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# SORONG FAULT TECTONISM AND DETACHMENT OF SALAWATI ISLAND: IMPLICATIONS FOR PETROLEUM GENERATION AND MIGRATION IN SALAWATI BASIN, BIRD'S HEAD OF PAPUA

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## ABSTRACT

Sorong Fault, bordering the Salawati Basin to the north and west, has strongly influencedthe geology and petroleum system of the Salawati Basin since mid-Pliocene times. The fault reversed the basin's polarity from the basin with the southern depocenter before the Pliocene to the basin with the present northern depocenter. The subsidence of the basin to the north has resulted in thegeneration of petroleum from main source rocks of Miocene Kais-Klasafet carbonates and shales.

As the Sorong Fault continued to deform the basin, Salawati Island, once attached to the mainland of the Bird's Head of Papua, detached. The island rotated counter-clockwise, opening the Sele Strait wide at the north end,close to the main trace of the Sorong Fault and narrow at the south, close to the pivot point of rotation. Following this rotation, Salawati Island translated southwestward, emplacing it into its present position.

Counter-clockwise rotation and southwestward translation of Salawati Island is considered to havedeformed surfaces within Kais, Klasafet and Lower Klasaman, resulting in anticlinorium belts forming regional noses, trending dominantly northwest-southeast. These regional noses have proven to be main pathways of migration in the Salawati Basin. Petroleum generated in the northwest-northern depocenter has migrated along the regional noses and away from the adjacent regional lows.

Reconstruction of the Salawati Island rotation and translation, relative to the optimum time of generation and migration, as well as formation of the regional noses, has revealed which areas in the Salawati Basin receive maximum charging of petroleum through effective migration. Integrated studies,comprising basin evolution, structure, carbonate sedimentology and petroleum geochemistry have reduced exploration risks related to migration and trapping of petroleum.

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## INTRODUCTION

Sorong Fault in Eastern Indonesia is a major left-lateral strike slip fault, with a total length of 1900 km, from Banggai area in East Sulawesi to northern Papua New Guinea. At present, the faulthas becomea border between the northern margin of the Australian Plate at the Bird's Head of Papua and the southern margin of the Philippine Sea Plate. Salawati Basin, located at the northwestern part of the Bird's Head, has been very significantlyshaped by the Sorong Fault. Basin evolution during the Neogene, the basin's structural styles, and generation-migration-preservation of petroleum are, among others, aspects affected by the Sorong Fault tectonism.

The paper discusses the controls of Sorong Fault tectonism for: (1) subsidence of the basin resulting in generation of petroleum, (2) opening of the Sele Strait and detachment of Salawati Island from its origin to its present position, and (3) the implications of this detachment on the presence of regional noses where migration of petroleum has taken place.

Considering basin dynamics, taking into account all implications of the Sorong tectonism to petroleum geology and petroleum system of the Salawati Basin, have decreased the risks in exploring this mature basin.

## METHODS

To address aspects that need to be known, a number of regional studies of the Salawati Basin were conducted, including: basin evolution, structural revisit, carbonate sedimentology, and petroleum geochemistry. Summaries of these studies were published in part by Satyana et al. (2000, 2008, 2009) and Satyana and Wahyudin (2000) for petroleum geochemistry; Satyana (2001) and Satyana and Setiawan (2001) for basin evolution; Satyana et al. (2002) for structural revisit, and Satyana (2003, 2007) for carbonate sedimentology.

Basin evolution study resulted in knowledge of basin dynamics of the Salawati Basin from its formation, evolution and development, up until its present configuration. The most important point of this study is the knowledge that the Salawati basin once reversed its polarity. The reversal of polarity was important for petroleum generation and migration. A structural revisit study analyzed all structural grains of Salawati Basin. The study confirmed that all structures of the Salawati Basin had resulted from Sorong Fault tectonism, and that Salawati Island once detached and moved to its present position from the mainland of the Bird's Head. Carbonate sedimentology evaluated development and microfacies of Kais carbonates as related to dynamics of the basin. Petroleum geochemistry study characterized all oil and gas accumulation in the basin, their sources and history of generation and migration. A number of wells, seismic lines, geochemical, and petrographic data were used for these studies.

The results of these studies were analysed,synthesized and integrated to address the goal of the paper, comprising: how Sorong Fault tectonism subsided the basin, detached Salawati Island and how the detachment of the island formed regional noses as the places for migration fairways.

## RESULTS & DISCUSSIONS

### Geologic Setting of Salawati Basin

Salawati Basin is an E - W trending asymmetric foreland basin located on the northern margin of the Indo-Australian Plate (*Figure 1*). The basin is presently bounded to the north and west by the deformed zone of the left-lateral Sorong Fault. The basin is terminated to the south and east by uplifted Miocene carbonates of the Misool - Onin Geanticline and the Ayamaru Platform, respectively. The Salawati Basin records stratigraphic and tectonic history from Paleozoic times to Recent (Satyana, 2001).

The oldest stratigraphic sequence of the Salawati Basin is the continental basement rocks of the Siluro-Devonian Kemum metamorphics and Carbo-Permian Aifam continental margin sediments (*Figure 2*). Overlying the basement are Mesozoic sediments (Tipuma and Kembelangan groups), which developed only in the southern part of the basin, due to either non-deposition or northern erosional uplift in the Late Cretaceous.

Tertiary sediments of the Salawati Basin begin with the Late Eocene to Early Oligocene transgressive carbonates of the Faumai Formation. Overlying the Faumai carbonates are the Late Oligocene shallow marine clastics of the Sirga Formation. Thick carbonates of the Miocene Kais Formation cover the Sirga clastics.

Kais carbonates developed in various environments from lagoonal, bank, to deeper water facies, resulting in various types of carbonate sediments from low-energy organic-rich carbonate muds, through moderate-high energy reefal carbonates, to fine crystalline carbonates. Transgressive carbonates of the Kais Formation grew in stages to accommodate changes in sea level fluctuations. Three stages (I-III) are recognized. Further information on the sedimentology and evolution of the Kais carbonates can be found in Satyana (2003). Contemporaneous with the Kais carbonate deposition, Miocene lagoonal Klasafet fine calcareous clastics were deposited. The Pliocene Klasaman clastics ended the Tertiary stratigraphic sequences. Molassic deposits of the Sele conglomerates were deposited in Pleistocene time as sediments eroded from the deformed zone of the Sorong Fault.

The main structural framework of the Salawati Basin is the Sorong Fault, which bounds the basin to the north. This is a major left - lateral fault which has been active since the upper Early Pliocene (mid-Pliocene). Present structural style of the basin is dominated by NNE - SSW normal faults formed as a conjugate of the Sorong Fault. The Sorong Fault has also developed en echelon folds and synthetic left-lateral faults with normal slip (such as the “Line Six” and Salawati faults) in Salawati Island. This movement has reactivated older normal faults (started as rifts in the Late Paleozoic - Mesozoic time), such as the Cendrawasih Fault, to become antithetic right-lateral faults. Discussion on evolution and structural styles of the deformation of Salawati Basin is provided by Satyana et al. (2002).

### Sorong Fault Tectonism

A great left-lateral strike-slip fault system trending E-W transects the northern coast of Papua and

Papua New Guinea (*Figure 3*). This fault system is connected to the similar fault system in the vicinity of Banggai-Sula in Eastern Sulawesi,resulting in a total length of 1900 kms (Hutchison, 1989). One-thousand kilometers of the fault zone is submarine from west of Salawati to narrow Sula Ridge. The remaining 900 kms is located in Papua and Papua New Guinea. In the vicinity of the Bird's Head, this fault was called the Sorong Fault system by Visser and Hermes (1962).

This fault is part of a large global transcurrent zone that separates the westward moving Pacific oceanic (Caroline and Philippine Sea) plate from the relatively stable Australian continental plate (Froidevaux, 1977). The collision of the Ontong-Java Plateau with the Caroline Plate to the north of eastern New Guinea might have triggered this transcurrent fault in its eastern sector. At its western sector, around the Bird's Head, this fault system was triggered by the clockwise rotation of the Philippine Sea plate since 5 Ma (basal Pliocene) (Packham, 1996).

Visser and Hermes (1962) mapped the Sorong Fault zone striking approximately E-W through Sorong township. The zone is characterized by a chaotic jumble of blocks of many kinds of rock units. It consists of chunks, lenses, and slabs, of all sizes up to 10 km, of varied mafic and ultramafic rocks, Jurassic to Miocene deep- and shallow-water sedimentary rocks, and some acid to intermediate rocks and metamorphic rocks, set in an extremely sheared matrix. Large-scale faulting has obviously occurred, giving rise to what can perhaps best be described as a huge tectonic breccia. These breccias have been united under the name Jefman breccia. Left-lateral strike-slip motion is concluded from the focal solutions of earthquakes occurring along the Sorong Fault system (Hutchison, 1989). The width of the fault zone varies between 4 and 10 kms; locally, however, the fault system may cover a much wider area. Froidevaux (1977) put the 8-13 km wide fault zone in the northern Salawati area, where a mixture of rocks of all kinds has been recognized in a disorderly assemblage.

A number of estimates have been made as to when the Sorong Fault zone became an active feature. These include the Oligocene (Pigott et al., 1982), Early Miocene (Hermes, 1968, 1974; Tjia, 1973; Hall, 1997), Early-Mid Miocene (Hamilton, 1979), post-Mid Miocene (Visser and Hermes, 1962), Late Miocene (Charlton, 1996), Early Pliocene (Dow and Sukamto, 1984), and mid-Pliocene (Froidevaux, 1977). We suggest Mio-Pliocene time as the beginning of the regional Sorong Fault and the fault started to strongly control the Salawati Basin, since mid-Pliocene.

