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Tectonic Control on Karstification in The Faumai Formation, Bird's Head, West Papua, Indonesia

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ABSTRACT - This study investigates tectonic control on karstification within Eocene Faumai Formation in Bird's Head region, West Papua, Indonesia. An integrated workflow is applied using surface outcrop observations, drilling indicators (including total mud losses, weight on bit, standpipe pressure, and equivalent circulating density), drilling events, and 3D seismic data from Tangguh area. The aim is to identify the distribution of karstified intervals, evaluate role of structural deformation, and reconstruct tectono-stratigraphic evolution associated with karst development. Faumai Formation is subdivided into four sequences, with karst development most pronounced in Faumai-2 interval. Evidence of karstification includes cave occurrences in outcrops, significant drilling mud losses, and low-impedance or trough reflectivity to chaotic seismic anomalies interpreted as subsurface cavities and collapse-related features concentrated along fault-controlled zones. The results indicate that oblique convergence among Australian, Caroline, and Pacific plates drove Late Oligocene uplift, exposing carbonate units to subaerial conditions and enabling meteoric dissolution along structural highs, fractures, and fault networks. Grain-supported dolomitic textures in the Faumai-2 interval suggest more favorable rock properties for karst development than in other sequences. Younger tectonic reactivation during Pleistocene subsequently produces collapse features recognized in both seismic and outcrop data, indicating that karstification in Faumai Formation is a multi-phase process controlled by both tectonics and carbonate facies architecture.

Keywords: karstification, faumai formation, carbonate, tectonics

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INTRODUCTION

Karstification is the process by which carbonate rocks, particularly limestone and dolomite, are dissolved by meteoric water, producing caves, sinkholes, enlarged fractures, and underground drainage systems (Martel E.A 1894; Trudgill 1986). The process commonly develops in humid regions where carbonate rocks are exposed and sufficiently fractured to allow water infiltration. Where carbonate platforms and reefs are tectonically uplifted, subaerial exposure and improved hydraulic connectivity can accelerate dissolution and karst evolution (Cvijić 1989; Zhang et al., 2020).

In Bird's Head and Bird's Neck area of West Papua, extensive karstification within carbonate formations and are documented from both surface and subsurface observations. In subsurface, karstified intervals are commonly recognized during drilling by partial to total mud losses caused by the penetration of caves, vugs, or highly fractured zones (Birt et al., 2015; Riangguna et al., 2016; Prabowo et al., 2025). At the surface, these carbonate successions are commonly grouped within the New Guinea Limestone Group, with ages ranging from Eocene to Miocene. Their distribution extends widely across Bird's Head and Bird's Neck regions and continues into Bird's Body area. This study focuses specifically on

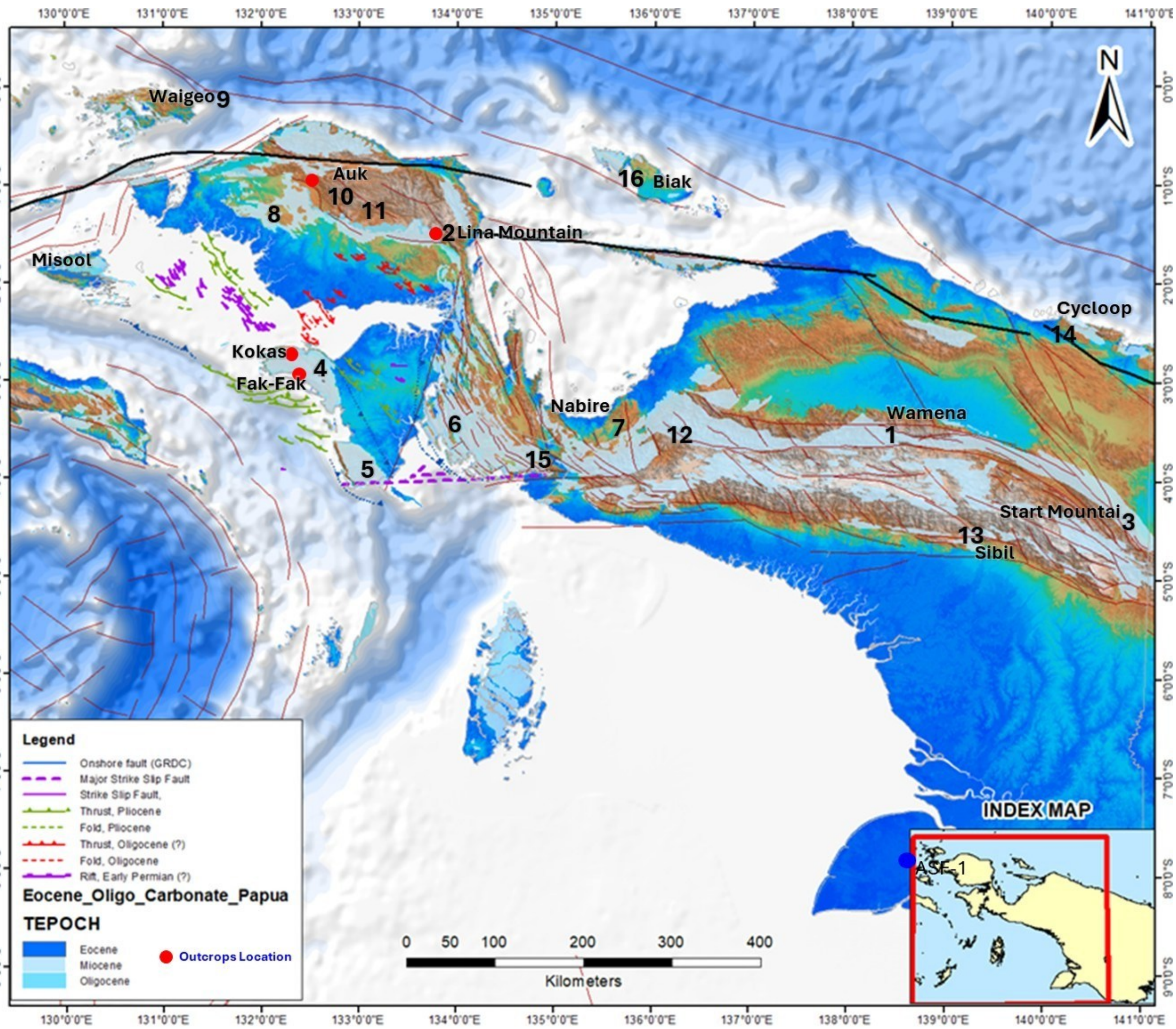

Figure 1. Distribution of karstified Formation in Papua. 1. Baliem Valley, Wamena, Baliem Wolo, Trigora Range, 2. Lina Mountain, 3. Star Mountain, 4. Fak-Fak, 5. Kaimana, 6. Lenguru, 7. Nabire, 8. Ayamru plateau, Kladuk, 9. Misool, Gam, Waigeo, 10. Aouk, 11. Auf-Manaway, 12. Paniai, 13. Sibil, 14. Cycloop, 15. Yamur, 16. Biak (Modified from Benassi 2019). Table 1. Cave based on depth (meter) (Benassi 2019).

Table 1. Cave based on depth (meter) (Benassi 2019).

Cave name	Location	Depth (m)	Expedition period
Lomos Longmot (2)	Lina Mountain	-360	1996
Sibil Buk I (3)	Star Mountain	-349	1992
Lomos Iono Besar (2)	Lina Mountain	-315	1996
Yogoluk (1)	Baliem Wolo	-300	1986
Gua Kwalinga (1)	Baliem Valley	-229	1990
Gua Yerakna (1)	Baliem - Wolo Pass Valley	-211	1990
Lomes Sura (2)	Lina Mountain	-204	1996
Gua Dogwri (1)	Baliem Valley	-187	1990
Gua Ikat (1)	Baliem Valley	-178	1990
Aouk-Keek (8)	Ajamaru Plateau	-170	2018
Gua Aleya Kulip (1)	Trikora Range	-145	1990
Gua Jugumen - Tinginna (1)	Baliem Valley	-142	1990
Adbon Buk (3)	Star Mountain	-113	1992
Taladol Buk V (3)	Star Mountain	-103	1992
Sibil Buk II (3)	Star Mountain	-93	1992
Kayah Tanhar (8)	Ayamaru	-80	2017
Ilgen Shaft (8)	Kladuk	-80	2018
Gua Lang (1)	Baliem	-79	1990
Gua Ilagun (1)	Baliem	-78	1990
Tamal Buk IV (3)	Star Mountain	-75	1992
Wallace Chamber (19)	Waigeo	-70	2018
Kutiape (1)	Baliem	-70	1990
Saptem Buk (3)	Star Mountain	-69	1992
Lubang Kayu Mera (4)	Fak-Fak	-55	1992
Taladol Buk IV (3)	Star Mountain	-55	1992
Taladol Buk I (3)	Star Mountain	-54	1992

Eocene carbonate succession of Faumai Formation (Visser & Hermes 1962; Binassi 2019). Despite the broad occurrence of karstified carbonates in West Papua, the spatial distribution and tectonic controls of karstification in Bird's Head area remain insufficiently documented. This study integrates outcrop observations, well data, drilling parameter, and seismic interpretation to better constrain the timing, distribution, and geological controls of karstification within Faumai Formation.

Tectonic setting

Tectonic evolution of Bird's Head Papua is shaped by interactions among Australian, Pacific, and Caroline plates, resulting in a complex geological history and present structural configuration (Figure 2). The earliest events began in Paleozoic with NW–SE trending grabens formed by rifting in Berau–Bintuni area. Later, during Late Triassic, these grabens were uplifted and eroded, creating Base Jurassic Unconformity. After this, Early Jurassic Lower Roabiba sediments accumulated on these eroded highs. Evidence from Tangguh area shows that Jurassic extension led to a thickening toward the southeast. In Mid-Jurassic, another major event occurred: the breakup phase that formed Callovian Unconformity and reactivated some older faults.

As the continents separated, a thin layer of passive-margin sediments developed from the Late Jurassic through Cretaceous. Continued to

Figure 2. Papua is bounded by Australia plate were moving to the north and Pacific moving to the West. Their interactions create a highly active zone of collisions and faults across Papua. Sorong Fault Zone (SFZ), Yapen fault zone (YFZ), Mamberamo Deformation Zone (MDZ), Bewani-Torricelli Fault Zone (BTFZ), Bismarck Sea Seismic Lineation (BSSL), New Guinea Fold-and-Thrust Belt (NGFTB), Moresby Trough (MT), Ransiki Fault Zone (RFZ) (Birt et al., 2015; Sapiie 1998).

Paleocene as deepwater turbidites, followed by growth of carbonate platforms. During Early Eocene, deposits reflected a transition from classic to carbonated deposition. Continued from Middle to Late Eocene, widespread carbonate sedimentation established platforms, reefs, and basin fans. In some areas, this carbonate development continued into Early Oligocene.

In Late Oligocene, oblique plate convergence caused significant folding and uplift, producing Base Oligocene Unconformity, which is well known in Bintuni Basin. After this tectonic event, Kais Carbonate Formation were deposited during early to middle Miocene. The region's evolution continued into late Miocene, when ongoing plate collision formed in Papuan Central Range. At the same time, extension in Cenderawasih Bay area contributed to the development of the Lengguru Fold-Thrust Belt and a deep foreland basin east of Tangguh (Bailly et al., 2009; Saputra et al., 2023).

Structural setting

Bird's Head area is bounded by several active strike-slip fault systems, such as northern part bounded by Sorong-Yapen faults. The southern boundary is marked by Tarera Aiduna Fault, while eastern edge is defined by Lengguru Fold Belt. To the west area is enclosed by misool–onin–kumawa (MOK) Ridge (Figure 3).

