

PROCEEDINGS, INDONESIAN PETROLEUM ASSOCIATION
Twenty Seventh Annual Convention & Exhibition, October 1999

**SIGNIFICANCE OF FOCUSED HYDROCARBON MIGRATION
IN THE SALAWATI BASIN : CONTROLS OF FAULTS AND STRUCTURAL NOSES**

Awang H. Satyana*
Yanto Salim**
Jim M. Demarest**

ABSTRACT

The Salawati Basin, Bird's Head of Irian Jaya, has been extensively explored. Exploration for oil in the basin began in 1906. Up to 1998, 160 exploration wells have been drilled in the basin. The efforts were rewarded with 35 commercial discoveries, 22 of which are still producing oil and gas. Yet, the basin is still interesting for exploration as shown by recent regional petroleum geochemistry and structural studies.

Regional evaluation on the present-day structure, paleo-structure, and timing of hydrocarbon generation versus proven hydrocarbon accumulations, have shown that *unique migration compartments* occurred within the Salawati Basin. The interplay between *fault trends* with *structural noses* appears to control the *focus* of hydrocarbon migration within the basin.

The study showed that the foredeep kitchen of the Salawati Basin is connected to the basin's updip areas through regional structural noses. Numerous normal faults are present within the basin, intersect or parallel to the regional noses. Generated hydrocarbons flowed updip through fault fractures and carrier beds of structural noses. Faults and noses control the hydrocarbon migration pathways.

High efficiency migration takes place in an area where fault trends are *parallel* with the structural dip. Proven hydrocarbon accumulations of the Salawati Basin discovered to date are located in such an area. The study has identified areas with high-efficiency faults and regional structural noses that act as migration fairways.

This concept of migration has explained the distribution of both proven hydrocarbon accumulations and dry wells within the Salawati Basin. The concept also provides a tool for evaluating migration risks for undrilled prospects.

INTRODUCTION

The Salawati Basin, Birds Head of Irian Jaya, is a mature basin. Since the first commercial oil discovery (Klamono-1) drilled in the basin by NNGPM (Nederlandsch Nieuw Guinea Petroleum Maatschappij) in 1936, approximately 160 exploration wells have been drilled in the basin. Most of the wells were drilled post-1970 after the introduction of Production Sharing Contracts (PSCs) in 1968. Impressive commercial oil discoveries in Kais reefs (Kasim and Walio fields) made by Petromer Trend (now Santa Fe Energy Resources) in the early 1970s have enhanced exploration drilling throughout the entire Salawati Basin both onshore and offshore. The last exploration well drilled in the basin was the Amuk-1 oil discovery (JOB Pertamina-Santa Fe Salawati, 1998), proving the Kais reef remains the main exploration target in the basin. Exploration efforts in the basin were rewarded with

* JOB Pertamina-- Santa Fe Salawati

** Santa Fe Energy Resources

35 commercial discoveries, 22 of which are still producing.

The hydrocarbon system of the Salawati Basin is well defined, however, distribution of oil accumulations coupled with a number of dry wells are intriguing. This has initiated additional regional studies to determine the remaining exploration potential within the basin. A series of regional studies comprising petroleum geochemistry, structure, and seismic re-mapping were carried out to evaluate the exploration risks in this mature basin. Studies showed that hydrocarbon migration pathways emerged as one of the highest risks for exploring the remaining potential. Furthermore, distribution of oil fields appears to be controlled by unique migration compartments, which can be explained by the concept of focused migration.

Previous published and unpublished works on hydrocarbon migration of the Salawati Basin was summarized by Livingstone (1992). Migration pre-faulting or post-faulting was the main concern of previous exploration programs because the Salawati Basin is intensively faulted and most fields are located within complex faulted areas. The relationship between fault systems and migration are thus important in the understanding of the migration complexity.

GEOLOGIC SETTING

The 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 Ayamaru Platform respectively. The Salawati Basin contains the stratigraphic and tectonic history from Palaeozoic time to Recent.

Stratigraphic Framework

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) developed only in

the southern part of the basin due to the northern uplift during the Late Cretaceous erosional or non-deposition.

Tertiary sediments of the Salawati Basin begin with deposition during the Late Eocene to Early Oligocene transgressive carbonates of the Faumai Formation. Overlying the Faumai carbonates, is 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 type of carbonate sediments from low-energy organic-rich carbonate muds, moderate-high energy reefal carbonates and fine crystalline carbonates. Contemporaneously with the Kais carbonate deposition, Miocene lagoonal Klasafet fine calcareous clastics were deposited. The Pliocene Klasaman clastics ended the Tertiary stratigraphic sequences. The Klasaman Formation caused the underlying source rocks to reach maturity and generate hydrocarbons. Molassic deposits of the Sele conglomerates were deposited in Pleistocene time as sediments from the deformed zone of the Sorong Fault were eroded.

Structural Framework

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 Late Miocene/Early Pliocene. Present structural style of the basin is dominated by NNE - SSW normal faults formed as 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" Fault). This movement has reactivated older normal faults (started as rifts in the Late Palaeozoic - Mesozoic time), such as the Cenderawasih Fault, to become antithetic right-lateral faults. Regionally, the Sorong Fault was responsible for inversion of the basin's polarity, opening of the Sele Strait causing subsidence of the northern depocenter and resulted in the emplacement of the Batanta - Waigeo erratic bodies.

PETROLEUM GEOCHEMISTRY: UPDATED

Geochemistry (hydrocarbon sources) of the Salawati Basin was discussed by Phoa and Samuel (1986), Robinson (1987), Livingstone (1992), and Livsey et al. (1992). The following is a discussion of some geochemical updates on source paleofacies/identification incorporating recent laboratory analyses. Thermal modeling, which is important to the understanding of the migration history, is also addressed in the discussion.

Source Paleofacies

Source identification was obtained by geochemistry of analyzed oils through oil to source rock correlation. The geochemical characteristics of Salawati oils show distinctive features listed below:

- Moderate content of sulphur aromatics suggesting a marine affinity because the sulphur is generally formed by microbial sulphate reduction of sea water and is normally associated with carbonate muds.
- Heavy carbon-13 isotope ratio mostly -19 ‰ to -22 ‰, suggesting a dominant contribution by highly anoxic algae, and organically very rich.
- Presence of a Tertiary higher plant biomarker *oleanane* indicating some fresh water run-off from terrestrial angiosperm and Tertiary age source sediments.
- Pristane to phytane ratios generally below 2.0 indicating organic-rich anoxic carbonate sequences.

Integration of the above characteristics, provide a specific model for the type of source rock for Salawati oils. Source rocks should be: Tertiary in age, organically very rich, have a significant marine influence, contain dominantly marine algal kerogens, have received minor terrestrial run-off, carbonate (lime mudstone) in part and in most cases have been deposited in an anoxic lagoonal (brackish water) environment. These characteristics point to Kais and Klasafet shales and carbonates. This agrees with Robinson (1987), Livingstone (1992), and Livsey et al. (1992). The richest of the analyzed Kais and

Klasafet source rocks have been analyzed for biomarkers and carbon isotope ratio at various times. This data shows significant correlations with existing produced oil. Biomarkers and carbon isotope data illustrates the compatibility of the Kais/Klasafet source rock to the Salawati oils.

Thermal Modeling

Petroleum generation and migration history from defined source beds was simulated using a 2-D thermal modeling program (Figure 3). Cross-section A-A' (Figure 11) running perpendicular to the basin outline, was selected to perform the modeling after 5.20 Ma (the Pliocene - Recent). 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). By 3.21 Ma (the Lower Late Pliocene), oil had migrated updip as far as the Matoa Field in the southern area of Salawati Island. Major gas generation occurred from about 3.0 Ma (Late Pliocene). At the same time oil had reached the Walio area. Oil generation from the paleo-kitchen declined from 2.5 Ma to about 1.95 Ma (Upper Late Pliocene), by which time gas migration had peaked. Reconstruction of hydrocarbon migration is based on this chronology.

RESULTS AND DISCUSSION

Mechanics of Migration

Hydrocarbon movement was driven by two forces: (1) buoyancy and (2) groundwater flow/ hydrodynamics (Allen and Allen, 1990; Hindle, 1997). Buoyancy is the vertical directed force caused by the difference in density/pressure between oil, gas and pore waters of carrier beds. Buoyancy/pore pressure gradients attempt to move all pore fluids (both water and petroleum) to areas of higher buoyancy and lower pressure. These regions are updip of the kitchens. Petroleum migration pathways can be viewed as restricted rivers or streams concentrated immediately below the sealing surface at the top of the carrier bed.

Petroleum will tend to move in a homogeneous carrier bed in the direction of the steepest slope. *This is perpendicular to its structural contours*, that is, in the true dip direction. Lines drawn at right angles (orthogonal) to the structural contours of the top

carrier bed/base seal horizon are known as orthocontours (Allen and Allen, 1990). Orthocontour maps illustrate focusing and de-focusing effects of structural features in prospect drainage areas (Figure 4).

