, 1984; Mujito et al., 1990; Hidayatillah et al., 2017). The tectonic forces responsible for generating this north-south-trending graben remain debatable. However, Daly et al. (1991) posited that the Sumatran basins were formed as a consequence of back-arc extension during the Eocene. This notion has been echoed in subsequent publications. Our research identified that most issues stem from a negative flower structure. We propose a revised perspective on the tectonic style involved in forming grabens resulting from extensional forces within a wrench system.

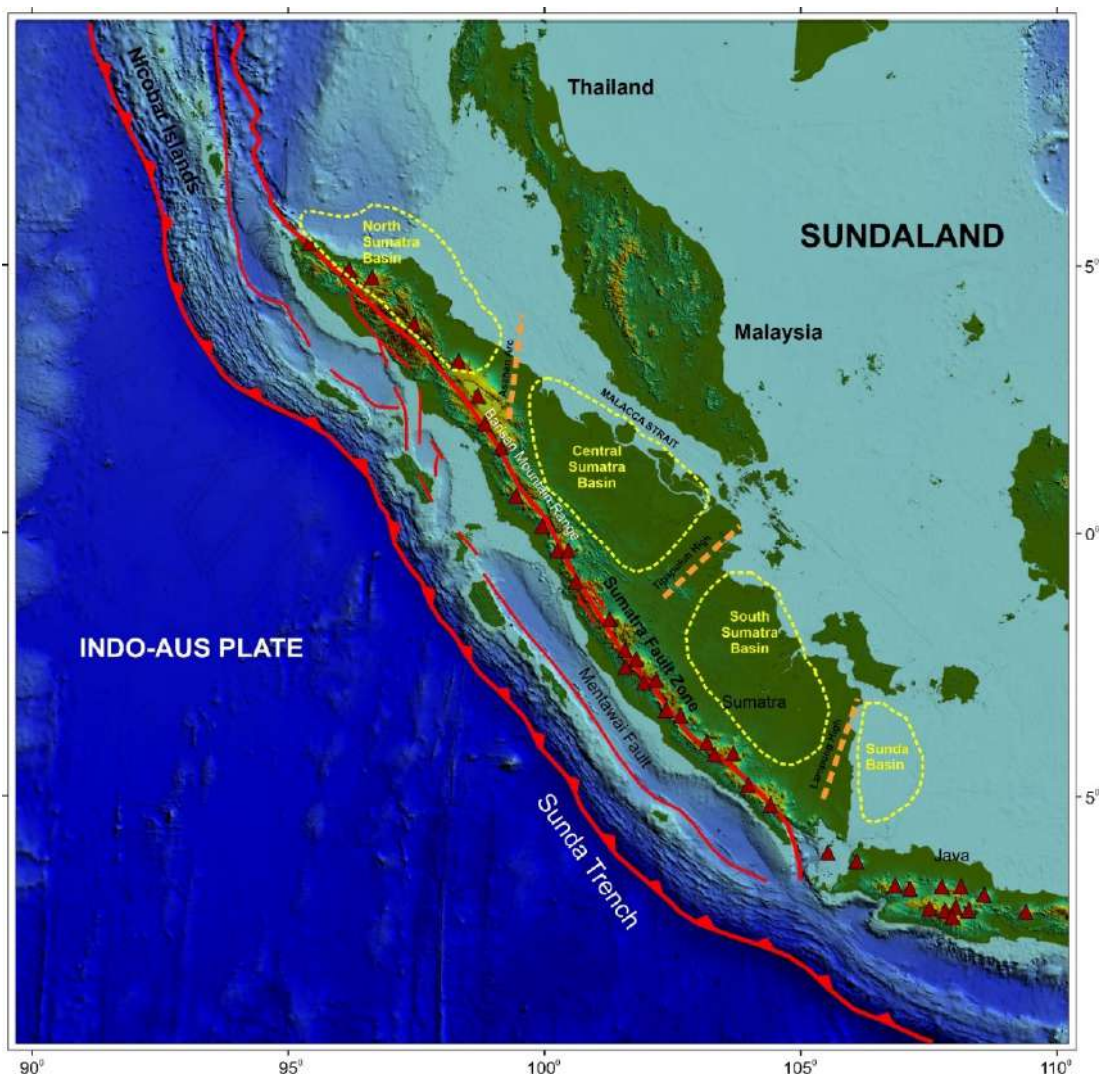


Figure 1. The physiography and tectonic framework of Sumatra Island, situated at the edge of the Sundaland continent, result from the oblique convergence of the Indo-Australian Plate, which is moving relatively northward. Several Paleogene (Eocene-Oligocene) basins are commonly believed to have formed through a back-arc system mechanism. These basins include the North Sumatra Basin (NSB), Central Sumatra Basin (CSB), and South Sumatra Basin (SSB). Image modified from Heidrick and Aulia (1993), McCaffrey (2009), and van Gorsel (2020), with overlay by bathymetry map of SIBATNAS (2019).

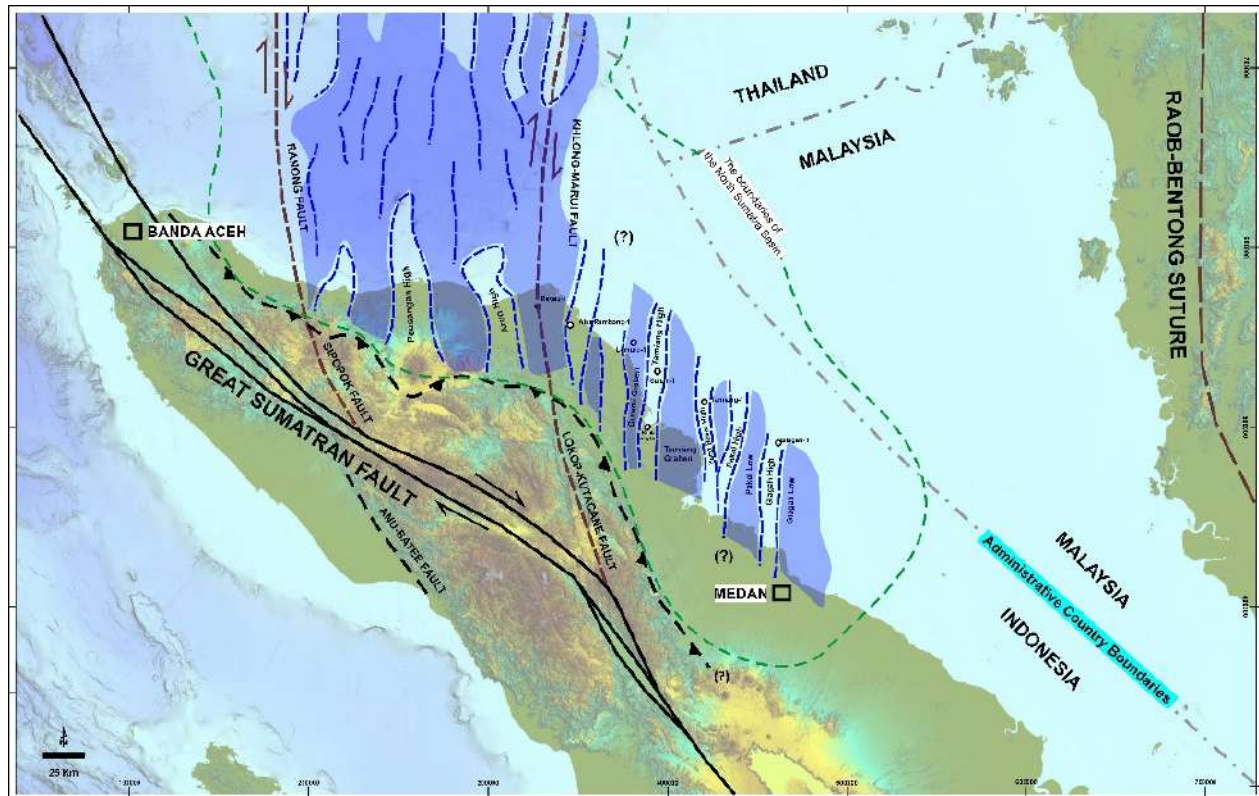


Figure 2. The regional map of the northern part of Sumatra Island highlights the location of the Gurami-Tamiang in the North Sumatra Basin, indicated by a red box. The regional fault lineament is taken from Mujito (1990). Meanwhile, the boundaries of the basin, along with the highs (horsts) and lows (grabens), are modified from Netherwood (2000).

Understanding the evolution of structures in this region necessitates a thorough knowledge of the tectonic activities that have been present since the formation of the graben. The primary objective of this research is to deepen our comprehension of the structural evolution of the Gurami-Tamiang Area within the North Sumatra Basin (NSB) through subsurface analysis and palinspastic restoration.

Regional geology

The tectonic evolution of Sundaland has been primarily shaped by convergent tectonics since the early Cenozoic era, as mentioned already. This area is characterized by highs and depressions that trend north-south, including features such as the Gurami Graben, Tamiang High, Tamiang Deep (also known as Tamiang Graben), Yang Besar High, Pakol High, Pakol Low, Glagah High, and Glagah Low (Figure 2). The geographical boundaries include the Malacca Strait to the east and north, the Bukit Barisan Mountains to the south, and the Arun High and Lokop-Kutacane Fault to the west (Figure 2).

During the Eocene, the direction of subduction of the Indo-Australian Plate against Sundaland shifted to an oblique angle. This change resulted from the

collision between the Indian Plate and the Eurasian Plate (Daly et al., 1991). This collision caused the extrusion and rotation of continental blocks toward Southeast Asia (Tapponnier et al., 1982). The oblique convergence led to the development of a strike-slip fault system, as described by Fitch (1972) and further elaborated upon by Barber et al. (2005).

Subsequently, the formation of the Sumatran back-arc basins began during the Eocene-Oligocene period. During this time, extensional sedimentation is believed to have occurred, resulting in the creation of organic-rich lake deposits in the newly formed basins. The fill of the basin is primarily marine, consisting of deeper marine claystone and shales in the northern region, along with shallow water reef limestones found in the structural highs (Doust & Noble 2008). Recent studies have provided stratigraphic charts of the North Sumatra Basin, including works by Tampubolon et al. (2017); Syarifuddin & Ariyanto (2018); and Lunt (2019). In this basin, the Eocene-Oligocene syn-extension deposits are represented by the Bruksah and Bampo Formations. The Bampo Formation is the potential source rock since it exhibits medium organic

material content (Musu et al., 2015). However, it was previously suggested that the Tampur sediments are associated with the syn-rift phase and are likely distinct from the fractured basement carbonates (Collins et al., 1996; Bahesti et al., 2015). Since the Tampur Formation has a different character from the rest of the basement, the Tampur Formation should be part of the early syn-rift.

During the Late Oligocene to Plio-Pleistocene, post-rift deposits are represented by the Belumai and Peutu Formations, along with the thick shale of the Baong Formation. The syn-inversion of the Keutapang, Serula, and Julu Rayeu Formations followed this period. Significant geographic changes occurred during the Miocene, with a notable shift in sediment sources from the Asahan High to the Barisan Uplift region. As a result, sediment deposits expanded beyond the boundaries of grabens and horsts, allowing channels and rivers to connect and facilitating broader sediment transport processes.

The NSB receives a significant sediment supply from the Barisan uplift, bolstered by the progradation system that stretches from Barisan Mountain to

the eastern offshore area. This system incorporates sediment contributions from Asahan High during the Late Miocene to Plio-Pleistocene, highlighting the robust geological processes. After the completion of the graben formation in the Miocene, thick sequences of sediment continued to transgress. This was accompanied by subsequent uplift due to contraction along the subduction path, a process that continues to occur today.

METHODOLOGY

The research area covers approximately 18,000 km² and includes 2D seismic data, in which the vintages are primarily from the 1980s and 1990s, and several drilling wells provided by Balai Besar Pengujian Minyak dan Gas Bumi “LEMIGAS” Jakarta, PUSDATIN, Pertamina Hulu Energy (PHE), and PETRONAS. Most 2D seismic cross-sections in offshore regions are of relatively high quality, whereas those in onshore areas tend to be lower quality, dating back to the 1990s. Fortunately, the identified graben are situated in the offshore area.

