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EVOLUTION OF THE SALAWATI STRUCTURES, EASTERN INDONESIA : A FRONTAL SORONG FAULT DEFORMATION

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ABSTRACT

Major Sorong Fault, a WSW-ENE trending left-lateral wrench fault terminates the Salawati Basin to the north and northwest. The fault has strongly controlled the basin's structures since the mid-Pliocene and responsible for the present structural style of the basin. Four structural grains can be recognized : normal faults, strike-slip faults, fold-reverse fault belts, and diapiric structures. Four structural trends can be recognized : Salawati, Klasofo, Walio, and Cenderawasih trends. Based on left-lateral strain ellipsoidal analyses, the structural evolution can be grouped into four episodes commenced by the Sorong Fault initiation in the mid-Pliocene and peaked in the Pleistocene time when structures in the Sele Strait took place. Sequential shear-strain ellipsoids show that the Salawati structures evolved and rotated counter-clockwisely in constant magnitude of 25º relative to the present Sorong Fault from the mid Pliocene to the Pleistocene. Sorong Fault tectonism strongly controls the petroleum system of the Salawati Basin.

INTRODUCTION

The Salawati Basin is located frontal to a major fault zone in Eastern Indonesia called the Sorong Fault (Figure 1). Accordingly, the structural style of the basin is strongly controlled by the Sorong Fault tectonism. Normal faults, reverse faults, strike-slip faults, folds, and diapiric structures form the structural grains of the Salawati Basin.

The study is based on seismic mapping, geological surface mapping, and radar (SLAR) data. The structural elements obtained from these data are plotted on the basemaps. The structural trends are analyzed using Ross diagram. The relationship among the structural grains are interpreted using strain ellipsoids since all structures are actually related to strike-slip deformation. Structural evolution can be derived from this analysis. The role of the structures to hydrocarbon implications is also addressed in the paper. The study will provide a deformation model for other basins terminated frontally by major wrench fault.

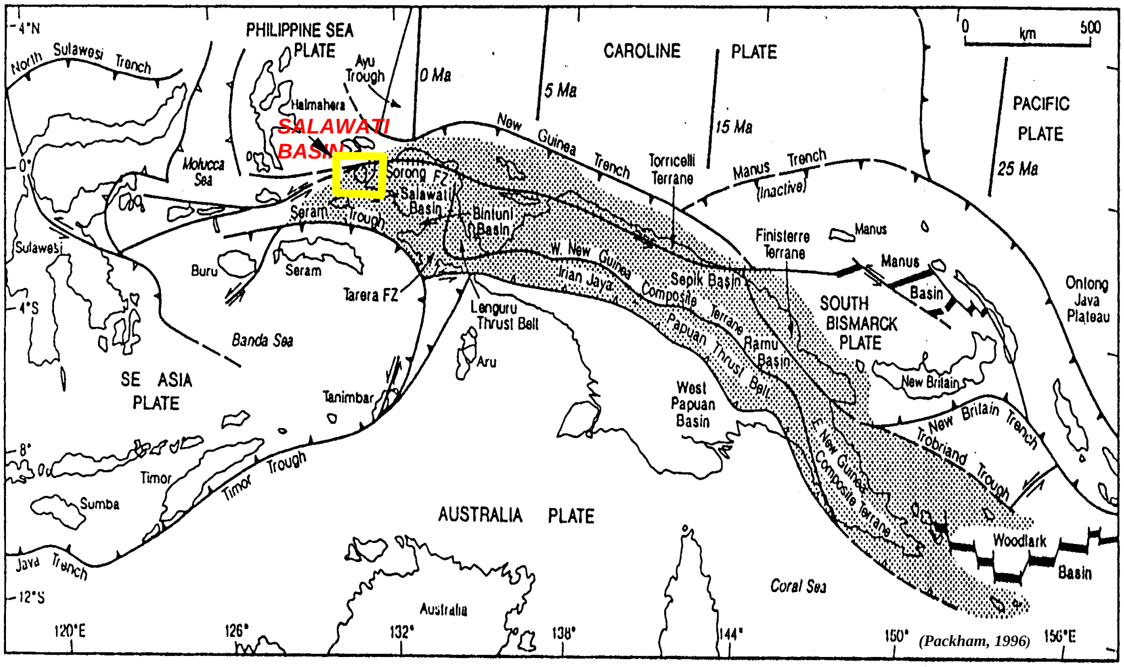

Figure 1 Location of the Salawati Basin in the regional tectonics of Eastern Indonesia.

GEOLOGIC SETTING OF THE SALAWATI BASIN

The Salawati Basin is an east - west trending foreland asymmetric basin located on the northern margin of the Indo-Australian Plate (Figures 1, 2). The deformed zone of the left-lateral Sorong Fault presently bounds the basin to the north and west. The basin is bordered to the south and east by uplifted Miocene carbonates of the Misool - Onin Geanticline and the Ayamaru Platform, respectively. The present dominant structural style of the basin is typified by normal faults trending southwest-northeast. Approaching the Sorong Fault, there are fold and fault belts which are parallel-subparallel to the Sorong Fault.