Faulting influences source-to-trap migration (Figure 5). *Tensional fractures developed in the crestal zones of anticline structures may allow migration of petroleum* (Allen and Allen, 1990). Fault zones can act as both conduits (non-sealing) and barriers (sealing) to secondary migration depending on a variety of factors such as normal stress across a fault, the nature of the fault surface and strata cut by the fault (Yielding et al., 1997). A recent study by Dholakia et al. (1998) showed that development of faults, from pre-existing discontinuity to a breccia zone, creates a path of increased permeability for hydrocarbon flow. In tight carrier beds of carbonate or calsi-clastic sediments, the presence of faults connecting the kitchen source with traps will accommodate the hydrocarbon migration.

Migration through Faults

Structural studies showed that the Salawati Basin is intensively faulted. Normal faults generally trending SW-NE and SSW-NNE formed genetically as en-echelon extension fractures to the Sorong Fault. The onset of tectonism began during the Late Miocene/Early Pliocene, but development of the main fault system and major basin subsidence occurred throughout the Late Pliocene. Plio-Pleistocene oil generation and migration is interpreted from thermal modeling and therefore migration of hydrocarbons mostly would have to be post-faulting. 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 to the downdip kitchen by normal faults (Figures 5 and 6) suggesting that faults and fractures in the Salawati Basin are avenues for secondary hydrocarbon migration. These faults generally trend parallel to the migration updip through structural contours. In this matter, faults have enhanced migration flow. Conversely, faults trending perpendicular to the orthocontours tend to block hydrocarbon migration.

To understand the role of fault trends on hydrocarbon migration in the Salawati Basin, faults were classified based on their relative trends to the adjacent structural dips and the results presented in the fault efficiency map (Figure 7). This map shows normal faults of the basin, which either enhance or block hydrocarbon migration. High efficiency faults (green color) trend 0° - 30° (parallel - subparallel) relative to the structural dip. Medium/moderate efficiency faults (yellow color) trend 30° - 60° (oblique) relative to the structural dip. Low efficiency faults (red color) trend 60° - 90° (subperpendicular - perpendicular) relative to the structural dip.

The map shows that high efficiency faults occur in the Walio area. These faults have enhanced migration. This can be seen from the distribution of the oil fields within the area and the basin's maximum migration distance (around 35 kms) relative to the kitchen boundary is reached in this area (South Walio fields).

Migration through Structural Noses

Structural morphology strongly controls migration pathways (Hindle, 1997). Fluid will concentrate in crestal zones (structural noses), at the steepest slopes of the structural morphology. Furthermore, primary and secondary oil migration tends to disperse oil along the flanks of the basin. Such dispersal will be counteracted if there were broad regional structural noses extending into the kitchen (Momper, 1978; Pratsch, 1988 in Hindle, 1997).

Migration pathways through structural noses are well expressed in the TBA and TBC area (Figure 8). The map shows that migration pathways move updip from the north kitchen southwards to charge the TBA and TBC areas. Hydrocarbon pathways may be split or divert when encountering a low. Figure 9 shows a simplified general direction of migration pathways in the Salawati Basin. Each proven hydrocarbon accumulation in the updip areas can be traced as connected by a series of pathways to a downdip kitchen. Unpublished detail maps actually show that in the TBA-TBC, Koi, Matoa-SWO, Klamono, and Arar areas, migration pathways are mainly controlled by structural noses. In areas of South Walio, Salawati A,C,D,E,F and Kasim-Walio complex, migration pathways are controlled by both a structural nose and faults.

Reconstruction of Migration Pathways (Paleomigration)

Having obtained the pattern of present day hydrocarbon migration, it is important that migration maps are reconstructed to understand the earlier migration pathways. Isopaching allows production of paleostructure maps that help modeling the paleomigration routes. Thermal modeling shows that major migration in the Salawati Basin had occurred since 3.4 Ma (intra-Pliocene time). The isopach map of the intra-Klasaman marker (age of this marker is approximately 3.5 Ma) to top Kais Formation will accommodate this requirement (Figure 10).

To obtain this goal, the kitchen outline was first restored by omitting sediments deposited after 3.5 Ma (Upper Klasaman sediments) and assuming that geothermal gradients have remained constant in the Salawati Basin for the last 3.5 million years. The 3.5 Ma's kitchen down stepped towards the present basin's depocenter reducing the area but still maintaining a similar outline with the present kitchen. *The paleomigration map shows that migration routes at about 3.5 Ma were basically similar with those of the present time.* This suggests that the regional structural trend of the Salawati Basin has remained constant for the last 3.5 million years.

Focused Migration in the Salawati Basin

Evaluation of regional Kais structure map resulted in recognition of some broad *Kais regional noses* (Figure 11). These regional noses were obtained by simplifying the Kais time structure map through enlarging the contour interval and restoring the contour into the condition of pre-structurization. The study has recognized seven parallel regional Kais structural noses extending from updip areas of the Salawati Basin and plunging into the kitchen. They are, from the southwest to the northeast: (1) the TBA - TBC, (2) Koi, (3) South Salawati, (4) Matoa - Walio, (5) Moi, (6) Klamono, and (7) Arar regional noses. The South Salawati and Moi noses are minor noses and considered as flanking splays of the larger Matoa - Walio nose. These regional noses have existed since Pliocene time.

Combination of these regional structural noses with fault trends have focused migrating hydrocarbons into traps. This interplay has resulted in broad unique migration fairways (compartments) within the

Salawati Basin (Figure 11). Migration pathways are concentrated along structural noses and away from the flanking structural lows. Generated hydrocarbons first concentrate (focus) around the plunging regional noses, flow updip and eventually their migration pathways are controlled and enhanced by faults.

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 are located within the Matoa-Walio regional nose. Areas flanking the regional noses are regional low/synclinal areas, *most dry wells of the Salawati Basin are located within these regional low areas.* Migration pathways will be away from structurally low areas and these areas will not contain hydrocarbons (migration waste zone - Demaison and Huizinga, 1991).

Migration efficiency, under control of the presence of regional structural noses and related fault trends, was defined for every focused migration area. This is presented in the migration efficiency map (Figure 12) which is the overlay between maps of regional noses and fault efficiency. The map shows that outside the kitchen area, *the highest migration efficiency occurs in two areas, Koi and Matoa - Walio where the interplay between faults and structural noses are at their best.* The TBA-TBC, Klamono, and Arar areas have moderate efficiency since hydrocarbon migration in these areas are mainly due to structural noses and areas lacking migration enhancing faults. Regional structural low areas east of the Walio Block have the lowest efficiency due to the absence of both a regional nose and migration enhancing faults.

Exploration Implications

Proper understanding of the migration pathways of the Salawati Basin can provide advantages in planning future strategic exploration efforts. *The study has identified areas with active charge system, hence defining areas receiving petroleum charge.* The maps of focused migration and migration efficiency illustrates areas either receiving or hindering hydrocarbon migration and petroleum charging. Detail migration route maps may explain individual pathways for individual traps. This will aid in the detail evaluation of the petroleum system of undrilled prospects to reduce migration risks.

Regional migration maps also contribute to the selection of potential areas for future relinquishments. This concept of migration can explain the distribution of both proven hydrocarbon accumulations and dry wells within the Salawati Basin.

CONCLUSIONS

- The study has identified areas in the Salawati Basin with active petroleum charge system or less risk. This knowledge is important for defining future exploration strategy of the basin.
- The mature Salawati Basin is not necessarily closed for new exploration. Integrated studies comprising petroleum geochemistry, structural revisit, migration modeling, and dry well analysis have shown that exploration ventures in a mature basin could still have good potential. The basin's remaining hydrocarbon potential may be identified through such integrated studies.
- Interplay between faults and structural noses has controlled the focused hydrocarbon migration pathways within the Salawati Basin to become unique compartments of migration fairways. Recognition of such focused migration patterns, rather than dispersive mechanisms, helps to predict the location of additional plays and their potential petroleum richness.

ACKNOWLEDGMENTS

We would like to thank the management of JOB Pertamina-Santa Fe Salawati, Santa Fe Energy Resources, Pertamina BPPKA and partners (Pertamina EP, Moeco Salawati Inc., Cieco Salawati Inc., Coparex Indonesia B.V, American Energy Ops. Inc.) for permission to publish this paper. Seismic maps formed the base maps for the study, and thus credit is due to Isjmiradi, Isnaini, Indra, Mimi, Imron Rustamadji, and Medianto. Steve Thompson (Robertson Research International Ltd.) provided the work on thermal modeling (figure 3). Nana Djumhana provided the block diagram of migration by faults in the Walio area (figure 5). Allan Fenwick and Atik Retno produced computer version of migration

efficiency map (figure 12). Thanks is also extended to Sartono and Sugiri for drafting figures and Iin for secretarial work. Brad Sincock from IPA edited the paper.