Stratigraphy

Bird's Head area displays a complete stratigraphic succession ranging in age from Paleozoic to Quaternary. This sequence includes, in order from

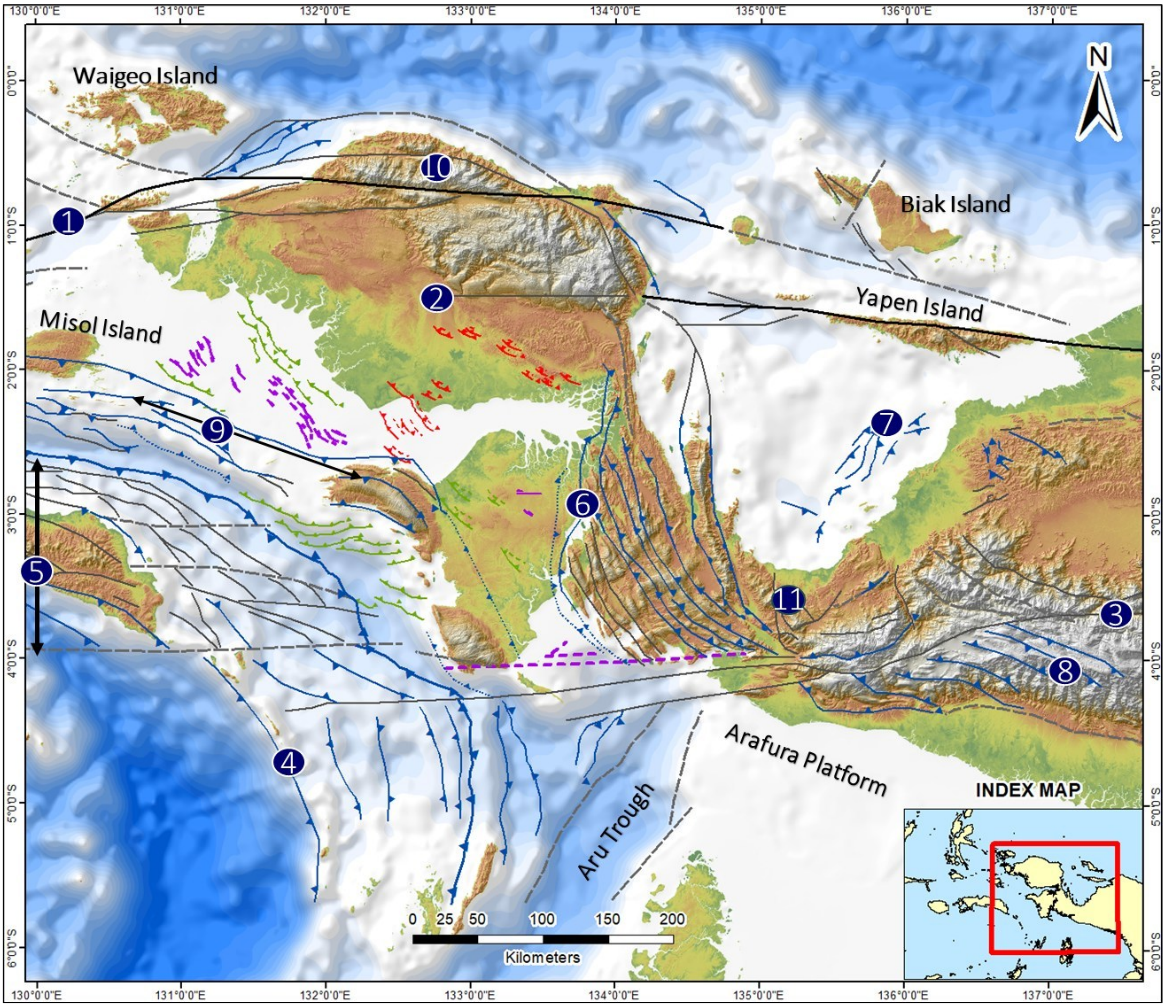

Figure 3. Area of Bird's Head, bounded by Sorong Fault to the north, Tarera-Aiduna Fault to the south, Lengguru Fold Belt to the east, and Misool–Onin–Kumawa (MOK) zone to the west. The study area extends from Sorong and Manokwari down to Kokas and Fak-Fak area. 1. Sorong Fault Zone (SFZ), 2. Yapen Fault Zone (YFZ), 3. Tarera-Aiduna Fault Zone (TAFZ), 4. Banda Trench, 5. Seram Fold-Thrust-Belt (SFTB), 6. Lengguru Fold-Thrust-Belt (LFTB), 7. Cendrawasih Bay Fold-Thrust-Belt (CBFTB), 8. Central Range Fold-Thrust-Belt (CRFTB), 9. Misool-Onin-Kumawa Ridge (MOKR), 10. Kemum High, 11. Weyland Overthrust (Modified from Sapiie et al., 2012).

oldest to youngest, Kemum Formation, Aifam Group (comprising Aimau, Aiduna/Aifat, and Ainim Formations), Tipuma Formation, Kembelangan Group (Lower and Upper Kembelangan), Daram - Waripi Formation, New Guinea Limestone Group (which includes Faumai and Kais Formations), Klasafet, Steenkool and Quaternary/Sele Formations. This study focuses specifically on New Guinea Limestone Group, with emphasis on Faumai Formation. Tectonostratigraphic framework of the area and main features of Faumai Formation are outlined in Figure 4.

The New Guinea Limestone Group consists of two main formations: Faumai and Kais Formations. In Outcrops, Faumai Formation is generally divided into four sequences, starting in Eocene (~40 to 32 Ma), Lower Middle Eocene, Middle Eocene and Upper Eocene (Thery et al., 1999). The earliest Faumai deposits are identified in Ayamaru high, where fossils from Upper Lutetian (~40 Ma) mark the initial development of the formation. In some locations, Faumai Formation lies conformably above Daram–Waripi Formation, while in other areas, it is separated by an unconformity caused by late Oligocene compression and uplift. This unconformity sometimes divides Faumai from older Cretaceous and Devonian–Silurian rocks. Similar fossil records are found from the Central Range extending to Papua New Guinea.

Changes in facies during the Middle Eocene indicate deposition in more open and energetic marine environments, with packstone containing abundant red algae. By Late Eocene, environment became shallower, shifting to lagoonal and shallow marine settings that supported the development of reefal limestone. Based on regional understanding Faumai Formation was mainly deposited in shallow marine environments in Southern are of Kemum high to Bintuni Basin and it transitions to deeper water carbonate facies farther south in Kokas and Fak-Fak (M. Suparman & G.P. Robinson 1990; Birt et al., 2015). Outcrops based on Field mapping by BP Exploration team in 2009 confirmed that in Fak-Fak to Kokas, Carbonate age is Oligocene to Miocene, the Oligocene carbonate mostly marly and deposited in Middle to Upper Bathyal zones. In Bintuni Bay, Top of Eocene carbonate as unconformity, this is most likely due to uplift at Late Oligocene (Norvic 2001, Birt et al., 2015. Soeryowibowo et al., 2022).

METHODOLOGY

The methodology of this study combines subsurface and surface analyses followed by regional integration and geological reconstruction to develop a tectono-karstification model for Faumai Formation. The workflow includes interpretation of drilling indicators and well data, seismic facies analysis,

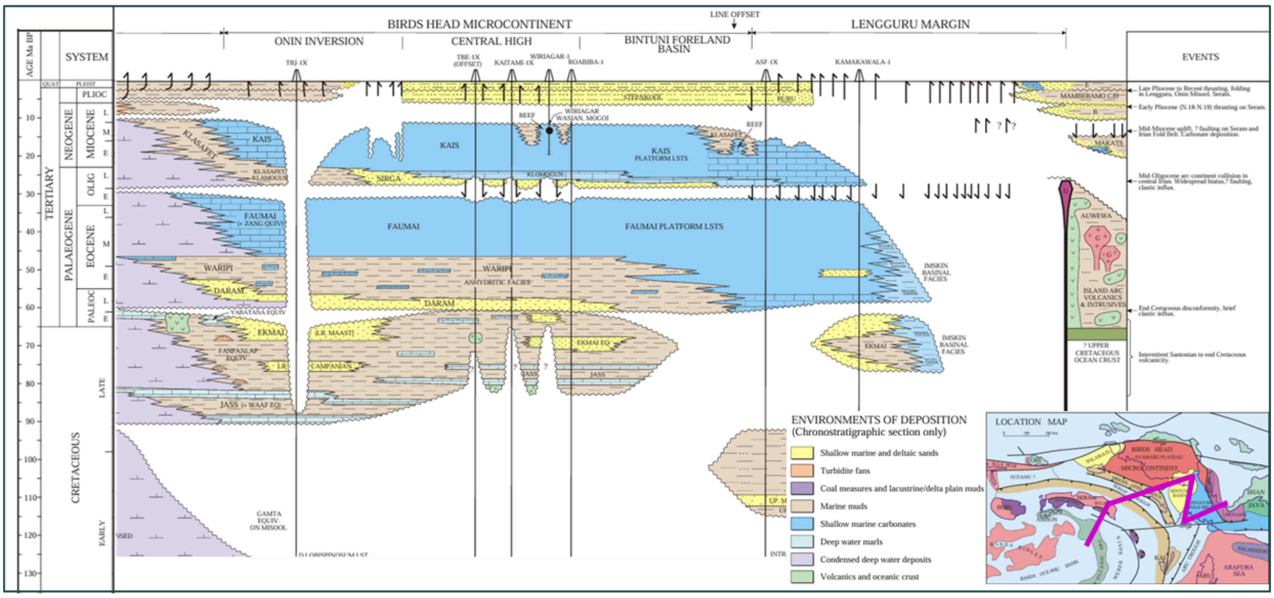

Figure 4. Chronostratigraphy at Bird's Head area, highlighted Faumai Formation is the main interest interval (Norvic 2001).

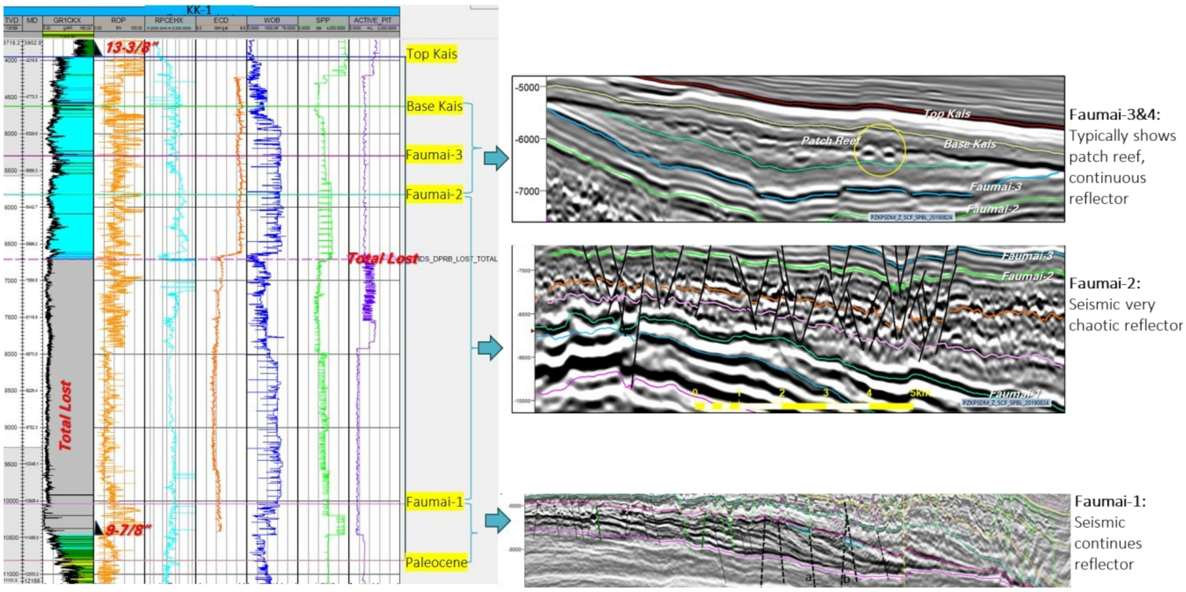

Figure 5. In well KK-1, Faumai-3 and Faumai-4 intervals were drilled without significant operational issues. In contrast, Faumai-2 interval exhibited total loss circulation, indicating intense karstification. Faumai-1 interval showed only minor drilling disturbances, including slight vibration and reductions in WOB, suggesting limited or absent karstification (BP data 2026).

outcrop observations, biostratigraphic correlation, and reconstruction of uplift and geological model of karstification process.

Subsurface data: wells and seismic

Subsurface analysis began with well data, focusing on indicators such as partial to total fluid losses, reductions in weight on bit (WOB), equivalent circulating density (ECD), and standpipe pressure (SPP). These well events correlated with seismic data, specifically the Tangguh 3D seismic (Riangguna et al., 2016; Prabowo et al., 2025, Birt et al., 2015). By integrating calibrated well and seismic data, the study was able to map the distribution of karstified zones using detailed seismic facies analysis. Advanced seismic mapping tools (Bluware) were employed to further interpret and classify facies.

