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Origin of Pliocene Deep-Water Sedimentation in Salawati Basin, Eastern Indonesia : Deposition in Inverted Basin and Exploration Implications

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ABSTRACT

Salawati Basin is a foreland basin located at the frontal edge of the Indian-Australian continental plate. Sorong Fault, a major strike-slip fault in Eastern Indonesia and terminating the basin to the north, has inverted the basin's polarity in the Late Pliocene by subsiding the whole northwestern part of the basin. Before this inversion, the Salawati Basin had a southern depocenter.

The newly formed northwestern depocenter has subsided rapidly since the inversion as an isostatic compensation to the southern and eastern uplifts. This condition resulted in the accommodation space for northwestern deep-water sedimentation. Sediments were eroded from the uplifted areas and deposited rapidly into the subsiding basin as debris flow deposits of Pliocene Klasaman sediments within bathyal depositional environment. The depocenter was increasingly subsided by tectonic loading of the contemporaneous Upper Klasaman multiple thrust sheets.

Thick deep Klasaman deposits became burial sediments for the Miocene source rocks once deposited in the lagoonal environment to attain a depth of oil window. Rapid Klasaman deposition triggered overpressuring and shale diapirism. The deposition was too fast for the sediments to compact and dewater in normal way. Overburden pressure and lack of permeable conduits caused the overpressuring. The Klasaman overpressuring presents a drilling hazard as undergone by all wells drilled in the area. Low densities of overpressured Klasaman shales caused the shales flowed upward as diapirs. Sorong Tectonism controlled these diapirs as shown by their parallel trends with the Sorong Fault. The Klasaman diapirism may relate with hydrocarbon traps of faulted domal structures, dragged beds below the diapirs' overhang zones, faulted beds in the peripheral sinks, and turtle structures.

INTRODUCTION

Recent success of exploring hydrocarbons in deep-water reservoirs throughout the world has enhanced the understanding of deep-water sedimentation. Concepts within seismic sequence stratigraphy have contributed very significantly to this success. However, understanding of the depositional system relating to various tectonic setting has not been fully understood. This paper contributes some concepts to this understanding by addressing the case in the Salawati Basin, Eastern Indonesia.

The Salawati Basin, Eastern Indonesia, based on our recent regional evaluation, is a poly-history basin with the history of basin's polarity inversion during its evolution. Sorong Fault Tectonism bordering the Salawati Basin to the north and west has strongly controlled the basin since the Pliocene. The Sorong Fault has inverted the basin's polarity from the old pre-Pliocene southern depocenter to the new Pliocene northwestern depocenter. Within the Pliocene, the new depocenter has subsided rapidly forming a deep-water basin. The Pliocene Klasaman sediments eroded from the

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southern and eastern uplifted areas were deposited very rapidly into the subsiding deep basin. The rapid Klasaman deposition triggered overpressuring and shale diapirism. Exploration implications of this Pliocene deep-water sedimentation are also addressed in the paper.

GEOLOGIC SETTING

The Salawati Basin is an east - west trending asymmetric foreland basin located on the northern margin of the Indo-Australian Plate. The deformed zone of the left-lateral Sorong Fault presently bounds the basin to the north and west. The present structural style of the basin is dominated by NNE - SSW normal faults formed as conjugates of the Sorong Fault. The Sorong Fault has also developed en echelon folds and synthetic left-lateral faults with normal slip in the Salawati Island. (*Figure 1*).

The Salawati Basin records the stratigraphic and tectonic history from Paleozoic time to the Recent (*Figure 2*). The oldest stratigraphic sequence of the basin is the continental basement rocks of the Siluro-Devonian Kemum metamorphic and Carbo-Permian Aifam sediments. Overlying the basement are Mesozoic sediments (Tipuma and Kembelangan groups). Tertiary sediments of the Salawati Basin began with the Late Eocene to Early Oligocene transgressive carbonates of the Faumai Formation. Overlying the carbonates, is the Late Oligocene shallow marine clastics of the Sirga Formation. Thick carbonates of the Miocene Kais Formation cover this formation. The thick Kais carbonate deposition was contemporaneous with the Klasafet lagoonal deposits. The Pliocene Klasaman clastics ended the Tertiary stratigraphic sequences composing the thickest sediments in the Salawati Basin. This paper discusses these sediments. Molassic deposits of the Pleistocene Sele conglomerates end the stratigraphy of the basin.