REFERENCES

- Allen, P.A. and Allen, J.R., 1990, Basin analysis : principles and applications, Blackwell Scientific Publications, Oxford.
- Demaison, G. and Huizinga, B.J., 1991, Genetic classification of petroleum systems, AAPG Bulletin, v. 75, p. 1626-1643
- Dholakia, S.K., Aydin, A., Pollard, D.D., and Zoback, M.D., 1998, Fault-controlled hydrocarbon pathways in the Monterey Formation, California, AAPG Bulletin, v. 82, p. 1551-1574.
- Hindle, A.D., 1997, Petroleum migration pathways and charge concentration : a three- dimensional model, AAPG Bulletin, v. 81, p. 1451-1481.
- Livingstone, H.J., 1992, Hydrocarbon source and migration, Salawati Basin , Irian Jaya : extended abstract from Eastern Indonesia Symposium, Pertamina-Simon Petroleum, Jakarta.
- Livsey, A.R., Duxbury, N., and Richards, F., 1992, The geochemistry of Tertiary and pre-Tertiary source rocks and associated oils in Eastern Indonesia, Proceedings Indonesian Petroleum Association, 21st annu. conv., p. 499-520.
- Phoa, R.S.K. and Samuel, L., 1986, Problems of source rock identification in the Salawati Basin, Irian Jaya, Proceedings Indonesian Petroleum Association, 15th annu. conv., p.405-421.
- Robinson, K.M., 1987, An overview of source rocks and oils in Indonesia, Proceedings Indonesian Petroleum Association, 16th annu. conv., p.97-122.
- Yielding, G., Freeman, B., and Needham, D.T., 1997, Quantitative fault seal prediction, AAPG Bulletin, v. 81, p. 897-917.

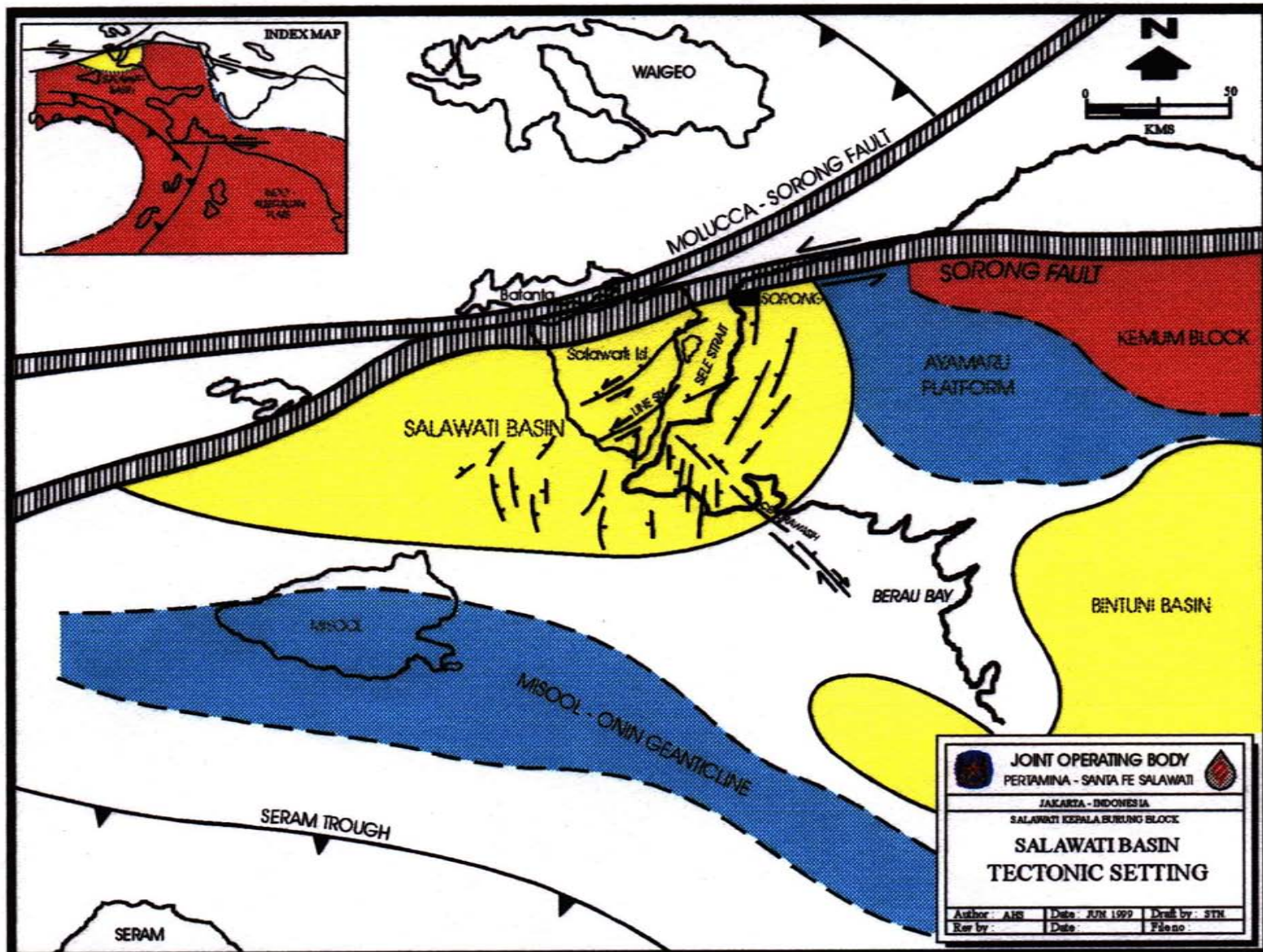
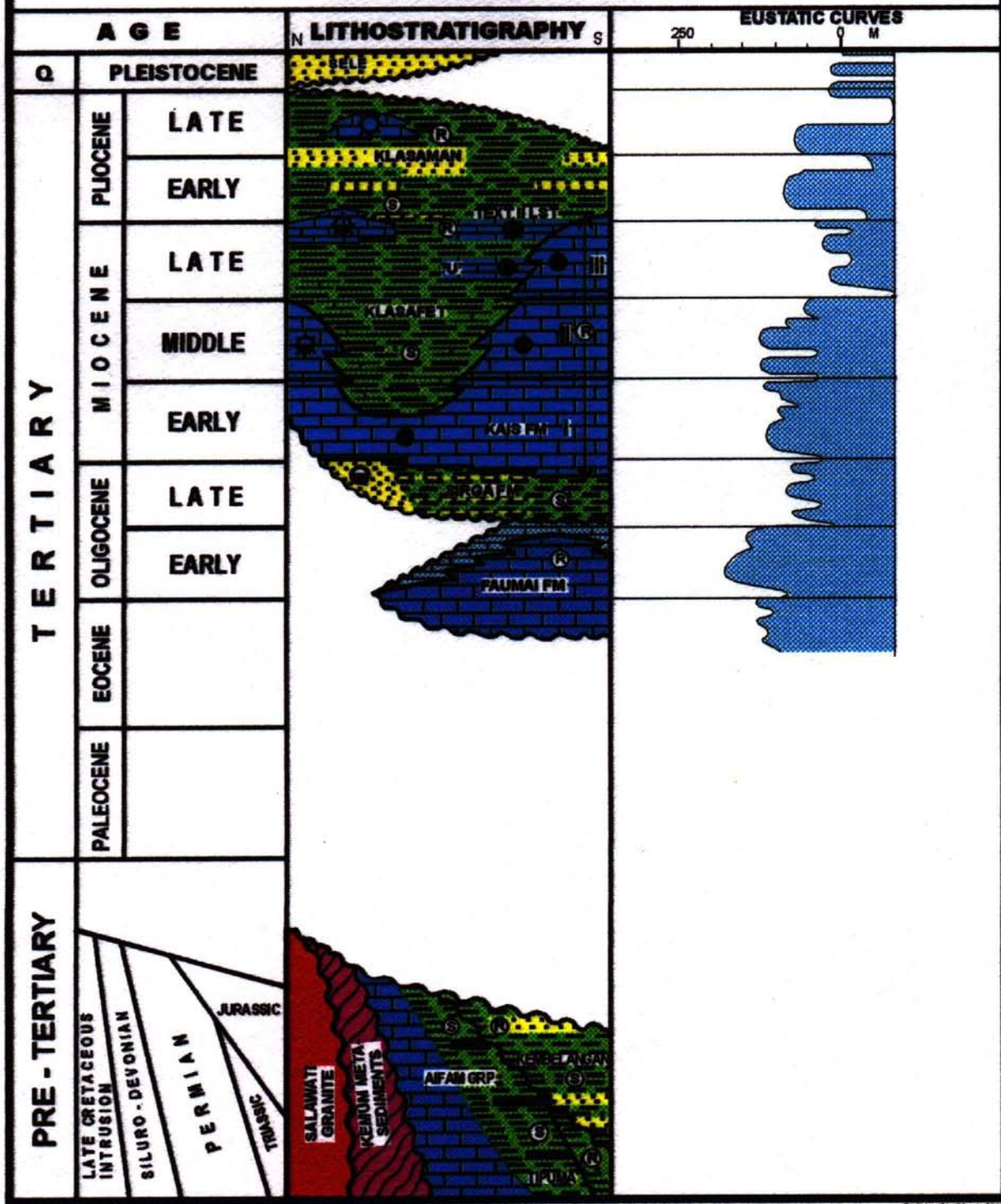


FIGURE 1 - Tectonic setting of the Salawati Basin showing main geological elements bordering the basin. General configuration of the Salawati main faults are displayed. Index map in upper left corner shows the foreland position of the Salawati Basin relative to the Indo-Australian Plate.