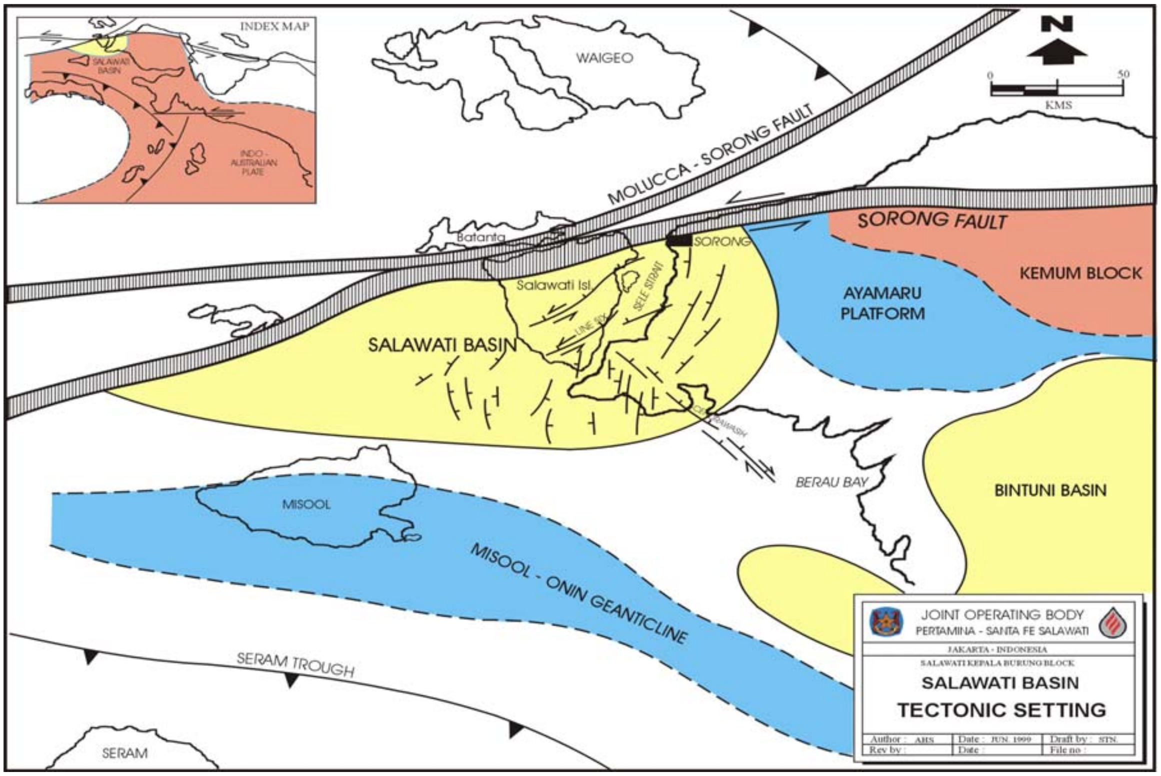

Figure 2 Geologic setting of the Salawati Basin as located at the northern margin of the Indo-Australian Plate and is frontal to the Sorong Fault Zone.

The Salawati Basin records the stratigraphic and tectonic history from the Palaeozoic to the Recent (Figure 3). The basin underwent a polarity reversal from tilting southward during the Paleozoic to early Pliocene to become tilting northward since the Late Pliocene. This reversal is related with the advent of the Sorong tectonism into the Salawati Basin. The pre-reversal basin's stratigraphy is composed of the Late Paleozoic Kemum and Aifam Groups, Mesozoic Tipuma and Kembelangan Group, and Early Tertiary to Mio-Pliocene Faumai, Sirga, Kais, Klasafet and Klasaman formations which regionally are included into the New Guinea Limestone Group. Thick Upper Klasaman sediments and the Sele molassic deposits compose the post-reversal stratigraphy.

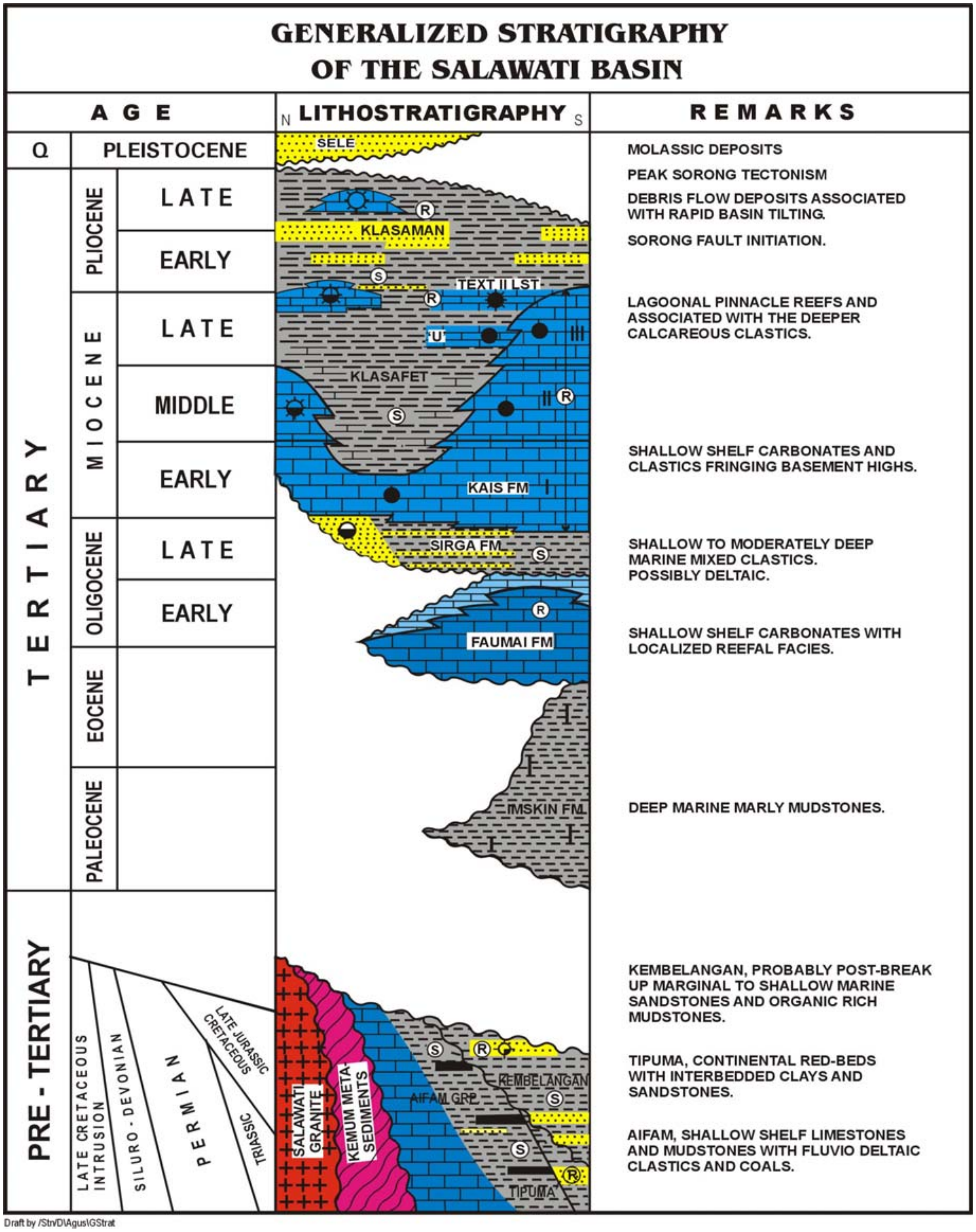

Figure 4 Generalized stratigraphy of the Salawati Basin and significant structural and stratigraphic events.