ORIGIN OF PLIOCENE SALAWATI DEEP-WATER BASIN

The Sorong Fault presently bounding the Salawati Basin to the north has strongly controlled the evolution of the basin. Regionally, 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. The fault trends east-west as left-lateral (sinistral strike-slip) fault.

Based on the thickness of the formations, it is known that the Salawati Basin has had a long history of dipping southward into which sediments from the Late Paleozoic to the Miocene thickened (*Figure 3*). Some formations onlapped to the north. However, this basin's polarity was disturbed significantly when the Sorong Fault Tectonism strongly controlled the basin's configuration.

At the Middle-Late Miocene time, the Salawati Basin started tilting southwestward possibly due to initial plates readjustment around the Northern Irian Jaya and Southwest Pacific. This had shifted the depocenter slightly to the southwest and consequently, the eastern part of the basin was uplifted. At the Mio-Pliocene, the Salawati Basin started to undergo significant tectonic changes. This was possibly related with the changes in plates movement around the north of Irian Jaya and the Southwest Pacific. The Sorong Fault was formed to accommodate the oblique convergence between the Philippine Sea Plate and northern Australian Continental Plate. The southern, southeastern, eastern and northeastern parts of the basin were increasingly uplifted. Consequently, the western, northwestern, and northern parts of the basin were subsided. This configuration resulted in the condition of reversed basin's polarity as compared to the conditions of the pre-Miocene periods.

In the end of mid-Pliocene, the Salawati Basin started to tilt significantly to the north, northwest and west providing large space of accommodation for depositing sediments eroded from the uplifted areas (*Figure 4*). Upper Klasaman sediments were rapidly deposited into this new basin which was contemporaneously subsiding. In this area, the Upper Klasaman reached its maximum thickness constituting more than two third of the basin's strata. The new basin, consequently, was more subsiding due to very thick burial loads. The basin also subsided due to tectonic response of isostatic compensation to the southern and eastern uplifting. Contemporaneously, the Sorong Tectonism was also taking place to deform the Upper Klasaman during the Late Pliocene. This has also subsided the new basin due to tectonic loading of the contemporaneous Upper Klasaman multiple thrust sheets.

Thus, there are at least three mechanisms which caused the inversion/reversal of the Salawati Basin's polarity resulting in a deep-water basin. They are : (1) subsidence due to isostatic compensation to uplifting, (2) subsidence due to very thick burial sediments, and (3) subsidence due to tectonic loading of multiple thrust sheets. These three mechanisms are related to each other and triggered by the Sorong Tectonism.

DEEP-WATER SEDIMENTATION OF KLASAMAN

Uplifted areas in the southern, eastern, and northeastern parts of the Salawati Basin became the provenances of the Pliocene Klasaman sediments deposited in the subsiding northern and western basin. These provenances were : (1) to the south and east were the uplifted Miocene Kais carbonates of the Misool-Onin Geanticline and the Ayamaru Platform respectively and (2) to the northeast was continental basement, metasediments, oceanic fragments, and some Kais/Klasafet sediments of the Kemum High.

Klasaman sedimentation was started by the deposition of the Early Pliocene Lower Klasaman in inner to outer sublittoral environments with lagoonal facies developed in some areas. This formation mainly consists of calcareous shales with limestone and siltstone stringers indicating provenances of uplifted Klasafet and Kais carbonates. The Lower Klasaman slightly thickens to the north revealing the first emergence of the northern depocenter. Before this, all pre-Lower Klasaman formations thickened to the south. This indicates that the inversion of the Salawati Basin's polarity initially occurred in the Early Pliocene.

Significant deep-water sedimentation took place when the Late Pliocene Upper Klasaman sediments were deposited. This period was contemporaneous with the initiation of major episode of the Sorong Tectonism. The Kemum High at the northeastern part of the basin contributed most of the sediments. Huge volume of the Upper Klasaman sediments was deposited into the basin mostly as turbiditic debris flow within bathyal setting. Marly clays with a more or less silts and sands dominate the deep-water sedimentation in the northwestern area (*Figure 5*). The sediments close to the provenance (in the Sele Strait area) are characterized dominantly by coarse sands with significant lithic content. More to the west and northwest, the depositional environment was increasingly deeper since the basin was more tilting. In this area, the bathyal condition was reached and the sediments obtained their highest rate of sedimentation (*Figure 6*). Three wells penetrating the sediments in this region generally consist of rapid alternation of clays, siltstones and sandstones.