GENERALIZED STRATIGRAPHY OF THE SALAWATI BASIN



Draft by A/S/1 March 1989

FIGURE 2 - Stratigraphy of the Salawati Basin. Tertiary stratigraphy is dominated by New Guinea Limestone Group comprised of Oligocene to Miocene aged Faumai, Sirga, Kais and Klasafet formations. Main hydrocarbon sources are Klasafet shales and the main reservoir is Kais carbonates. Pre-Tertiary sediments are limited due to Late Cretaceous to Early Tertiary major uplift and erosion.

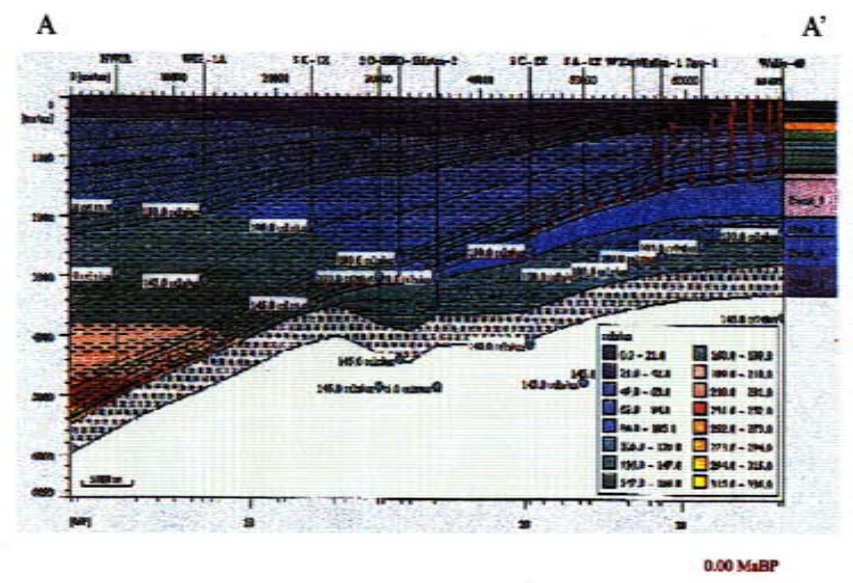
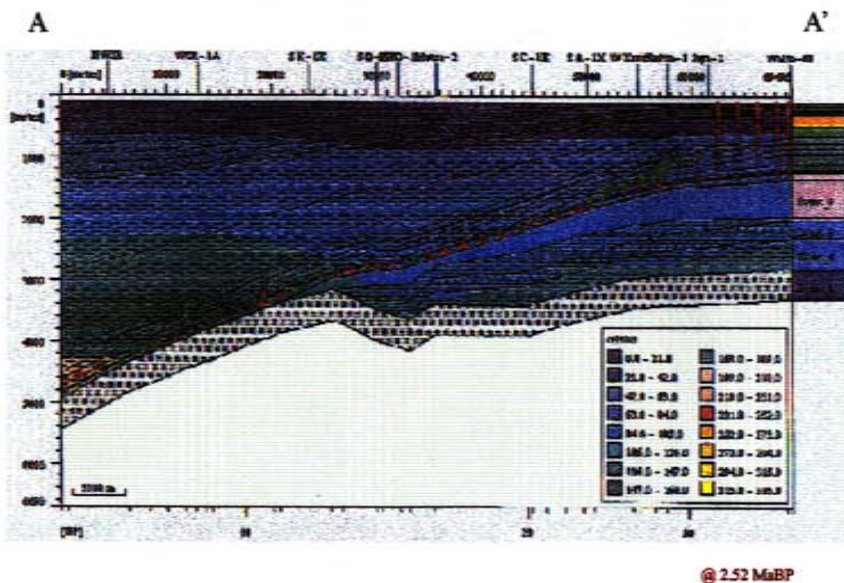
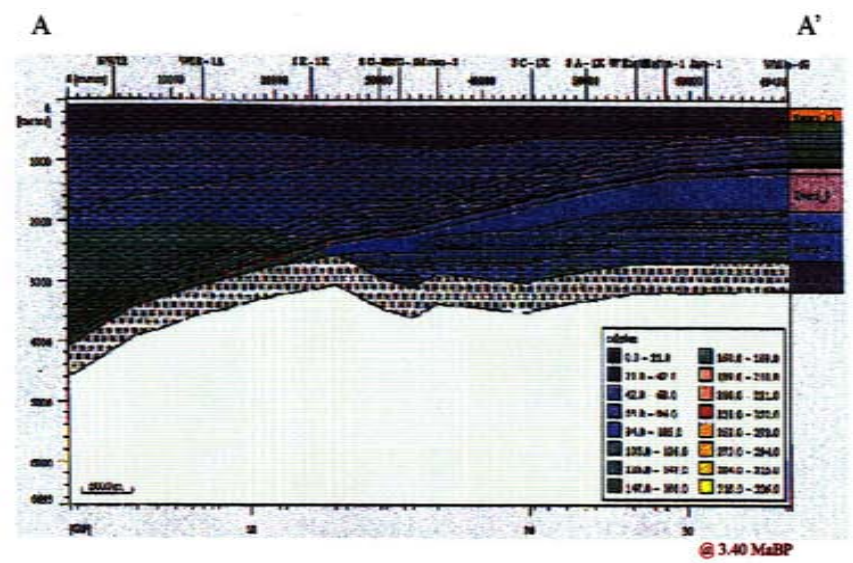
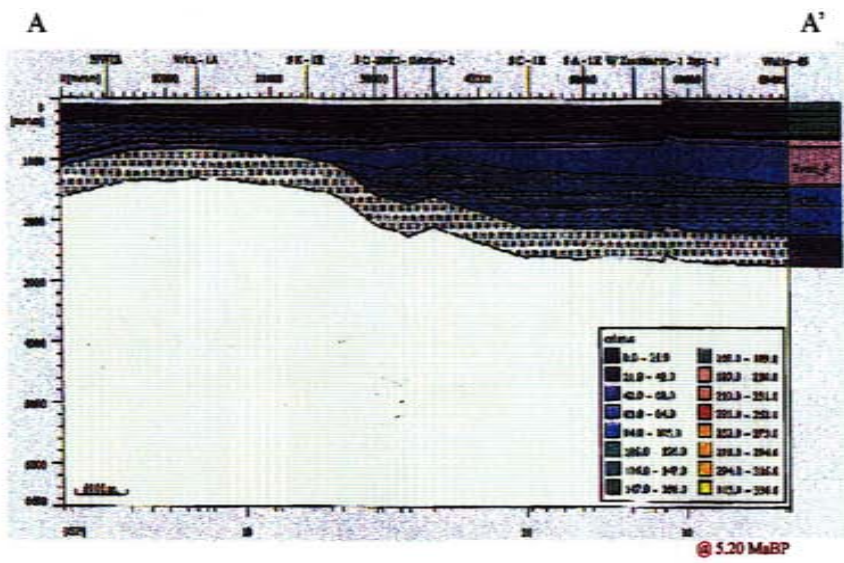
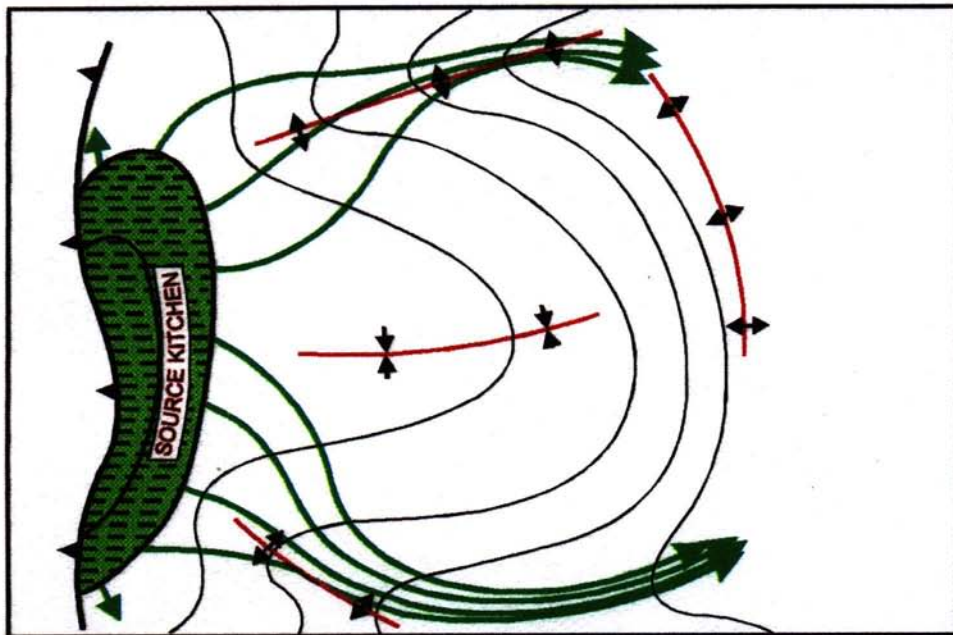
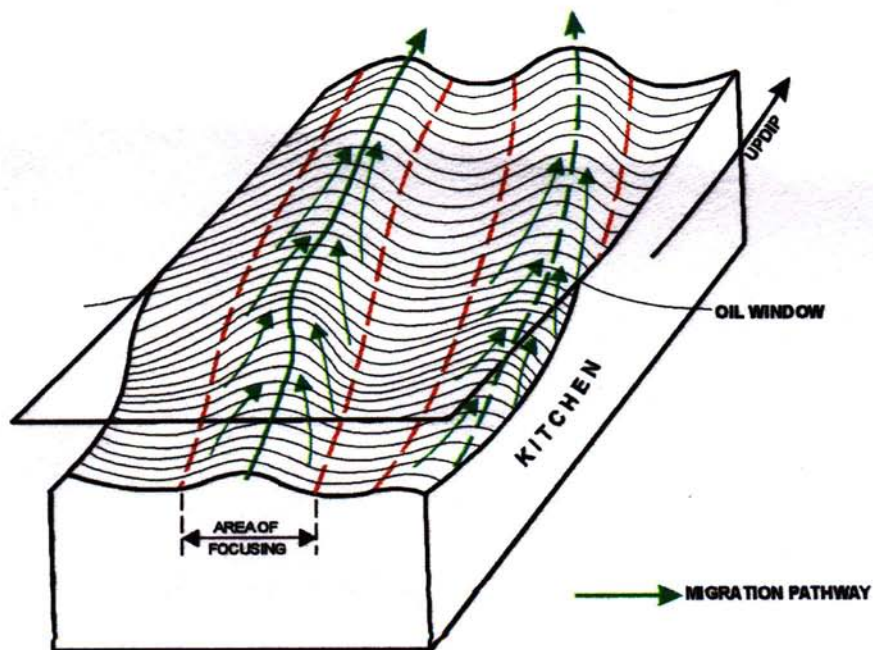