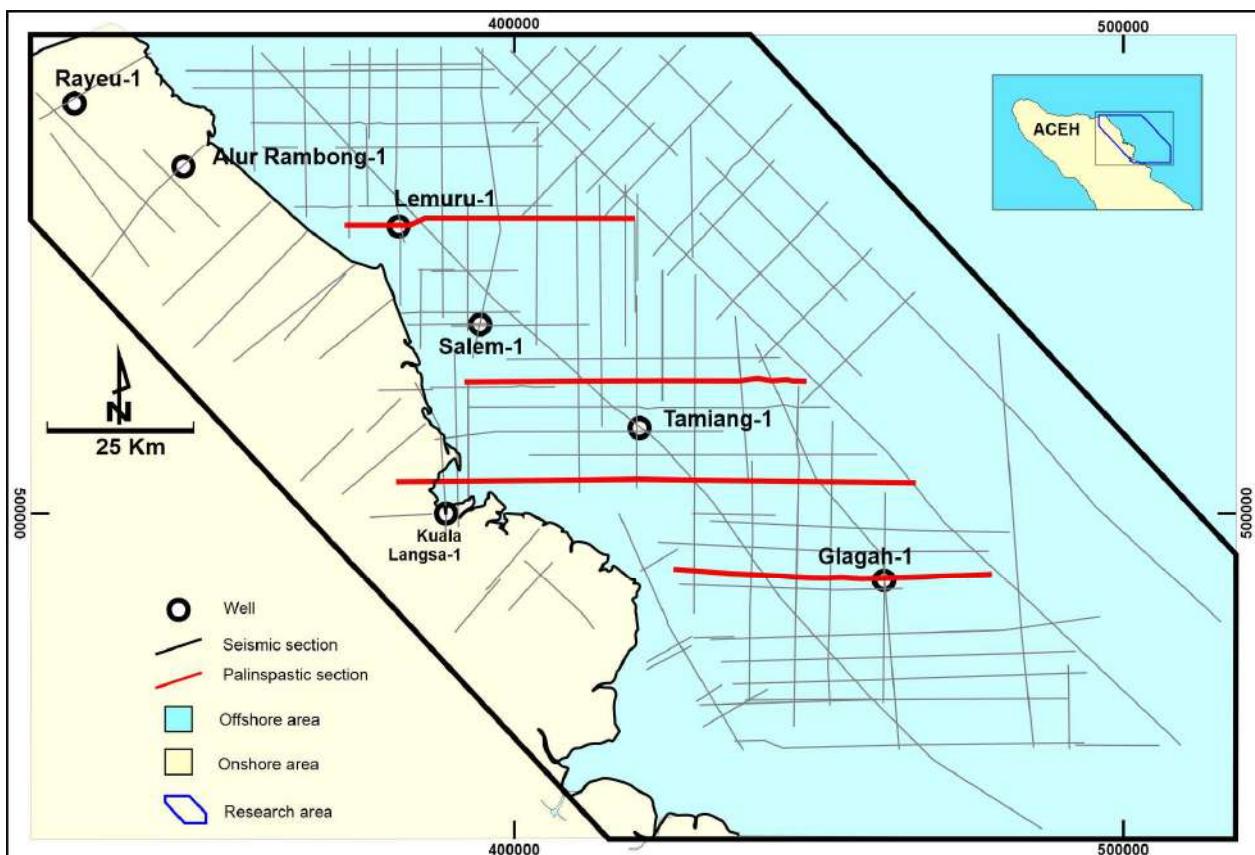


Figure 3. The distribution of 2D seismic and well data in the Gurami-Tamiang area showing that most seismic and well data are offshore by origin.

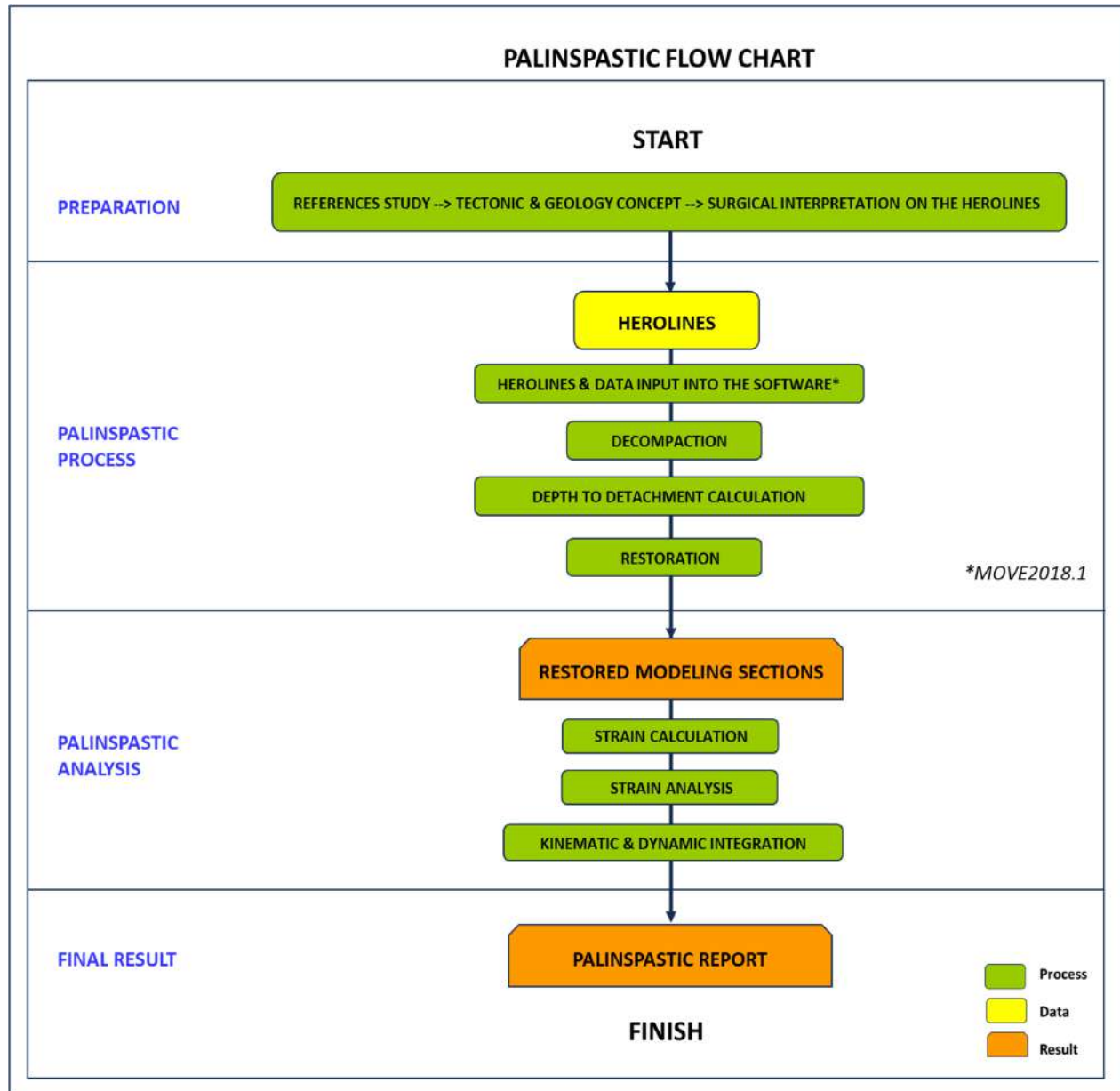


Figure 4. The flowchart for palinspastic restoration begins with geological cross-sections and includes decompaction, depth to detachment, restoration, and strain calculations.

There are seven exploration wells; however, only five are used in the seismic and palinspastic interpretation of the cross-section: Lemuru-1, Salem-1, Tamiang-1, Kuala Langsa-1, and Glagah-1 (Figure 3). These wells are crucial for determining the age and depositional environment. The Glagah-1 and Kuala Langsa-1 wells provide complete data on age and depositional environment, while the other three contain incomplete data; however, these still contribute valuable information for producing check-shot plots. The research methodology involves several key steps (Figure 4): mapping the structural features of 2D seismic data, constructing

herolines, palinspastic restorations, and strain analyses. Several key markers are used to map the key horizons; later, these markers are also utilized in palinspastic analysis. Palinspastic is a method used to restore geological cross-sections to a specific time before they were deformed (Yin & Groshong 2006), a technique employed to examine the geological structure of an area by reconstructing past paleogeographic, geological, and environmental conditions over geological time scales. The initial step in this analysis is to create a reconstructed geological cross-section that incorporates both structure and stratigraphy, including the amount

of erosion from any missing sections in a well or through reconstructed stratigraphy. A decompaction process is applied to restore the geological horizon to its precompaction condition. This enables the calculation of strains, which aids in understanding the processes of extensional or shortening within the cross-section. Strain calculation involves determining the difference in length after an object has been restored compared to its original length. A negative result for strain indicates a contraction or shortening, while a positive result signifies an extension or lengthening.

The commonly used computer application for palinspastic processes is MOVE2018.1 (2D Kinematic Modelling 2018), combined with manual drawing techniques. The palinspastic stage is illustrated in detail in Figure 3. Initially, the horizon markers were decompacted to ascertain their original thickness, followed by measuring the depth of the detachment, which set the stage for restoration.

A range of structural geology techniques were employed in this palinspastic restoration process, as outlined in the MOVE2018 guidebook. Several methods were detailed, including: (i) Simple Shear Unfolding, a straightforward shear process that restores the horizon to its original linear shape or a less steep slope; (ii) Flexural Slip Unfolding, which utilizes pins and a slip system aligned with a benchmark to regulate the layer's opening; (iii) Line Length Unfolding, aimed at straightening a curved horizon; and (iv) Move-on-fault, a technique that returns the horizon to its original configuration by employing a fault plane with simple shear, fault parallel flow, fault bend folds, and fault propagation. The decompaction is already done for this palinspastic restoration. The depth to detachment for faulting is complex since the calculations for four cross-sections suggest depths ranging from 5 to over 12 km.

RESULT AND DISCUSSION

Stratigraphic marker & tectonic phase

Several stratigraphic markers have been developed that are consistent with the regional tectonic framework of the North Sumatra Basin. This research has revealed that graben formation is linked to the wrench system. To maintain consistency with the concepts of structural geology, the terminology associated with rift stages has been revised from pre-rift, syn-rift, and post-rift to pre-

extensional, syn-extensional, and post-extensional. All markers are based on biostratigraphy and seismic stratigraphy observations from the Lemuru-1, Salem-1, Tamiang-1, and Glagah-1 wells (Figure 5). The details are as follows:

- **Horizon 1:** The Top Pre-extensional - serves as the boundary between the pre-extensional and syn-extensional phases, approximately older than 45 Ma. In the southern region near Glagah-1, the lithology predominantly consists of highly folded limestone and dolomite. According to Bachtiar et al. (2014), this formation is part of the Permo-Triassic Peusangan Group, which encompasses the Batumilmil Formation, Kaloi dolomite, and Kualu shale formations. Subsequently, early syn-extensional deposits were laid atop this horizon. In a tectonic setting, during this period, the India Block began moving northward, resulting in regional strike-slip and transtensional activities. This pre-Tertiary lithology has a significant secondary reservoir due to fracturing (SAmerican petroleum institute ie et al., 2017).
- **Horizon 2:** The Top Tampur and Bruksah Formation, approximately 32 Ma. No wells in the Gurami-Tamiang Area have penetrated these formations. But, according to Ryacudu and Sjahbudin (1994), the Tampur Formation primarily consists of carbonate limestone. In contrast, the Bruksah Formation is characterized by thick basal breccia-conglomerates, representing alluvial fans (Lunt 2019). Above these are layers of light to dark grey, micaceous, and poorly sorted quartz sandstone, siltstone, and mudstone (Cameron et al., 1980). The seismic features of the clastic sediment show low to medium amplitude with parallel terminations found in the Tamiang deep area. Conversely, the Tampur carbonate displays strong amplitude parallel terminations. These formations represent an early syn-extensional deposit.
- **Horizon 3:** Top Intra Bampo Fm, approximately 25 Ma. The Bampo Formation consists of shale, siltstone, and minor sandstone deposited in littoral to shallow middle neritic environments. This formation is popular to be a source rock in the petroleum system. In the meantime, the Bampo Formation consists of carbonate limestone as a reef that, in certain areas, evolves into reef carbonate limestone.
- **Horizon 4:** Top Bampo and Arun Formation, approximately 22 Ma. The Bampo Formation

consists of shale, siltstone, and minor sandstone deposited in littoral to shallow middle neritic environments. The Carbonate Arun is deposited in the inner neritic to shallow middle neritic. The Bampo and Arun Formation is categorized as a middle to late syn-extensional deposit.

- Horizon 5: The Top of the Belumai Sandstone, approximately 17 Ma, refers to a Lower Miocene sandstone that is part of the Belumai Formation. This formation is primarily composed of fine to medium-grained sandstones, and in the lower section, is intercalated with shale; this formation was deposited in shallow to open marine environments. It is classified as sagging or post-extensional deposits and serves as a significant hydrocarbon reservoir within the basin.
- Horizon 6: The Top Belumai Limestone, ap-

proximately 15 Ma, is part of the Belumai Formation, also known as the Malacca Formation. It primarily comprises carbonate rocks, such as limestone, and often exhibits characteristics indicative of a reefal depositional environment. It is classified as sagging or post-extensional deposits

- Horizon 7: The Top Middle Baong Sandstone, or "MBS," approximately 11 Ma. It consists of layers of sandstone that formed as the area shifted towards the sea. The MBS often sits on top of alternating layers of shale and sandstone found in the Lower Baong Formation, which mainly consists of shale. Both the Lower and Middle Baong formations are seen as marine deposits, made up of deeper water shale and shallower sand layers. The Middle Baong Sand-