SORONG FAULT TECTONISM

Sorong Fault has strongly controlled the geology of the basin since the late Pliocene. The fault was responsible for the reversal of the basin polarity, subsidence of the basin depocenter to the north-northwest, the uplifting of the basin platform to the south-east-northeast, the rotation of the Salawati Island, the opening of the Sele Strait, the detachment of the Banggai-Sula mass, the emplacement of the Batanta-Waigeo erratic bodies, the generation of hydrocarbons, the development of compensating structures, and the deposition of Upper Klasaman and Sele clastics.

A Megashear in Eastern Indonesia

A great left-lateral strike-slip fault system trending E-W transects the northern coast of Irian Jaya and Papua New Guinea (Figure 1). This fault system is connected to the similar fault system in the vicinity of Banggai-Sula in Eastern Sulawesi making total length of 1900 kms (Hamilton, 1979; Hutchison, 1989, Packham, 1996). One thousand kilometers of the fault zone is submarine from the west of the Salawati Island to the narrow Sula Ridge. The remaining 900 kms is located in Irian Jaya and Papua New Guinea. In the vicinity of the Bird's Head, Visser and Hermes (1962) called this fault as the Sorong Fault system, named after Sorong town. This fault is part of a large global transcurrent zone that separates the westward moving Pacific oceanic (Caroline and Phillipine Sea) plate from the relatively stable Australian continental plate.

Geology of the Sorong Fault

Although great in magnitude, the geology of the Sorong Fault zone is relatively poorly known. Various lineaments have been proposed as the main fault strands in this system (Charlton, 1996). Visser and Hermes (1962) proposed E-W river valley and ridges and stressed zones as evidences. The zone is characterized by a chaotic jumble of blocks of many kinds of rock units perhaps best be described as a huge tectonic breccia. Mylonitization of the rocks contained in the fault zone indicates considerable stress. The width of the 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 have been recognized in a disorderly assemblage.

Tjia (1973) and Hamilton (1979) recognized the Sorong Fault zone as a polymict melange terrain. Hamilton (1979) considered that the type strand of the fault system apparently is a belt of pre-Pliocene subduction melange, misidentified as a strike-slip fault, and the entire fault system within the Bird's Head may be a suture zone though it also have left-lateral slip. Any presently active strands of the Sorong Fault system must serve as transforms to the south ends of the subduction zones of Sangihe, Halmahera, and Phillipine Trench systems. Transcurrent fault movements in northern New Guinea are attributed to the continued westward movement of the Caroline/Phillipine Sea plate at a rate of 12.5 cm per year (125 kms per million years) relative to the Australian plate (Simandjuntak and Barber, 1996).

Age of the Sorong Fault Tectonism

A number of estimates have been made as to when the Sorong Fault zone became an active feature (Charlton, 1996). These include the Oligocene (Pigott et al., 1982), early Miocene (Tjia, 1973; Hall, 1997) *in* Charlton (1996), 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). This study suggests mid-Pliocene to lower late Pliocene as the beginning of the Sorong Fault to strongly control the Salawati Basin. This is based on the seismic data (Satyana, 1999). The fault system is still active today. Some of the records of shallow earthquake activities along the transect of Eastern Sulawesi and Northern Irian Jaya may be related to the continued movement of this fault system. The earthquake focal solutions consistent with left-lateral strike-slip motion (Hutchison, 1989).

STRUCTURES OF THE SALAWATI BASIN

Structural Grains

Seismic, geologic, and radar data reveal that the Salawati Basin is intensively structurized (Figure 4). Normal faults dominate the structural style. The faults trend generally southwest-northeast and south southwest-north northeast and down to the north or west to which the present basin subsides.