FIGURE 3 - Thermal modeling showing the generation, expulsion and migration of hydrocarbon within the Salawati Basin. Color plates at the lower right corner represents rock temperature in degree Celsius. Presented figures are selected to show the important events. There are no hydrocarbon generation in the base of Pliocene (5.2 Ma), peak oil generation and migration during the Late Pliocene (2.5 Ma) and present configuration (0 Ma). The location of this section is indicated on Figure 11.



(Allen and Allen, 1990)



SCHEMATIC MIGRATION THROUGH STRUCTURAL NOSES

FIGURE 4 - This schematic figure shows hydrocarbons migrating along pathways through carrier beds, which have the steepest slope (structural nose). This direction is perpendicular to the structural contour. Pathways are illustrated as lines drawn at right angles (orthogonal) to the structural contours.

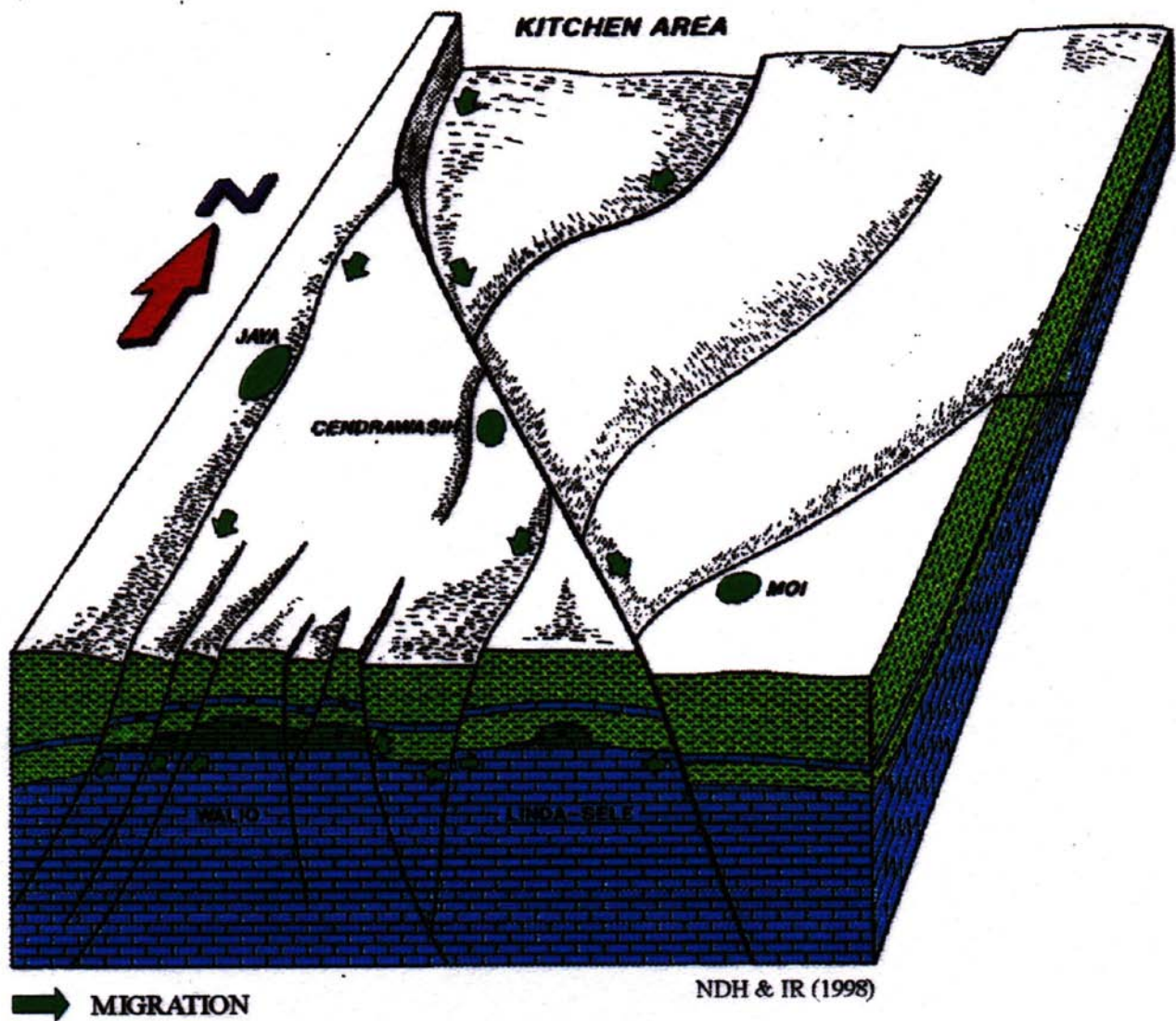


FIGURE 5 - Faulting influences source to trap migration. Numerous normal faults in the Walio Block are considered to have been used as conduits for hydrocarbon migration. Each field within this block is connected to its downdip kitchen by normal fault. See related map in figure 6.