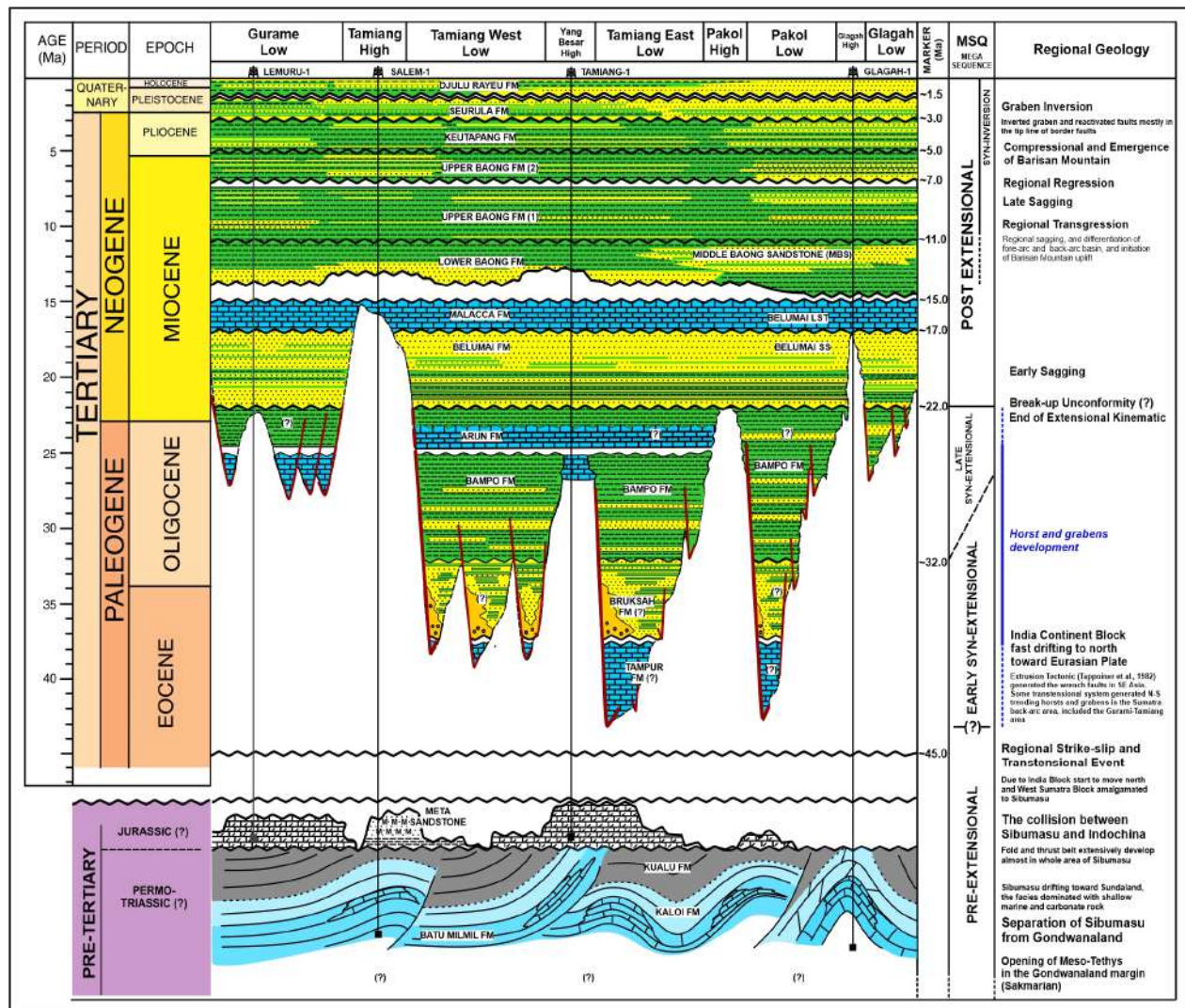


Figure 5. The tectonochronostratigraphic chart of the Gurami-Tamiang area, which cross-cuts through wells Lemuru-1, Salem-1, Tamiang-1, and Glagah-1, alongside seismic interpretations among these wells to confirm the lithological lateral distribution, enhancing our understanding of the subsurface stratigraphy in this region.

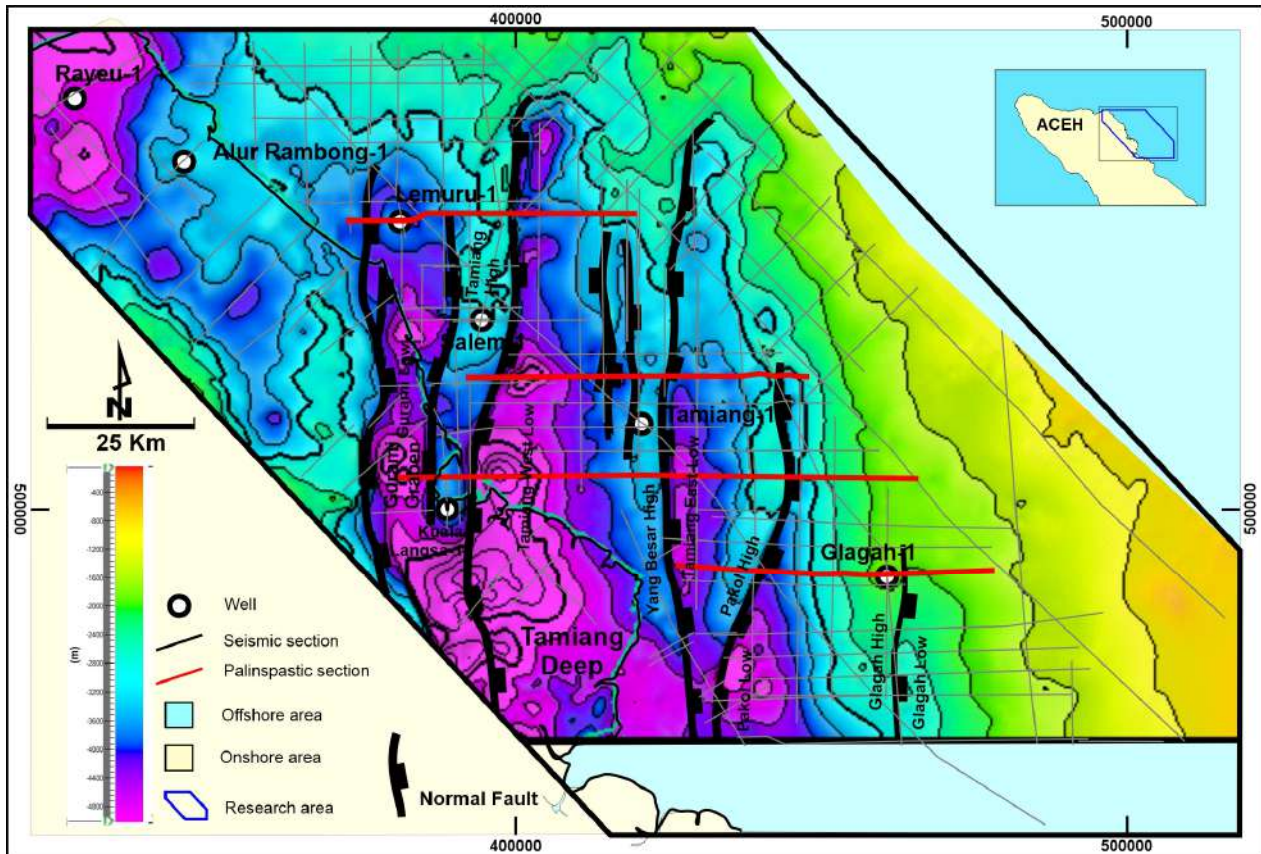


Figure 6. The depth structure map of the Gurami-Tamiang area, specifically for the 45-million-year (Ma) marker, shows the top of the pre-extensional and outlines a horst-and-graben configuration. There are at least five major faults trending north-south, and the depocenter is observed to deepen toward the south in the Tamiang Deep.

stone is important because it has good potential reservoir for holding oil and gas, the sand layers within the shale sequence.

- Horizon 8: The Top Upper Baong 01 Formation, approximately 7 Ma. The Baong Formation consists of interbedded mudstone, sandstone, and limestone layers. This formation reflects the late stage of sagging post-extensional deposition. An unconformity distinguishes Upper Baong 01 from Upper Baong 02, which may have been caused by regional regression related to the initiation of the Barisan Mountain uplift. Some inverted border faults are believed to have happened during the Barisan Mountain Uplift.
- Horizon 9: The Top Upper Baong 02 Formation, approximately 5 Ma. This formation shares a similar lithology with Horizon 7, but it differs due to the gap in seismic stratigraphy data.
- Horizon 10: The Top Keutapang Formation, approximately 3 Ma, consists of shale dominated in the lower part and shale intercalated with

sandstone in the upper part, deposited in deep middle neritic to outer neritic. This formation was deposited as the Barisan Mountains were compressed and emerged.

- Horizon 11: The Top Seurula Formation, approximately 1.5 Ma, consists of shale in the lower part and sandstone in the upper part. It was deposited in shallow middle neritic to outer neritic environments.
- Horizon 12: The Djulu Rayeu Formation, of the Recent age, consists of interbedded sandstone and mudstone deposited in littoral to inner neritic environments.
- As illustrated in Figure 5, all these markers and the tectonic setting have been effectively combined and integrated into a comprehensive tectonostratigraphic chart.

Depth structure map

A series of depth structure maps was developed to evaluate the extent of the graben associated with the syn-extensional phase. One notable structure map highlights the top of the pre-extensional package, and

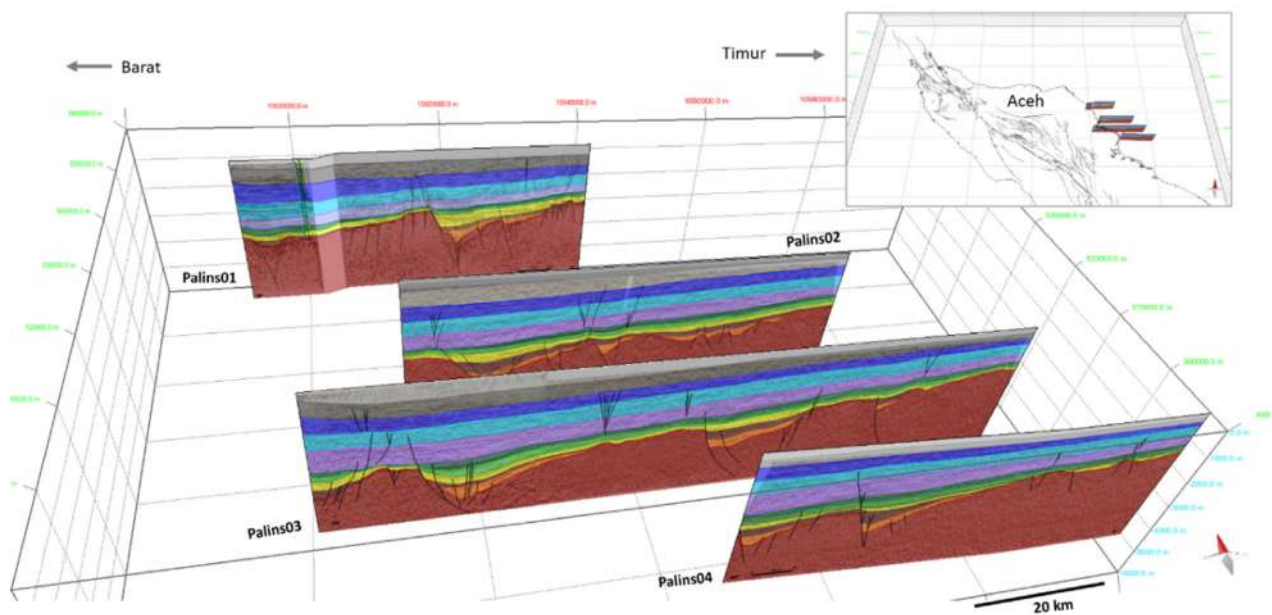


Figure 7. The 3D geological cross-sections provide a clear perspective on the formation and distribution of structures within each section.

it becomes clear that the deepest region is located in the central area, known as the Tamiang Graben or Tamiang Deep. At least five significant faults can be identified, trending north-south and mostly dipping eastward, resulting from the Eocene extensional system (Figure 6).

Palinspastic restoration

Four seismic sections (shown in red) trend west-east (Figure 6) and the structure variation can be seen clearly in 3D view (Figure 7) are used in the palinspastic restoration of the Gurami-Tamiang Area: (1) Seismic Section Palins01: A west-east trending section about 48 km long that passes through the Lemuru-1 well, (2) Seismic Section Palins02: A west-east trending section about 57 km, not intersect any wells but crosscuts at least two large grabens, (3) Seismic Section Palins03: The longest section in this palinspastic analysis, about 86 km and trends west-east, it does not pass through any wells, but three near reference wells are available: Tamiang-1 in the north, Kuala Langsa-1 in the southwest, and Glagah-1 in the southeast, and (4) Seismic Section Palins04: This section is a west-east trending cross-section measuring about 54 km in length and crosscut the Glagah-1.

All of these sections are already represented in meter depth units with a vertical-to-horizontal ratio of 1:4 and have undergone processes of decompaction,

as well as depth-to-detachment calculations. The possible depth of detachment range for the four cross-sections shows depths ranging from 5 to 12 km, or even more. These varying Figures indicate that the fault is not based on a planar or listric detachment, which is common in extensional systems. Instead, it suggests the presence of another mechanism that may be causing this fault, such as a strike-slip system with a sub-vertical to vertical fault plane. However, an oblique component also allows accommodation space to form, similar to what is observed in normal faults.