KLASAMAN SHALE DIAPIRISM

Shale-dominating Lower Klasaman and coarser rapid deposits of Upper Klasaman triggered the Klasaman shale/mud diapirism. Mud diapirism is mostlikely to develop in clay sequences underneath the thick, rapidly deposited regressive sandy sequences (Allen and Allen, 1990). Subsidence of the Salawati Basin is approximately equaled by the rise of the Klasaman diapir. The deposition of the Upper Klasaman was too fast for the Lower Klasaman clays to compact and dewater in normal way. Low densities of overpressured Klasaman clays caused the clays flowed upward as diapirs. Doming and piercing of diapiric materials occur primarily because the density of the plastic materials is lower than that of the overlying sediments (O'Brien, 1968; Lemon, 1985). This density inversion causes gravitational instability or tectonic vertical stress.

The distribution of the Klasaman diapirs shows an alignment with the major structural element (*Figure 7)*, indicating that these diapirs were triggered tectonically by the horizontal stress of the Sorong Fault Tectonism.

Seismic sections (*Figures 8,9*) show that the Klasaman diapirs had passed through all stages of diapiric development : (1) pillow, (2) diapir, and (3) post-diapir stages. Structures associated with these three stages are observed. Rim synclines were formed right to the diapirs and are increasingly steeper towards the younger section. The peripheral sinks immediately adjacent to the rim synclines were the sites of active subsidence and therefore the sites for considerable thickening of the sediments being deposited at that time. At the upper section, reverse and thrust faults were formed within the peripheral sinks. The faults generally verge to the south. Turtle structure is also observed to form. Underlying the diapirs, the Klasafet and Kais formations are deformed by normal faults down to the north. These faults are compensating faults due to the basin subsidence to the north. Overlying the diapirs, the uppermost section of the Klasaman was deformed as surface anticlines or faults, partly forming the fold and thrust belts of North Salawati.

EXPLORATION IMPLICATIONS

Deep-water Klasaman sedimentation have some implications on hydrocarbon exploration. Three aspects are discussed : presence of diapiric traps, maturation of hydrocarbon sources, and drilling hazard due to overpressuring.

The Klasaman diapirism may relate with hydrocarbon traps (*Figures 8, 9*). The flowing and doming of plastic materials at deep levels play an important role in the formation of oil and gas traps in overlying strata (Wang Xie-Pei *et al.*, 1982). Evidence that the Klasaman diapirism is closely related with the hydrocarbon accumulation is shown by numerous oil and gas seeps at the fold and thrust belts of North Salawati. These fold and thrust belts partly represent the faulted domal structures overlying the diapirs. The dragged Intra-Klasaman sand beds against the walls of the diapirs and below the overhang zones of the diapirs also provide the diapiric traps. Faulted beds in the upper sections of the Klasaman Formation and turtle structures within the peripheral sinks are potential hydrocarbon traps as well. Reservoir quality of Intra-Klasaman sands and the presence of faults for vertical migration conduits connecting mature Lower Klasaman, Klasafet and Kais sources with the Intra-Klasaman traps seems to hold the keys for hydrocarbon accumulation. In the absence of these conduits, then the interbedded Intra-Klasaman shales should be mature and have generative capacity to make the accumulation possible.

Miocene Klasafet/Kais shales and carbonates are the proven main source rocks of the Salawati Basin. The sediments were deposited in lagoonal environment at the northern area when the basin still tilted to the south (*Figure 10*). As the basin's polarity inversion took place, the area subsided to the north and was immediately deeply buried by the Klasaman sediments to attain a such depth of the oil window. Hydrocarbons were generated and started to migrate updip. Thermal modeling revealed that 3.8 Ma (mid-Pliocene time) as the initiation of major oil generation from the Klasafet/Kais and this was contemporaneous with the commencement of the basin's polarity inversion. The Early Pliocene Lower Klasaman shales are also proven source rocks and they also became mature when very thick Upper Klasaman sediments buried these sources.