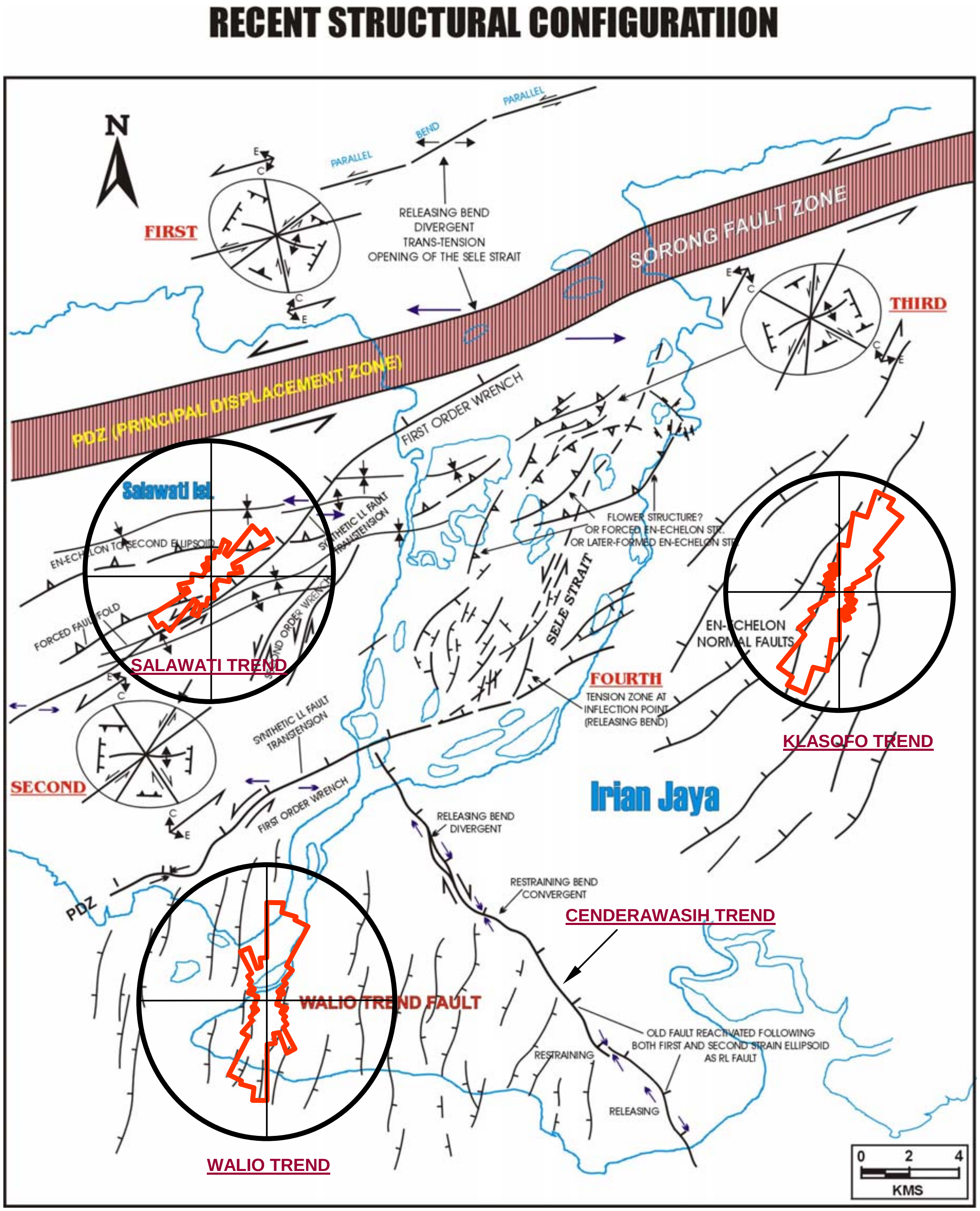

Figure 4 Recent structural configuration and recognition of four structural trends.

Left-lateral Sorong Fault zone trending west southwest-east northeast forms the principal displacement zone and terminating the basin to the north. Synthetic left-lateral faults of "Line Six" and Salawati faults transverse the Salawati Island in southwest-northeast direction. These faults conjugate to the Sorong Fault. The “Line Six” and Salawati faults also show a normal slip and partly have accommodated the basin subsidence to the north. Antithetic right-lateral Cenderawasih Fault trending northwest-southeast from the south Sele Strait southeastwards extending into the area close to the Bintuni Basin. This fault is considered originally as Late Paleozoic or Mesozoic fractures which was reactivated as dextral slip by the Sorong Fault tectonism.

In the North Salawati Island, the fold and reverse fault belts dominate the structural style. No significant folding is observed outside this area. The folds and reverse faults formed tight parallel belts trending west southwest-east northeast. The folds and faults formed as en echelon structures relative to the synthetic Salawati Fault. Seismic data reveal that the fold and reverse fault belts of the Northern Salawati Island occupy same places with the diapiric structures within the Upper Klasaman sediments. This may indicate a relationship between the formation of the folding and faulting with diapirism (Satyana and Setiawan, 2001).

Fault Trends

Detail statistical analyses of fault trends (normal fault) have been recorded. Regional time structure map of top Kais horizon is the basic data for this analysis. Plot of fault trends is displayed through set of Ross diagrams. The length and trends of more than 750 identified fault traces have been measured. Based on statistical analyses, faults in the Salawati Basin can be grouped into four trends: (1) Salawati Trend, (2) Klasofo Trend, (3) Walio Trend, and (4) Cenderawasih Trend (Figure 4).

Salawati Trend-Faults are mainly located at the Salawati Island with its northeast (Sele Strait) and southwest offshore. There are 123 fault traces (16 %) identified in this area with average trend of 55° NE (SW - NE trend). Klasofo Trend-Faults are located at the mainland of the Bird’s Head. There are 199 faults (26 %) identified in this area with average trend of 30° NE (SSW – NNE trend). Walio Trend-Faults are located at the southern basin area. There are 360 faults (48 %) identified in this area with average trend of 10° NE (N – S trend). Average trend of these three trends is 20 – 30° NE (SSW – NNE trend). These trends are en echelon in their direction relative to the Sorong Fault zone (75° NE or WSW – ENE), then it can be expected that the Walio-, Klasofo-, and Salawati- faults are related to the Sorong Fault. They were formed as en echelon extension fractures or synthetic extension fractures conjugates of the Sorong Fault.

There are faults identified both from surface and seismic mapping with trends opposite to these trends. Based on the regional data, these faults are expected to be old faults and called the Cenderawasih Trend. These faults are dominantly reactivated while still maintaining the original trends. There are 72 (10 %) faults identified as old faults with average trend of 125° NE (NW – SE trend). Within the setting of the Sorong Fault tectonism, these faults may be reactivated as antithetic extension fractures.

Evolution of the Structures

All structures within the Salawati Basin relate with the Sorong Fault tectonism. They developed as associated structures of wrench tectonics. Being connected with the Sorong wrenching/strike-slip faulting, understanding on the origin and evolution of the Salawati structures is conducted using strain ellipsoid principle (Harding, 1974; Lowell, 1985). A strain ellipsoid accommodates wrench assemblage consisting of principal strike-slip fault, synthetic strike-slip fault, antithetic strike-slip fault, en echelon folds, normal fault, and thrust or reverse fault. The strain ellipsoids provide the kinematics on the origin of the structures.

Based on the Sorong Fault tectonism, four stages of structural evolution/development can be recognized. Seismic data show that the structurization took place after the mid-Pliocene. The chronology of the deformation is sequential from the mid-Pliocene to the Pleistocene. All major strike-slip faults in the Salawati Basin (Sorong, Salawati, "Line Six", Cenderawasih, Sele Faults), seismically, have characteristics of wrench fault assemblage as outlined by Wilcox *et al.* (1973), Harding and Lowell (1979), Harding (1985), and Harding (1990). The structures associated with wrench faults are more diverse than those of any other style and include most elements that are fundamental to other styles. Wrench assemblages have both compressional and extensional features.

Mid-Pliocene Time

The first stage of evolution took place when the main Sorong Fault dissected the northern margin of the Salawati Basin at about 3.5 Ma (mid-Pliocene time) (Figure 5). The Sorong Fault acted as the principal displacement zone. Within this period, SSW-NNE trending normal faults (Klasofo Trend-faults) were formed as extension fractures of the Sorong Fault. Significant normal faults such as the Salawati and "Line Six" Faults were formed as WSW-ENE trending synthetic left-lateral strike-slip faults relative to the Sorong Fault. These faults developed a stress couple between normal and wrench slips (Salawati Trend-faults). All formations up to the Lower Klasaman were affected by these structures.