Palinspastic section palins01

This section (Figure 8) describes the well Lemuru-1, located in the western region of the Ikan Horst. As it moves eastward, it encounters an elevation where late syn-extensional deposits, spanning from 25 to 22 Ma, thin out toward a footwall block of a border fault. A half-graben is found in the middle of the section, characterized by a fault dipping to the east, where syn-extensional deposits aged 32, 25, and 22 Ma fill the graben with growth strata. To determine the strain changes, the positive value of extension (e^+) indicates that the section has likely experienced lengthening (extensional), while the negative value of extension (e^-) indicates that the section likely experienced shortening (compressional). Palinspastic results of

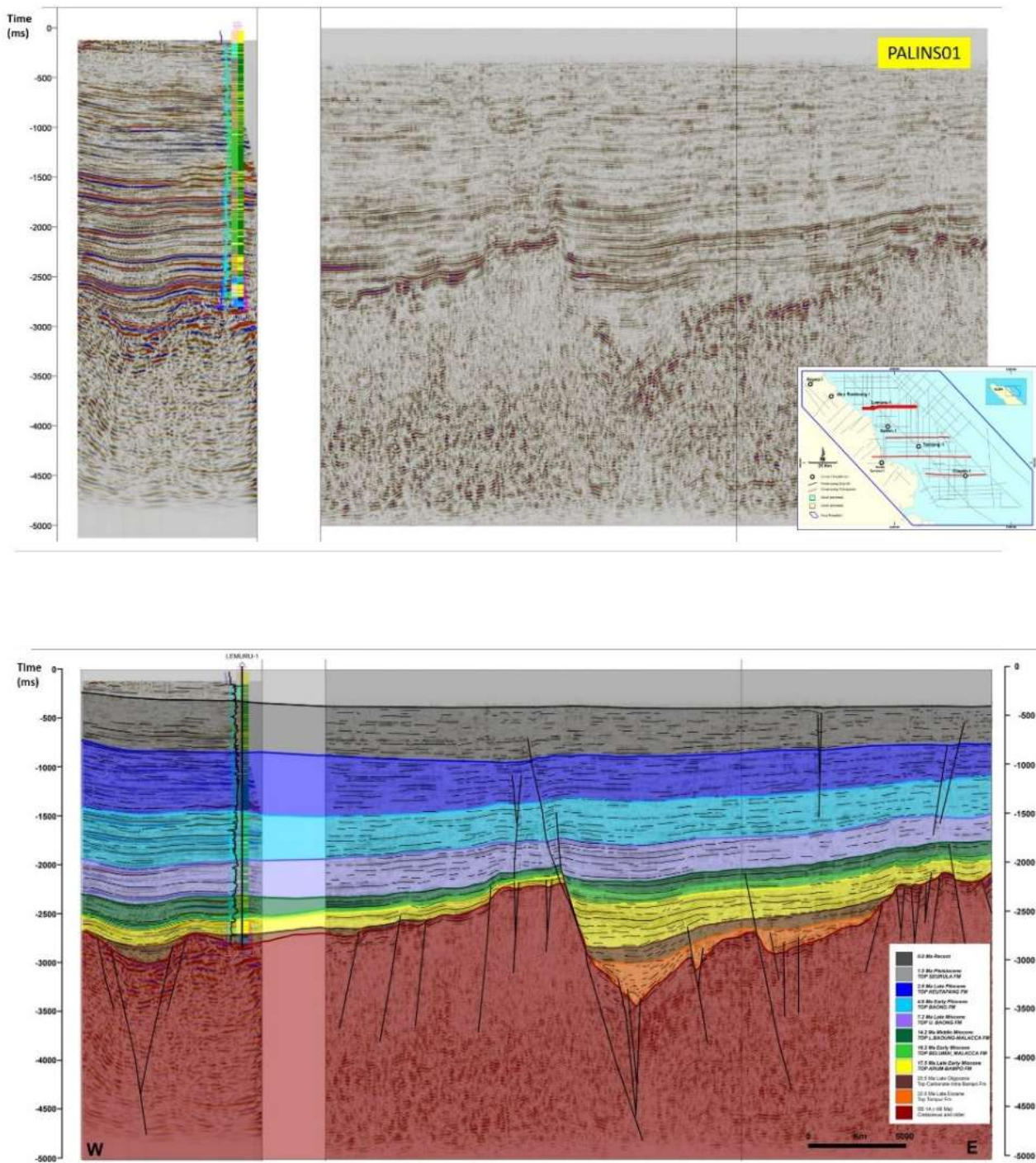


Figure 8. The uninterpreted and interpreted seismic sections of Palins01 reveal the development of a graben that acts as a sedimentary basin, indicated by the presence of growth strata within layers dating back to 32 Ma, 22 Ma, and 17 Ma. In a broader regional context, it is noted that this graben is situated at the northern end of Tamiang Deep.

Structure Evolution and Palinspastic Analysis of The Gurami-Tamiang Area, North Sumatra Basin, Indonesia
(Dumex Pasaribu et al.)

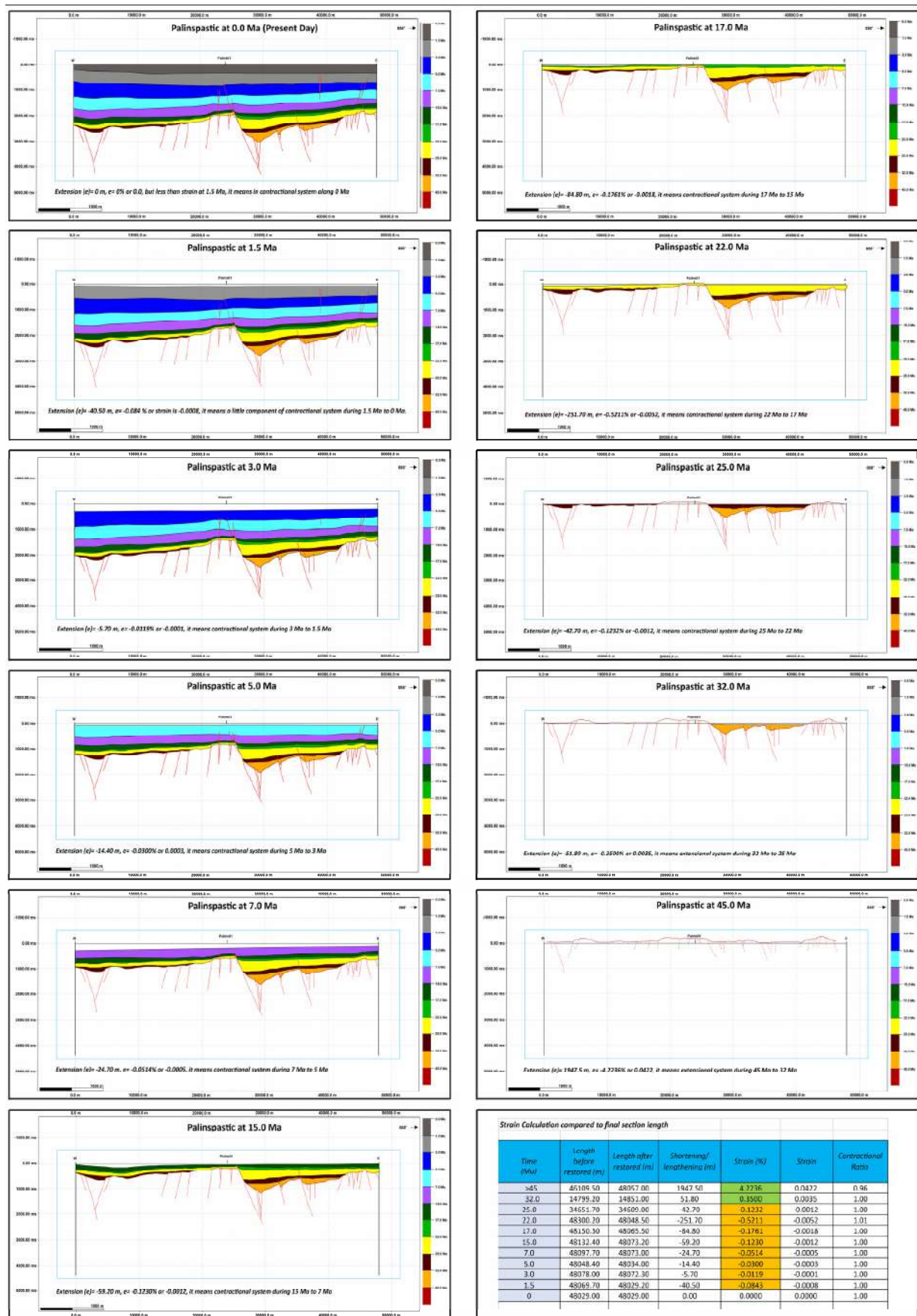


Figure 9. Composite graphic for the palinspastic section 1 (Palins01).

section Palins01 (Figures 8 and 9) are as follows:

- Palinspastic at 45 to 32 Ma, a positive extension (e^+) of 1947.50 meters, which corresponds to an elongation strain of 4.22% or a value of $e=(+0.0422)$.
- Palinspastic at 32 to 25 Ma, a positive extension (e^+) of 51.80 meters, equivalent to an elongation strain of 0.35% or a value of $e=(+0.0035)$.
- Palinspastic at 25 to 22 Ma, a negative extension (e^-) of -42.70 meters, equivalent to a shortening strain of -0.12% or a value of $e=(-0.0012)$.
- Palinspastic at 22 to 17 Ma, a negative extension (e^-) of -251.70 meters, equivalent to a shortening strain of -0.52% or a value of $e=(-0.0052)$.
- Palinspastic at 17 to 15 Ma, a negative extension (e^-) of -84.80 meters, equivalent to a shortening strain of -0.18% or a value of $e=(-0.0018)$.
- Palinspastic at 15 to 7 Ma, a negative extension (e^-) of -59.20 meters, equivalent to a shortening strain of -0.12% or a value of $e=(-0.0012)$.
- Palinspastic at 7 to 5 Ma, a negative extension (e^-) of -24.70 meters, equivalent to a shortening strain of -0.05% or a value of $e=(-0.0005)$.
- Palinspastic at 5 to 3 Ma, a negative extension (e^-) of -14.40 meters, equivalent to a shortening strain of -0.03% or a value of $e=(-0.0003)$.
- Palinspastic at 3 to 1.5 Ma, a negative extension (e^-) of -5.70 meters, equivalent to a shortening strain of -0.01% or a value of $e=(-0.0001)$.

strain of -0.01% or a value of $e=(-0.0001)$.

- Palinspastic at 1.5 to 0 Ma, a negative extension (e^-) of -40.50 meters, equivalent to a shortening strain of -0.08% or a value of $e=(-0.0008)$.

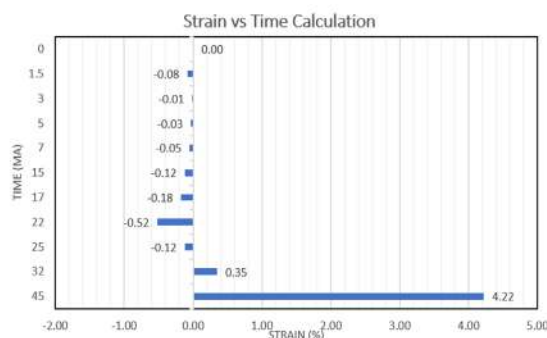
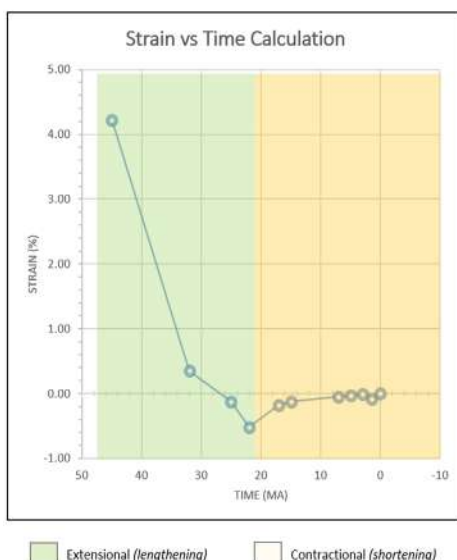
Strain calculation & analysis of section palins01

- Overall, for the section Palins01 (Figure 9), the strain values obtained varied from 0 to (+4.22) % for lengthening and from 0 to (-0.52) % for shortening.
- From 45 to 32 Ma, the Gurami-Tamiang area experienced an extensional system, resulting in a lengthening of approximately two kilometers across the Palins01 section. During this period, a significant graben formation took place. From 32 Ma to 25.5 Ma, the area underwent an additional lengthening of 51.80 meters. Since 25.5 Ma, the region has transitioned to minor shortening, exhibiting a small strain of less than 1%, which indicates a consistent but slight compression condition.
- The formation of a graben, which will be discussed later.

Palinspastic section palins02

This section does not intersect any wells (Figure 11); however, its position near the extensional center makes it valuable for palinspastic analysis. The two nearest wells that can be used as reference points for mapping the marker horizon are the well Tamiang-1 to the south and the Salem-1 to the northwest. To

Strain Calculation (%)
Section Palins01



Time	Length before restored (m)	Length after restored (m)	Shortening/lengthening (m)	Strain (%)	Strain	Contractual Ratio
45	46109.50	48057.00	1947.50	4.2236	0.0422	0.96
32	14799.20	14851.00	51.80	0.3500	0.0035	1.00
25	34651.70	34609.00	-42.70	-0.1232	-0.0012	1.00
22	48300.20	48048.50	-251.70	-0.5211	-0.0052	1.01
17	48150.30	48065.50	-84.80	-0.1761	-0.0018	1.00
15	48132.40	48073.20	-59.20	-0.1230	-0.0012	1.00
7	48097.70	48073.00	-24.70	-0.0514	-0.0005	1.00
5	48048.40	48034.00	-14.40	-0.0300	-0.0003	1.00
3	48078.00	48072.30	-5.70	-0.0119	-0.0001	1.00
1.5	48069.70	48029.20	-40.50	-0.0843	-0.0008	1.00
0	48029.00	48029.00	0.00	0.0000	0.0000	1.00

Figure 10. Strain calculation and analysis of the palinspastic section 1 (Palins01)

the west, there is a significant graben known as the Tamiang Graben. As it moves eastward, there is an elevation where the late syn-extensional deposits, dating from 22 Ma, thin out towards the Malacca Platform. Along this eastern trajectory, multiple grabens align to create a basin characterized by distinct geological features. Palinspastic results of section Palins02 (Figure 12) are as follows:

- Palinspastic at 45 to 32 Ma, a positive extension (e+) of 5942.00 meters, equivalent to an elongation strain of +11.64% or a value of $e=+0.1164$).
- Palinspastic at 32 to 25 Ma, a negative extension (e-) of -1013 meters, equivalent to a shortening strain of -2.50% or a value of $e=(-0.0025)$.
- Palinspastic at 25 to 22 Ma, a negative extension (e-) of -146.40 meters, equivalent to a shortening strain of -0.26% or a value of $e=(-0.0026)$.
- Palinspastic at 15 to 7 Ma, a negative extension (e-) of -132.20 meters, equivalent to a shortening strain of -0.23% or a value of $e=(-0.0023)$.
- Palinspastic at 5 to 3 Ma, a negative extension (e-) of -100.58 meters, equivalent to a shortening strain of -0.10% or a value of $e=(-0.0010)$.

sion (e-) of -918.7 meters, equivalent to a shortening strain of -1.77% or a value of $e=(-0.017)$.