Klasaman overpressuring presents a drilling hazard. Three wells drilled in this area : Waipili-1 (1956), Waibu-1 (1957), and West Island Reef (WIR) -1 (1993) all encountered drilling problem due to penetrating overpressured Klasaman shales. Waipili-1 found gas activity and a blowout in the shallow Upper Klasaman sediments. Waibu-1 and WIR-1 encountered severe technical difficulties in the overpressured Klasaman shales and each well was sidetracked into four sidetrack holes due to pipe sticking. Later seismic data (1991) show that both Waipili-1 and Waibu-1 wells are located at the diapiric surface anticlines.

CONCLUSIONS

- The Salawati Basin, Eastern Indonesia, records the deep-water sedimentation of the Late Pliocene Upper Klasaman sediments. This deep-water basin was formed by the inversion of the basin's polarity and was strongly controlled by the Sorong Tectonism.
- The Upper Klasaman sediments were deposited very rapidly into the subsiding basin and the sedimentation has triggered the diapirism within the deep basin.
- Rapid deposition of the Upper Klasaman sediments has three exploration implications : (1) to subside the Salawati Basin to the depth of oil window, (2) to provide diapiric hydrocarbon traps, and (3) to present drilling hazard due to diapiric overpressuring.

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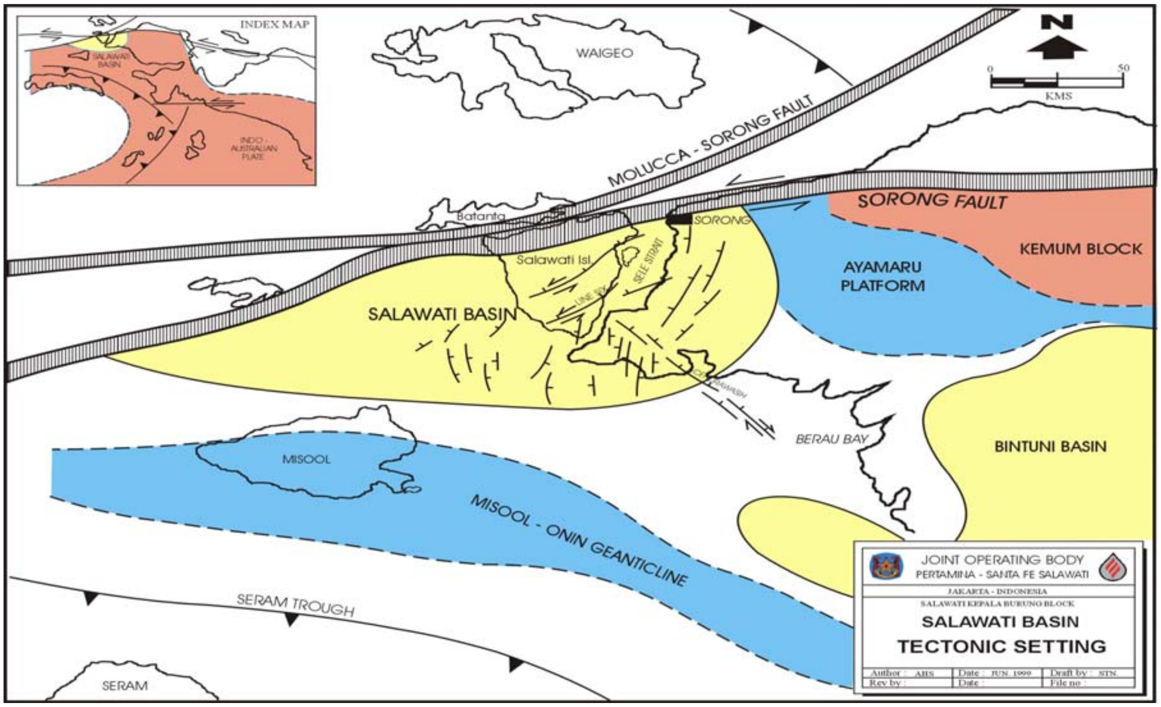


Figure 1 Salawati Basin tectonic setting and major structural elements.