Constraints to the age of Sorong Fault initiation can be provided by Neogene stratigraphic and structural data of the Salawati Basin. This probably suggests that the basin was formed largely as a result of transtension on the Sorong system, resulting in elliptical geometry. As most of the Tertiary stratigraphic thickness that gives rise to elliptical shape is accounted for by the Pliocene-Quaternary clastic sequences, and additionally as the basin in particular shows little evidence of fault-related deformation prior to the Early Pliocene, it is likely that movement on the Sorong Fault zone occurred primarily during the Pliocene and Quaternary periods. The absence of significant pre-Pliocene faulting, together with the largely non-clastic nature of the Miocene basin fill, suggests that the Miocene Kais carbonate pre-dated (and is therefore genetically unrelated to) the development of the Sorong Fault system.

**Polarity Reversal and Subsidence of the Salawati Basin**

Basin polarity shows geometric configuration of depocenter (downdip) and platform (updip) of the sedimentary basin. The basin depocenter is a locus of sedimentary deposition, whereas the basin platform is a locus of sedimentary provenance. In petroleum system consideration, a depocenter mostly acts as a mature kitchen where hydrocarbons are generated. The hydrocarbons migrate updip from basin depocenter to basin platform.

Salawati Basin is a poly-history basin with various polaritiesthroughout its history. The location of the basin depocenter and platform has rotated to accommodate changes in basement configuration, due to plate readjustment. Reversal of basin polarity marks the final compensation of the basin to basement readjustment. Sorong tectonism, which has been triggered by plate readjustment around the northern Papua and SW Pacific Ocean, is responsible for the rotation and reversal of the Salawati Basin polarity.

Present stratigraphic setting of the Salawati Basin shows that the basin records the stratigraphic succession from Paleozoic to Recent times. Regional seismic data show that all stratigraphic sequences before the mid-Klasaman time (around mid-Pliocene time) indicate a south- and southeastward thickening. This reveals the presence

of southern depocenter until the mid-Pliocene time. This condition had been since Paleozoic time.Schematic sections showing the evolution of the Salawati Basin are displayed at *Figure 4*.
Pre-Tertiary evaluation shows that the Mesozoic formations are absent in northern Salawati Basin and start to thicken southward from the line to the south of present Salawati Island. By Late Cretaceous times, the proto-Salawati Basin had been situated at its present position and converged with the Pacific oceanic plate which was actively spreading to the south. The Pacific Plate subducted beneath the Kemum-Aifam basement. The northern margin of the proto-Salawati Basin was uplifted and became the provenance for Paleogene sediments. Late Eocene to Early Oligocene carbonates of the Faumai Formation onlappedin the vicinity of central Salawati Island and thickened to the south. The Late Oligocene Sirga clastic formation shows a similar northern onlapping and southward thickening. All of these sequences indicate northern non-deposition and southern depocenter.

The condition of the southern basin depocenter/ southern open sea and northern basin platform/ northern landmass was still preserved when Miocene Kais carbonates were deposited (Satyana, 2003). The carbonates were formed by sea transgressing northward. An extensive Walio carbonate bank developed in the southern area at a zone of free clastic input. A lagoonal facies developed in between the carbonate bank and basement high to the north. Marly carbonates were deposited within the lagoon (such as those found in Matoa field). Shoal reefal carbonates also grew in various parts of the lagoon, some backreefs within the lagoon grew as 'lagoonal' pinnacle reefs (Kasim complex).

At the end of Miocene time, lagoonal setting of the Salawati Basin was still preserved. Walio carbonate bank to the south and basement high with carbonate cover to the north became the barriers. However, the open sea had actually been rotated clockwise from the south to the west and the sea transgressed eastward. This was contemporaneous with the downwarping of the lagoon area.

The southern depocenter began to cease due to initial uplifting. The northern basement high where most Paleogene and Miocene sediments onlapped started to subside isostatically. Textularia bioclastics (the uppermost Klasafet Formation), Klaili reefs, and Lower Klasaman Formation were deposited within this period. Thickness of the sediments is relatively uniform across the basin.

This condition can be connected to regional plate movement around western Papua occurring between the Miocene and the basal Pliocene and was associated with the Neogene Melanesian orogeny which resulted from the oblique convergence of the Australian and Philippine Sea (and Caroline) plates. Isostatic compensation due to this crustal readjustment has been taken up by the Salawati Basin in the way of southern uplift and northern subsidence.

By the time of the late Pliocene (upper early Pliocene), at 4.2 Ma, the Sorong Fault commenced controlling the Salawati Basin. The basin underwent significant tectonic change. The Salawati Basin reversed its polarity, shifted its depocenter (which had previously been to the south, since the Paleozoic/Mesozoic) to the north-northwest. The Sorong Fault uplifted the northeastern corner of the basin (Kemum High) and became the source of Upper Klasaman sediments. The basin to the north and west of the present Salawati Island subsided due to loading resulting from multiple thrust sheets within Upper Klasaman sediments. The basin was terminated to the south and east by uplifted masses of Misool-Onin Genticline and Ayamaru Platforms, respectively. Present structural configuration of the basin formed in this period and developed either as compensating structures due to subsidence or structures associated with the Sorong Fault tectonism (synthetic, en echelon, antithetic structures). Shale diapirs developed in northern areas where rapid deposition of the Upper Klasaman sediments took place (Satyana and Setiawan, 2001).

Sorong tectonism attained its peak activity during the Pleistocene. The Salawati Basin gained its present asymmetric geometry at this time. The new northern depocenter continued to subside due to loading by multiple thrust sheets within the Klasaman Formation. Extensional structures continued to develop as the basin subsided. The structures were mainly formed as compensating structures to the subsidence, as shown by their down to north-northwest blocks. The uplifted masses of the northern and northeastern borders of the Salawati Basin have become the provenances of the Sele conglomeratic sediments, deposited as molassic fanglomerates frontal to the uplifted area.

**Reversal of the Basin and Generation-Migration of Petroleum**

2D basin modeling showing the generation and migration of petroleum is displayed in *Figure 5*.

Miocene Klasafet/Kais shales and carbonates are the main source rocks of the Salawati Basin. All existing hydrocarbon accumulation within the basin is sourced by these rocks (Satyana et al., 2000). Klasafet and Kais source rocks were deposited as lagoonal sediments at the northern basin platform in the Miocene time when the basin depocenter was to the south. When the polarity reversal of the Salawati Basin took place, the platform to the northsubsided. The Klasafet and Kais source rocks were subsided and deeply buried by Upper Klasaman sediments to attain such a depth as exhibited by oil windows. Hydrocarbons were generated and started to migrate updip. Viable traps located either frontal to the kitchen or far updip from the kitchen trapped the hydrocarbons.

The petroleum generation and migration history from the defined source beds was simulated using a 2-D thermal modeling program. The cross section running perpendicular to the basin outline was selected to perform the modeling after 5.20 Ma (the Pliocene - Recent time). The modeling showed that, in the deepest part of the basin, oil generation and expulsion started between 4.30 Ma (early Pliocene time) and 3.40 Ma (middle Pliocene time) when the basin started to tilt northward, reversing its polarity.

The reversal of the Salawati Basin polarity has developed compensating normal faults which have partly acted as conduits for hydrocarbon migration. Structural studies show that the Salawati Basin is intensely faulted. Almost all of the oil fields within the Salawati Basin are connected with the downdip kitchen by normal faults, suggesting that faults and fractures in the Salawati Basin are the avenues for secondary hydrocarbon migration. These faults generally trend parallel with the migration updip through structural contours. In this matter, the faults have enhanced the migration flows. Conversely, faults trending perpendicular to the orthocontours will tend to block hydrocarbon migration.

**Detachment of the Salawati Island**

The concept of Salawati Island detachment (separation/drifting) from the mainland of the Bird's Head by means of tectonic rotation and translationwas firstly discussed by Froidevaux (1977). This idea has never received proper attention by later workers of the basin. However, we indicated that the distribution of oil accumulation and the presence of subtle parallel belts of Kais/Klasafet anticlinorium in the Salawati Basin (will be discussed later) can be well explained by applying the idea of Salawati Island detachment. The following discussion will explain pieces of evidence, mechanisms and effects of the detachment of Salawati Island to structural configuration of the basin and its petroleum system significances.

Radar photo mosaics and a DEM (digital elevation model) map (*Figure 6*) show the true cartographic pattern of the Salawati Island and the mainland of the Bird's Head. At the first glance, it can be seen that the eastern coastal line of Salawati Island will fit perfectly with the western coastal line of the Bird's Head area if we put back both coastal lines. Even Warir Island left a bay to the SW of Dore Hum ridge, with the bay shape resembling the eastern coastal line of Warir Island. The mainland rivers have filled up the eastern part of the bay with Pleistocene alluvial deposits. The outline of the coastal alluvial plain corresponds to the shape of the drifted island. Warir Island should have positioned this bay before separation.

Northern uplifted areas, both in Salawati Island (Waibu ridge) and the Bird's Head (Dore Hum ridge) are geologically similar. Both are made of oceanic volcanics and tectonic breccia of Sorong Fault. The two ridges are separated presently by the northern Sele Strait. There is no submarine ridge reported underlying the Sele Strait. Islets to the west of Dore Hum Ridge (Dom, Jefman) are made of tectonic breccia slivered during the Sorong Fault movement.

The Waibu and Dore Hum ridges should form a continuing ridge before separation. Some granite outcrops at the northeast Salawati Island match similar exposures near Sorong town. The two granite exposures are Triassic in age and formed a unity before separation. Both the main part of Salawati Island and the Bird's Head mainland are surfaced by upper Klasaman sediments as radar mosaics show similar surface pattern and. This indicates that Salawati Island and the Bird's Head were in one depositional pattern before separation.

Froidevaux (1977) used a widespread basaltic intrusion in the weakness zone of the Sorong Fault at the northern Sele Strait and associated with antithetic dextral fault along the Sele Strait as the mechanism triggering Salawati Island separation (*Figure 7*). The intrusion played a role like an axe which has a wedging effect. However, the presence of this intrusive body is questionable and has never been confirmed. Antithetic strike-slip fault is misinterpreted, since in the strain ellipsoid of left-

lateral fault, and the principal displacement zone is aligned with the Sorong Fault, the strike-slip in Sele Strait should be synthetic (Satyana et al., 2002).
We suggest a model that posts Salawati Island starting to separate from the Bird's Head mainland when the Banggai-Sula mass located to the north of Salawati Island was dragged west-southwestwards by the Sorong Fault. It is considered by some workers (like Charlton, 1996) that the Banggai-Sula mass and the Salawati Island once formed one entity before separation. This detachment and movement affected the last stages of Kais carbonate development and mainly affected the formation of regional noses critical for petroleum migration.