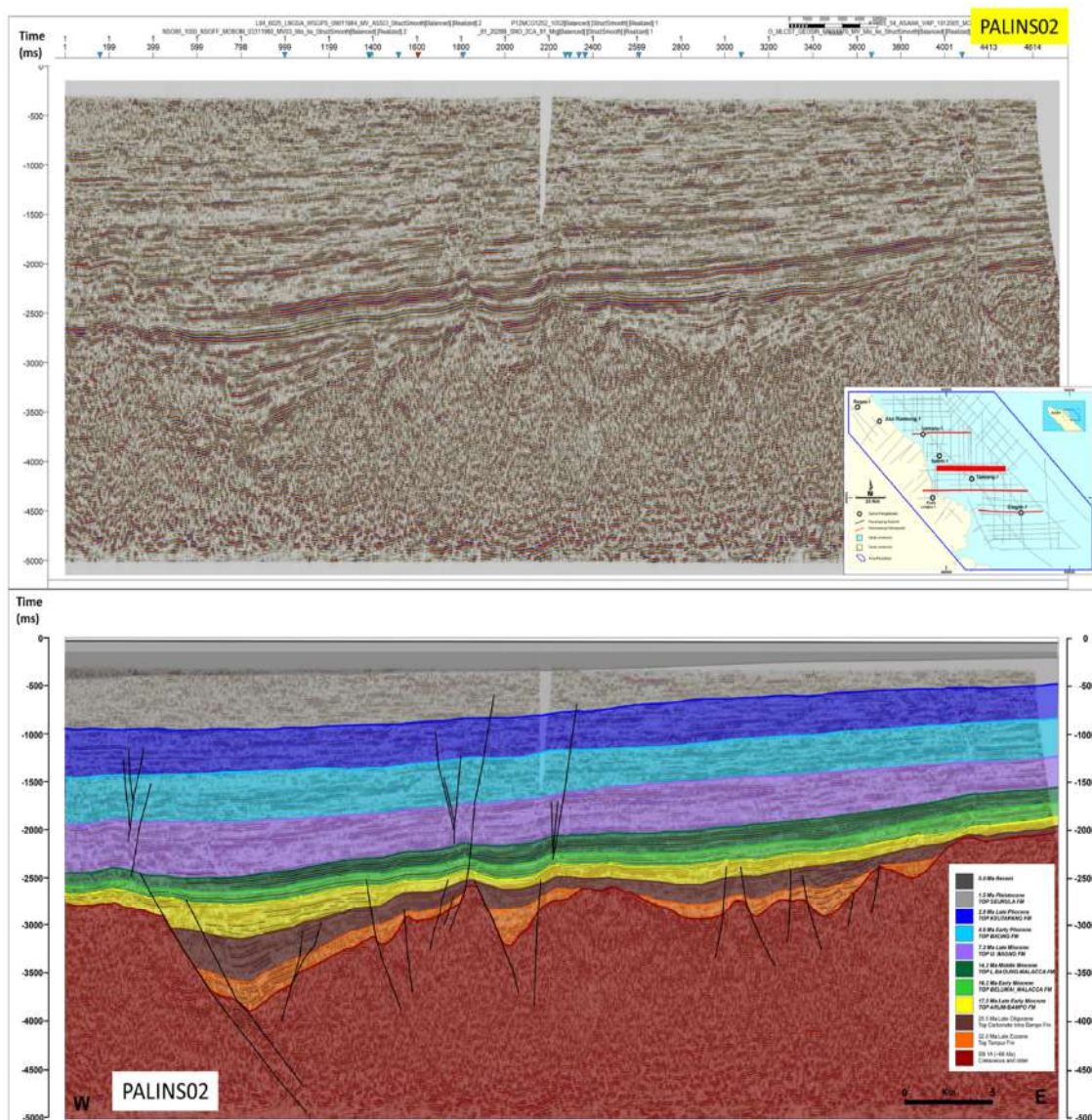


Figure 11. The Palins02 section features a prominent graben, specifically the Tamiang Graben, located to the west. Moving eastward will encounter a series of grabens arranged to create a basin, which also contains syn-extensional deposits.

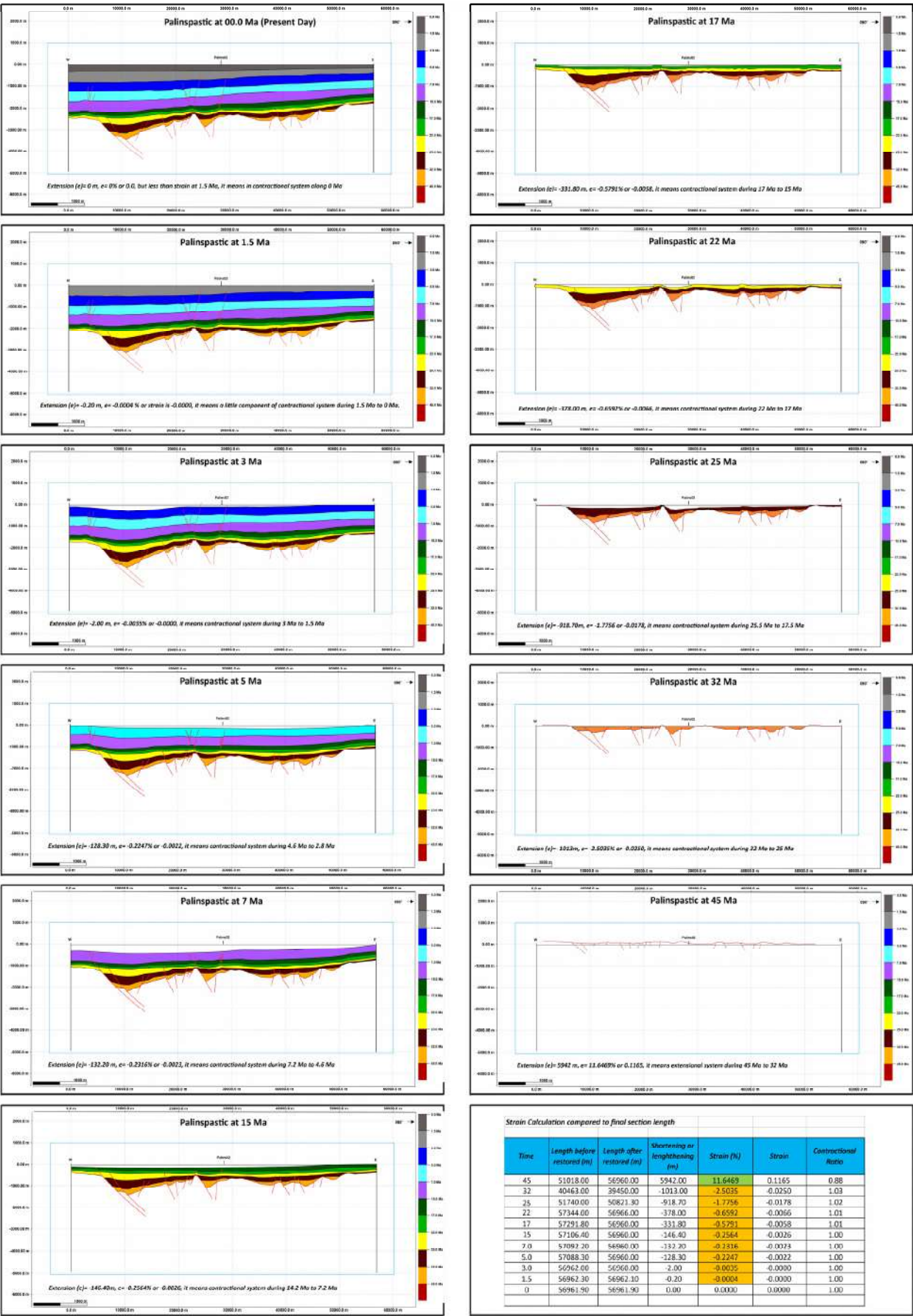
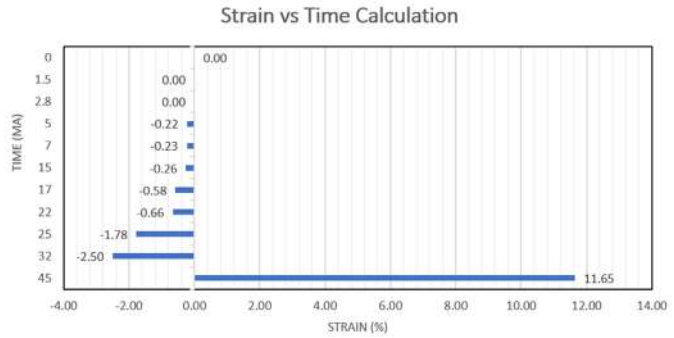
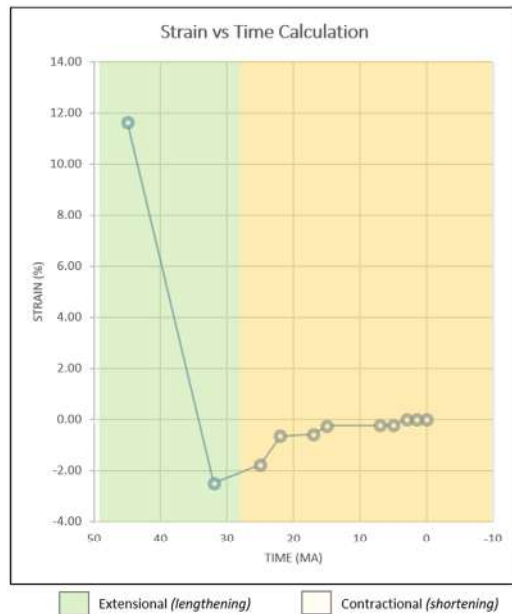


Figure12. Composite graphic for the palinspastic section 2 (Palins02).

Strain Calculation (%) Section Palins02



Time	Length before restored (m)	Length after restored (m)	Shortening or lengthening (m)	Strain (%)	Strain	Contractual Ratio
45	51018.00	56960.00	5942.00	11.6469	0.1165	0.88
32	40463.00	39450.00	-1013.00	-2.5035	-0.0250	1.03
25	51740.00	50821.30	-918.70	-1.7756	-0.0178	1.02
22	57344.00	56966.00	-378.00	-0.6592	-0.0066	1.01
17	57291.80	56960.00	-331.80	-0.5791	-0.0058	1.01
15	57106.40	56960.00	-146.40	-0.2564	-0.0026	1.00
7	57092.20	56960.00	-132.20	-0.2316	-0.0023	1.00
5	57088.30	56960.00	-128.30	-0.2247	-0.0022	1.00
3	56962.00	56960.00	-2.00	-0.0035	-0.0000	1.00
1.5	56962.30	56962.10	-0.20	-0.0004	-0.0000	1.00
0	56961.90	56961.90	0.00	0.0000	0.0000	1.00

Figure 13. Strain calculation and analysis of palinspastic Section 2 (Palins02)

sion (e-) of -128.30 meters, equivalent to a shortening strain of -0.22% or a value of $e = (-0.0022)$.

- Palinspastic at 3 to 1.5 Ma, a negative extension (e-) of -2.00 meters, equivalent to a shortening strain of -0.0035% or a value of $e = (0.000)$
- Palinspastic at 1.5 to 0 Ma, a negative extension (e-) of -0.20 meters, equivalent to a shortening strain of -0.0004% or a value of $e = (-0.0000)$, very low strain value.

Strain calculation & analysis of section palins02

Overall, for the Palins02 section, the strain values (Figures 12 and 13) observed ranged from 0 to (+11.65) % for extension, about 6 km of lengthening and then followed by up to (-2.50) % for contraction.

Between 45 and 32 million years ago, the Gurami-Tamiang area experienced an extensional system, leading to an approximate lengthening of 6 kilometers across the Palins02 section. This significant strain extended the initial extensional that occurred from the Early Eocene through the Oligocene, and several graben formations developed. From 32 million years ago to the present, the area has gone through a contractional process.

Palinspastic section palins03

This section does not intersect any drilling wells (see Figure 14); however, its location is ideal for

palinspastic analysis because it is situated near the extensional center, much like section Palins02. The three closest wells to this section, which can serve as reference points for mapping marker horizons, are the Tamiang-1 well to the north, the Kuala Langsa-1 well to the west, and the Glagah-1 well to the southeast (see Figure 6). Several grabens are present along this Palins03 section. Starting from the west, the first feature is half of the graben visible as the eastern edge of the Gurami Graben. Moving eastward, there is the Tamiang High, which separates the Gurami Graben from the Tamiang Graben.