Seismic data also facilitated the identification of faults and horizons, improving understanding of the stratigraphic sequences and regional depositional framework of Faumai Formation. Additional well logs, including gamma ray (GR1CKX) and resistivity (RPCEHX), provided further insight (Figure 5). Cuttings from the Faumai Formation were also analyzed to determine depositional environments and rock properties. In addition, carbonate isotope analysis was conducted on a single well to constrain the timing of structural evolution.

Surface data: outcrops

Karstified formations in outcrops area are found throughout Ayamaru (Auk River), Kemum (Lina Mountain), Kokas, and Fak-Fak. Cave systems in these regions can reach diameters of up to 47 meters and depths of -315 meters (Thery et al., 2009, Geological Research Department Center (GRDC)). The karstification extends beyond Bird's Head, continuing into Bird's Neck and Bird's Body (Benassi 2019). These observations provide important evidence of karstification in carbonate rocks. Age of these outcrops from Miocene to Eocene-Oligocene.

Integration of Surface and Subsurface Data

Surface and subsurface datasets were integrated using nannofossil biostratigraphy and cuttings data (Figure 7). The results show that the carbonate successions exposed at surface and encountered in subsurface are broadly Eocene–Oligocene in age, although some intervals are absent in outcrop.

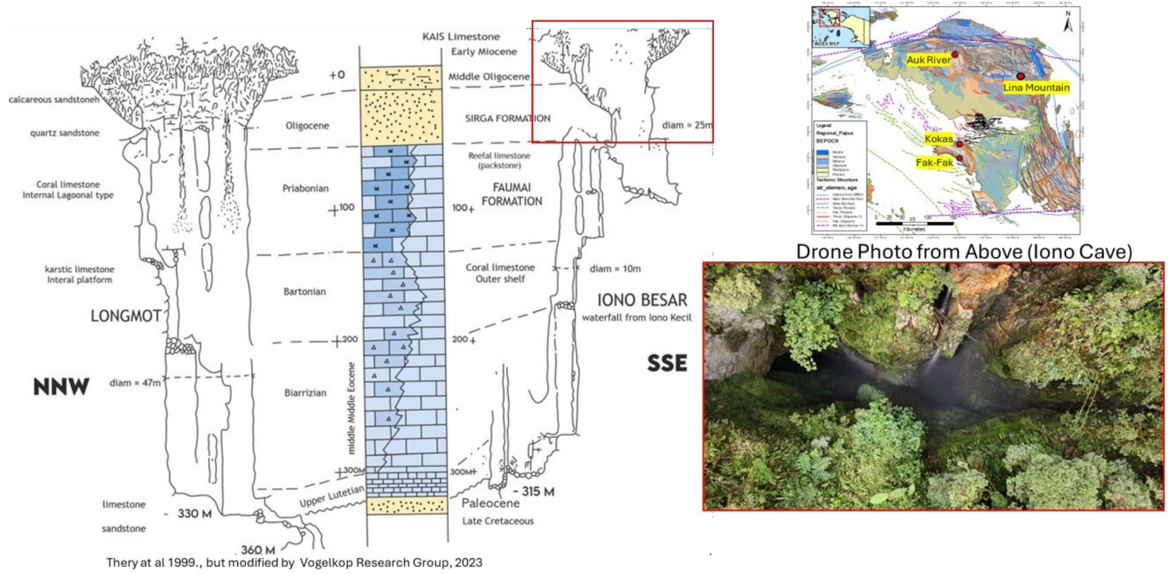

Figure 6. Outcrops of Faumai Formation at Lina Mountain display a stratigraphic sequence made up of four main sequences, which align with offshore stratigraphy (Thery et al., 1999 modified by Vogelkop Research Group., 2023; Birt et al., 2015). Drone images taken from above highlight numerous cave entrances that follow a prominent northwest –southeast fault line. The location where the drone photo was captured is indicated by a red box (left figure).

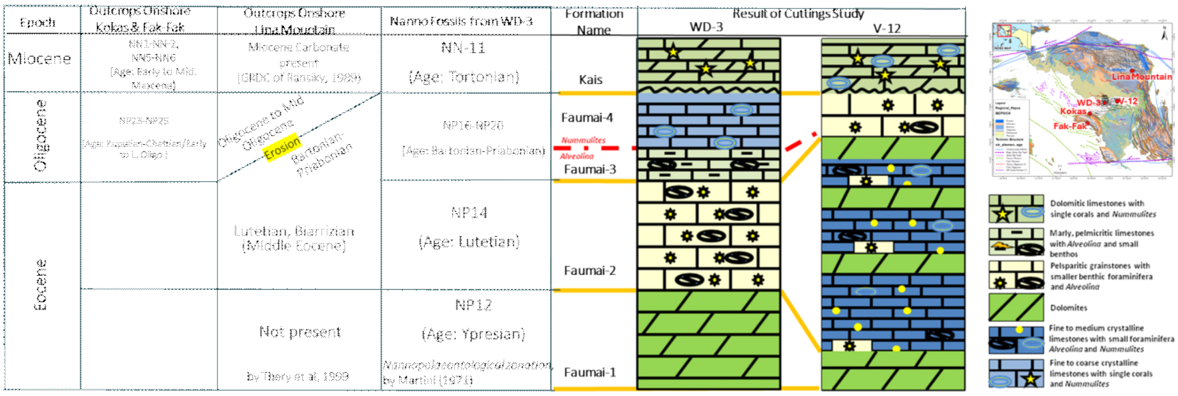

Figure 7. Integrated nannofossil biostratigraphy and cuttings data from subsurface based on wells and surface based on outcrops data. (BP data 2026).

Faumai-1, for example, has only been identified in subsurface of Bintuni Basin from well and seismic data. In contrast, outcrops in Kokas and Fak-Fak areas are mainly early Oligocene, whereas wells such as Lengkuas-1 and Bedidi Deep-1 confirm Eocene carbonates. The absence of Oligocene carbonate in Bintuni Basin subsurface is most likely due to erosion, while equivalent strata are preserved on the northern flank of Kemum High and extend into Salawati Basin as clastic Sirga Formation (Figure 8).

Overall, this integration refines depositional interpretation and supports the use of modern karst systems as analogues for identifying subsurface karstification from well and seismic data. It also indicates that Eocene–Oligocene Faumai Formation extends from surface exposures into the subsurface, implying that karstification has remained active through meteoric-water infiltration to the present day. This interpretation is consistent with data from Auk River, where water depths reach about 5 m and channel widths range from 10 to 20 m flow through cave (Benassi 2017) (Figure 9).

Reconstruction of karstification processes

Geological reconstruction will be based on seismic flattening methods from Top Paleocene and Top Faumai to better understanding, model of deposition and uplift. Subsequently, strontium isotope analysis of carbonate provides insights into provenance and detailed timing of uplift. This methodology enables comprehensive explanation of karstification model, highlighting connections between tectonic activity observed from seismic data and chronological information derived from isotope carbonate dating.

Data

Onshore data include outcrops from Indonesia's Geological Research Department Center (GRDC), published references by Benassi (2017, 2018, 2019), Thery et al, 1999 in Lina Mountain and BP geological mapping in Kokas and Fak-Fak. Offshore data include seismic 3D of Ocean Bottom Node which was acquired in Bintuni Basin (BP Tangguh 2018,). This seismic was depth-tied to wells for horizon interpretation. 31 wells data from BP Tangguh and PUSDATIN.

This well is penetrated Eocene-Oligocene carbonate. These wells are: Vorwata-1 (V-1), Vorwata-12ST (V-12ST), VRB-7, Roabiba-2ST2 (R-2ST2), Kepe-Kepe-1 (KK-1), Wiriagar Deep-3 (WD-3), Wiriagar Deep-1(WD-1), Ofaweri-1 (Ofa-1), ASAP-1X-ST, East Onin-1X4, Bedidi Deep-1X, ASF-1, Lengkuas-1, TBJ-1X, Uba Deep-1, Gunung-1, Agung-1, Aimau River-1, TBF-1X, Merak Emas-

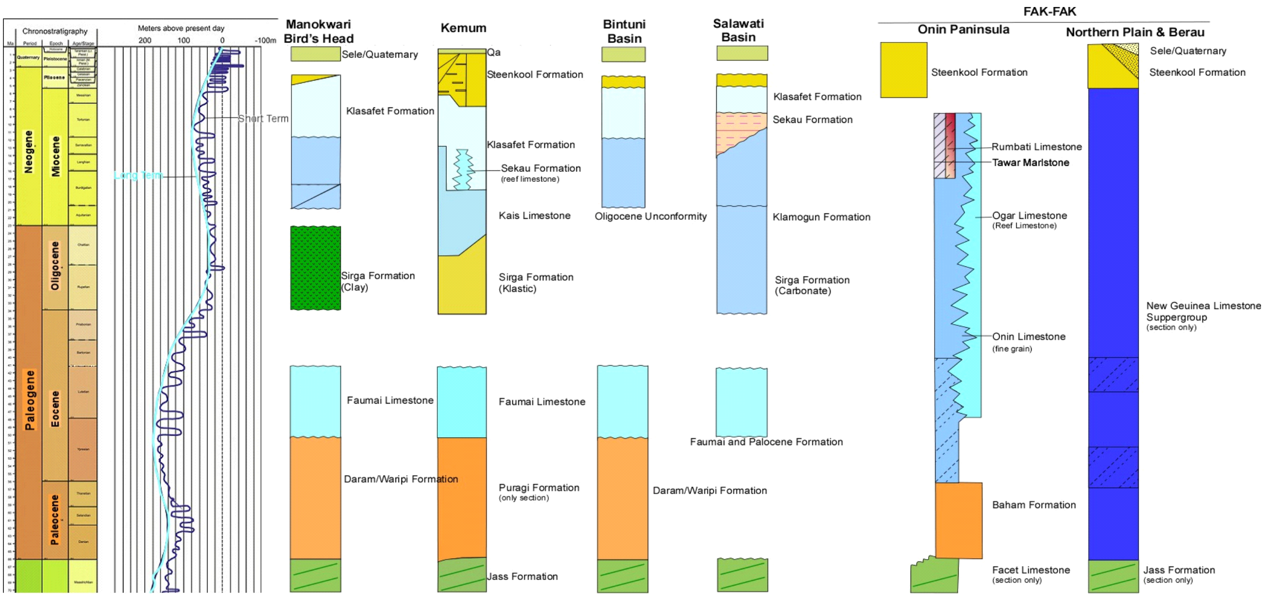

Figure 8. Faumai Formation extends from Bird's Head to Bird's Neck, carbonate deposits more continuous in Fak-Fak than those in Bintuni Basin to the north of Kemum and Salawati Basin (GRDC).
The unconformity interval aligns with a global sea level drop (Gold et al., 2019).

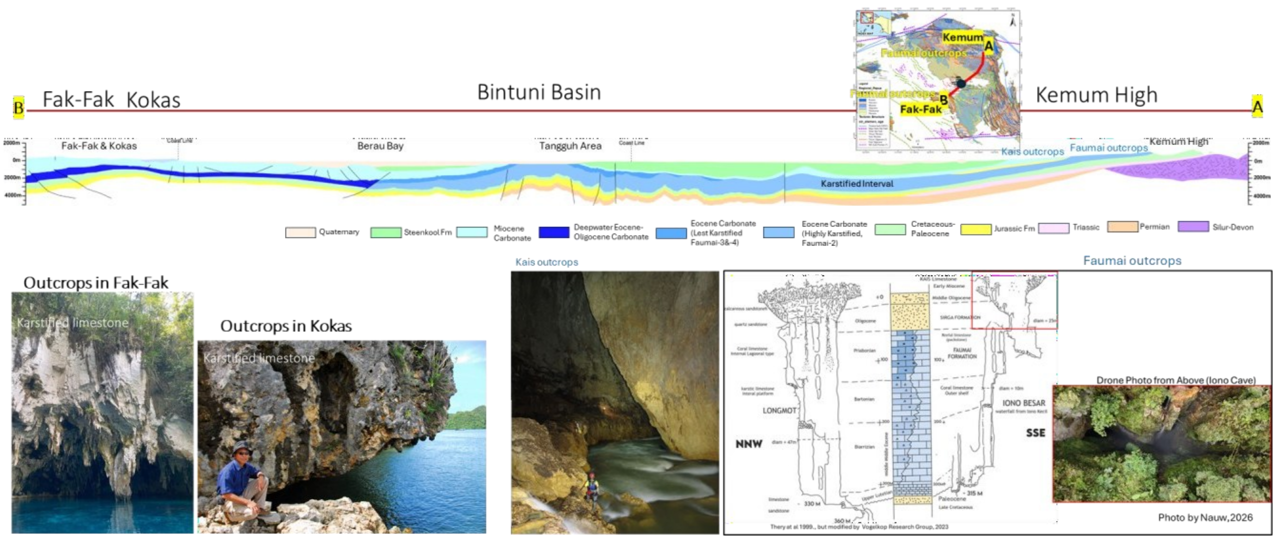

Figure 9. Correlation of Faumai Formation from Kemum high to Bintuni Basin and toward to onshore io Kokas and Fak-Fak area (Modified from GRDC., 1990, 1989; Bailly dkk., 2009; BP data 2025).