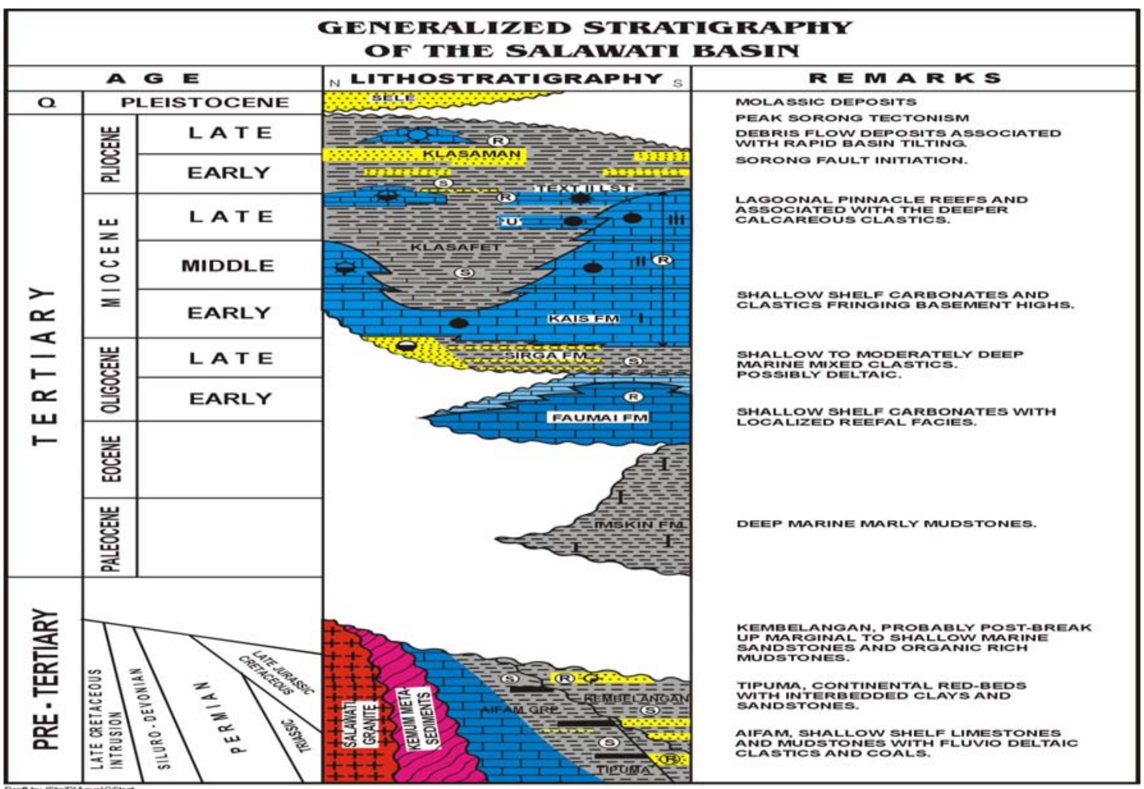


Figure 2 Generalized stratigraphy of the Salawati Basin and significant geologic episodes.