Further east, the boundary between the Tamiang Graben and the Pakol Graben is delineated. Continuing to the east, we encounter the Pakol High, followed by the Glagah Graben. The entire graben traversed by this section was well developed during the extensional system, as seen from the presence of syn-extensional deposits aged 32 Ma, 25.5 Ma, and 17.5 Ma. The further east, the thinner the layers, indicating that the eastern part is often located on a high, namely the Malacca Platform (Figure 14).

Palinspastic results of section Palins03 (Figures 15 and 16) are as follows:

- Palinspastic at 45 to 32 Ma, a positive extension (e+) of 7528.10 meters, equivalent to an elongation strain of 9.593% or a value of $e = (+0.0959)$.

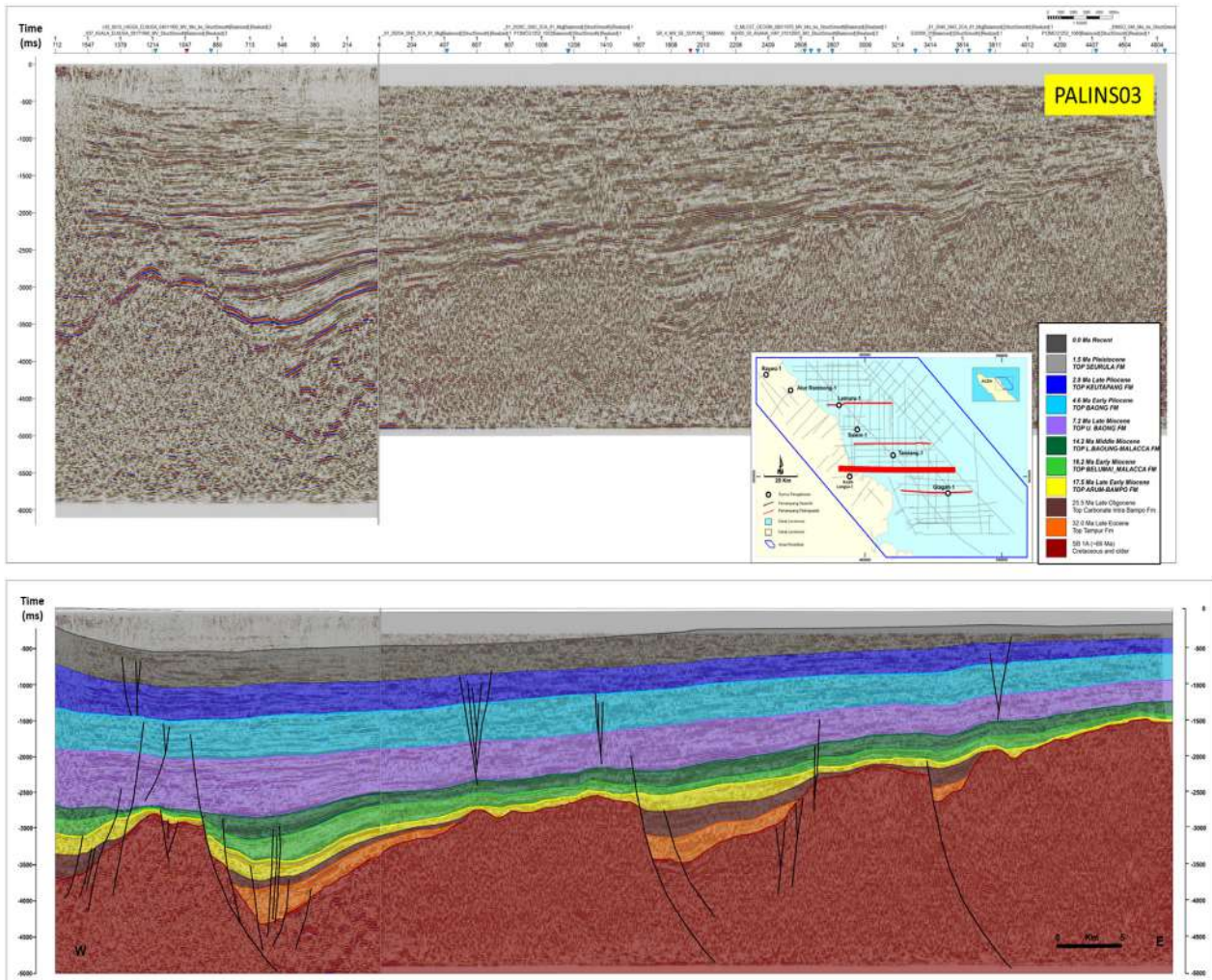


Figure 14. This cross-section Palins03, positioned around the center of the extensional system, is ideal for palinspastic analysis, although it does not intersect any wells. It includes several grabens, starting with the Gurami Graben on the western end. Moving east, the Tamiang High separates the Gurami and Tamiang Grabens, while the Yang Besar High delineates the Tamiang and Pakol Grabens. Further east, the Pakol High is followed by the Glagah Graben. The eastern section displays thinner layers, often situated on the elevated Malacca Platform.

- Palinspastic at 32 to 25 Ma, negative extension (e-) of -500.80 meters, equivalent to a shortening strain of -1.55% or a value of $e=(-0.155)$.
- Palinspastic at 25 to 22 Ma, a negative extension (e-) of -942.00 meters, equivalent to a shortening strain of -0.12% or a value of $e=(-1.76)$.
- Palinspastic at 22 to 17 Ma, a negative extension (e-) of -651.00 meters, equivalent to a shortening strain of -0.75% or a value of $e=(-0.0075)$.
- Palinspastic at 17 to 15 Ma, a negative extension (e-) of -196.90 meters, equivalent to a shortening strain of -0.23% or a value of $e=(-0.0023)$.
- Palinspastic at 15 to 7 Ma, a negative extension (e-) of -128.40 meters, equivalent to a shortening strain of -0.15% or a value of $e=(-0.0015)$.
- Palinspastic at 7 to 5 Ma, a negative extension value (e-) of -12.70 meters, equivalent to a shortening strain of -0.01% or a value of $e=(-0.0001)$.
- Palinspastic at 5 to 3 Ma, a negative extension (e-) of -66.20 meters, equivalent to a shortening strain of -0.08% or a value of $e=(-0.0008)$.
- Palinspastic at 3 to 1.5 Ma, a negative extension (e-) of -4.50 meters, equivalent to a shortening strain of -0.01% or a value of $e=(-0.0001)$.
- Palinspastic at 1.5 to 0 Ma, a negative extension (e-) of -0.5 meters, equivalent to a shortening strain of -0.005% or a value of $e=(-0.0000)$.

Strain calculation & analysis of section palins03

Overall, for the Palins03 section (Figure 16), the strain values observed ranged from 0 to (+9.6) % for extension, and contractional from 0 up to (-1.8) %.

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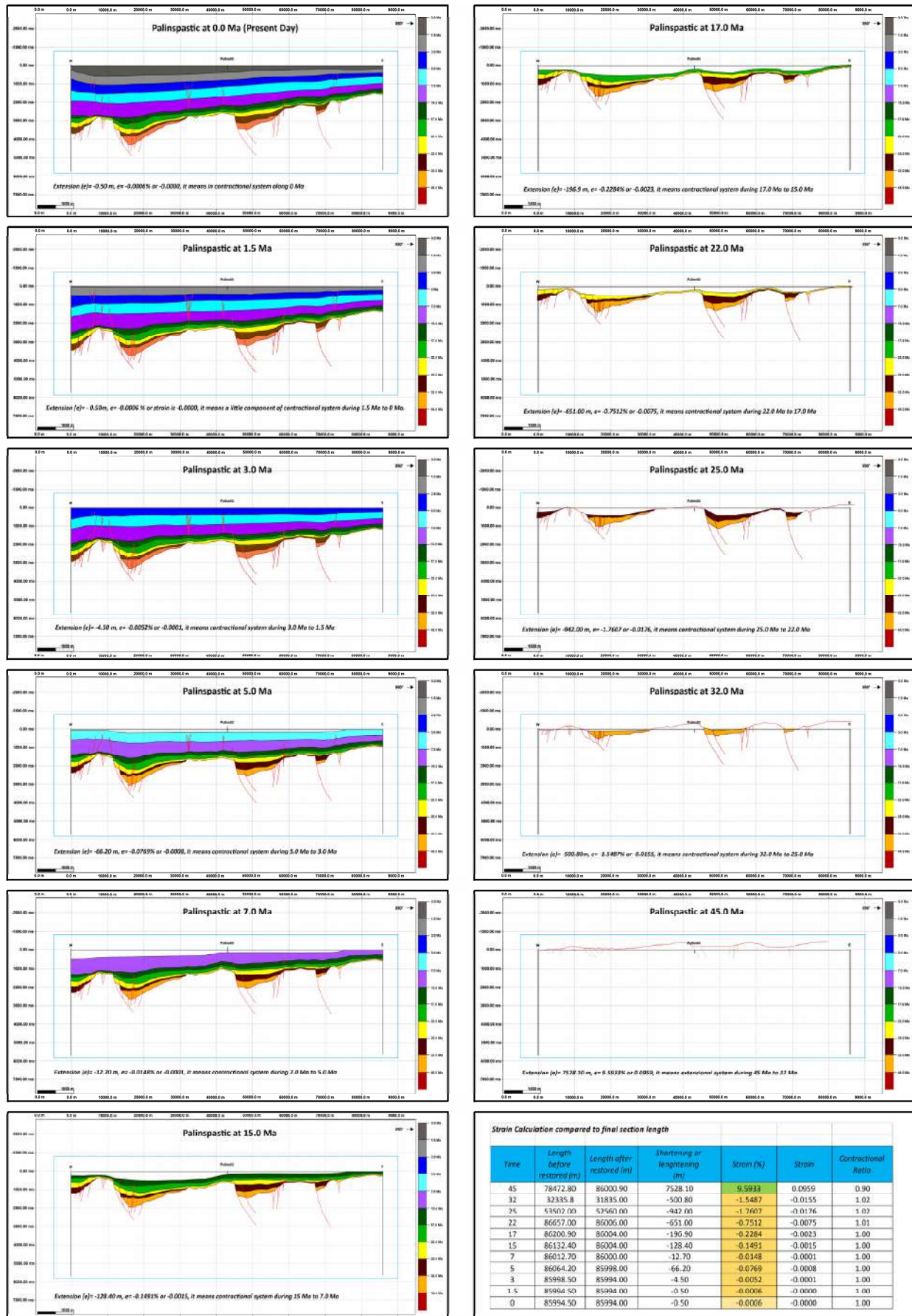


Figure 15. Composite graphic for the palinspastic section 3 (Palins03).

Strain Calculation (%) Section Palins03

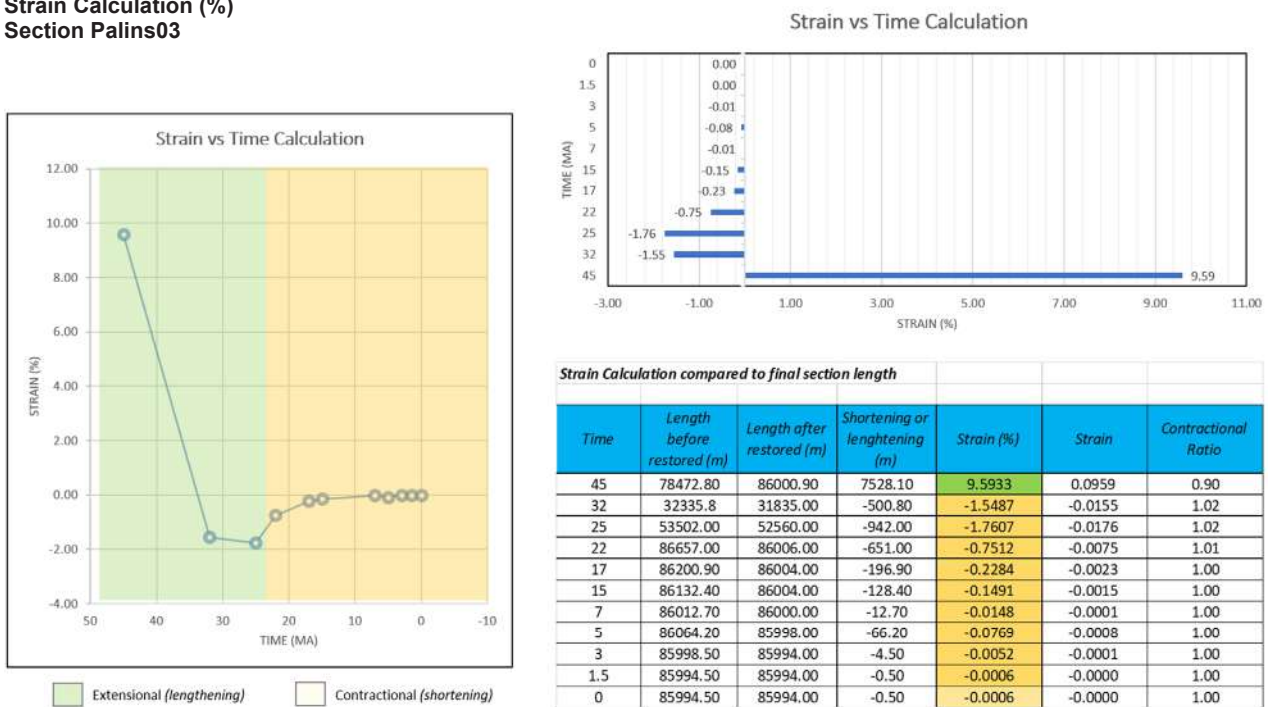


Figure 16. Strain calculation and analysis of palinspastic Section 3 (Palins03)

Between 45 and 32 million years ago, the Gurami-Tamias area experienced an extensional system, leading to an approximate lengthening of 7.5 kilometers across the Palins03 section. This significant strain extended the initial extensional system that occurred from the Early Eocene through the Oligocene, and several graben formations developed, such as Gurami Graben, Tamias Graben, and Pakol Graben. From 32 million years ago to the present, the area has gone through a contractional process.