1, 330-340, Mogoi Deep-1, Aimau River Deep-1, Andalan-1, Besiri River-1, Kama Kawala-1, Kembelangan-1, Daram Selatan-1, CS-1X and Sakauni-1. Biostratigraphy nannofossils data came from wells KK-1, WD-3, V-12ST and Lina Mountain outcrops (Thery et al., 1999), while field mapping provided constraints for Kokas and Fak-Fak. Cuttings studies are available from WD-3 and V-12ST. The complete data of drilling parameters can only be observed in BP Tangguh operation area include WOB, SPP, ECD and other wells events such as stuck, pack off from well of Kepe-Kepe-1 and VRB-07. The data of carbonate isotope available only at KK-1 well. It is important to clearly define an appropriate analogue for karstification process as a main consideration. Tarim Basin in Xinjiang, northwestern China, serves as a suitable analogue for karstification in Bird's Head area. The Tarim Basin's geological record includes deposition from Cambrian to Middle Ordovician, followed by tectonic uplift that caused karstification from Late Ordovician to Early Carboniferous as an epigenic process. Afterwards, collapse and infilling took place during Permian, and sedimentation continued from Silurian to Quaternary. This has resulted in a complex, multi-phase evolution of carbonate and karst systems (Zhao et al., 2014), (Figure 10).

RESULT AND DISCUSSION

Regional seismic framework

To enhance our understanding of present-day tectonics in Bird's Head region, particularly within Bintuni Basin, seismic data plays a crucial role. The current geological framework of Bintuni Bay is that of a foreland basin, primarily influenced by Lengguru Fold Belt. This tectonic activity has supplied sediments ranging from Steenkool Formation to Quaternary. Beneath these layers lies a continuous interval of strong seismic amplitude associated with carbonate deposition, known as the Kais Formation. Below this, a regionally extensive unconformity marks the top of Faumai Formation, which is also composed of carbonate rocks. Beneath the Faumai Formation, clastic sediments of Paleocene, Cretaceous, Jurassic, and Permo - Triassic age are present. These stratigraphic relationships are observed in productive fields such as Vorwata and Roabiba.

The Tangguh area contains three principal fault sets. The oldest faults, which control the Permo–Triassic stratigraphy, are related to rifting (Pigram & Panggabean 1984; Soeryowibowo et al., 2022; Lelono et al., 2010). A second set cuts the Eocene

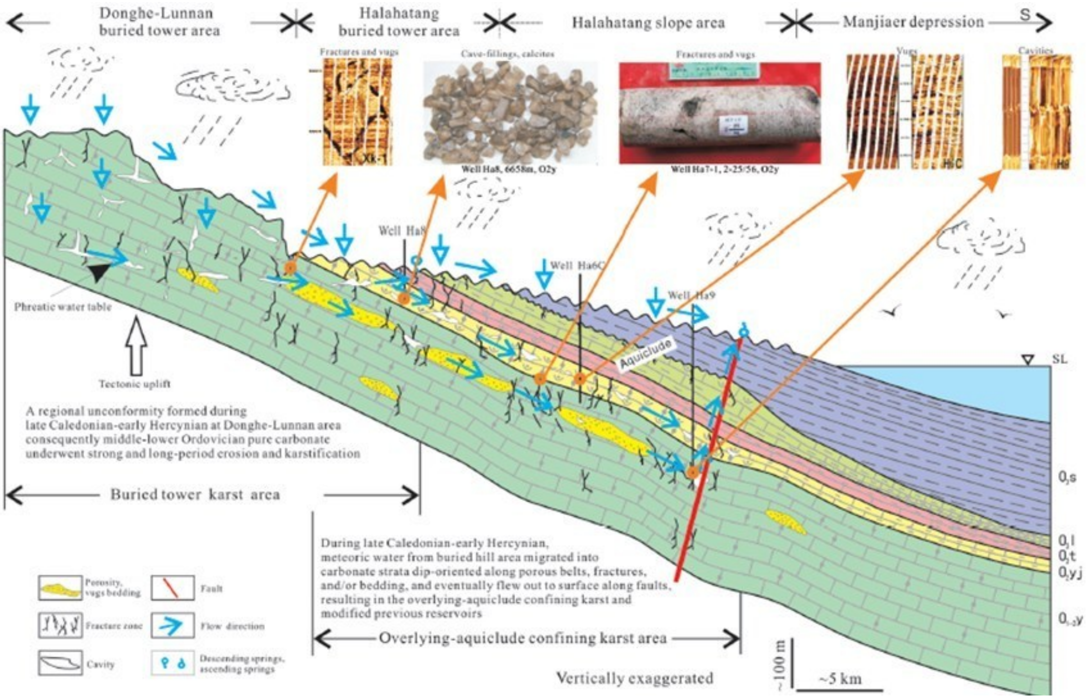

Figure 10. Karstification within Tarim Basin, located in Xinjiang, northwest China, is primarily governed by tectonic activity (Zhao et al., 2014).

carbonates and reflects reactivation of older structures during oblique convergence between Australian and Pacific plates (Hall 2012; Hill & Hall 2003). The youngest faults cut Steenkool Formation and Miocene carbonates and represent renewed reactivation associated with development of the Lengguru Fold Belt (Bailly et al., 2009; Decker et al., 2009; Hill & Hall 2003) (Figure 11).

Stratigraphy

Faumai Formation stratigraphy, derived from well and seismic data, comprises four sequences: Faumai-1 through Faumai-4. Seismic analysis indicates thinning toward south and thickening northward (Figure 12). Faumai-1 showing progradation and downlap to the south. Well cuttings from WD-3 and V-12 reveal lithological differences: Faumai-1 is predominantly fine-grained dolomite with occasional coarse-crystalline limestone; Faumai-2 features pelsparitic grainstone; Faumai-3 contains marly, pelmicritic limestone; and Faumai-4 is mainly fine- to coarse-crystalline limestone with isolated coral fragments. Stratigraphy in Tangguh aligns with stratigraphy in surface at Lina Mountain data (Thery et al., 1999). All wells which have been drilled in Bintuni Basin, onshore and offshore extending to Salawati Basin often experience partial to total losses in Faumai Formation. The well of WD-3 and VRB-12 experienced partial losses. Based on the experience from existing wells during operation before getting into total mud losses will experience increase of dolomite from 5% to >20%. This indicates rock changes most likely due to rock diagenesis, this could increase of rock quality to better rock properties (Omar et al., 2020). Yet, this cannot be confirmed due to limited data and absence of comprehensive studies. Internal study done by BP suggested Faumai formation porosity is estimated at 40–60%.

Gamma ray log from WD-3 well delineate clear patterns aligned with the sequence stratigraphy of Faumai Formation. Faumai-1 demonstrates an overall coarsening-upward trend, Faumai-2 exhibits a fining-upward pattern, while both Faumai-3 and Faumai-4 revert to coarsening-upward trends (Figure 13). Cutting descriptions from Faumai-2 further reveal a higher abundance of coarse dolomitic material and grain-supported, pelsparitic textures. This potential is indicative of better rock quality compared to Faumai-1, Faumai-3 and Faumai-4 which marly, coral fragments and pelmicritic.

Structural control

The oblique transpressional interaction between the Australian and Pacific plates in Late Oligocene was the main tectonic driver of karstification in the Bird's Head (Hall 2012; Birt et al., 2015). This phase caused strike-slip faults, uplifts, and folding Faumai Formation, exposing for the erosion. Seismic data from BP Tangguh show a dominant

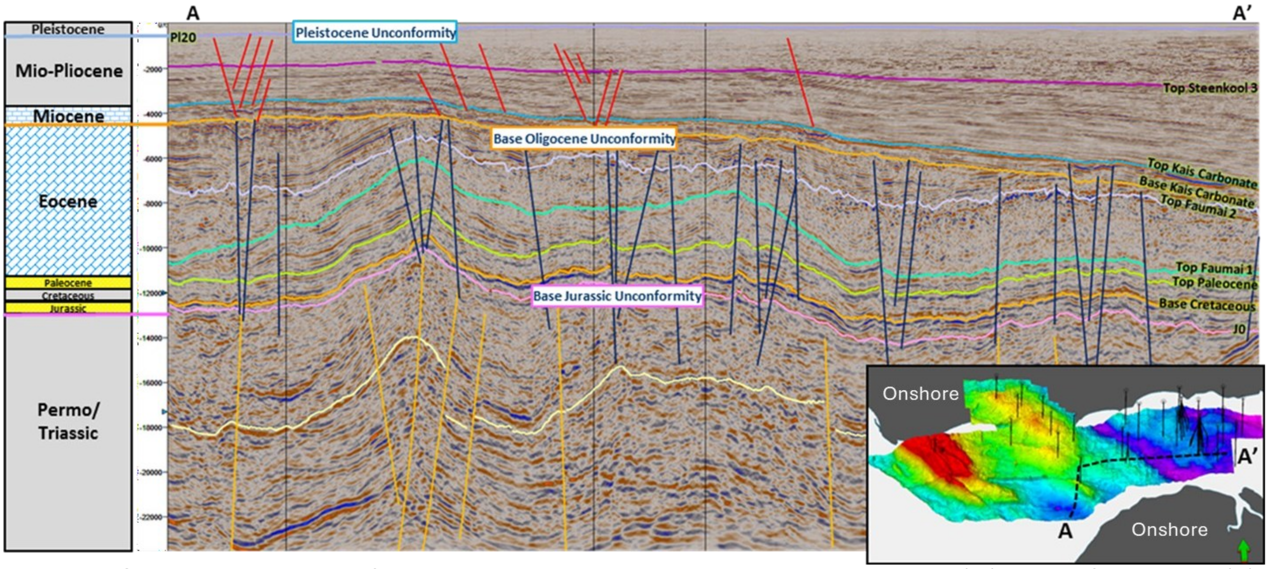

Figure 11. Seismic cross section of Tangguh Area, illustrating basin tilting toward the east (A') and uplift to the west (A). This study focuses on Eocene carbonate formation, which is equivalent to Faumai Formation. (BP data 2026).