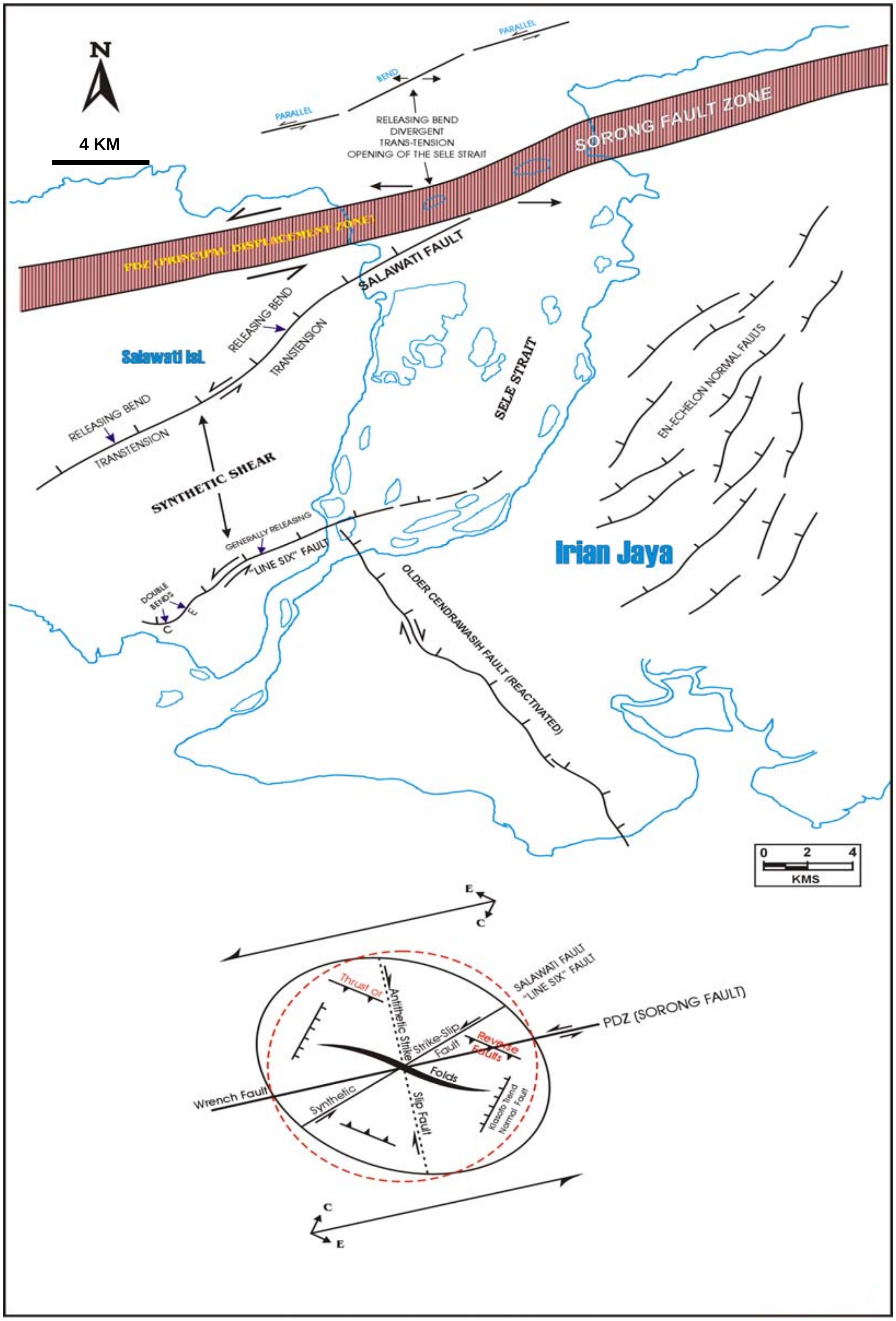

Figure 5 The initiation of the Sorong Fault in the mid-Pliocene and associated structures formed by the tectonism.

Late Pliocene Time

The second stage of structural evolution developed when the “Line Six” and the Salawati Faults acted as the principal displacement zones at the Late Pliocene time (Figure 6). Synthetic left-lateral strike-slip faults of the East Salawati and Sele Strait Faults, trending SW-NE to SSW-NNE, were developed in this period. North-south trending normal faults developed in the southern basin (Walio Trend-faults). En echelon folds and reverse faults trending east-west were formed around the Salawati Fault thin-skinnedly deforming the Upper Klasaman sediments resulting in the North Salawati Fold and Fault Belts. These belts were closely related with diapiric structures. Old Cenderawasih Fault was effectively reactivated during this period as dextral slip of antithetic strike-slip fault.