We propose a model (*Figures 8-10*) showing when the northern margin (Banggai-Sula?) separated from the Bird's Head, the rest of the entity would compensate by moving north-northeastward (counter-clockwise rotation). As the Sorong Fault continued to push away the Banggai-Sula?, Salawati Island also continued to rotate and started to open up Sele Strait. Warir Island was attached to Salawati Island and drifted away as one entity from the mainland of the Bird's Head. In this model, the pivot point of the rotation was to the south of Salawati Island.

Salawati Island rotated counter-clockwise, encircling the southern pivot point presently located around the Kasim field (*Figure 9*). As a consequence, the northern Sele Strait is much wider than the southern one. Froidevaux (1977) put an angle of rotation as 13° (based on strain ellipsoid study). A translation movement succeeded the rotation. A rotation alone can account for a large part of the opening of the Sele Strait, but it is not sufficient to explain of how Salawati Island became situated at its present position. A comparison on the position of the island after its 13°counter-clockwise rotation with its present location indicates a subsequent southwestwards translation of the island as far as 17.5 kms (*Figure 10*). This southwestwards translation is also actually a counter-clockwise rotation.

The chronology of the Salawati Island rotation and translation can be anticipated from the thicknesses of sediments deposited before and after Salawati detachment. The separation of Salawati Island opened the Sele Strait, which would become a local basin where sediments were deposited. Sediments deposited contemporaneously with the Sele Strait opening would show the increase of thickness across the strait. Seismic sections showed that a distinct increase of thickness occurs for sediments deposited later than intra-Klasaman marker or after 3.5 Ma (mid-Pliocene). This suggests that separation and translation of the Salawati Island occurred in Late Pliocene to Pleistocene time.

## Implications of the Salawati Island Detachment to Petroleum Generation and Migration

Structural morphology strongly controls migration pathways. Fluid will concentrate in structural noses, at the areas of higher buoyancy and lower pressure. The presence of the regional noses will counteract the dispersal of primary and secondary oil migration along the flanks of basins (Hindle, 1997).

The translation movement of Salawati Island resulted in tangential force propagating parallel with the direction of translation. Compressive regional stress trending SW-NE was formed. This force was taken by sedimentary strata deposited during pre-translation (mainly upper Kais, Klasafet and Lower Klasaman formations) in forming anticlinorium belts trending generally NW-SE, perpendicular to the direction of the translation (*Figure 10*). These compressive belts form as regional noses in the Salawati Basin. The belts are subtle and can only be resolved by simplifying the Kais regional map through enlarging the contour interval, removing main faults, and restoring the contour to the condition of pre-deformation. Thermal modeling showed that at about 3.0 Ma (Late Pliocene time) the oils generated had reached the southern end of the Matoa-Walio nose. The reconstruction shows (*Figures 10-11*) that the Matoa-Walio nose was perfectly perpendicular and plunging into the long axis of the kitchen at 3.0 Ma, causing excellent charging from the kitchen to and along the nose, and it was in this time that optimum charging took place.

There are seven parallel noses extending from updip areas of the Salawati Basin at the south to the north depocenter, plunging into the kitchen. From the southwest to the northeast, the regional noses are called: the TBA-TBC, Koi, South Salawati, Matoa-Walio, Moi, Klamono and Arar (*Figure 12*). The South Salawati and Moi noses are minor noses and considered as flanking splays of the larger Matoa-Walio nose. The Klamono and Arar noses are considered to have been formed contemporaneously with the early rotation of Salawati Island, causing the two noses to have different trends (east-west).Hydrocarbon migration pathways in the Salawati Basin have been focused along the seven

regional noses and away from the flanking structural lows (Satyana et al., 2000).
This results in unique migration compartments/fairways of the Salawati Basin. Interesting fact about these migration focused-noses are that all existing oil and gas fields within the Salawati Basin are located within these regional noses. Almost 70 % of the basin's hydrocarbon reserves to date are located within the Matoa-Walio regional nose. The Matoa-Walio nose is the first and largest nose formed when Salawati Island firstly translated. The areas flanking the regional noses are regional low/synclinal areas, most dry wells of the Salawati Basin located in these regional low areas. The migration pathway will be away from structurally low areas and such areas will not receive petroleum.Currently, the kitchen of the Salawati Basin is still at the northwestern depocenter. Petroleum from younger sources also starts to generate petroleum, migrating updip to the south, southeast, east and northeast. Presence of faults will enhance the migration (*Figure 13*).

## CONCLUSIONS

Sorong Fault tectonism has strongly controlled the geology of the Salawati Basin since mid-Pliocene times by reversing the basin polarity from southern depocenter to northern depocenter, generating petroleum from Kais/Klasafet source rocks, separatingSalawati Island from the mainland of the Bird's Head of Papua through rotation and translation, opening the Sele Strait, and forming structures related to wrench tectonism.

Each episode of the Sorong tectonism has implications for the petroleum system of the Salawati Basin. The basin polarity reversal has subsided the main sources of Klasafet/Kais/Lower Klasaman shales and carbonates to a depth of a hydrocarbon window. Rotation and translation of Salawati Island formed belts of regional noses at Kais/Klasafet/Lower Klasaman levels to which hydrocarbon migration has taken place. This leads to identification of areas with an active petroleum charge system. Wrench tectonism developed normal faults, which partly act as migration conduits and structural traps at Kais and Intra-Klasaman levels.

Integrated studies of the Salawati Basin include factors such as: basin evolution, structure, carbonate sedimentology and petroleum geochemistry, all of which have opened new opportunities and reduced risks of exploring a mature basin.

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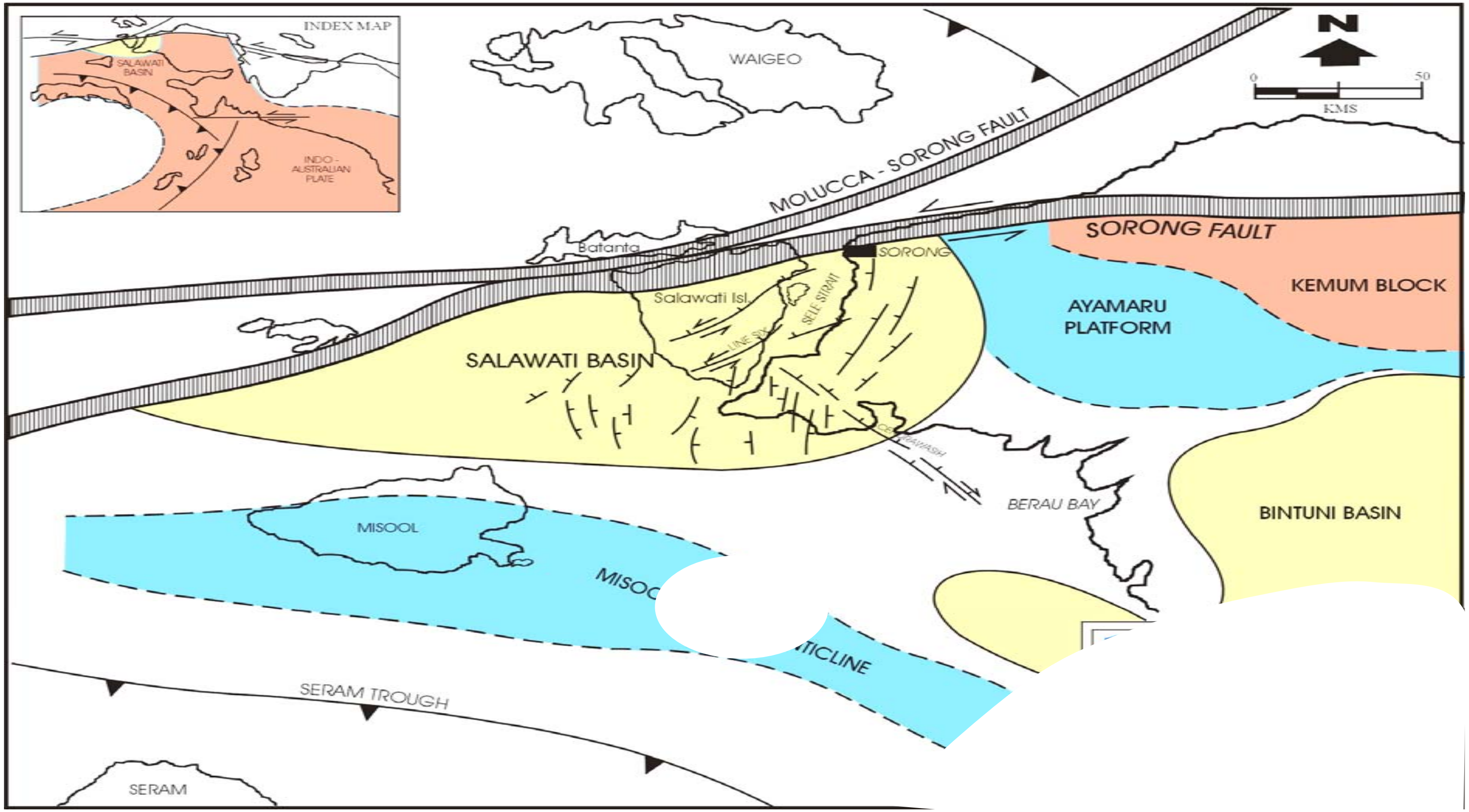


**Figure 1 -** Geologic setting of the Salawati Basin showing elements that border the basin. The basin is located frontal to the Sorong Fault northward. The fault strongly controlsthe geology of the basin. Structural grains related to the Sorong Fault tectonism are displayed. The index map shows that the Salawati Basin is situated at the northern margin of the Indo-Australian plate.