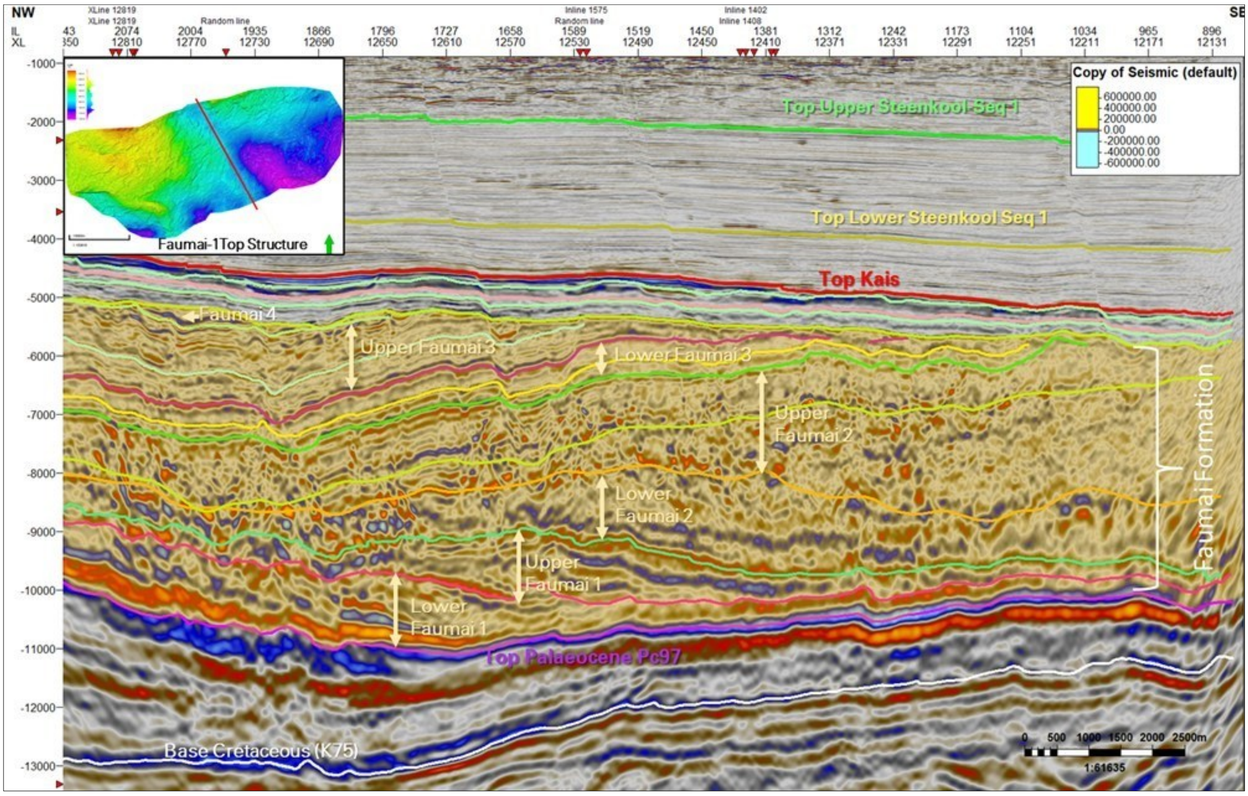

Figure 12. Faumai Formation thins towards the southeast. Faumai-1 shows downlap feature, whereas Faumai-2, Faumai-3, and Faumai-4 are truncated by the Base Kais (Oligocene) unconformity (Vinson & Rogers 2020).

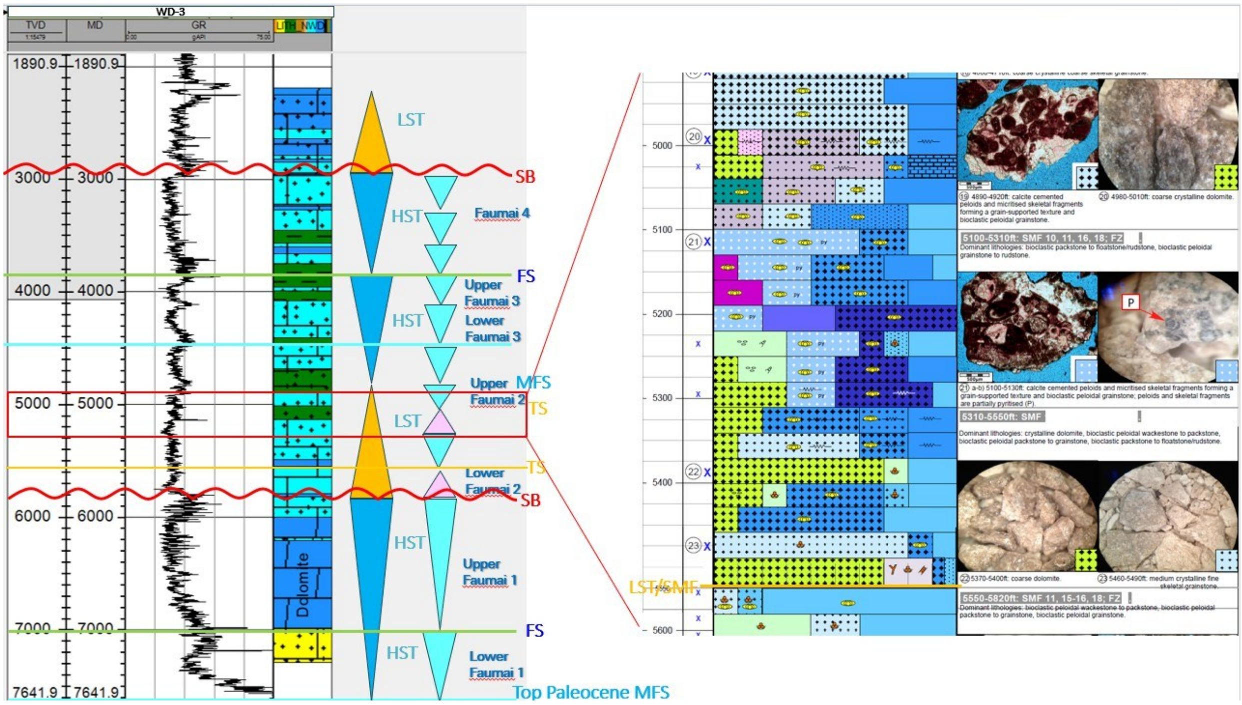

Figure 13. WD-3 log shows distinct patterns that correspond to the sequence stratigraphy of Faumai Formation. Sequence Boundary (SB), Flooding Surface (FS), Lowstand System Tracts (LST), Highstand System Tract (HST), Maximum Flooding Surface (MFS). http://www.sepmstrata.org/Terminology.aspx?id=systems%20tract.

NW–SE anticline orientation accompanied by extensive faulting along three principal trends: East–West, ENE–WSW, and NE–SW. Integration with image log data, particularly from Wiriagar Deep, indicates that the maximum principal stress (σ_1) is oriented approximately 45° to the NE–SW direction, while the minimum principal stress (σ_3) is oriented NW–SE (Roger & Vince 2020) (Figure 14).

Structural control is seen in Faumai formation outcrops as driving for karstification process (Figure 15). This may serve as an analogue for subsurface karstification processes. The Younger tectonic activity greatly affects the collapse of karstified formations. Seismic data show collapse features linked to faults (Figure 16), and similar features are visible in onshore outcrops, especially at Auk River (Figure 17).

Seismic Facies Mapping

Seismic facies mapping is fundamentally based on correlation with well events. Studies have confirmed that seismic facies indicative of caves and karstification are characterized by chaotic seismic patterns, trough reflectivity, and isolated features (Riangguna et al., 2016; Sahidu et al., 2025). Utilizing these classifications, advanced interpretation tools were applied to map the

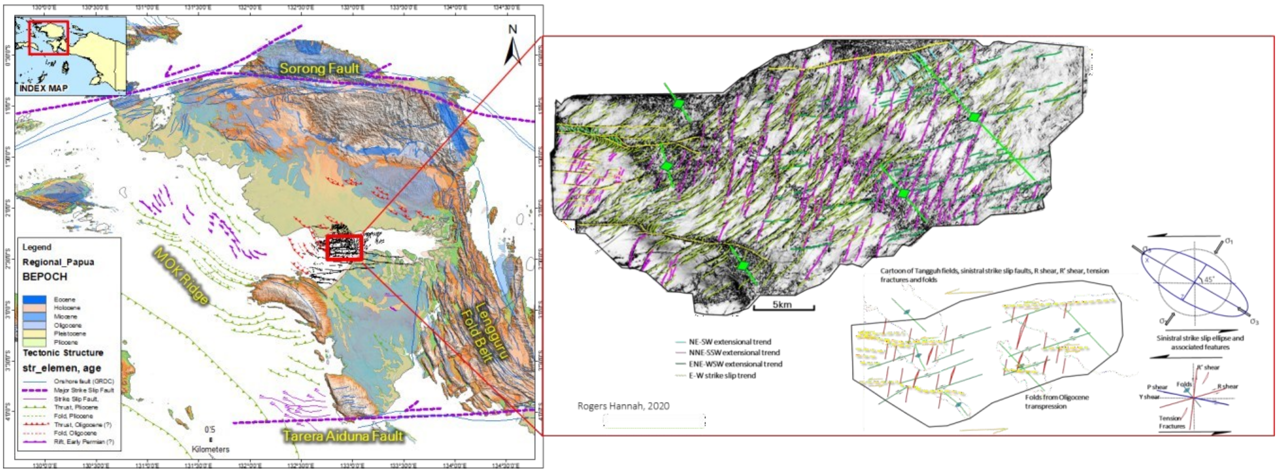

Figure 14. The left figure shows current regional structure of Bird's Head area, the right figure shows seismic depth coherency in the Faumai-2 interval, highlighting Late Oligocene tectonic effects (Rogers & Vinson 2020).

Figure 15. The photo was taken at Lina Mountain near Iono Besar Cave. The NE–SW fault trend is consistent with offshore structural data and suggests a Pleistocene origin. The left panel highlights fractures, vugs, caves, and stalactites. Thin soil covers, dense vegetation, and a cool, humid climate (at night 10-15 deg) provide favorable conditions for ongoing karstification. (Photo by Nauw 2025).

distribution of caves (Figure 18 and Figure 19). The seismic facies maps show that patch reefs and sinkholes are concentrated mainly in Faumai -3 and Faumai-4 intervals, whereas in Faumai-2 patch reefs are restricted largely to the Wiriagar area (Birt et al., 2015; Riangguna et al., 2016).

In Tangguh area, seismic data also indicate collapsing structures, sinkholes, and caves. Forward modelling of cave size and fill reproduces responses consistent with the observed seismic signatures, suggesting brine-filled features approximately 6–20 m in size. These results support the interpretation of collapsed cave systems with variable degrees of infill (Riangguna et al., 2016).

Outcrops mapping

Outcrops of Faumai Formation are observed in Lina Mountain area, extending both eastward and westward. These outcrops are characterized by

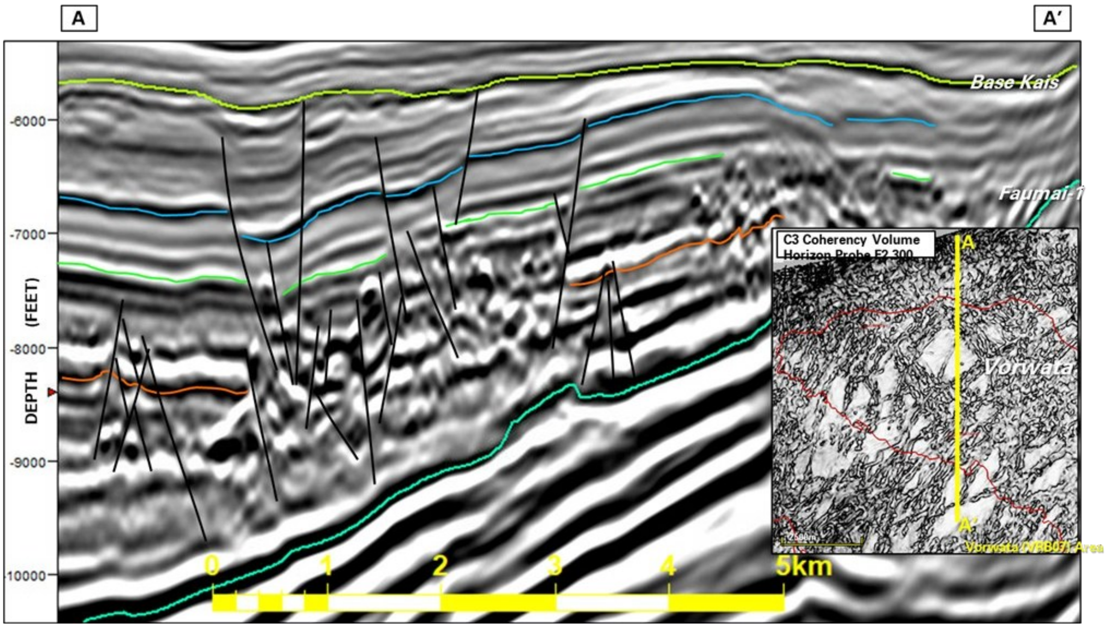

Figure 16. Seismic data from Vorwata Field shows distinct collapse features associated with faulting. These features indicate post-depositional tectonic activity affecting the Faumai Formation and are aligned with the fault planes. (Rogers & Vinson 2020).