Palinspastic section 4 (palins04)

The Palins04 seismic section delineates the southernmost portion of the research area. This section (Figure 16) intersects with the Glagah-1 well, located in the Glagah High. Two significant grabens traverse this section: the Yang Besar Low and the Pakol Low, where the syn-extensional deposits thicken in growth strata towards the border fault, while thinning occurs to the east.

Palinspastic results (Figure 17) are as follows:

- Palinspastic at 45 to 32 Ma, a positive extension (e+) of 3929.80 meters, equivalent to an elongation strain of 7.91% or a value of $e = (+0.0791)$.
- Palinspastic at 32 to 25 Ma, a positive extension (e+) of 509.50 meters, equivalent to an elongation strain of 2.36% or a value of $e = (+0.0236)$.
- Palinspastic at 25 to 22 Ma, a negative extension (e-) of -394.50 meters, equivalent to a shortening strain of -1.25% or a value of $e = (-0.0125)$.

Between 22 and 17 million years ago, the area experienced a contractional process, leading to a shortening of 509.90 meters, equivalent to a shortening strain of -0.93% or a value of $e = (-0.0093)$.

- Palinspastic at 22 to 17 Ma, a negative extension (e-) of -509.90 meters, equivalent to a shortening strain of -0.93% or a value of $e = (-0.0093)$.
- Palinspastic at 17 to 15 Ma, negative extension value (e-) of -273.80 meters, equivalent to a shortening strain of -0.50% or a value of $e = (-0.0050)$.
- Palinspastic at 15 to 7 Ma, a negative extension (e-) of -272 meters, equivalent to a shortening strain of -0.50% or a value of $e = (-0.0050)$.
- Palinspastic at 7 to 5 Ma, a negative extension value (e-) of -259.90 meters, equivalent to a shortening strain of -0.48% or a value of $e = (-0.0048)$.
- Palinspastic at 5 to 3 Ma, a negative extension value (e-) of -37.60 meters, equivalent to a shortening strain of -0.07% or a value of $e = (-0.0007)$.
- Palinspastic at 3 to 1.5 Ma, a negative extension (e-) of -39.50 meters, equivalent to a shortening strain of -0.07% or a value of $e = (-0.0007)$.
- Palinspastic at 1.5 to 0 Ma, a negative extension (e-) of -234.50 meters, equivalent to a shortening strain of -0.43% or a value of $e = (-0.0043)$.

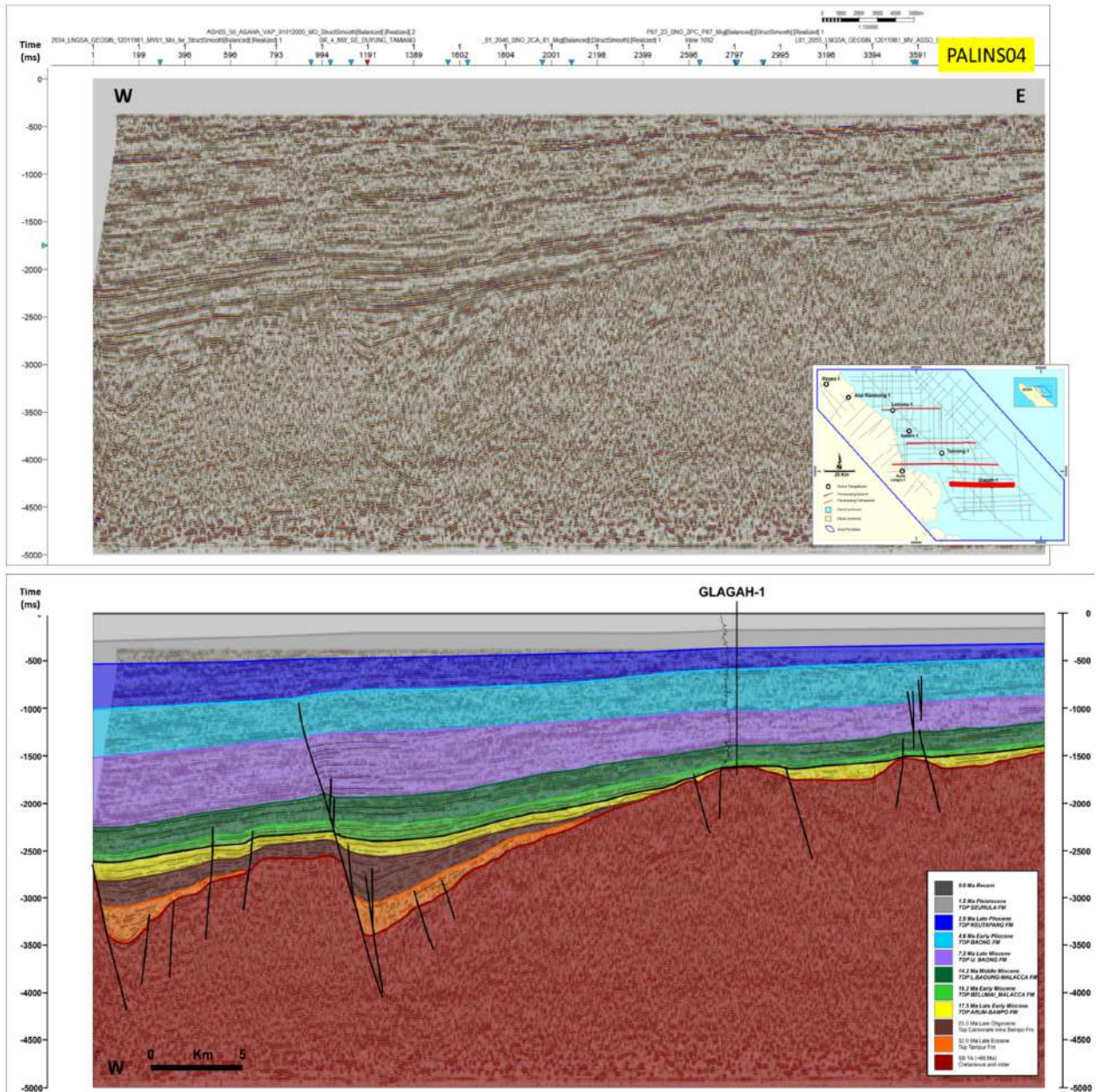


Figure 17. The Palins04 seismic section, before and after interpretation, shows that at least two grabens developed significantly during the extensional process, marked by syn-extensional deposits dated at 32 Ma, 25 Ma, and 17.5 Ma.

Strain Calculation & Analysis of Section Palins04

Overall, for the Palins04 section (Figure 18), the strain values observed ranged from 0 to (+7.9) % for extension, and contractional from 0 up to (-1.25) %.

Between 45 and 25 million years ago, the Gurami-Tamiang area surrounding Palins04 underwent an extensional tectonic process, resulting in an approximate lengthening of 3.9 kilometers. This strain extended the initial extensional system that took place from the Early Eocene through the Late Oligocene/Early Miocene, leading to the formation

of several graben structures, including the Yang Besar Low, Pakol Low, and Glagah Low. From 32 million years ago to the present, the region has experienced a contractional phase.

The composite strain graph (Figure 20) indicates that the sections Palins01 and Palins04 consistently decline in an extensional system, while Palins02 and Palins03 show slight stagnation or movement toward a contractional system during the Late Oligocene to Early Miocene. Following this period, all sections transition into a contractional system.

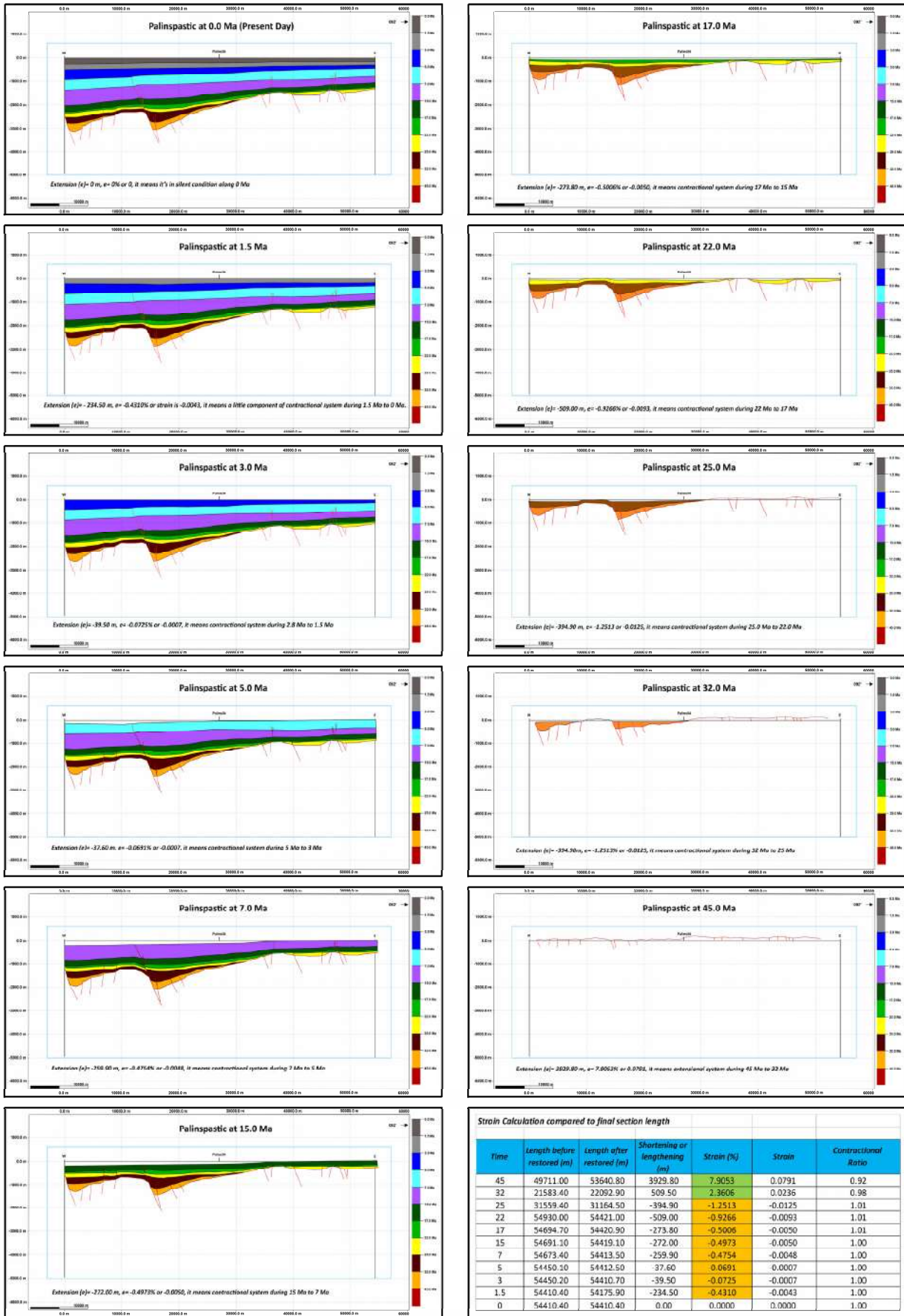


Figure 18. Composite graphic for the palinspastic section 4 (Palins04).

Strain Calculation (%) Section Palins04

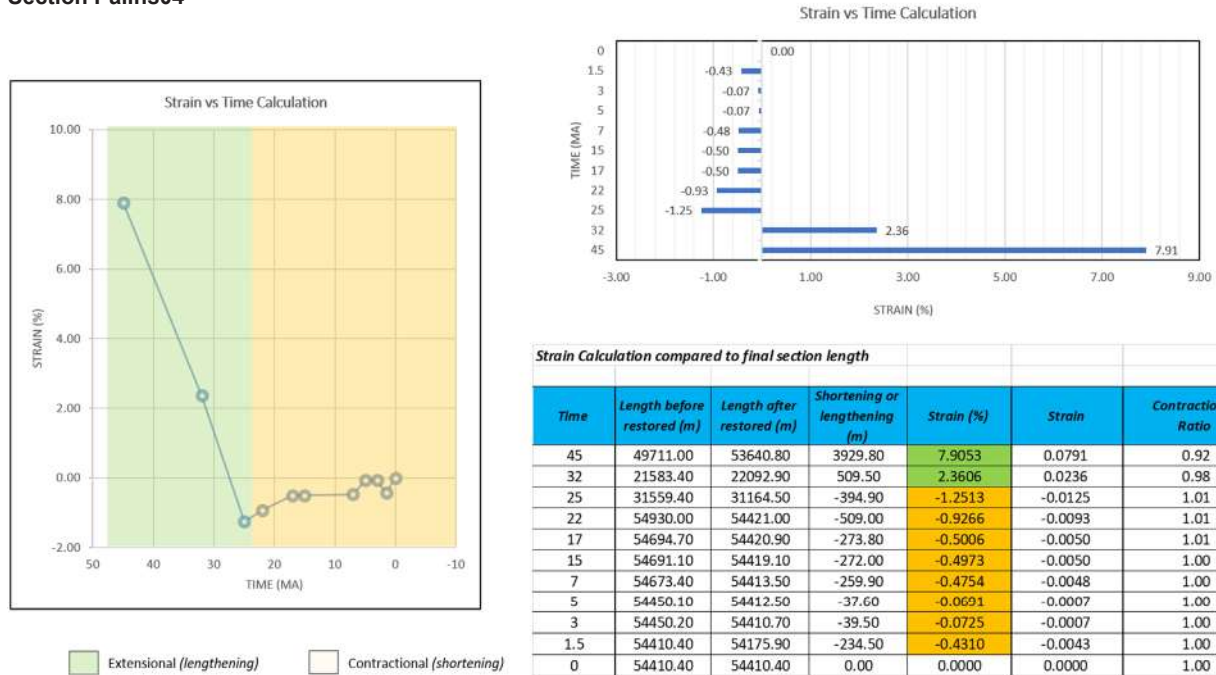


Figure 19. Composite graphic for palinspastic section 4 (Palins04)