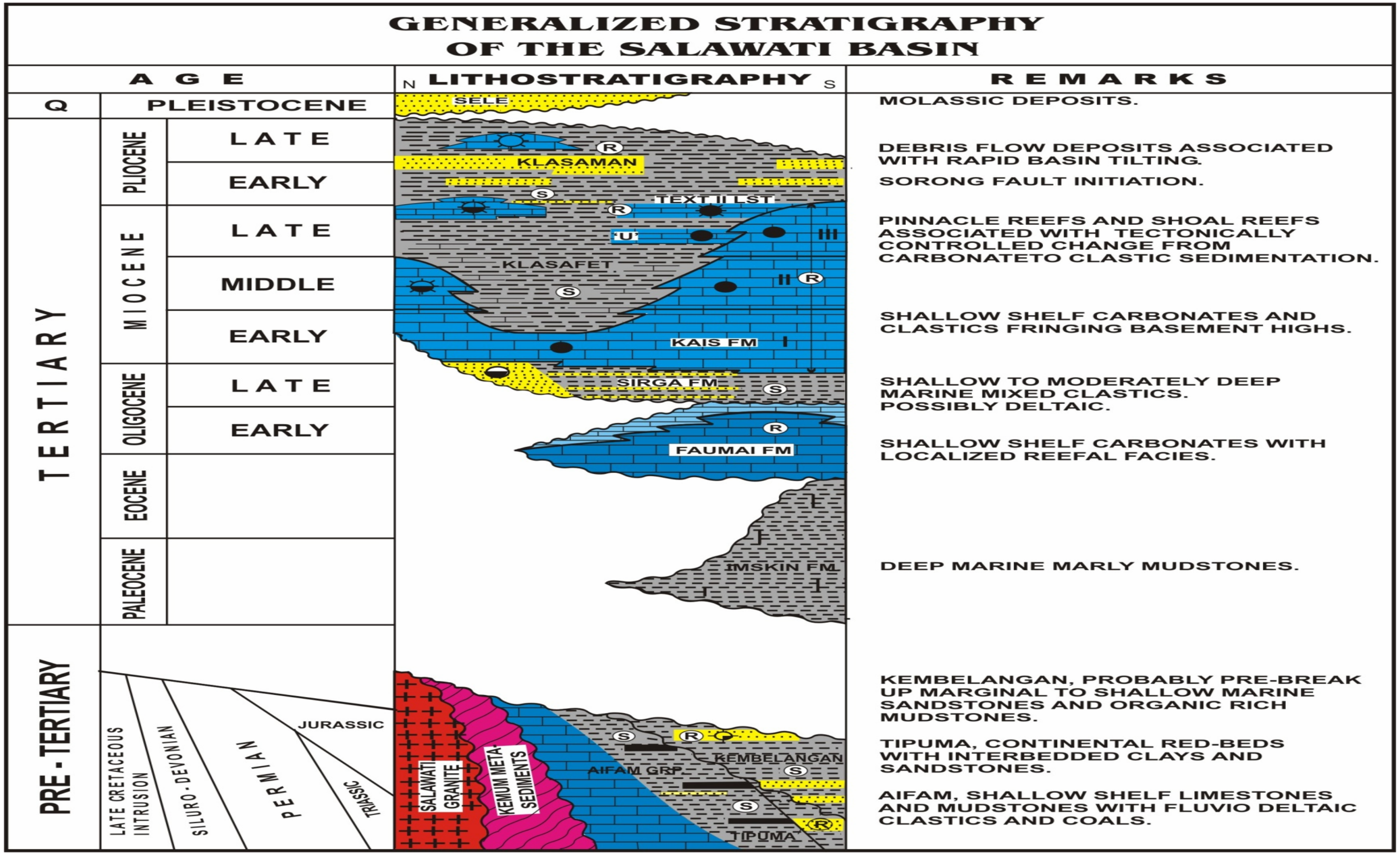


**Figure 2 -** Generalized stratigraphy of the Salawati Basin. Pre-Tertiary sections principally developed at the southern part of the basin. Due to the scarcity of wells penetrating the sections, the nature of the Salawati's pre-Tertiary stratigraphy is not well-known. Tertiary stratigraphy is dominated by carbonates developed in various phases. Kais carbonates are the main reservoirs. Klasafet shales and marls deposited in lagoonal setting are the main sources. The figure shows that the initiation of the Sorong Fault strongly controlling the Salawati Basin was during the early Pliocene.

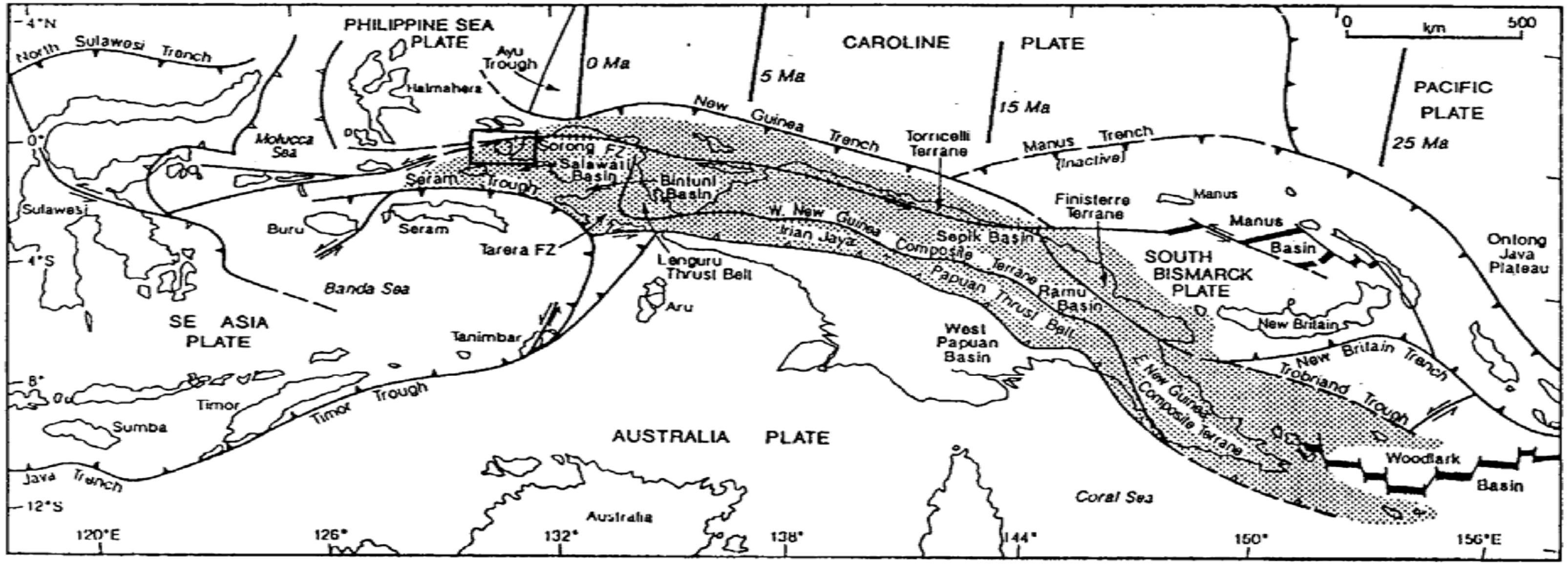


**Figure 3 -** Regional setting of Eastern Indonesia to Papua New Guinea, showing the presence of the Sorong Fault to the north of Papua New Guinea, Papua and continuing to the east of Sulawesi, making a total length of the fault zone as long as 1900 km. The Sorong Fault has left-lateral strike-slip, accommodating inter-plate deformation between the Australian Plate with the Philippine- and Carolina Sea plates. The box marks the location of the Salawati Basin, located frontal to the Sorong Fault (Packham, 1996).