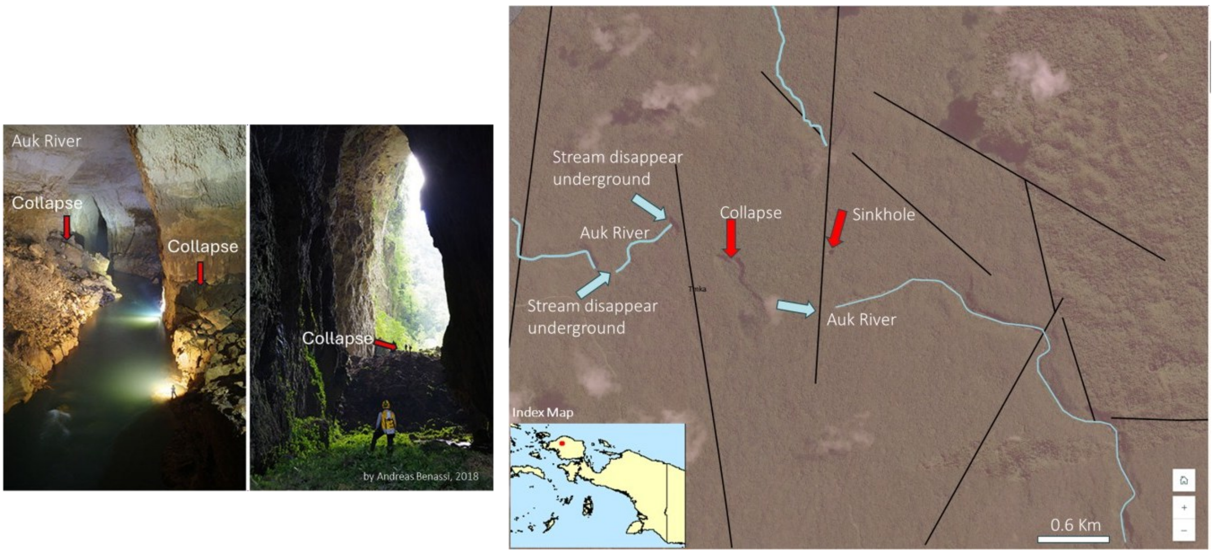

Figure 17. The left image illustrates a collapse at Auk River on Ayamaru platform. (Benassi 2019). This carbonate formation is part of Miocene carbonate sequence. The right image displays karst topography developed in Miocene carbonates, featuring collapse structures, sinkholes, and areas where streams flow underground.

significant fracturing and faulting. Although petrographic data are limited, Thery et al., (1999) describe the formation as a calcareous reefal limestone, turbidites and dolomitic components (Figure 19, Figure 20, and Figure 21). To the south, these outcrops extend into Kokas and Fak-Fak, where they are interpreted as representing middle to upper bathyal deposition. Lithology predominantly wackestone and packstone to mudstone, with some intervals composed of globigerinid to dolomitic limestone (Figure 22).

Reconstruction

The structural reconstruction of study area was based on 3D seismic data from BP Tangguh Field using seismic flattening. Flattening at the Top Paleocene horizon provided a consistent reference surface for interpreting depositional and uplift history. The results show that Faumai-1 prograded southward and was followed by deposition of thicker Faumai-2 interval, whereas Faumai-3 and Faumai-4 are comparatively thinner. A second flattening at the Base Kais Carbonate horizon

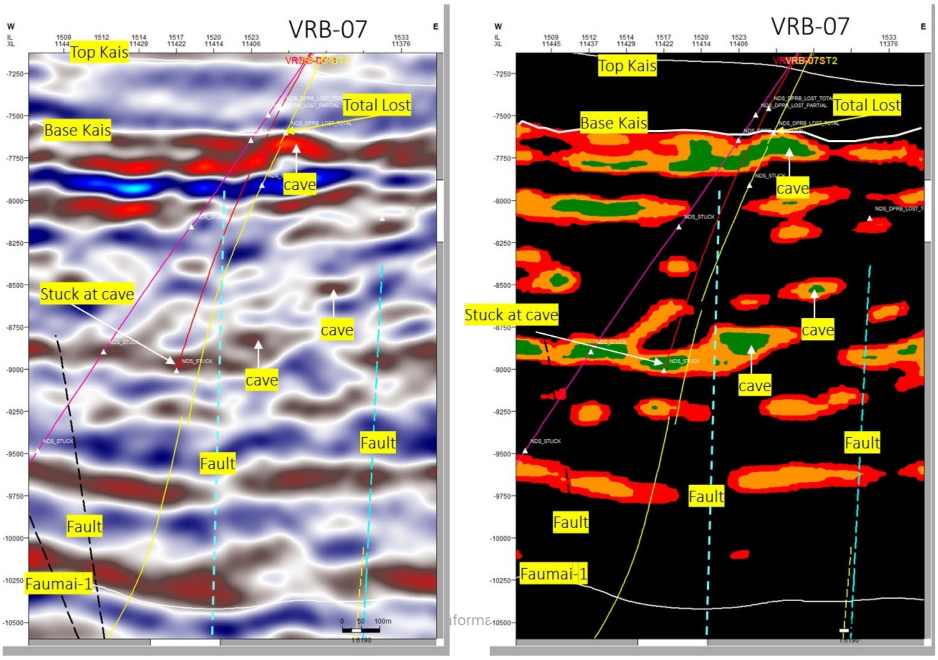

Figure 18. Trough reflectivity mapping (left) highlights cave-related seismic anomalies and constrains cave distribution (right). Wells that intersect bright or trough amplitude anomalies commonly experience total fluid losses. The right figure further indicates that Tangguh cave system is complex and highly interconnected. (BP data., 2020).

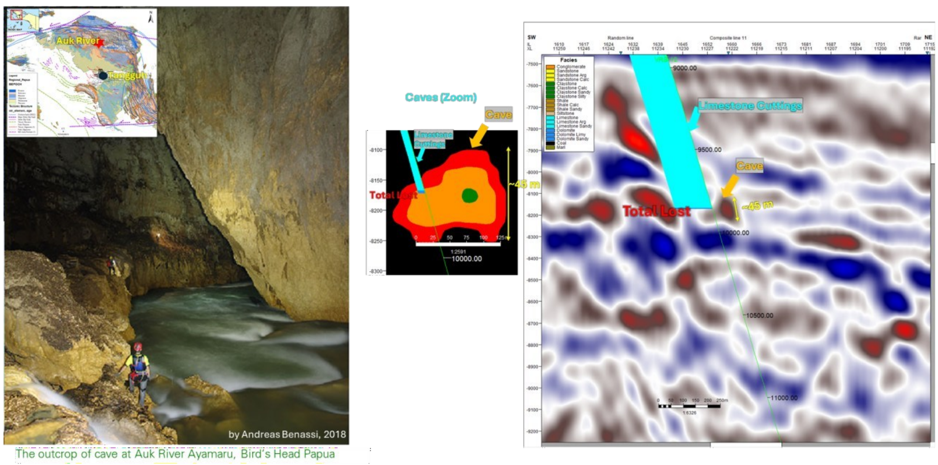

Figure 19. Well event in VRB-12, which involves drilling and experiencing total fluid losses (BP data 2026). According to seismic-based cave distribution data, the cave measures approximately 125 meters in length and 45 meters in height. For comparison, an analogue in Auk River reveals cave dimensions of 20–30 meters in width and 15 meters in height, featuring a water flow channel that is 10–20 meters wide and around 5 meters deep seismic (Benassi 2017)). That analogue is not feasible on seismic because below seismic resolution.

Figure 20. Outcrops at Iono Cave show Sirga formation (Thick > 20m).
Drone photo of the deepest accessible cave area (5–7 meters). (Photo by Nauw 2025).

Figure 21. Highly faulted Miocene outcrops were observed at Iono Besar. Outcrops of Faumai Formation were not accessible. However, it is likely that Faumai Formation exhibits similar characteristics of extensive faulting. (Photo by Nauw 2025).

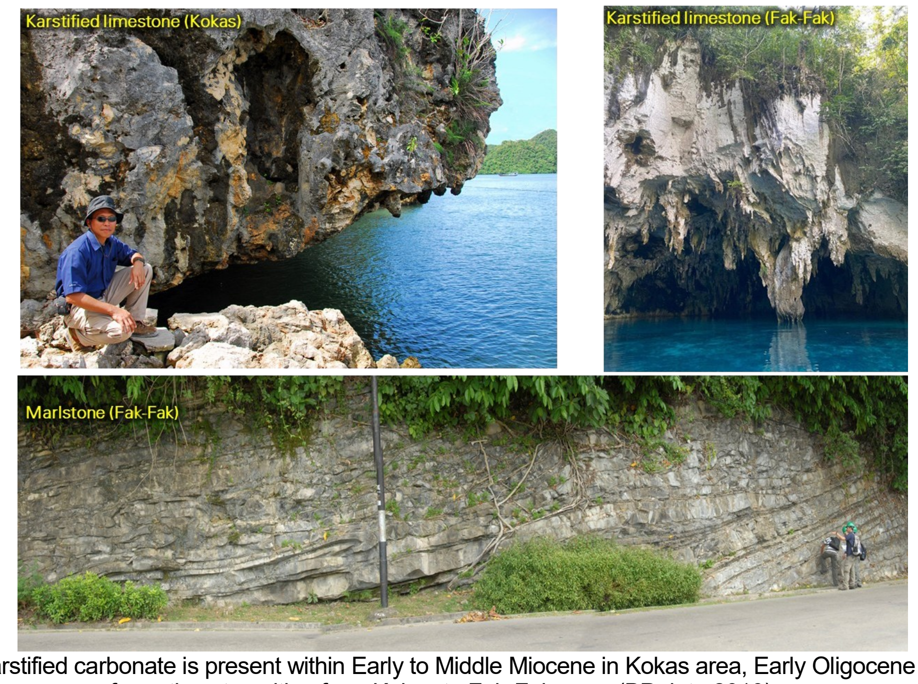

Figure 22. Karstified carbonate is present within Early to Middle Miocene in Kokas area, Early Oligocene marlstone formations transition from Kokas to Fak-Fak area. (BP data 2010).

highlights anticline development and associated erosion surfaces. Erosion decreases eastward and increases westward, with cumulative erosion estimated at Vorwata ~1,200 m, Ofaweri ~1,500 m, and Ubadari ~2,650 m. This reconstruction is consistent with the model from Yudhanto & Pasaribu (2012). The uplift of this area indicates ~500 m of basin shortening (Figure 23). After uplift, the basin was buried and shallow-marine Kais carbonates were deposited during Early to Late Miocene. Subsequent water-depth fluctuations as deep water produced clay-rich facies in the Lower Steenkool and sandier facies in the Upper Steenkool as shallow water. During Pleistocene, renewed tectonism formed a foreland basin, caused ~7° clockwise rotation, and reactivated faults, generating collapse structures across Bird's Head area.