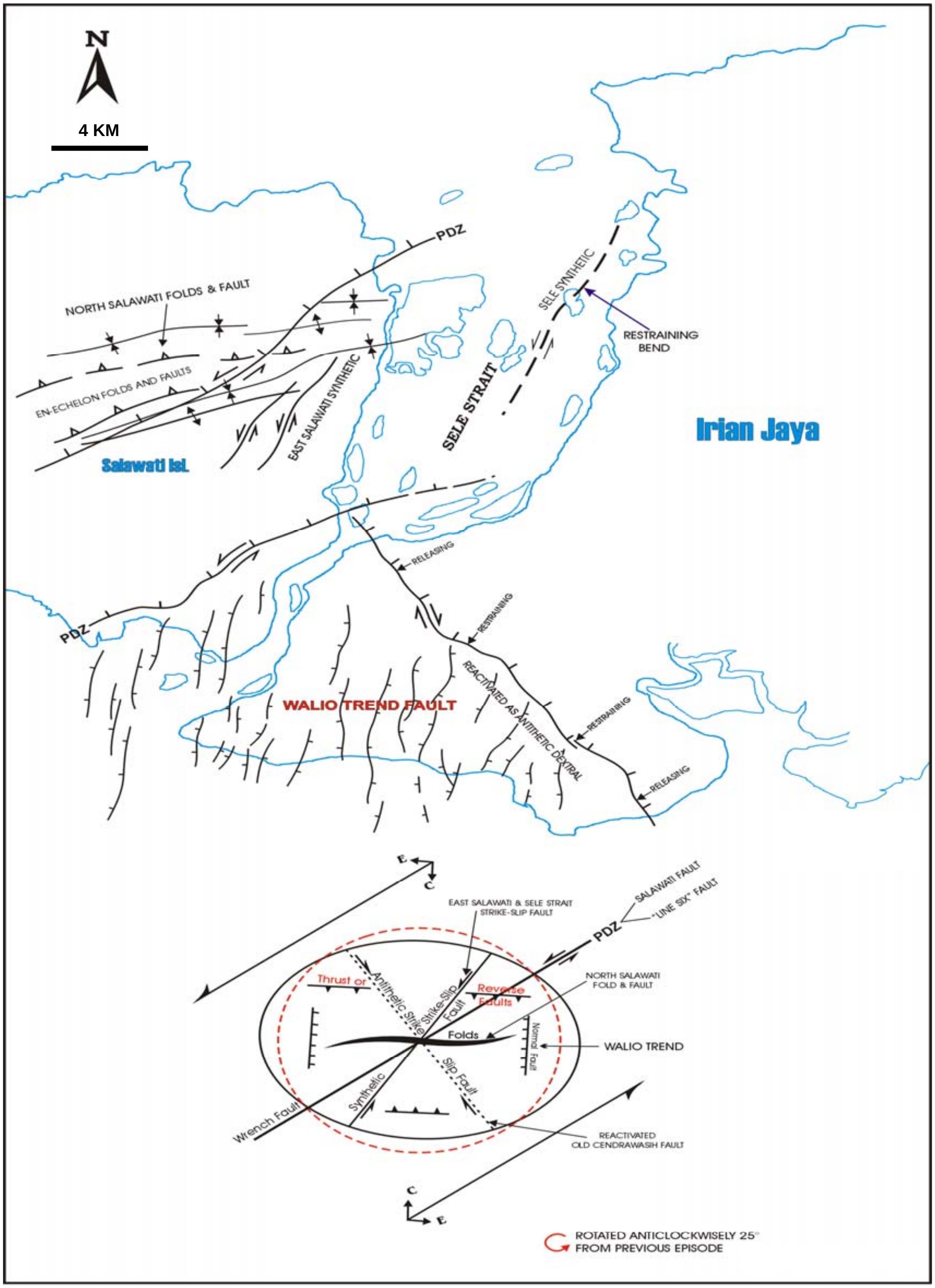

Figure 6 Structures formed in the Late Pliocene when the Salawati and "Line Six" Faults acted as the principal displacement zones.

Plio-Pleistocene Time

The third stage occurred in the Plio-Pleistocene time within the Sele Strait area where Upper Klasaman sediments obtain their maximum thickness (Figure 7). The Sele Strait Fault acted as the principal displacement zone. Folds and reverse faults occurred at the Upper Klasaman sediments and developed as either en echelon or flower structures relative to the Sele Strait Fault. The structures express as upward-spreading fault zone, whose elements usually have reverse separations. Convergent wrenching developed in the northern Sele Strait. Development of flower structures is enhanced where the strike slip is accompanied by components of convergence and where the rocks are highly mobile.

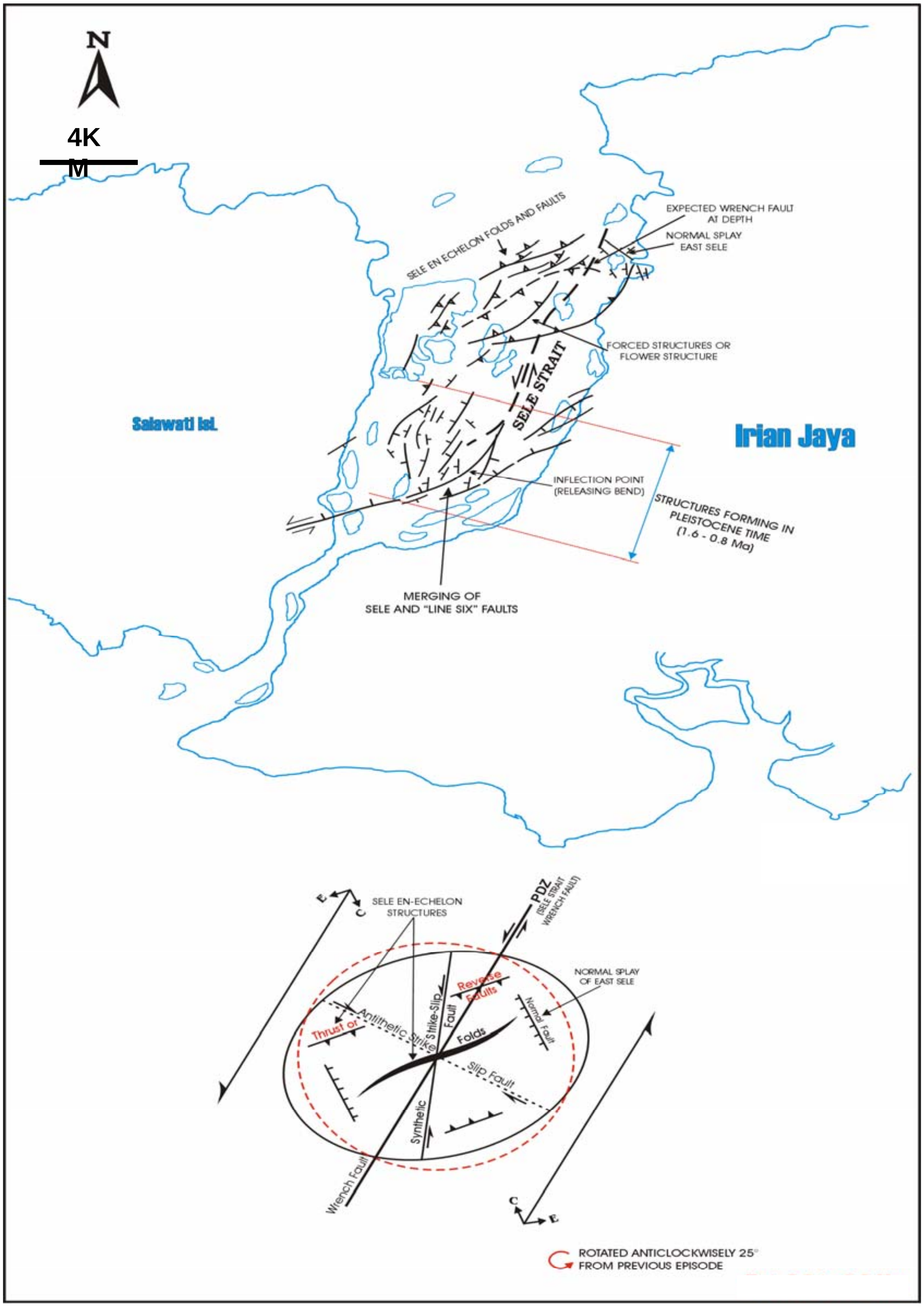

Figure 7 Structures formed in the Plio-Pleistocene when the Sele Fault acted as the principal displacement zones and there wa structural merging in the southern Sele Strait.