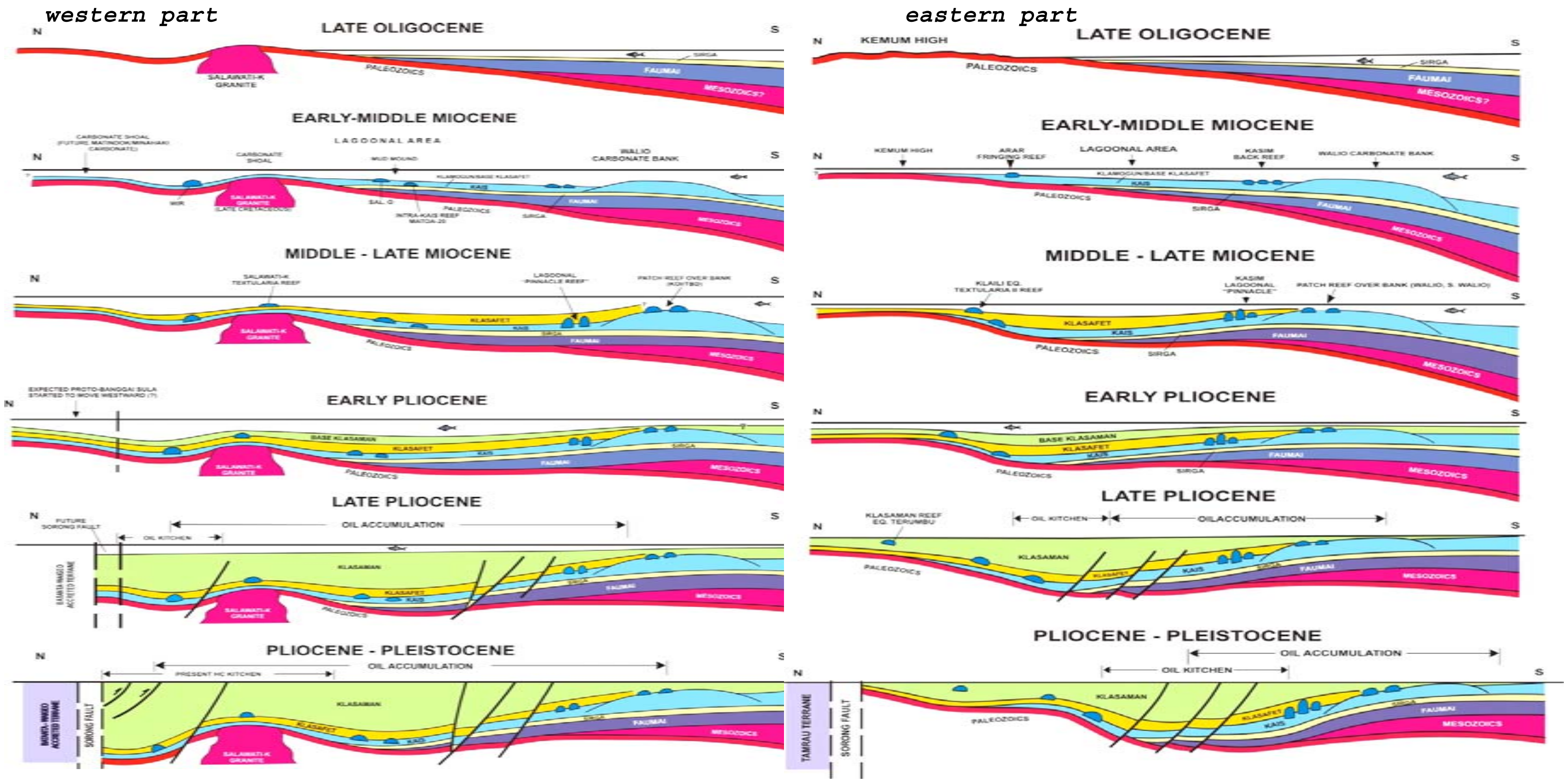


**Figure 4 -** Schematic section showing the evolution of the Salawati Basin for its western and eastern parts.Significant pattern is that the basin had southern depocenter from Paleozoic to Late Miocene, as shown by thickening of all sections of Late Miocene and older to the south. In early Pliocene, as the Sorong Fault initiated its control of the basin, the depocenter started to reverse to the north. In Plio-Pleistocene times the basin had its present configuration with a northern depocenter and became an active kitchen. Petroleum has been generated from the kitchen since the mid-Pliocene and migrated updip southward, charging many reefs and faulted carbonates of Kais Formation. The eastern part of the basin differed slightly in its evolution since the late Pliocene. The northern section of the eastern part was uplifted by the Sorong tectonism, whereas its western counterpart subsided (Satyana, 2001).

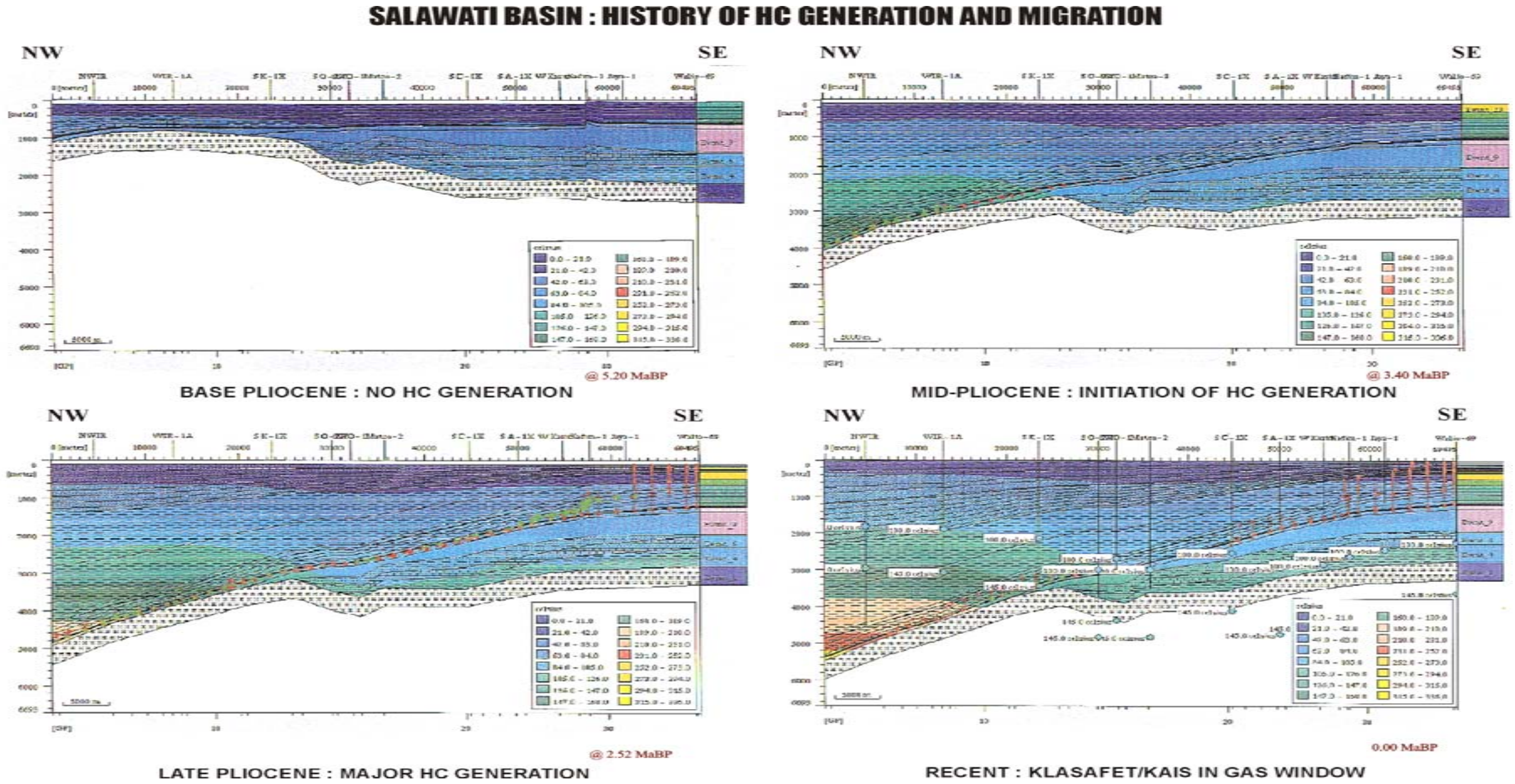


**Figure 5 -** 2D-geochemical basin modeling showing the evolution of the basin and the generation-migration of petroleum. In the base of the Pliocene, the basin still had a southern depocenter. In mid-Pliocene the basin had reversed its polarity to have a northern depocenter, becoming the kitchen. Petroleum was initially generated. in Late Pliocene, much of presently accumulated petroleum was generated and migrated updip to the south. Presently, the main source rocks of Klasafet shales are in a gas to dry gas window, whereas the Lower Klasaman shales are within the oil window. Solid black line is at the top of the oil window (Satyana et al., 2000).

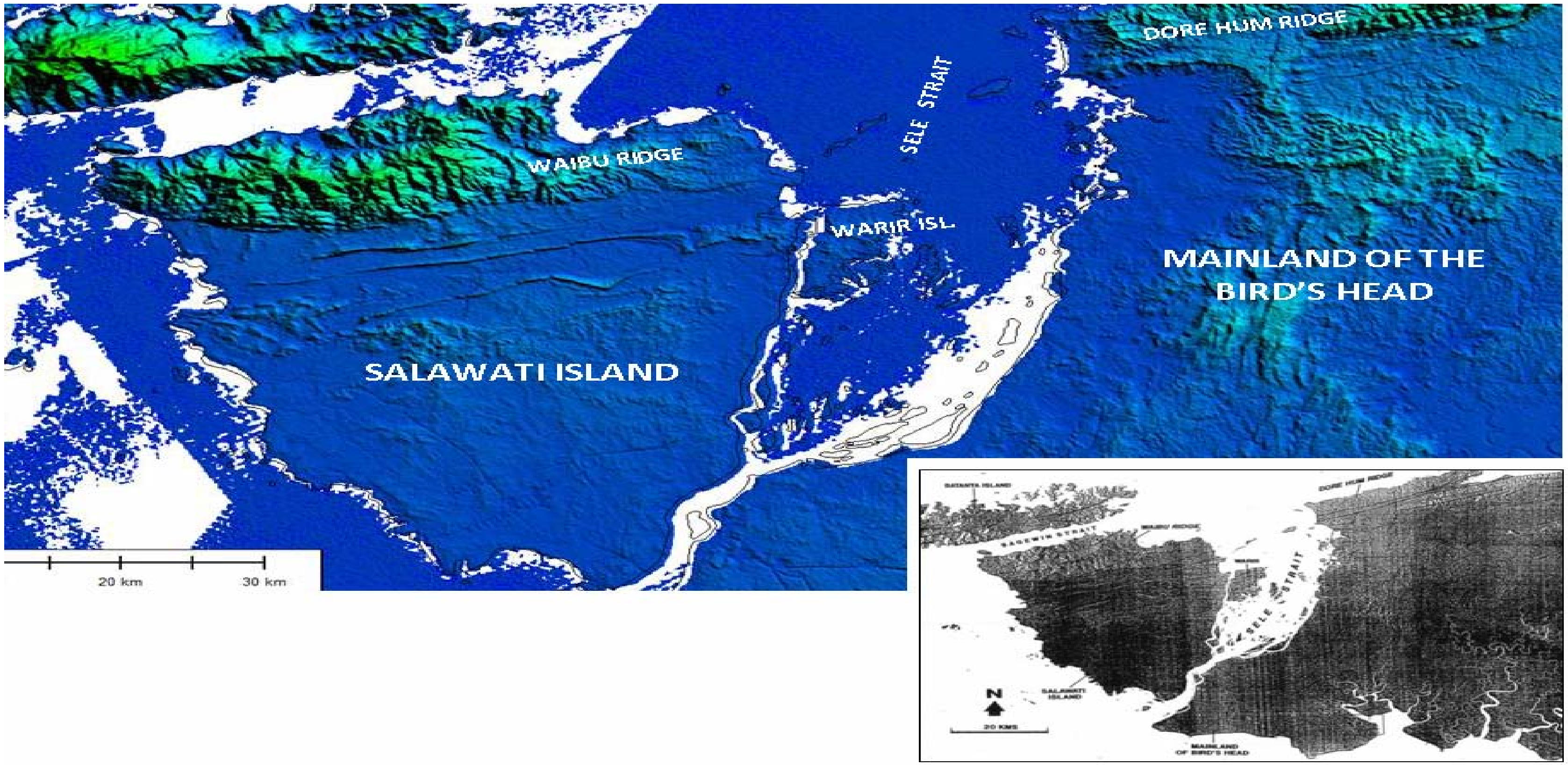


**Figure 6 -** DEM (digital elevation model) map and radar photo mosaic of Salawati Island, Sele Strait and mainland of the Bird's Head of Papua. The eastern coastal line of Salawati Island, including Warir Islet matches the western coastal line of the mainland of the Bird's Head if they are united. The Dore Hum ridge continues into the Waibu ridge. The coastal line, with numerous small bays to the southwest of Dore Hum Ridge, is considered a remnant of Warir Island before separation. Salawati Island seems to shift southwestward after separation. Geometric, geomorphologic, geological and geophysical pieces of evidence strongly suggest that Salawati Island was attached to the mainland of the Bird's Head.