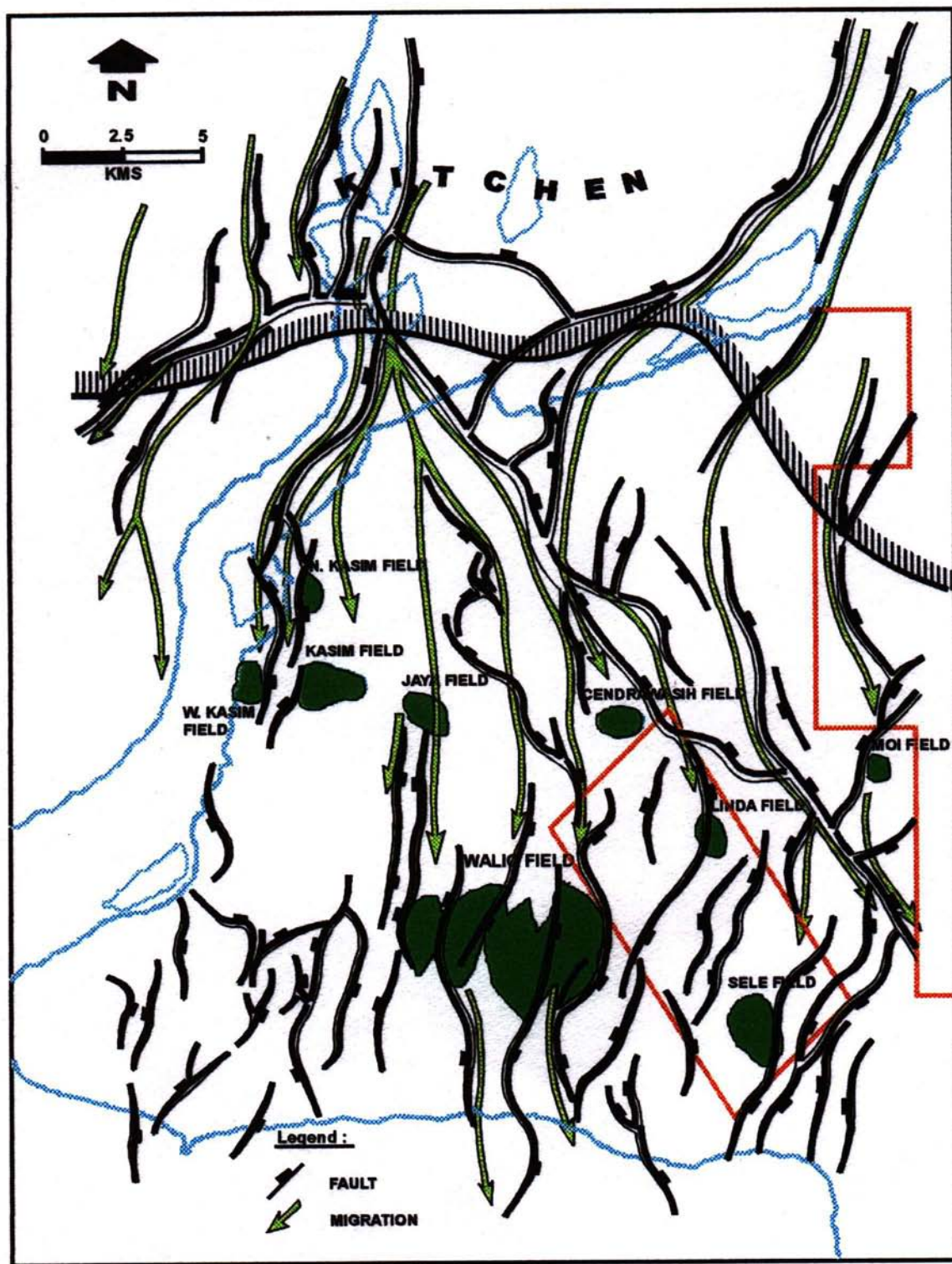


FIGURE 6 - Map showing numerous normal faults in the Walio Block have controlled migration pathways into oil fields. Each field within this block can be traced as connected to the downdip kitchen by faults. The contours are omitted for simplicity. These faults generally parallel migration along structural dip. The configuration has enhanced the migration flow (see related block diagram in Figure 5).

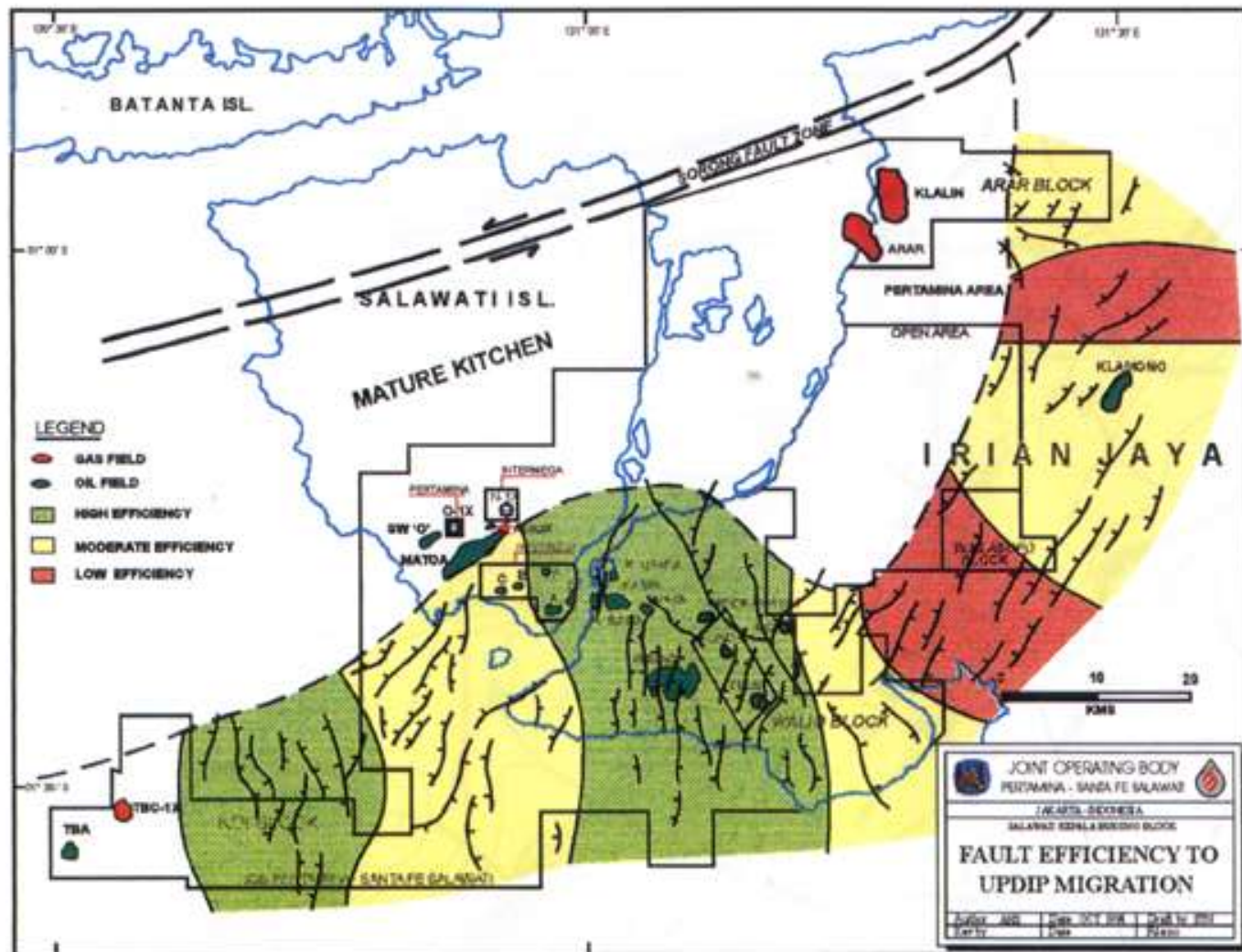


FIGURE 7 - General trends of normal faults of the Salawati Basin and their related effects to updip migration. High efficiency present in the Walio and Koi blocks are where faults are generally parallel with updip migration (see map in Figure 9 for updip migration).