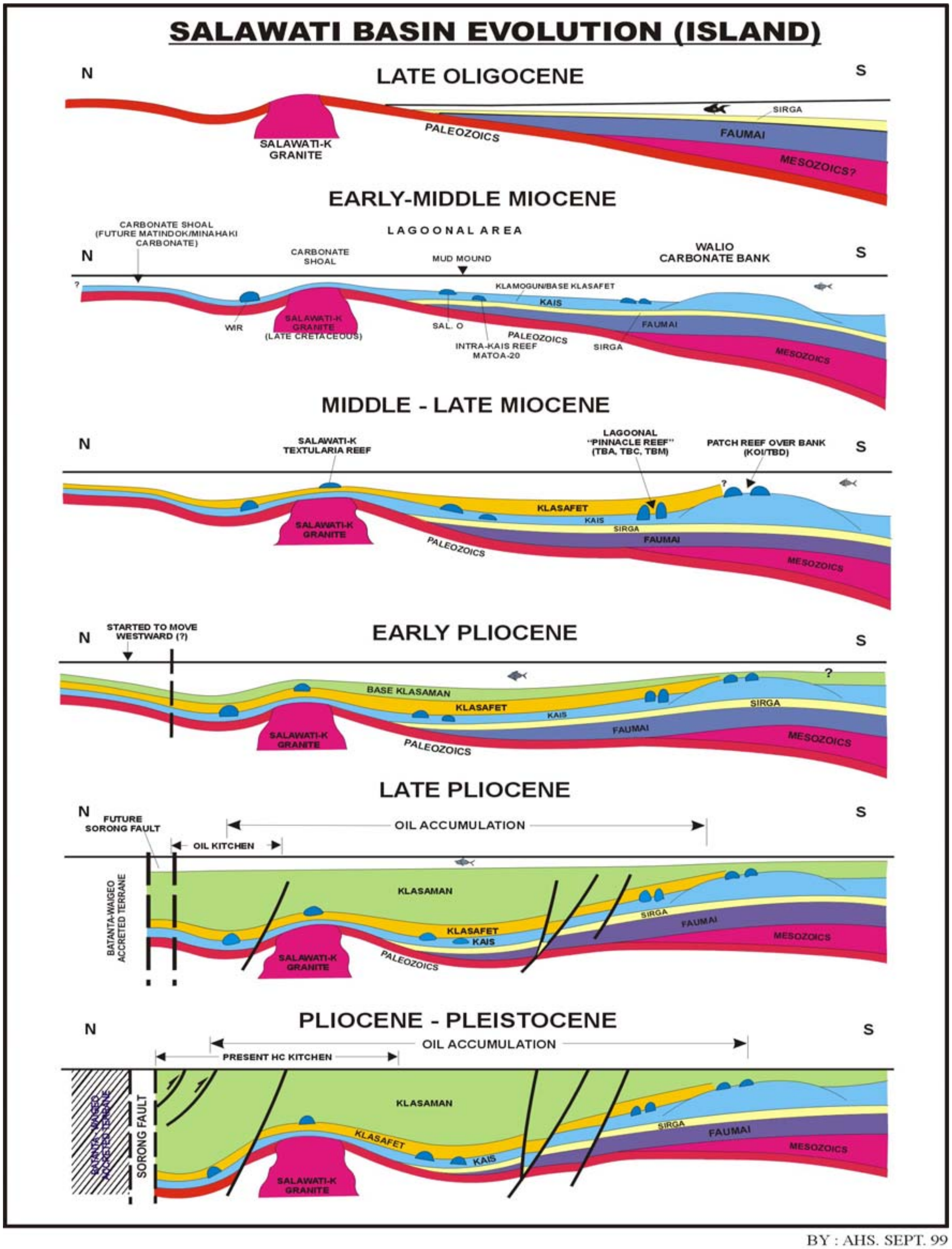


Figure 3 Salawati Basin evolution showing the inversion of the basin's polarity in Late Pliocene time.