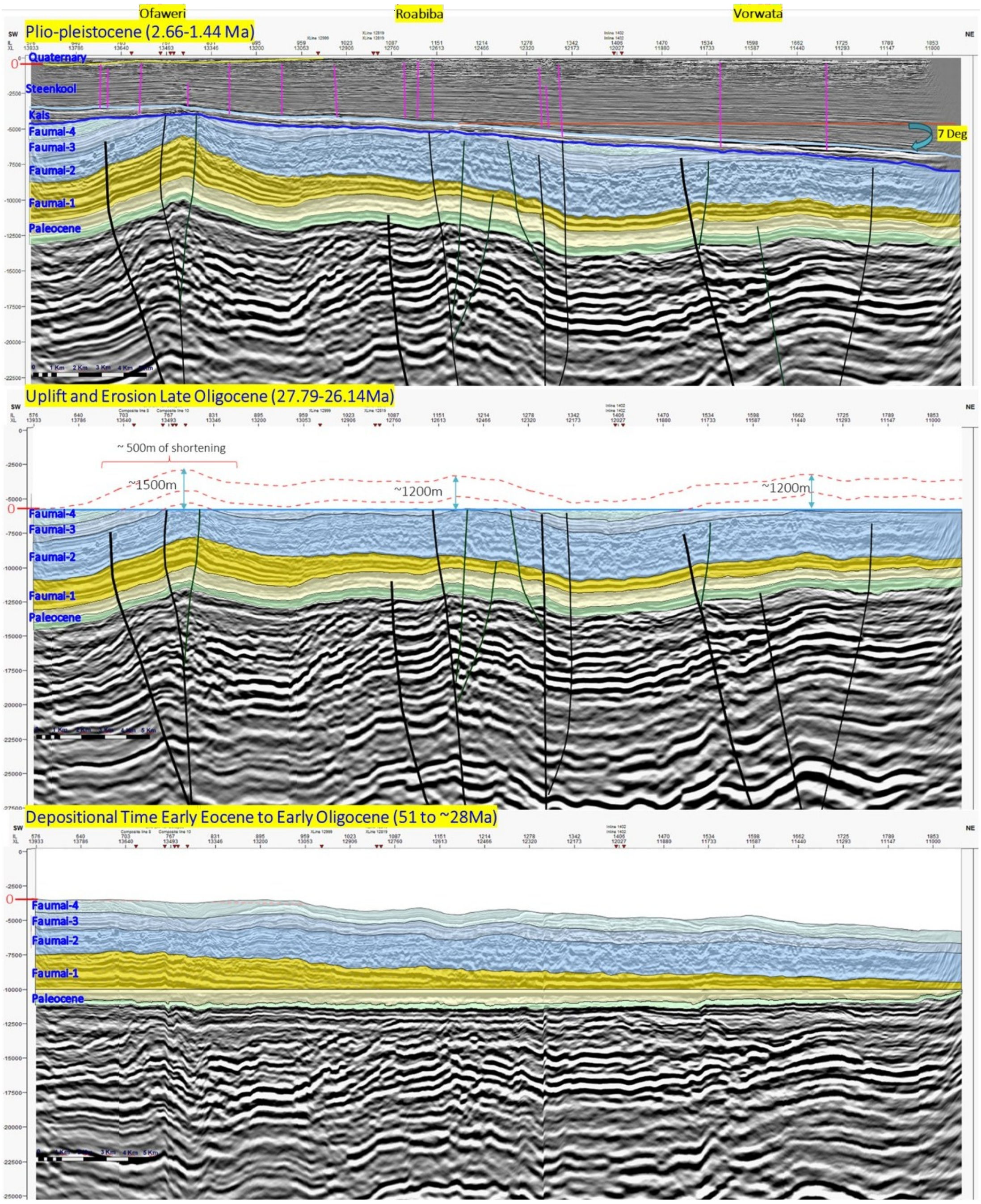

Figure 23. Reconstruction of Faumai Formation evolution using seismic 3D flattening techniques. The sequence initiates with the depositional phase spanning Early to Late Eocene, followed by significant uplift during the Late Oligocene, and subsequent rotational tectonic activity in Pleistocene. The seismic visualization, red horizon (0) delineates initial depositional surface during deposition. The age indicators are derived from carbonate isotope dating.

Reconstruction based on carbonate isotope

Better understanding of tectonic evolution is utilizing the data of carbonate isotope from KK-1 well. This data is to support better understanding of the weathering processes based on Sr isotope 87Sr/86Sr. The record begins at 32.46 Ma, showing a low strontium ratio of 0.707891, which suggests minimal continental influence during Eocene. By 27.79 Ma and 26.14 Ma, the ratios gradually rise to 0.708022 and 0.708088, indicating an increasing contribution from continental weathering possibly linked to early tectonic activity or subtle climatic changes. Although marine processes remained dominant, this trend marks the onset of enhanced continental input into the oceans. Evidence of uplift appears in the depositional model as terrestrial conditions (Gold et al., 2019), confirming carbonate exposure and interaction with meteoric water. Based on KK-1 carbonate isotope data, karstification occurred around 2 Ma, marking a significant phase in Faumai Formation's evolution. Karstification and cave development during Late Oligocene resemble present-day caves observed at Lina Mountain and along the Auk River. The Auk River as younger karst features occur within Miocene carbonates, indicating that karstification processes continued beyond the initial Oligocene phase most likely until present day. Onshore, karstification likely persisted at 11.1 Ma because strontium ratio increased to 0.708858, marking a significant shift toward greater continental influence. This change likely reflects Miocene climatic transitions, where increased river runoff delivered more radiogenic strontium to the oceans, subtly altering the marine isotope signature and indicating stronger land ocean interaction. By 2.66 Ma, the ratio rose sharply to 0.709066, signaling intensified continental weathering and major climatic changes associated with the onset of Pleistocene glaciations. The youngest sample, dated at 1.44 Ma, records the highest ratio of 0.709107, representing peak continental influence. This rise is attributed to intensified glacial activity (Panuju 2009; Lelono 2018), which accelerated erosion and weathering of continental rocks (Figure 24).

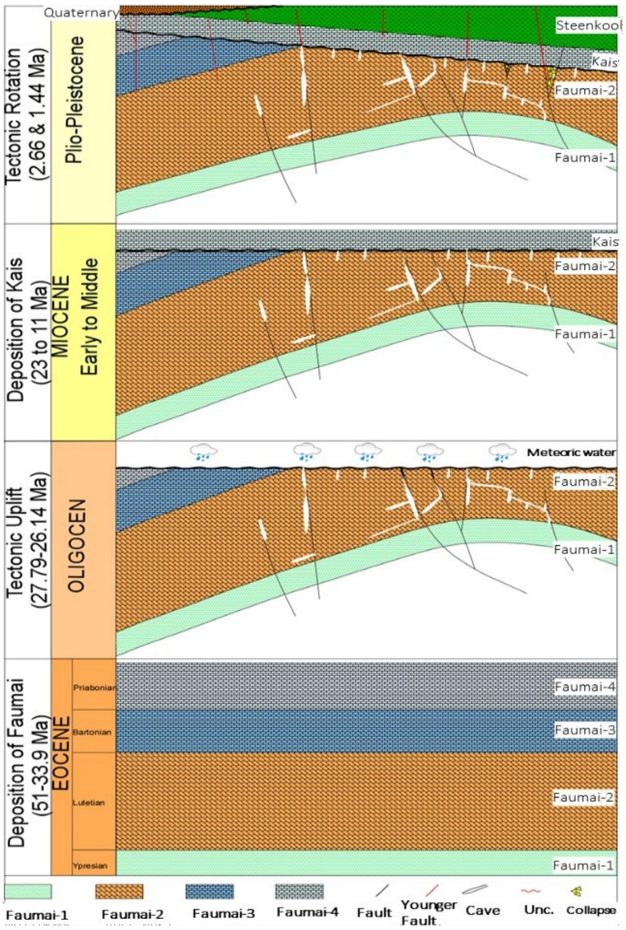

Figure 24. The reconstruction of Faumai formation-based carbonate isotope data. (Nauw 2026)

Karstified distribution

Based on well and outcrop data, Eocene carbonates show well-developed karstification in the Bird's Head and Bintuni Bay areas. However, its extent decreases toward the southern part of the Bintuni Basin (Figure 25). Present-day outcrop observations indicate that karstification processes continue within Miocene carbonates. In contrast, karstification is poorly developed in Eocene carbonates in Kokas & Fak-Fak, likely due to deposition in deep-water settings with higher mud content and most likely Oligocene unconformity is not present in Southern area of Bintuni Basin.

Geological Model of Karstification Processes

Cave development along fault planes is evident at Lina Mountain outcrops. It shows landslides and fractures in Limestone directly on faults (Figure 26). At Iono Cave, a major system follows a NW–SE fault zone (Figure 27). This possibility is supported by Shanov & Kastov's (2015) principle that caves often form along structural weaknesses. Similar patterns appear along Auk River in Ayamaru Platform, with collapse features aligned to fault zones, highlighting structural control of karst formation in Bird's Head. Tectonic deformation and folding also contribute to

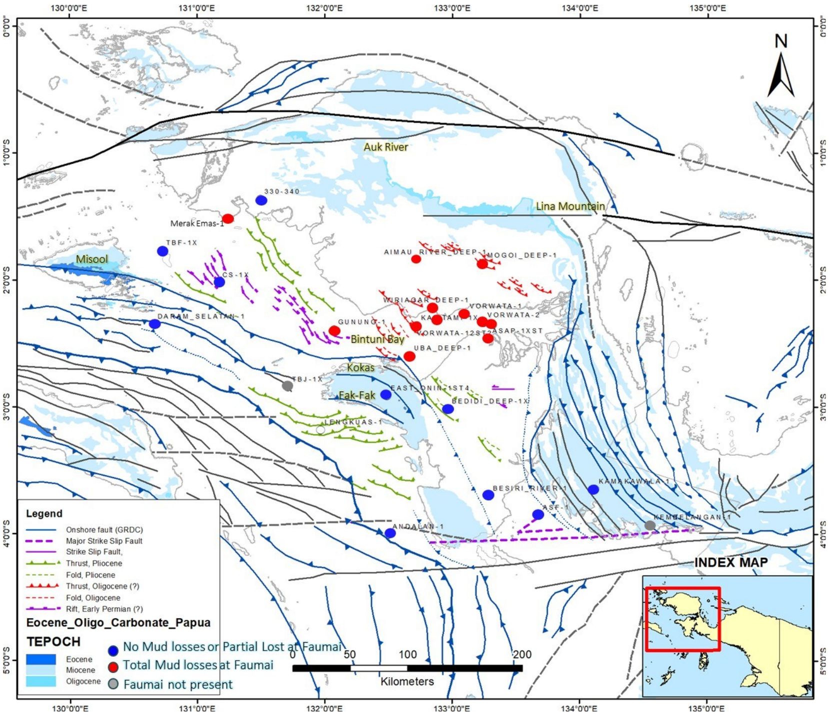

Figure 25. The distribution of Karstification is based on the presence of well data and outcrops (BP Data 2026; PPDSM data).

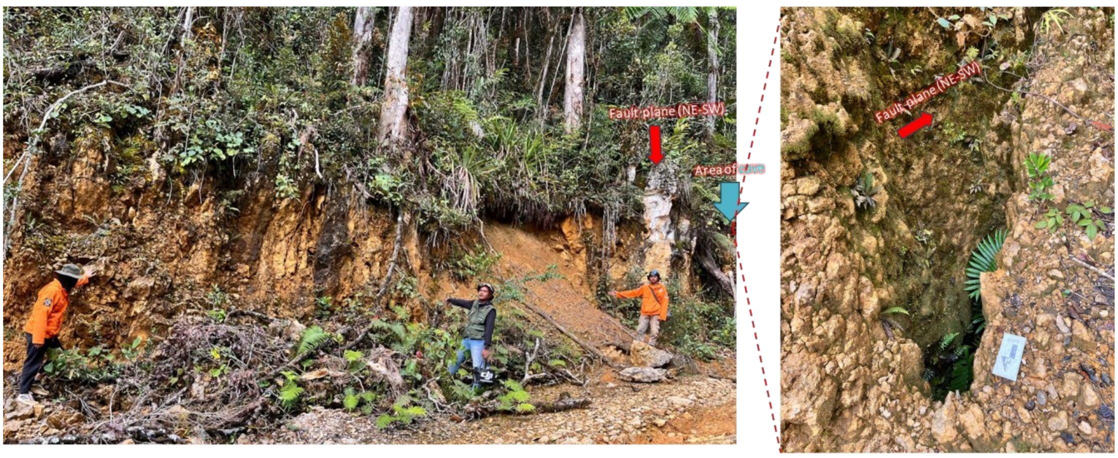

Figure 26. Miocene carbonate in Lina Mountain location shows landslide near a fault zone. The left image displays a 2x0.5 meter cave at fault zone. This fault trends NE-SW, consistent with offshore Plio-Pleistocene fault. (Photo by Nauw 2025).

karstification in Fak-Fak area. This tectonic event is slightly younger related to MOK structure (Figure 28). The case study from Ofaweri-1 well indicates immediate total losses once drilling reached top of Faumai-2, strongly suggesting karstification within this interval. Seismic data show trough reflectivity anomalies, interpreted as cave systems. On regional benchmarks from Tangguh and well-to-seismic correlations which supports high confidence of karstification along both crest and flanks. Although the flank area does not connect directly to the surface, it developed due to tectonic events that created fractures and joints. These features allowed meteoric water to infiltrate through epikarst zone, continue downward through the vadose zone causing vertical erosion, and then move laterally through phreatic zone, enlarging passages along structural weaknesses (Bakalowicz 2015; Goppert et al., 2011; Cross et al., 2021). (Figure 29 and Figure 30.) This process of karstification in the Bird's Head area likely continues to present day due to connectivity between surface outcrops and subsurface of Faumai formation.