Pleistocene Time

The fourth stage of structural evolution occurred in the South Sele Strait area in Pleistocene time when the Sele Strait sinistral wrench fault propagated southwestward and eventually merged with the eastern sector of the “Line Six” normal-wrench fault (Figure 7). The merging of the two large faults developed an inflection point of releasing bend (fault' trends change from SSW to WSW forming inflection angle of 120°) and has resulted in divergent wrenching where normal faults developed. “Negative” flower structures have also been observed at the Upper Klasaman and consist of shallow sags overlying upward-spreading strike- slip faults with normal separations.

The development from the first stage to the fourth stage shows a counter-clockwise rotation of the strain ellipsoids in constant magnitude (25°) relative to the present Sorong Fault (Figure 4). This indicates that all Salawati structures are related with the Sorong Fault tectonism.

PETROLEUM IMPLICATIONS

Structural evolution of the Salawati Basin have strongly controlled the petroleum system of the basin. The basin tilting caused the maturation of the source rocks. The structural noses and faults have become the conduits for hydrocarbon migration. Folding and faulting formed traps.

Focused Migration by Regional Noses

Seismic mapping at the top of Kais level shows the presence of parallel regional structural noses trending NW-SE and east-west connecting the updip areas in the southern and eastern regions with the basin’s subsiding kitchen in the northwestern areas. The rotation and translation of the Salawati Island is expected to be responsible for the formation of this unique structural elements (Satyana, 1999). These regional noses have caused the focused hydrocarbon migration taking place in the Salawati Basin (Satyana *et al*., 2000). Structural morphology strongly controls migration pathways. Fluid will concentrate in the crestal zones (structural noses) at the steepest slopes of the structural morphology. Primary and secondary oil migrations which tend to disperse oil along the flanks of the basin will be counteracted by the presence of broad regional structural noses extending from trap into the kitchen. All existing fields and discoveries within the Salawati Basin are located at or related with these noses. On the other hand, many the dry wells are located in the areas beyond these noses.

Faults as Conduits for Migration

Faulting influences source-to-trap migration. Tensional fractures developed in the crestal zones of anticline structures may allow migration of petroleum. Structural studies showed that the Salawati Basin is intensively faulted. The development of the main fault system and major basin subsidence occurred during the Pliocene. Plio-Pleistocene oil generation and migration is interpreted from the thermal modeling and therefore, migration of hydrocarbons mostly would be post-faulting. The distribution of oil accumulations in the Salawati Basin is best explained by migration into and through the present day structural framework.

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 through regional noses. In this matter, the faults have enhanced the migration flows. Conversely, faults trending perpendicular to the regional noses will tend to block hydrocarbon migration. The north-south Walio Trend-faults will enhance the migration, whereas the Salawati and the Klasofo Trend-faults tend to block hydrocarbons (Figure 8).

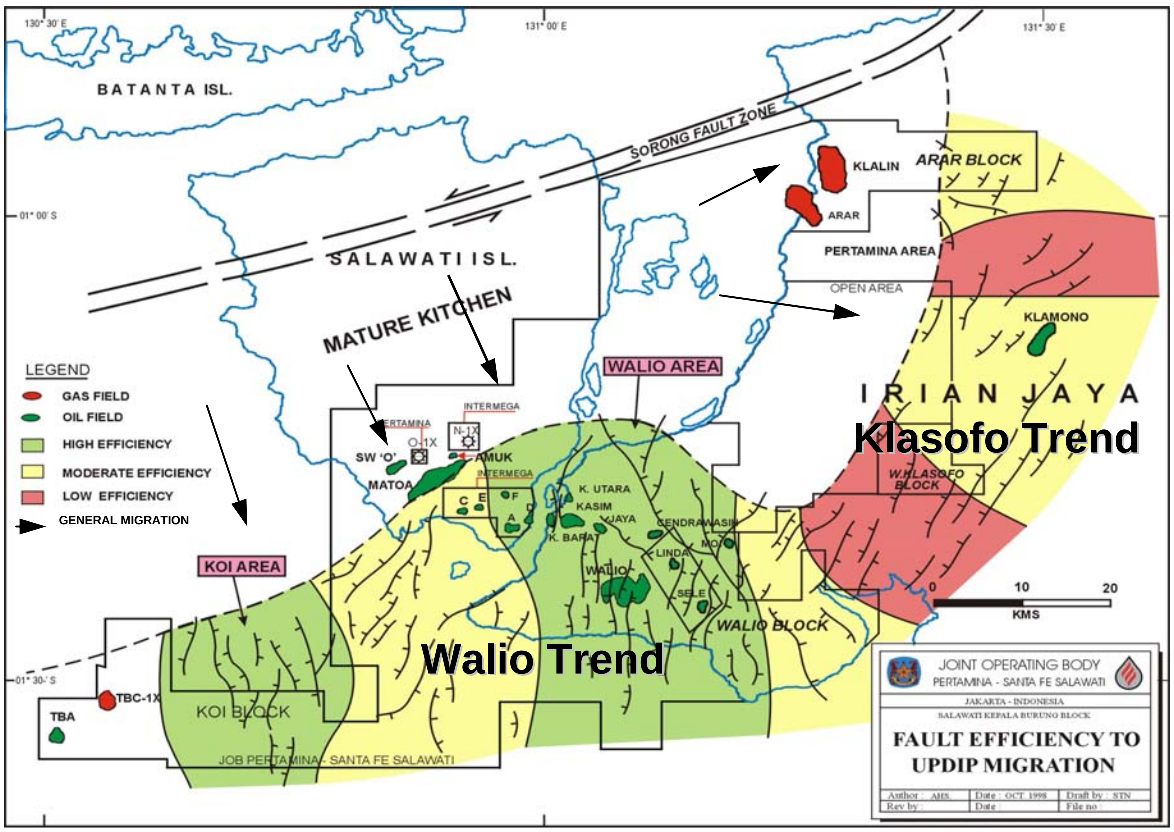

Figure 8 Implication of Salawati fault trends to hydrocarbon migration

Vertical migration through faults from deep sources to shallow reservoirs also occurs in the southern Salawati Basin. In this area, the Jurassic sources have been mature and within the gas window. Gas geochemistry study shows that the gas accumulated in Kais reservoirs at several discoveries like those at Maniwar, Lao-Lao, and Walio are not sourced by the Kais/Klasafet sources but by the underlying pre-Tertiary sources. This will need normal faults as hydrocarbon conduit.