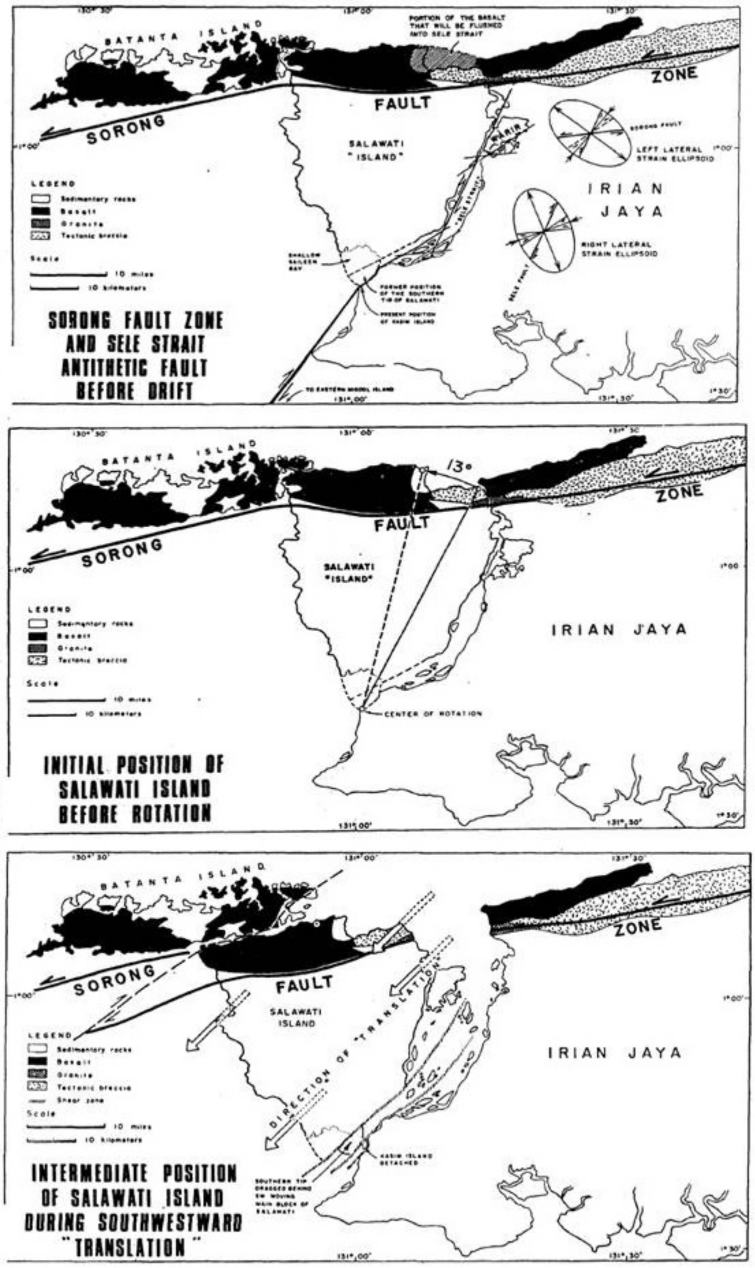


**Figure 7 -** Rotation and translation of Salawati Island from the mainland of the Bird's Head of Papua, according to the concept of Froidevaux (1977).SalawatiIsland was attached to the Papua mainlandduring the time of Miocene-lower Pliocene reefdevelopment, and it has drifted away in middlePliocene to Pleistocene time, opening the Sele Straitrift zone. The island moved 17.5 km southwestward after an initial counterclockwiserotation of 13°. The motion was triggered during a widespreadmagmatic intrusion of the Sorong fault zone,when the basalt infiltrated an antithetic right-lateral fault systemlocated in the area of the present Sele Strait.Drifting took place along three parallel majorleft-lateral strike-slip faults; these can be traced fromthe Sele Strait to the southern part of Salawati Island. Antithetic dextral of Sele Strait Fault was misinterpreted, Satyana et al. (2002) suggesting it was a synthetic sinistral fault.

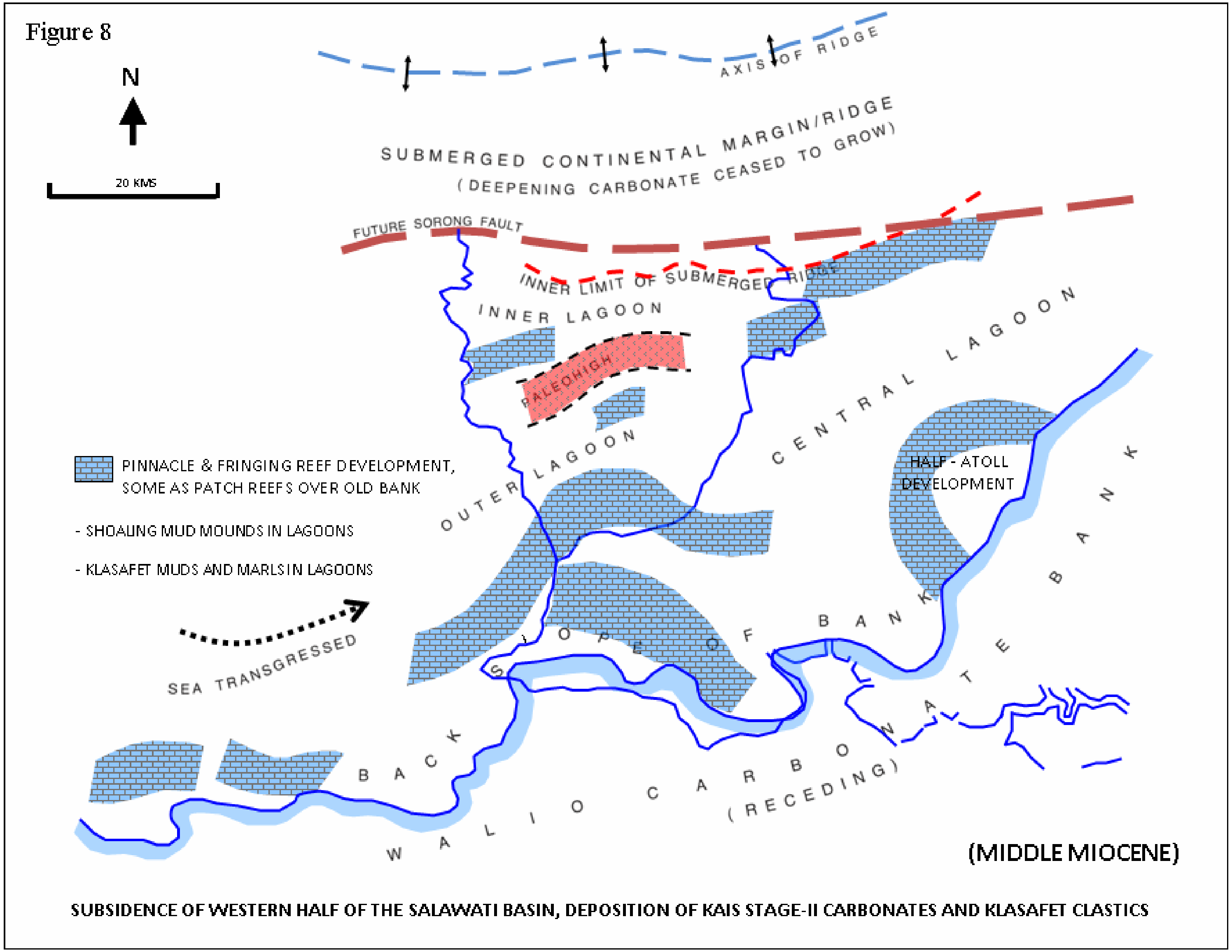


**Figure 8 -** Middle Miocene Salawati reconstruction. Salawati Island was attached to the mainland of the Bird's Head. The northern continental margin formed microcontinents attached to the Bird's Head of Papua, separated in later times. Kais carbonates were deposited in various environments.