Strain vs time calculation

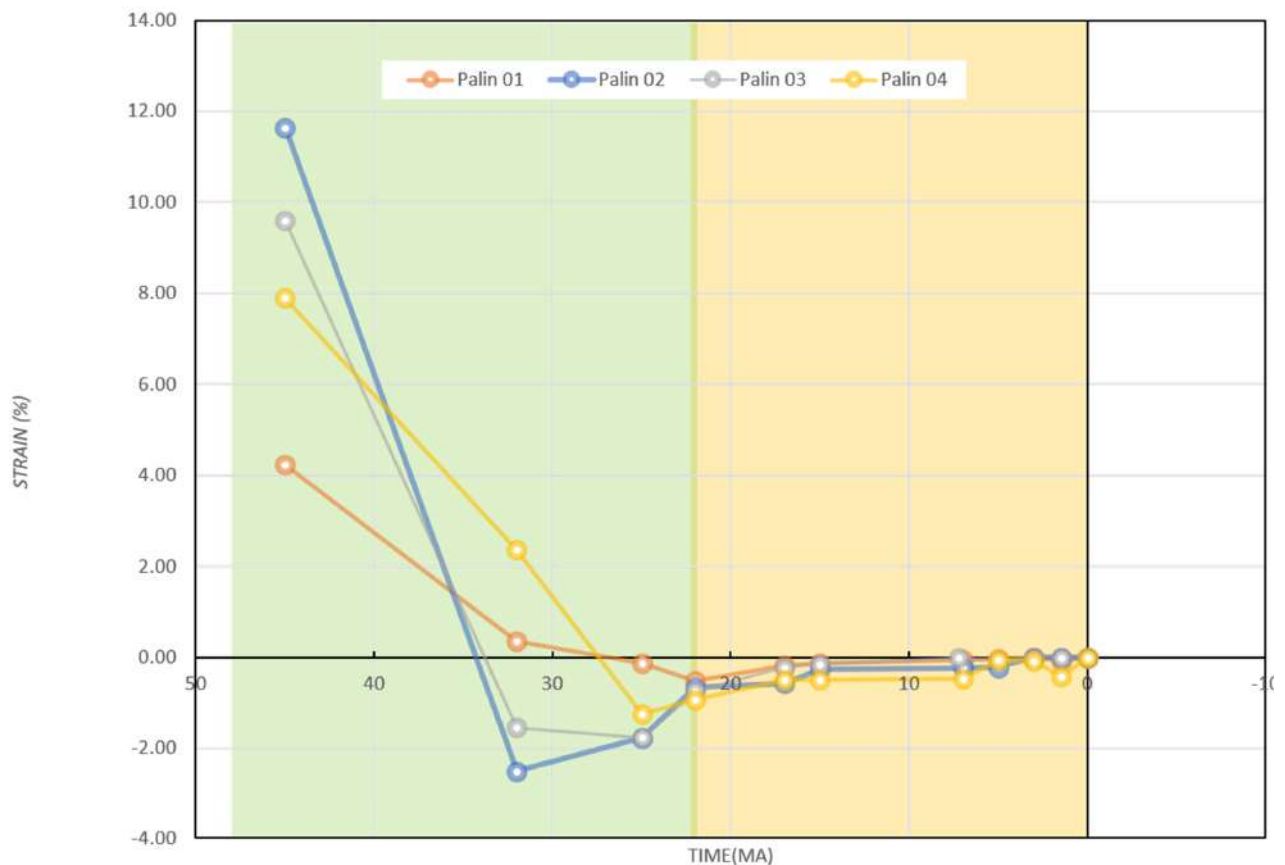


Figure 20. Composite strain calculations in curves showing the compilation of strain changes for palinspastic results of all cross-sections

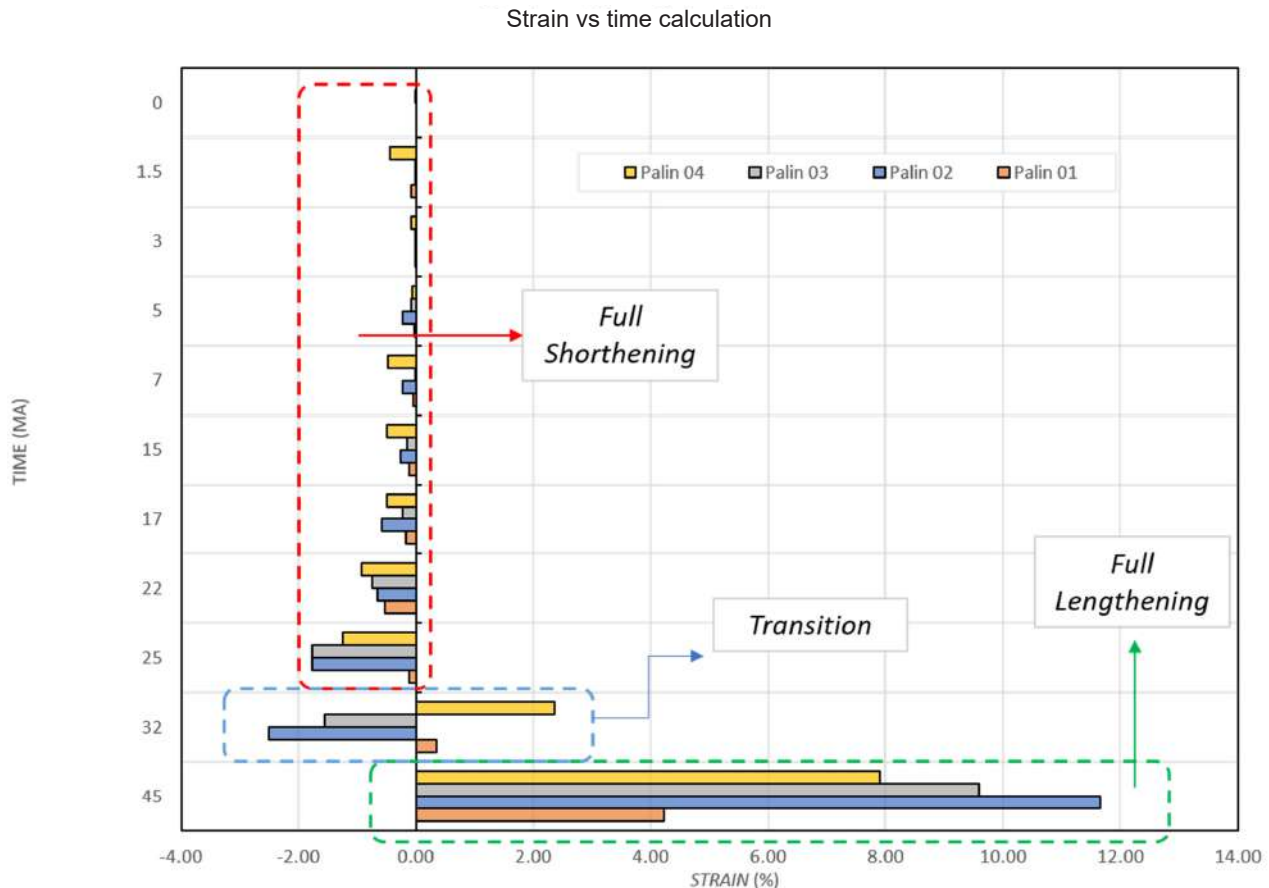


Figure 21. The bar chart shows strain variations, illustrating the palinspastic results for each analyzed cross-section. Each bar represents strain changes, clearly visualizing how different sections respond to stress and deformation over time.

Discussion

Based on the strain comparison from all four palinspastic sections and the tectonostratigraphic chart, the findings can be discussed as follows:

The strain analysis noted (Figures 20 and 21): (i) The Full Lengthening Phase occurred between 45 Ma and 32 Ma, displaying strain values ranging from (+4.2)% to (+11.64)%, with a peak observed in section Palins02. However, the most significant lengthening was noted in section Palins03, which extended up to 7.5 km. (ii) The Transition Phase, characterized by both positive and negative strains, took place between 32 Ma and 25 Ma. (iii) Finally, the Full Shortening Phase has been observed in strata that are younger than 25 Ma.

Extensional processes, leading to syn-extensional activities, predominantly occurred during the Eocene to Early Miocene period, approximately 45 million to 25 million years ago. This timeframe is marked by the presence of growth strata situated adjacent to the border fault, which serves as the depocenter. However, deposits from 25 million to 22 million

years ago still exhibit characteristics of growth strata, even as they begin to cover portions of the border fault. Since these growth strata are a key feature of syn-kinematic deposition, the deposits from 25 million to 22 million years ago should be classified as late syn-extensional deposits.

The post-extensional deposits were formed immediately following the cessation of extensional activity, specifically from 22 million years ago to the present day. Throughout this geological timeframe, the region experiences a contractional tectonic regime, characterized by slight inversion processes.

The predominant orientation of the faults and grabens is generally north-south (N-S), taking the form of a half-graben characterized by a border fault that slopes eastward. At its base, this structure exhibits a negative flower. Although calculating the depth to detachment for the base of faulting is not straightforward and may involve some errors, the depth-to-detachment calculations for four cross-sections indicate a possible range of depths between 5 to 12 km, or even greater. The observed variations

in the Figures indicate that the fault does not conform to a simple planar or listric detachment. This observation suggests that the underlying tectonic processes may extend beyond the characteristics of a back-arc graben.

In a sedimentary basin, both shortening and lengthening strains can occur simultaneously. This phenomenon is especially pronounced in regions characterized by strike-slip or wrench tectonics, where the intricate nature of fault systems enables the concurrent observation of these two strain types: tranpressional and transtensional (Cunningman and Mann, 2007). Milnes (1994) observed that basins exhibit more complex strain patterns than those seen in purely extensional or contractional regimes, highlighting the influence of these two effects concerning strike-slip or wrench systems. Consequently, the transitional phase in the Gurami-Tamiang area may, in part, be attributed to the dynamics of 'strike-slip' or wrench tectonic regimes.

The flower structure observed in the early extensional system during the Eocene, followed by a transitional phase, reflects a mixed-strain scenario characterized by both shortening and lengthening during the Oligocene to Early Miocene. These findings mark a significant advancement in our understanding of the tectonic history of the North Sumatra Basin, especially in the Gurami-Tamiang Area, which is bounded by the Khlong-Marui Fault, the Lokop Kutacane Fault, and the Sumatran Fault (see Figure 4). In this region, the northern Sumatra Fault aligns with the Medial Sumatra Tectonic Zone (MSTZ). Identifying the causes of this mixed-strain phase will be essential for determining the presence of structural formations, such as strike-slip or wrench-related grabens, in the Gurami-Tamiang Area.

Within the context of the petroleum system, this research may influence the new understanding of graben formation in the wrench system, indicating a north-south trend for sediment influx and depositional environments, particularly in the north-south depocenter trend (see Figure 6). This understanding has significant implications for exploration targets within the petroleum system, indicating that efforts should focus on deepening towards the southern region of the Gurami-Tamiang Deep. This area functions as the main depocenter during the extensional system and graben formation from the Middle Eocene to Early Miocene. Further research is necessary to explore this potential.

CONCLUSION

In light of the discoveries made in this research, it embraces the opportunity to summarize the integrated works as follows: 1). The Gurami-Tamiang Area, situated in the North Sumatra Basin and located in the back-arc of Sumatra, was formed during the Eocene epoch (approximately 45 million years ago). The predominant orientation of its border faults and grabens runs generally north-south (N-S), manifesting as a half-graben with an eastward-sloping border fault. At its base, this geological structure displays a negative flower structure and may be extended by additional tectonic systems beyond merely the back-arc basin configuration; 2). The palinspastic restoration and strain analysis reveal some structural phases in the Gurami-Tamiang Area, with integration of the surgical interpretation and the growth strata appearances, the phases summarized: (i) Extensional Phase (45 - 32 Ma) is characterized by growth strata and strain magnitudes of (+) 4.2% to (+) 11.64%, (ii) Transitional Phase (32 - 22 Ma) is displaying both positive and negative strains of (+) 2.3% to (-) 1.7%, with growth strata that are extending across grabens; and (iii) Contractional Phase (22 Ma – present) is characterized by negative strains of (-) 0.92% toward zero and mostly covered by post-extensional and syn inversion deposits; 3). The negative flower structure observed in the early extensional system during the Eocene, followed by a transitional phase, indicates a mixed-strain scenario characterized by both shortening and lengthening during the Oligocene to Early Miocene. This finding marks a significant advancement in understanding the tectonic history of the North Sumatra Basin, particularly concerning the formation of wrench-related graben formation in the Gurami-Tamiang Area; 4). In terms of hydrocarbon exploration, it suggests having more look at the southern part of Gurami-Tamiang Deep as the main depocenter during the Middle Eocene to Early Miocene, as this area possibly has more grabens in supporting source rock material, reservoir, and entrapment system.

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