Structural Trap Formation

The Matoa Field at the Salawati Island is a significant evidence that the structure has played important role for the formation of hydrocarbon trapping. The Matoa Field formed at an antithetic splay of the down to the north "Line Six" normal fault. Other possible structural trap formations are within the Sele Strait area and related with the wrench deformation. The trap occurs as either flower structures or en echelon structures at the level of Intra-Klasaman sands (Upper Klasaman Formation) of the Sele Strait. In the north Salawati Island, traps related with the diapirism are indicated (Satyana and Setiawan, 2001).

CONCLUSIONS

- All Neogene structures in the Salawati Basin are due to the Sorong Fault tectonism which initially influenced the basin in mid-Pliocene time and strongly controlled the basin's deformation during the Late Pliocene.
- Present structural style of the Salawati Basin is dominated by normal faults trending SSW-NNE forming as extension fractures conjugates to the Sorong Fault. In addition to this, are synthetic left-lateral faults ("Line Six", Salawati, Sele Faults), antithetic right-lateral fault (Cenderawasih Fault), and thin skinned-fault and fold belts in the north Salawati Island which associated with the diapirism.
- Structural trends were examined and show the close relationship with the Sorong Fault tectonism. The four structural trends are Salawati, Klasofo, Walio, and Cenderawasih Trends.
- The evolution of Salawati structures, based on strain ellipsoidal analyses, can be divided into four stages of development : (1) Sorong Fault period in mid-Pliocene time (2) "Line Six" - Salawati Faults period in Late Pliocene time, (3) Sele Fault period the Plio-Pleistocene time, and (4) South Sele Strait period in Pleistocene time. The development from the first stage to the fourth stage shows a counter-clockwise rotation of the strain ellipsoids in constant magnitude of 25° relative to the present Sorong Fault. This indicates that all Salawati structures are related with the Sorong Fault tectonism.
- Sorong Fault deformation has strongly controlled the petroleum system of the Salawati Basin. It has played roles on : (1) focused hydrocarbon migration by regional noses, (2) enhancement of migration by faults paralleling the nose's trends, and (3) trap formation associated with antithetic splay of normal faults, wrench deformation, and diapirism. Integrated understanding of the basin's structure plays a significant role for petroleum exploration.

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REFERENCES

Charlton, T.R., Correlation of the Salawati and Tomori Basins, Eastern Indonesia : a constraint on left-lateral displacements of the Sorong fault zone *in* Hall, R. and Blundell, D. (eds), *Tectonic Evolution of Southeast Asia*, Geological Society Special Publication, no. 106, p. 465-481, 1996.

Dow, D.B. and Sukamto, R., Late Tertiary to Quaternary tectonics of Irian Jaya, *Episodes*, vol. 7, no. 4, p. 3-9, 1984.

Froidevaux, C.M., Tertiary tectonic history of the Salawati area, Irian Jaya, Indonesia : *Proceedings IPA 6th annu. conv*., p. 199-220, 1977.

Hall, R., Cenozoic tectonics of SE Asia and Australasia *in* Howes, J.V.C. and Nobble, R.A. (eds), *Proceedings IPA Petroleum Systems of SE Asia and Australasia Conference*, Jakarta, Indonesia, May 1997, Indonesian Petroleum Association, Jakarta, p. 47-62, 1997.

Hamilton, W., *Tectonics of the Indonesian region, United States Geological Survey Professional Paper no. 1078*., United States Geological Survey, Denver, 1979.

Harding, T.P. and Lowell, J.D., Structural styles, their plate-tectonic habitats, and hydrocarbon traps in petroleum provinces : *American Association of Petroleum Geologists Bulletin*, v. 63, p. 1016-1058, 1979.

Harding, T.P., Petroleum traps associated with wrench faults : *American Association of Petroleum Geologists Bulletin*, v. 58, p. 1290-1304, 1974.

Harding, T.P., Seismic characteristics and identification of negative flower structures, positive flower structures, and positive structural inversion : *American Association of Petroleum Geologists Bulletin*, v. 69, p. 582-600, 1985.

Harding, T.P., Identification of wrench faults using subsurface structural data : criteria and pitfalls : *American Association of Petroleum Geologists Bulletin*, v. 74, p. 1590-1609, 1990.

Hutchison, C.S., *Geological evolution of Southeast Asia*, Clarendon Press, Oxford, 1989.

Packham, G., Cenozoic SE Asia : reconstructing its aggregation and reorganization *in* Hall, R. and Blundell, D. (eds), *Tectonic Evolution of Southeast Asia*, Geological Society Special Publication, no. 106, p. 123-152, 1996.

Satyana, A.H., Salawati Basin polarity reversal and rotation of Salawati Island, Irian Jaya : controls of Sorong tectonism and implications on petroleum system and new hydrocarbon reserves, *Prosiding Lomba Karya Tulis Kelompok Eksplorasi Pertamina EP*, 27-28 Oktober 1999, p. 9-38, 1999.

Satyana, A.H., Salim, Y., and Demarest J.M., Significance of focused hydrocarbon migration in the Salawati Basin : controls of faults and structural noses : *Proceedings IPA 27th annu. conv*., p. 513-530, 2000.

Satyana, A.H. dan Setiawan, I., Origin of Pliocene deep-water sedimentation in Salawati Basin, Eastern Indonesia : deposition in inverted basin and exploration implications : *Proceedings of FOSI 2nd Regional Seminar Deep-Water Sedimentation of Southeast Asia*, p. 53-65, 2001.

Simandjuntak, T.O. and Barber, A.J., Contrasting tectonic styles in the Neogene orogenic belts of Indonesia *in* Hall, R. and Blundell, D. (eds), *Tectonic Evolution of Southeast Asia*, Geological Society Special Publication, no. 106, p. 185-201, 1996.

Visser, W.A. and Hermes, J.J., *Geological results of the exploration for oil in Netherlands New Guinea*, Koninklijk Nederlandsch Geologisch Mijnbouwkundig Genootschap, ‘s-Gravenhage, 1962.

Wilcox, R.E., Harding, T.P., and Seely, D.R., Basic wrench tectonics : *American Association of Petroleum Geologists Bulletin*, v. 57, p. 74-96, 1973.