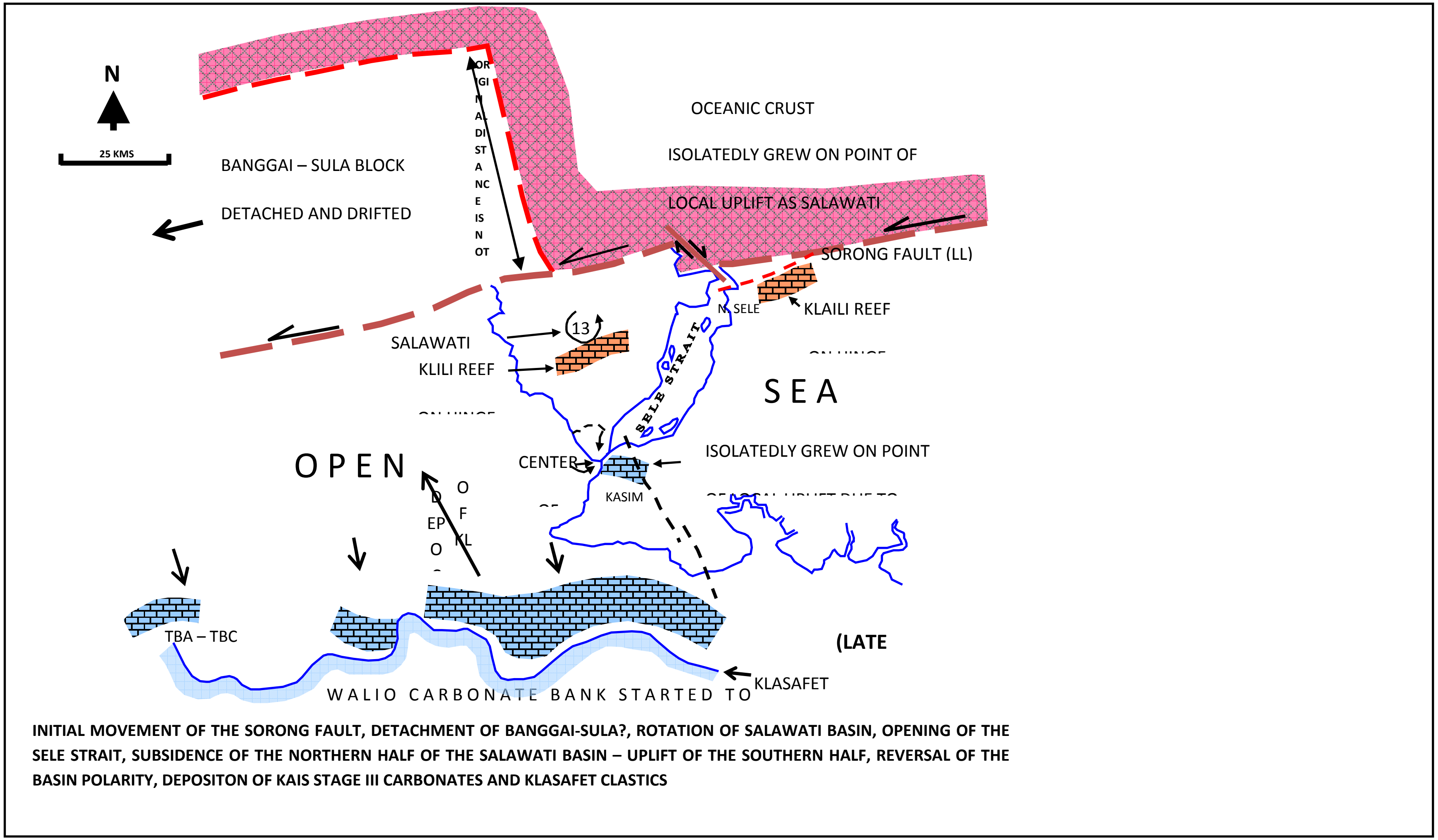


**Figure 9 -** Late Miocene Salawati reconstruction. Sorong Fault transected the northern margin of the Bird's Head. The microcontinents attached to the Bird's Head (Banggai Sula mass?) were pushed away westward. This caused Salawati Island to detach/ separate from the mainland of the Bird's Head in a counter-clockwise rotation. Ends of detachment, forming a rotational pivot point at the Kasim reef complex and area of Warir Island at the location of North Sele reef, resulted in the highest relief of reefs in the basin. Kais carbonates grew in this area at the compressive substrate due to detachment and rotation.

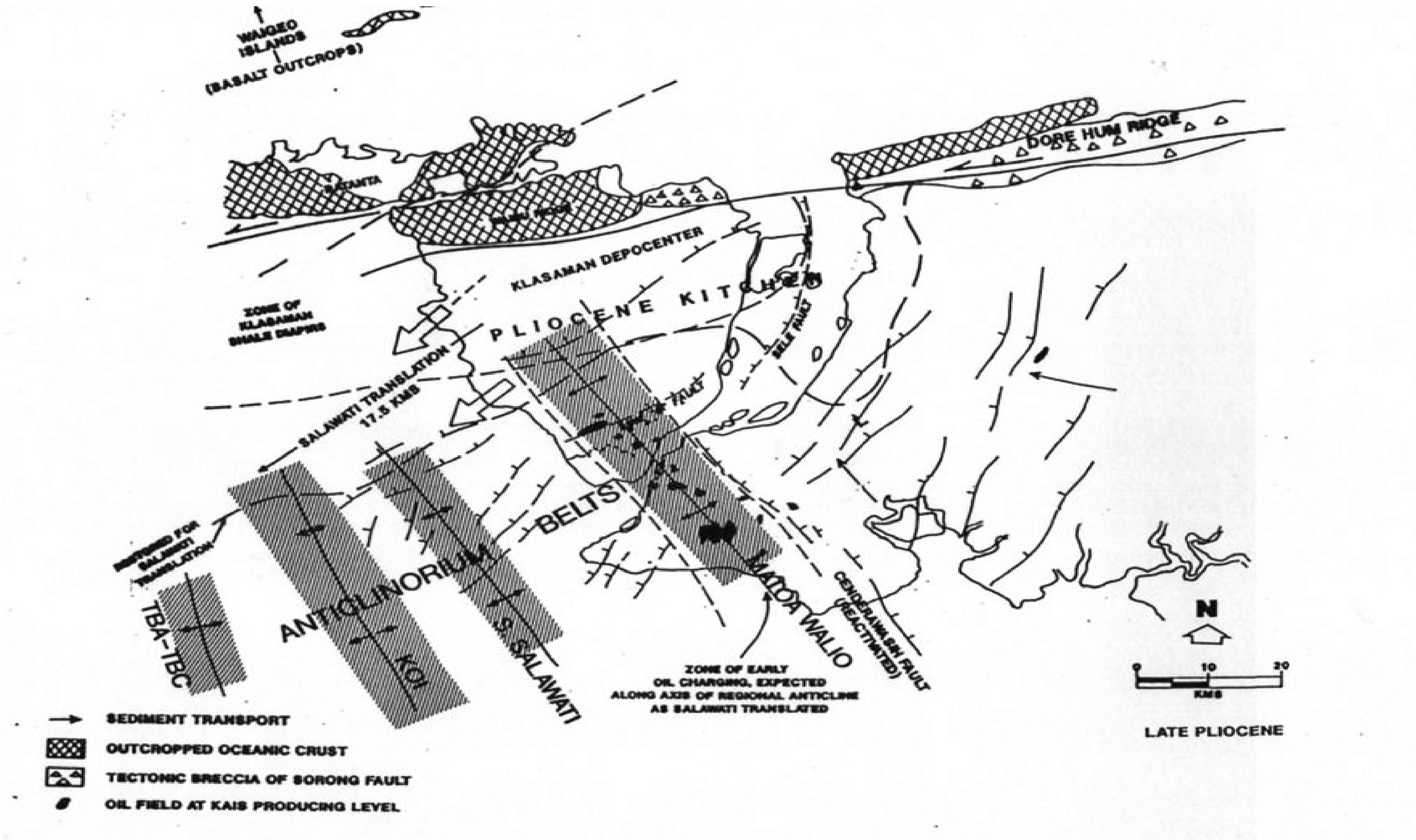


**Figure 10 -** Late Pliocene Salawati reconstruction. Salawati Island translated southwestward. The translation movement resulted in compressive anticlinorium belts (regional noses) trending NW-SE. Petroleum was generated within the subsiding kitchen and migrated along regional noses. Note the present oil fields of the Salawati Basin once formed one lineament along the nose, causing very effective petroleum charging. This nose has accommodated70 % of migrated petroleum in the basin.