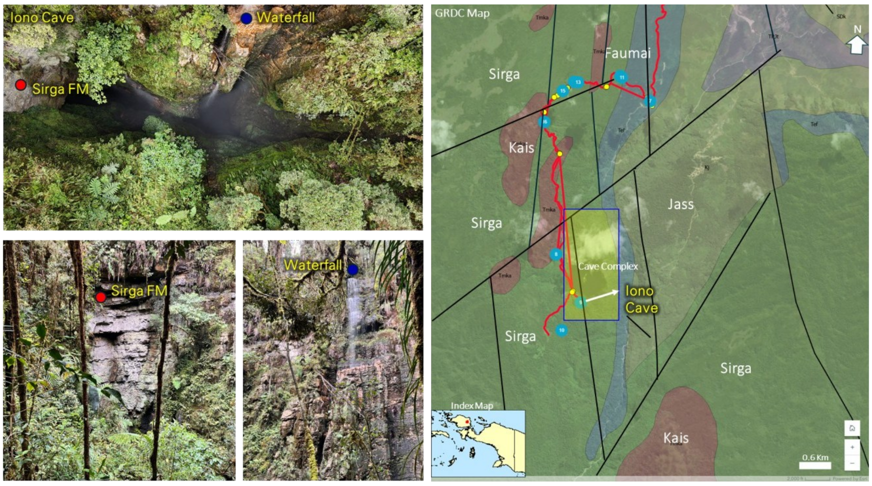

Figure 27. Iono Cave at Lina Mountain at the Top present of Sirga Formation, structurally linked to Faumai Formation (Thery et al., 1999). The cave passage follows a north–south fault zone, highlighting tectonic structural control. (Photo and fault model interpretation by Nauw 2025).

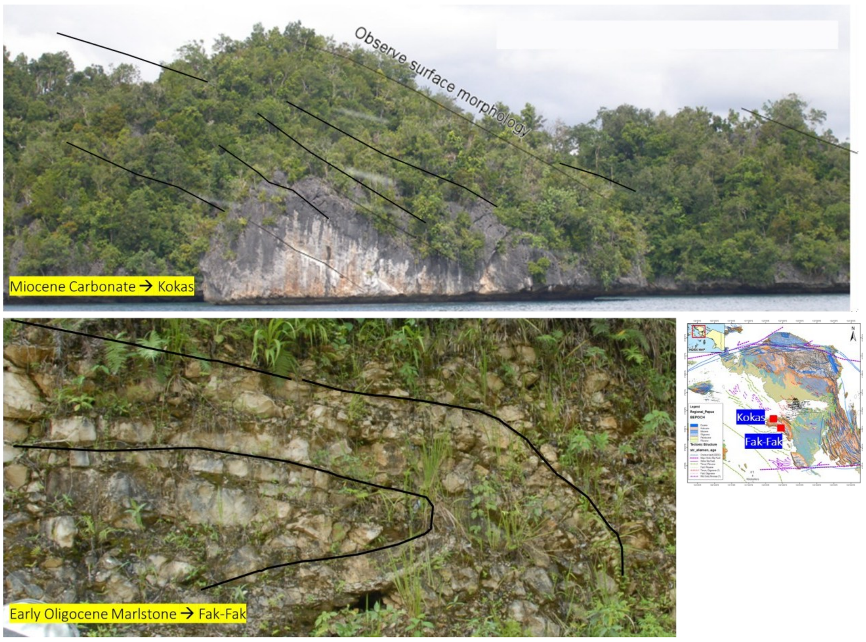

Figure 28. Tectonic deformation evident in Kokas and Fak-Fak area, where pronounced folding occurs in Early Oligocene marlstone in Fak-Fak. Additionally, sloping formations found in Miocene carbonates at Kokas further demonstrate tectonic activity. These geological features are related to younger tectonics of Pliocene events which connected to MOK Ridge. (BP data 2010).

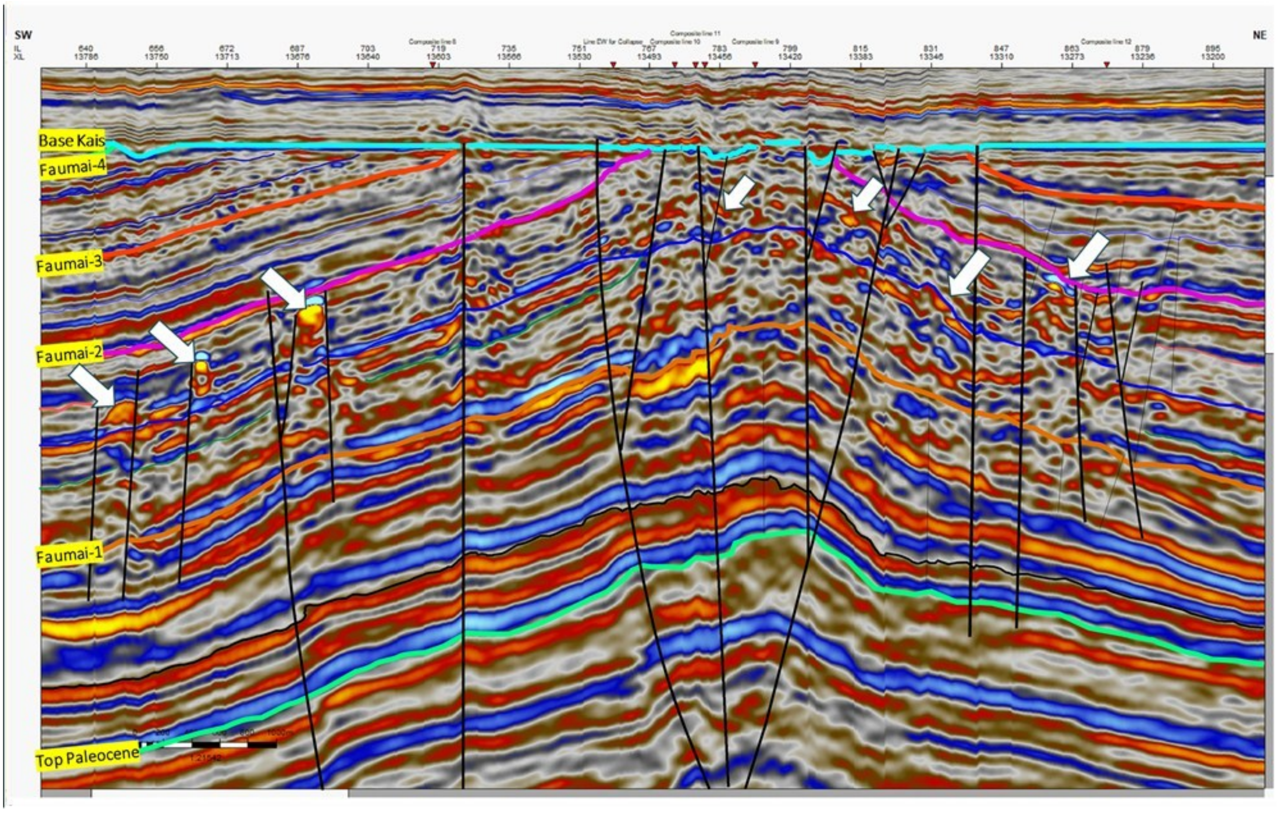

Figure 29. Seismic flattening at Top Kais Carbonate in Ofaweri reveals folding, uplift, erosion, and multiple faults that together form a flower structure. In Faumai-2 interval, discrete bright trough-reflectivity anomalies are fault-bounded and interpreted as cave features (white arrows). Regional drilling data from Tangguh indicate that wells intersecting these features commonly experience total downhole fluid losses. This isolated bright amplitudes/trough reflectivity are consistent with seismic signatures of sediment-filled caves, or speleosediments (Loucks & Ruppel 2000; Doherty & Meggs 1993; Riangguna et al., 2016). (Seismic data from BP 2026).

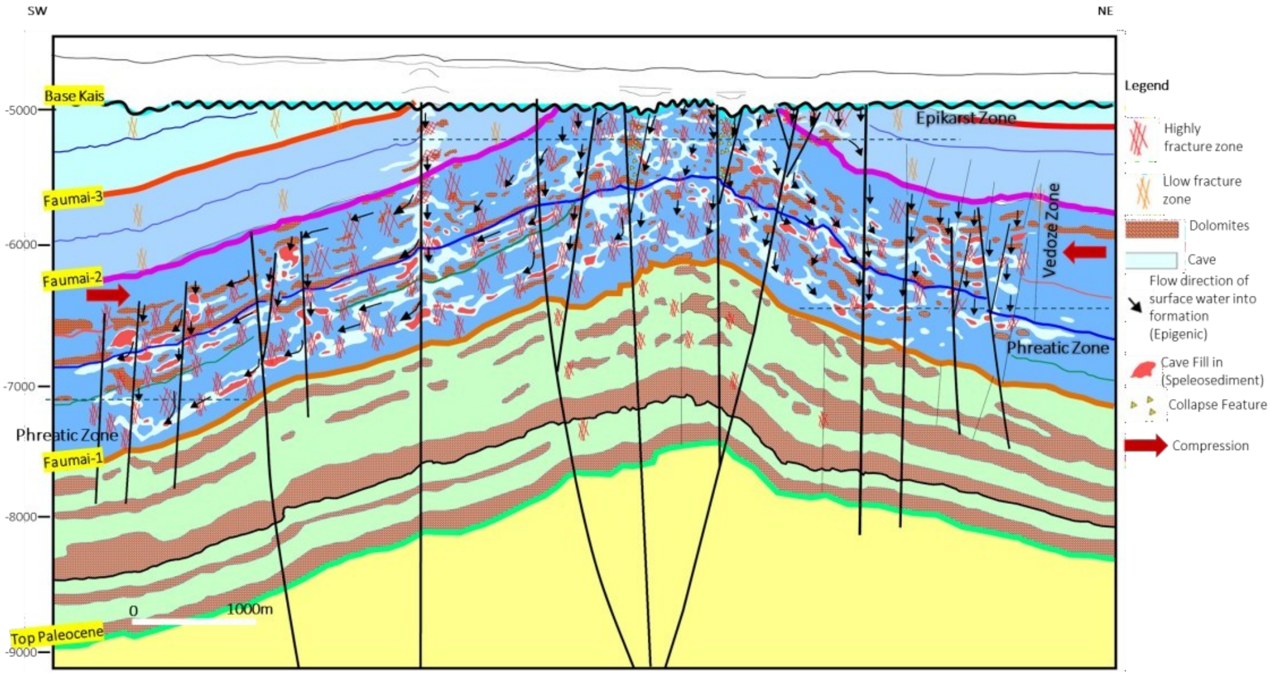

Figure 30. Karstification in Bird's Head began in the Late Oligocene, marked by development of the unconformity, and continued into the Pleistocene, when collapse features formed in both the subsurface and onshore. Tectonic activity created fracture networks that enabled vertical water flow through the epikarst and vadose zones and lateral flow through the phreatic zone, thereby promoting karst development. (Model by Nauw 2026).

CONCLUSION

The Faumai Formation comprises four depositional sequences (Faumai-1 to Faumai-4), with karstification most strongly developed in the Faumai-2 interval. Integrated well, seismic, and outcrop data indicate that Late Oligocene tectonic uplift exposed the formation to subaerial conditions and enabled meteoric water infiltration through anticlines, faults, and fracture vertically and laterally. Pleistocene tectonic reactivation subsequently generated collapse features that affected both the subsurface and surface expressions of the karst system. Karst development was further enhanced by favorable rock properties in Faumai-2, particularly grain-supported dolomitic textures with relatively low clay content compared to Faumai-1 which more fine grain, Faumai-3 and Faumai-4 are dominant by marly and coral fragment. Regionally, the most intense Eocene karstification is concentrated in location of Bird’s Head and Bintuni Basin, whereas southern areas such as Kokas and Fak-Fak show weaker development in Eocene carbonates. The karstification is developed in younger Miocene carbonate successions.

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DECLARATION

Author contribution

M. Nauw: conceptualization, methodology, investigation, data curation, formal analysis, software, visualization, writing original draft, writing review & editing. B. Sapiie., I. Gunawan., D. Nugroho: Supervision (co), visualization, methodology, validation.

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Competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

The use of AI or AI-assisted technologies

The authors used Deepseek Copilot to assist in reviewing wording and sentence structure. However, all content was critically reviewed and edited by the authors, who take full responsibility for the publication.

GLOSSARY OF TERMS AND SYMBOLS

Terms & Symbol	Definition	Unit
WOB	Weigh on bit	lbs/lbf
ROP	Rate of penetration	ft/hr
SPP	Standpipe pressure	psi
ECD	Equivalent circulating density	ppg
GR1CKX	Gamma ray	API
RPCEHX	Resistivity	Ohm
Losses	Mud Losses	bbl/hr
m	Meter	
MOK	Misool Onin Kumawa	
	Mud Losses	

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