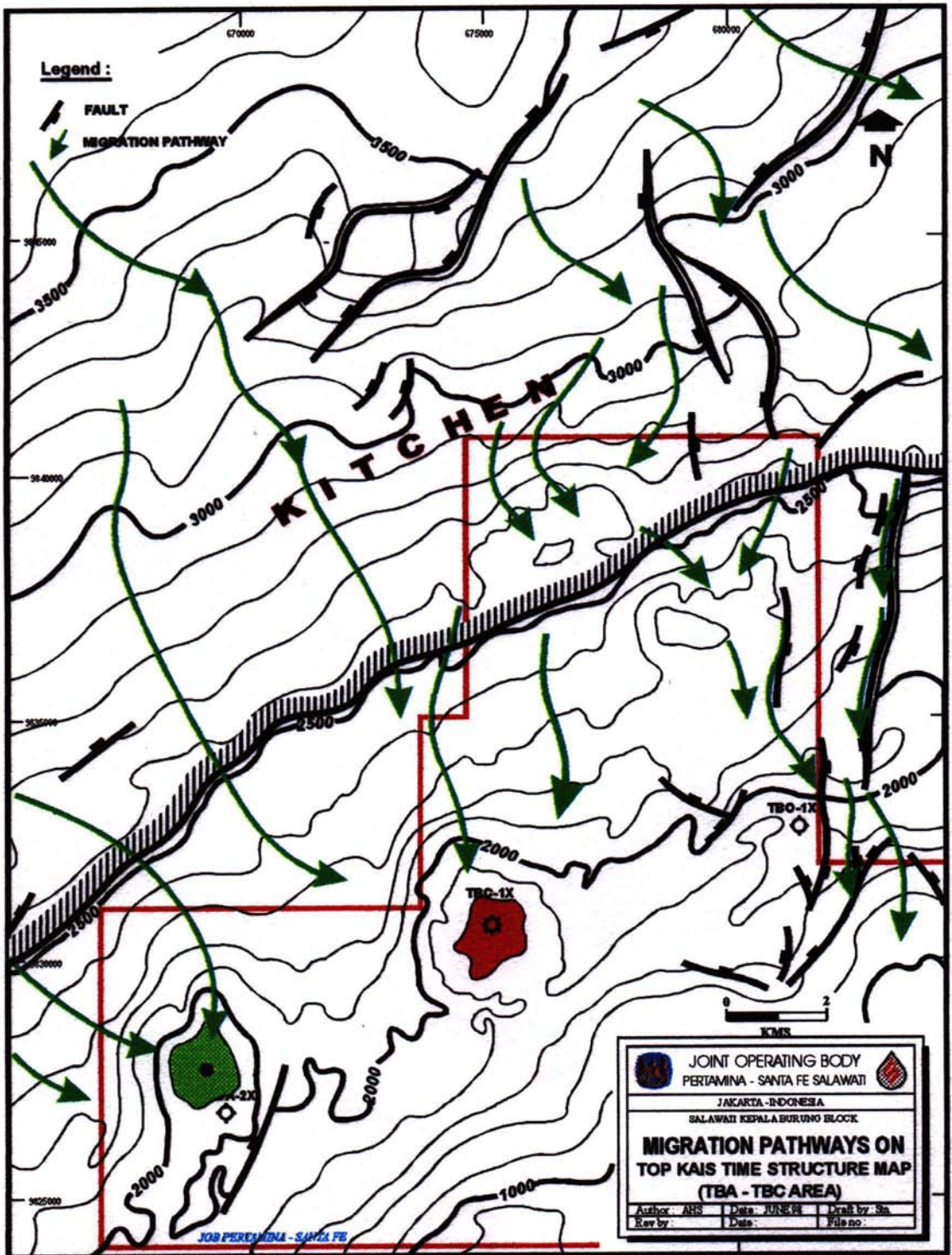


FIGURE 8 - Migration pathways in the TBA-TBC area, offshore southwest Salawati. The pathway is plotted on each recognized structural nose on the top Kais structure map.

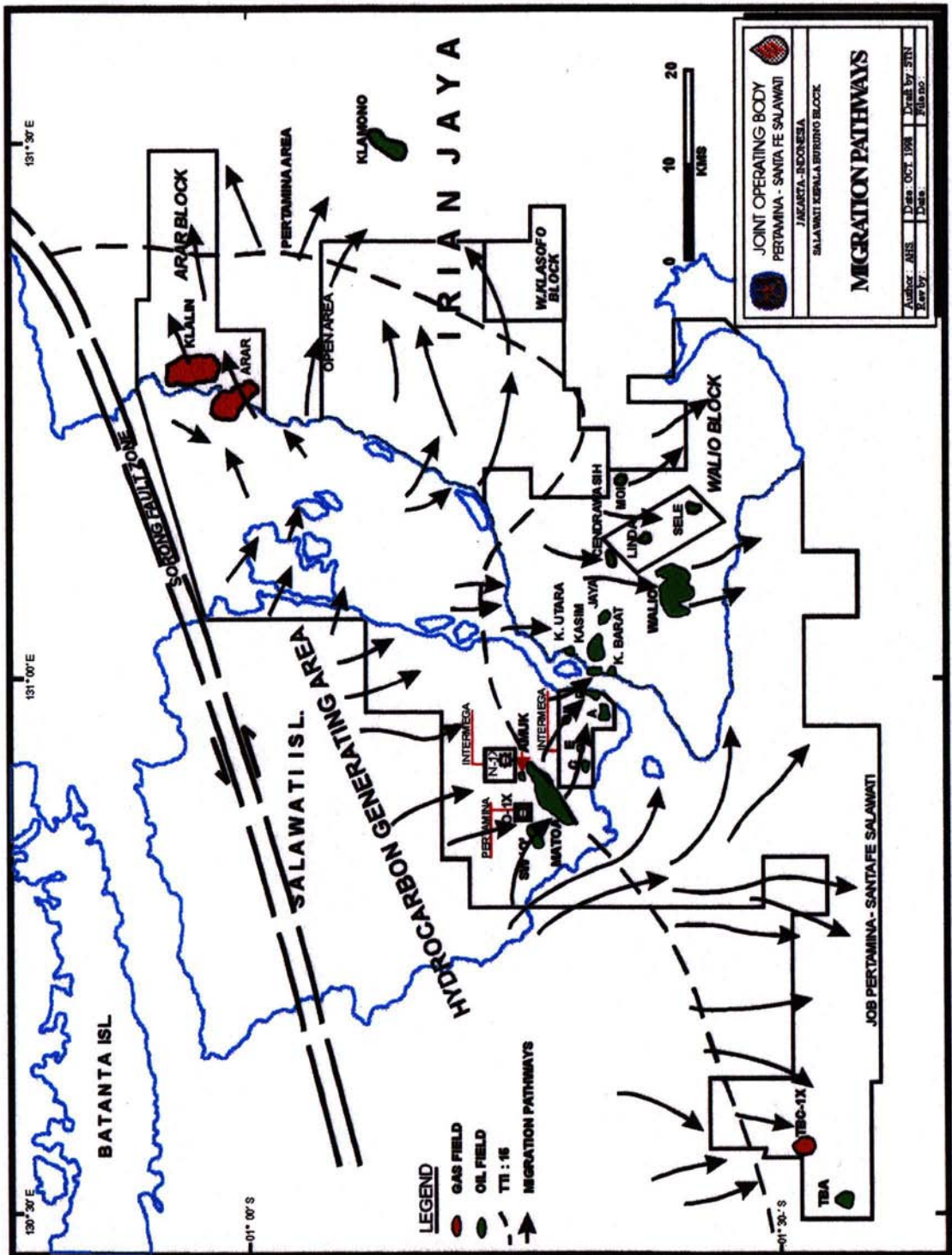


FIGURE 9 - General direction of hydrocarbon migration within the Salawati Basin mainly based on the structural noses.

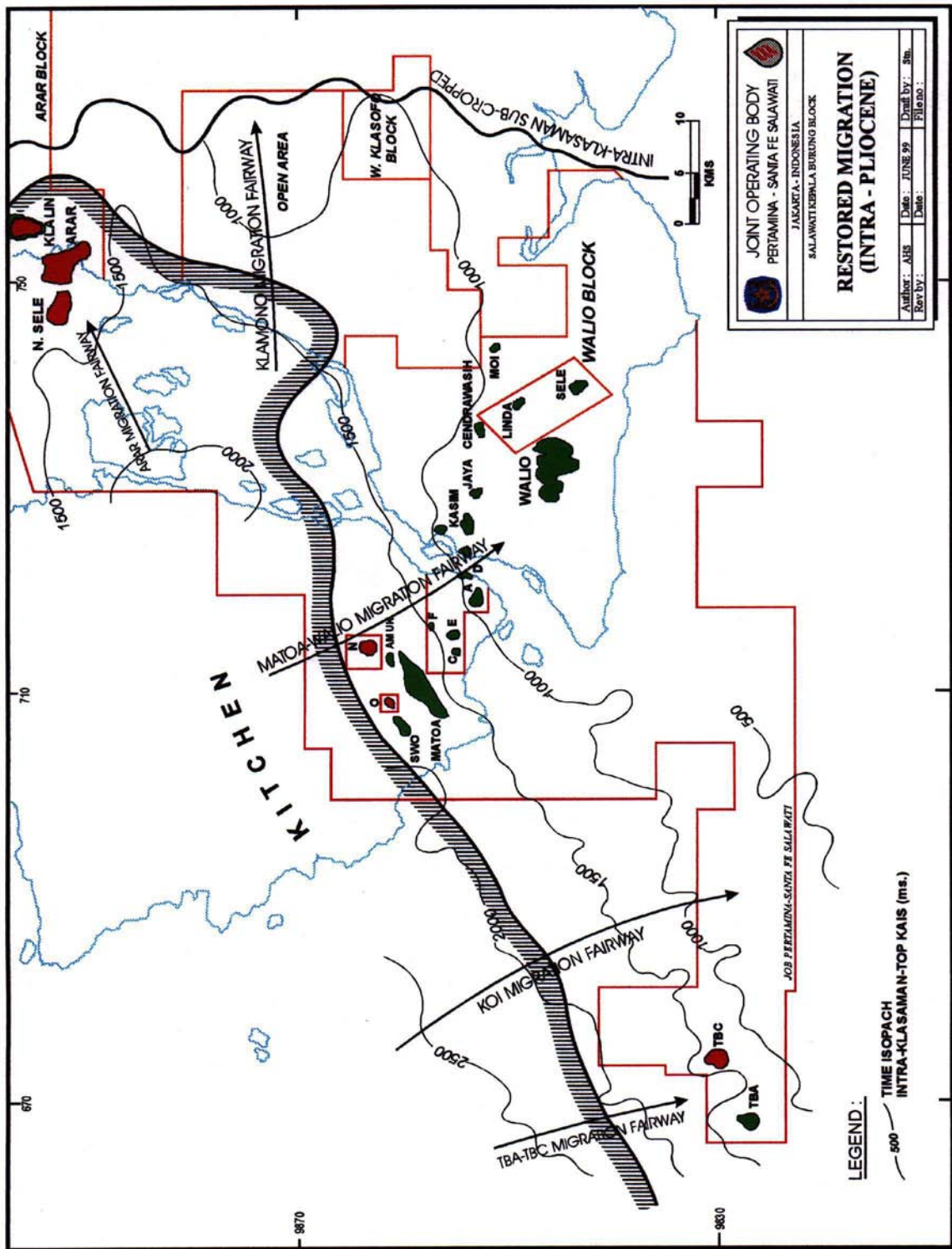


FIGURE 10 - Reconstructed migration pathways at intra-Pliocene time based on a time isopach map of intra-Klasaman (intra-Pliocene marker) to top Kais. Kitchen outline shifted downdip compared to the present kitchen. Each migration fairway exists at each regional structural nose. The map reveals that the general pattern of migration has remained constant for the last 3.5 million years (see Figure 11 for comparison).