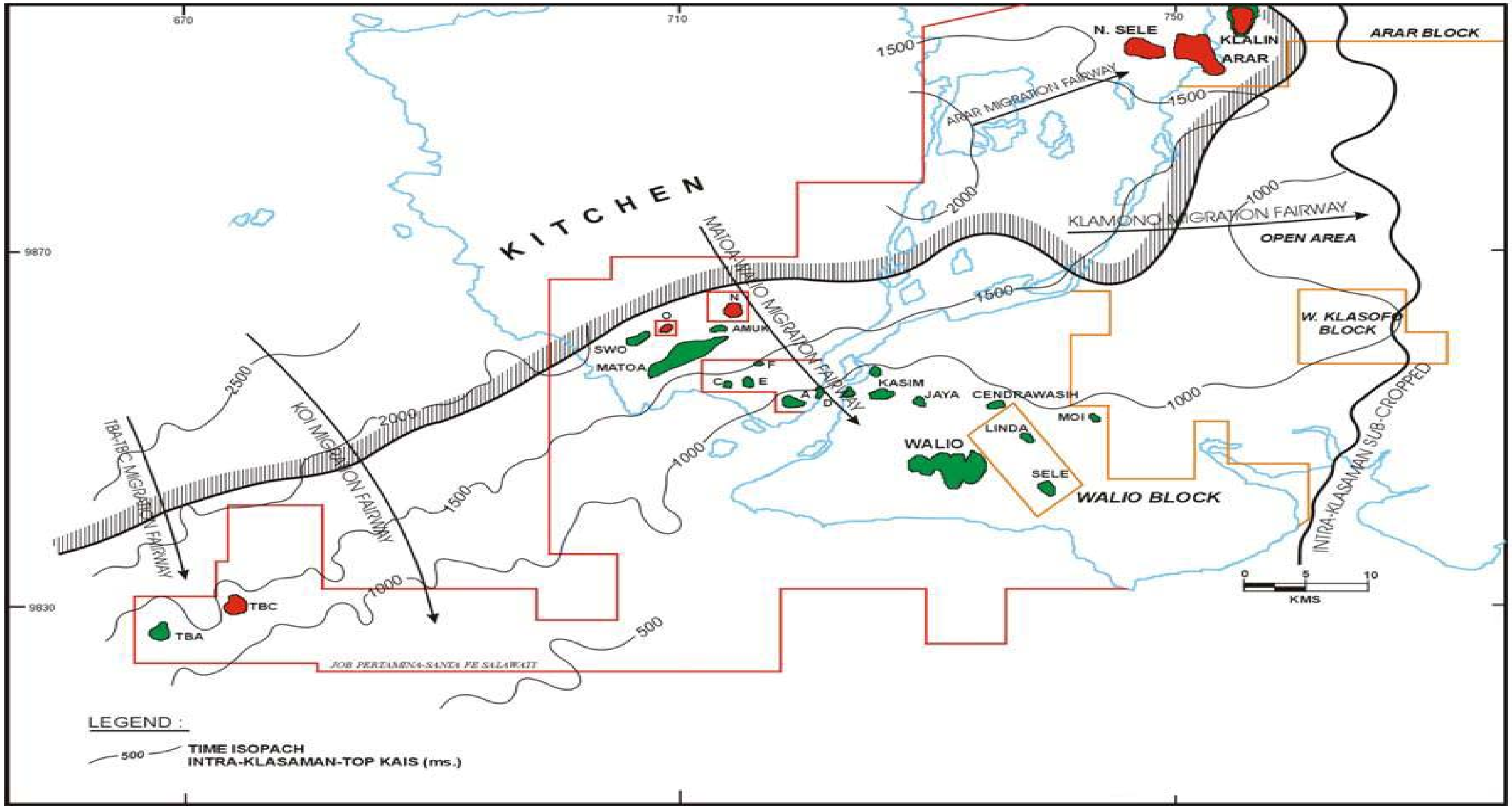


**Figure 11 -** Reconstruction of regional noses based on a time isopach map of Intra-Klasaman marker to top Kais, at around mid-Pliocene times (Satyana et al., 2003). These noses are considered to have resulted from translation of Salawati Island to the southwest. Kitchen outlines shifted downdip compared to the present kitchen. Each migration fairway exists at each regional nose.

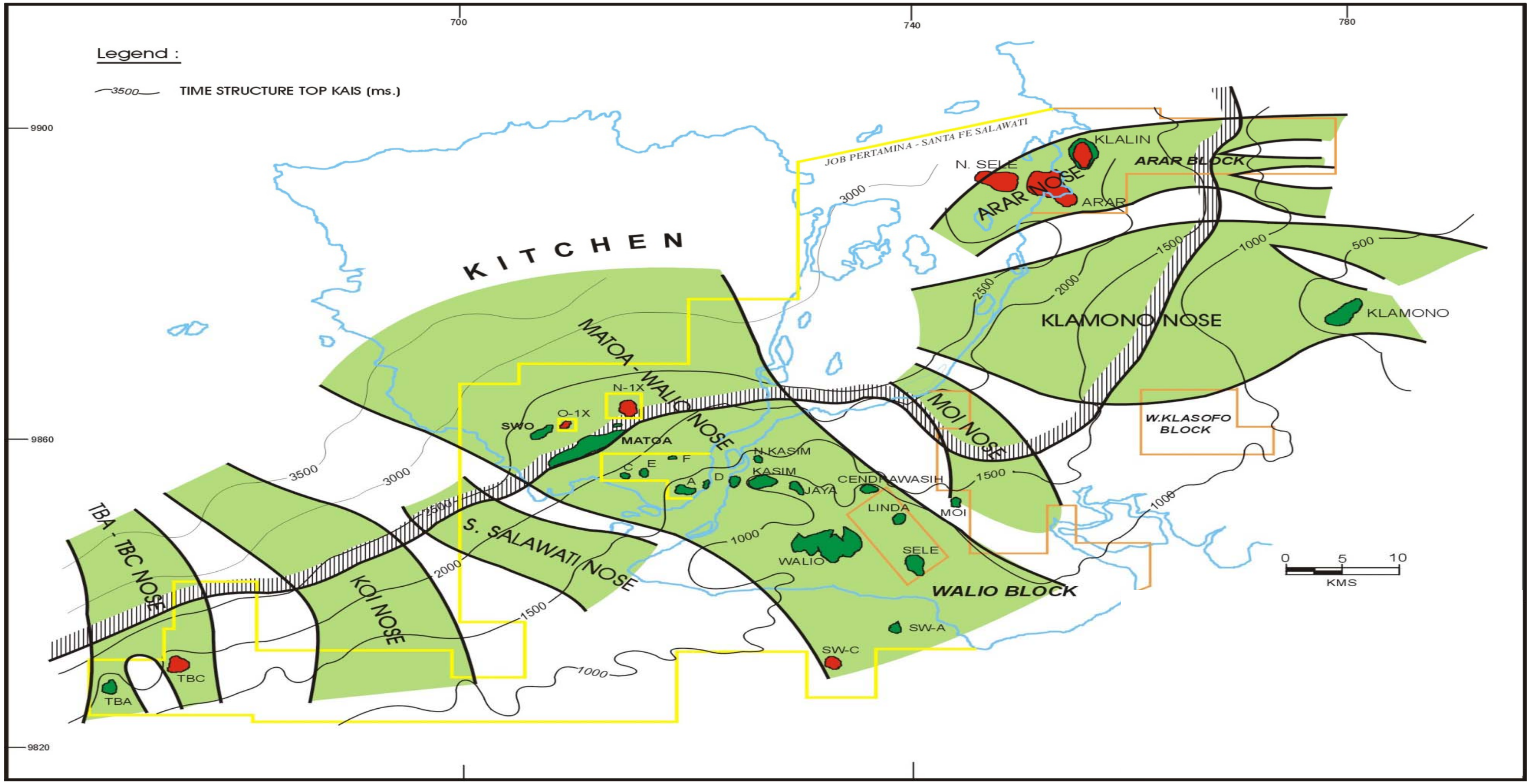


**Figure 12 -** Seven regional noses for migration compartments of the Salawati Basin (Satyana et al., 2003). The regional noses of the Salawati Basin have focused hydrocarbon migration to concentrate only in each nose and away from the flanking low areas. Note that all fields are located at the noses. A simplified and restored time Kais structure map is used as the basemap. Detachment and translation of Salawati Island is considered to be responsible for the occurrence of these parallel noses.

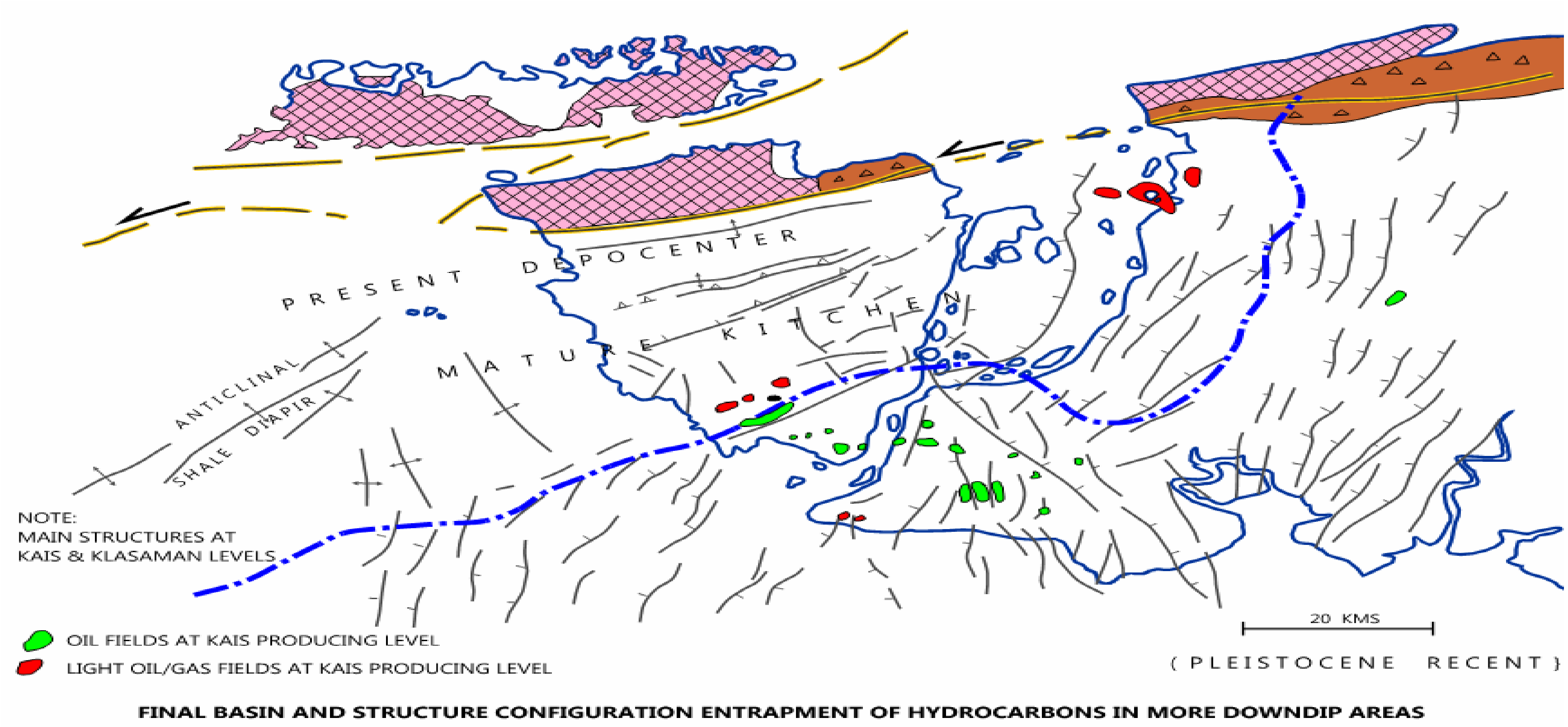


**Figure 13 -** Pleistocene to Recent configuration of the Salawati Basin. Salawati Island has taken up its present position. The nortwestern depocenter is the active kitchen, generating and migrating petroleum updip southward, southeastward, eastward and northeastward. Numerous faults exist in this basin as a response to the Sorong Fault tectonism. The faults have enhanced the migration pathways.