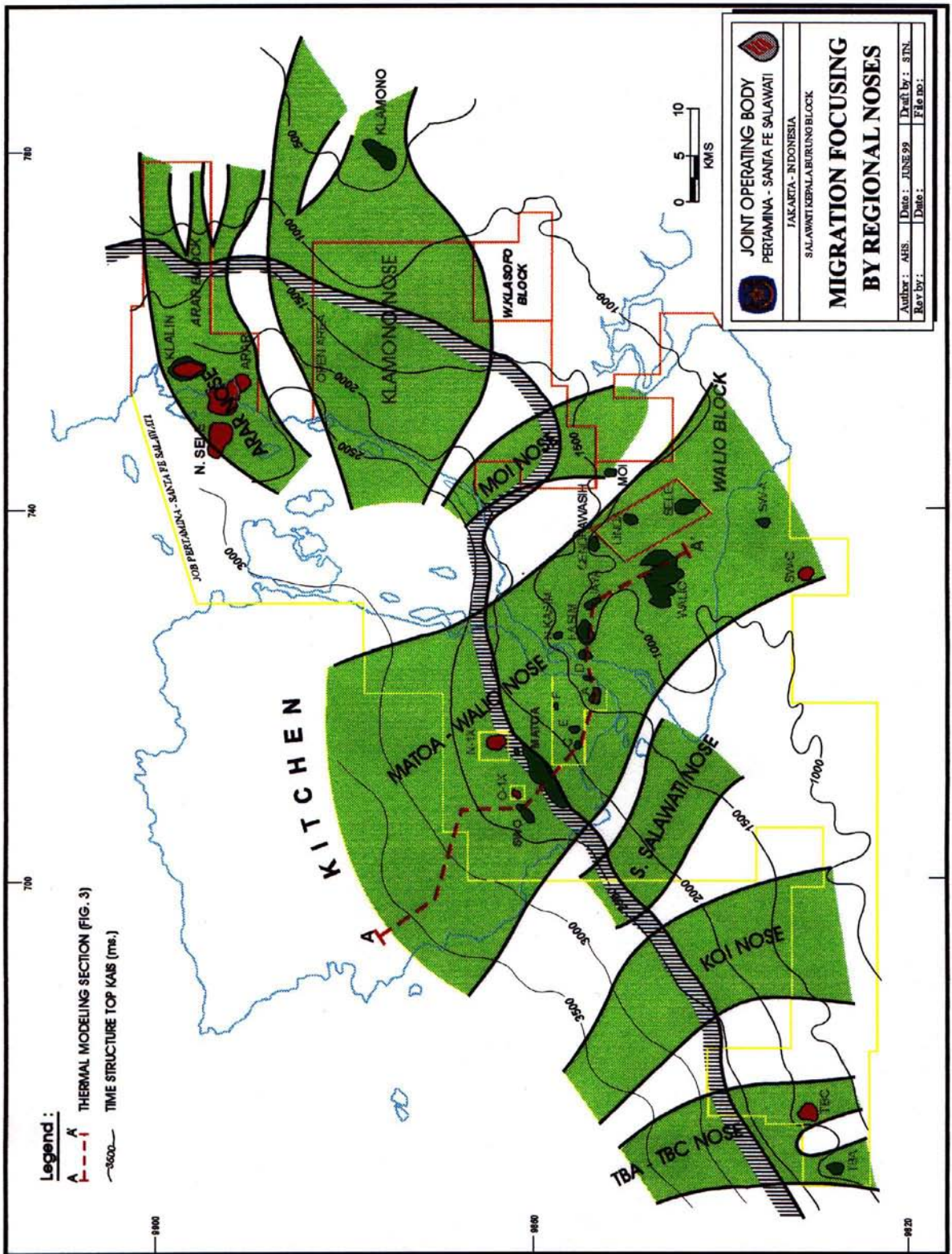


FIGURE 11 - Migration compartments of the Salawati Basin. Seven regional noses of the Salawati Basin have focused hydrocarbon migration to concentrate only in each nose and away from the flanking low areas. Note that all fields are located at the noses. Simplified and restored time Kais structure map is used as the basemap.

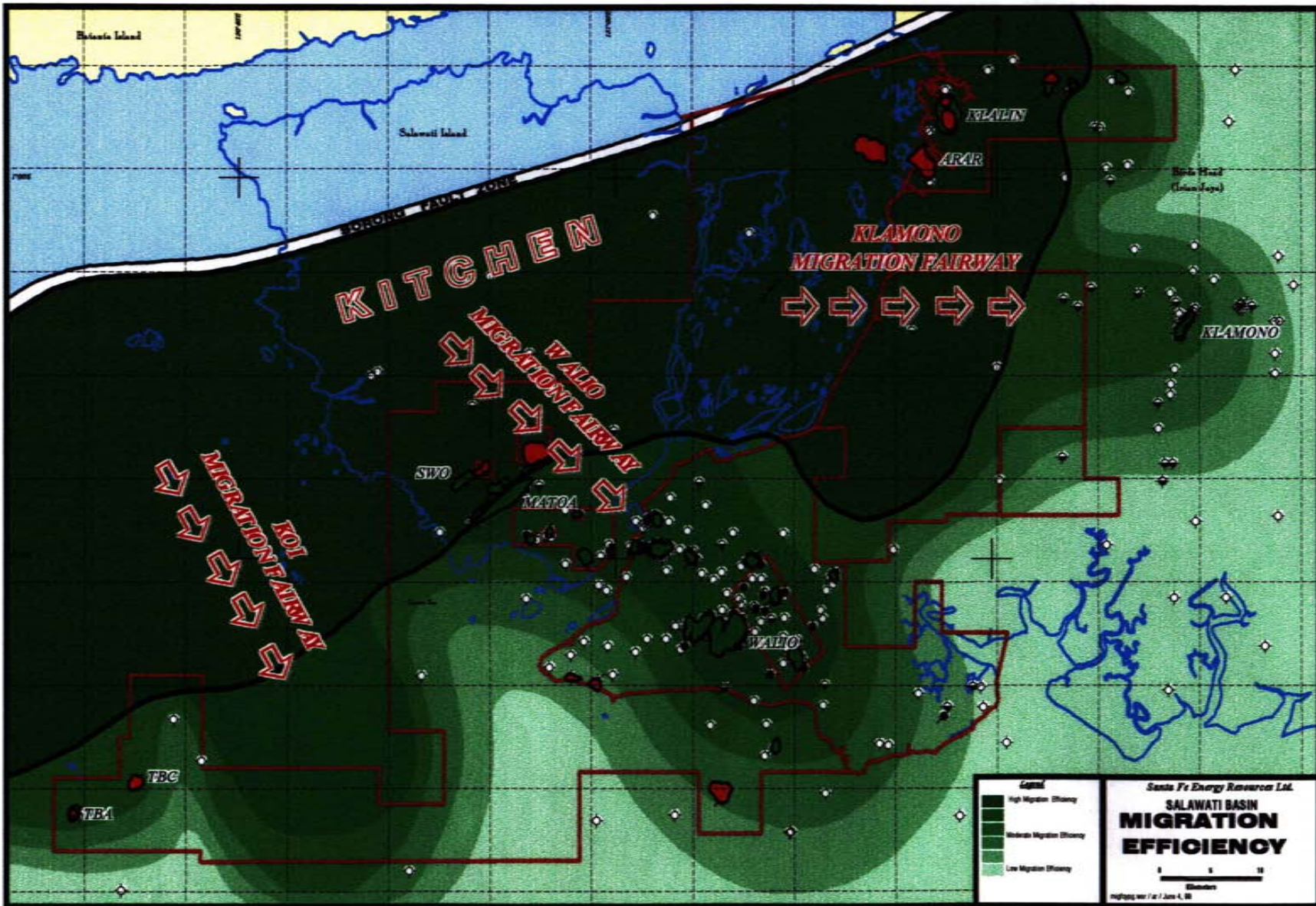


FIGURE 12 - Map showing migration efficiency of the Salawati Basin based on the presence of regional structural noses, fault trends and dry well analysis. The highest efficiency outside the kitchen occurs in the Walio and Koi areas where the interplay between structural nose and faults to control hydrocarbon migration reaches its best.