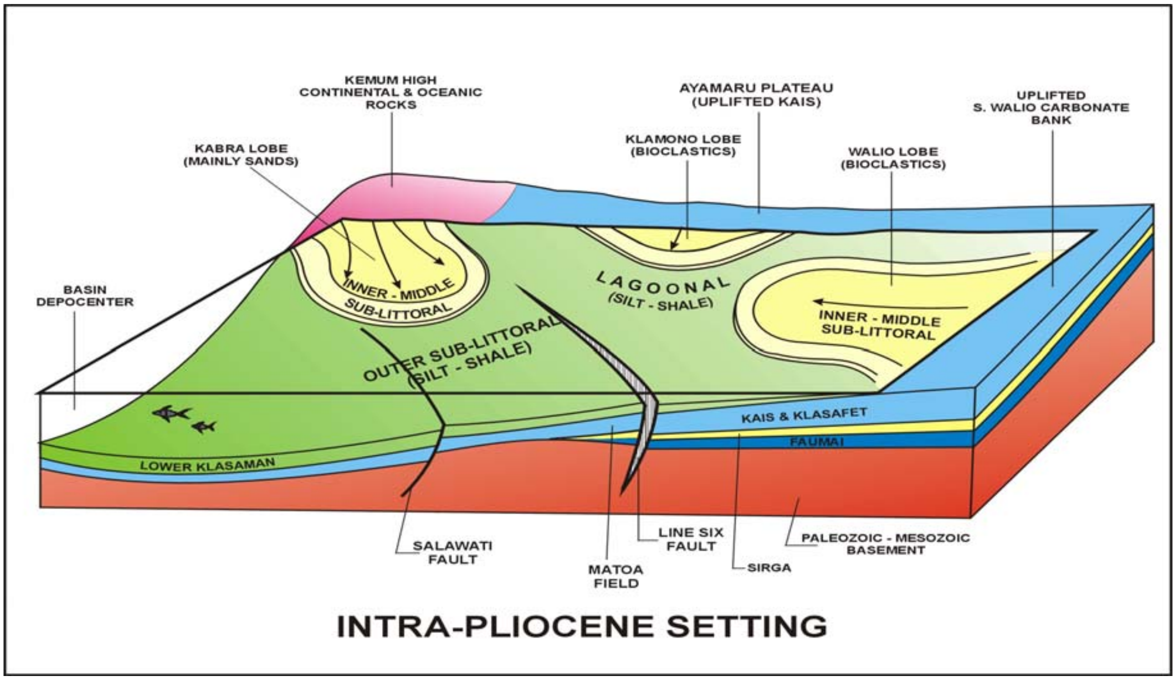


Figure 4 Deep-water setting of the northwestern part of the Salawati Basin depocenter.

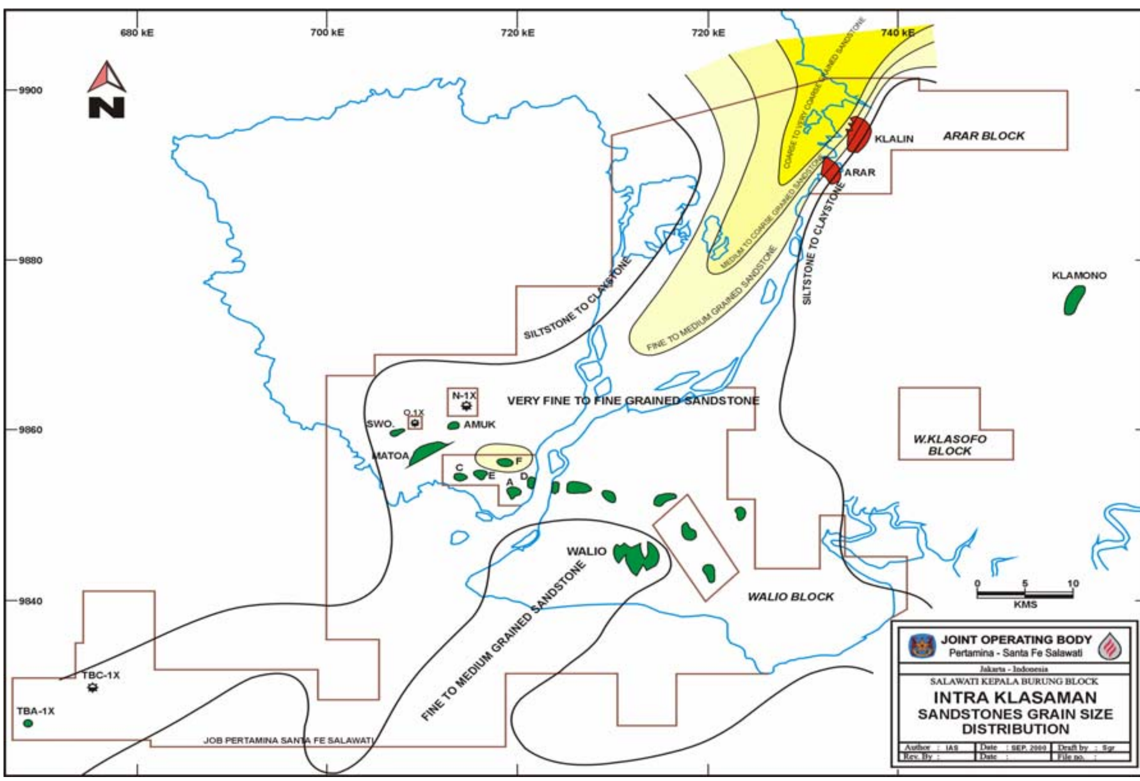
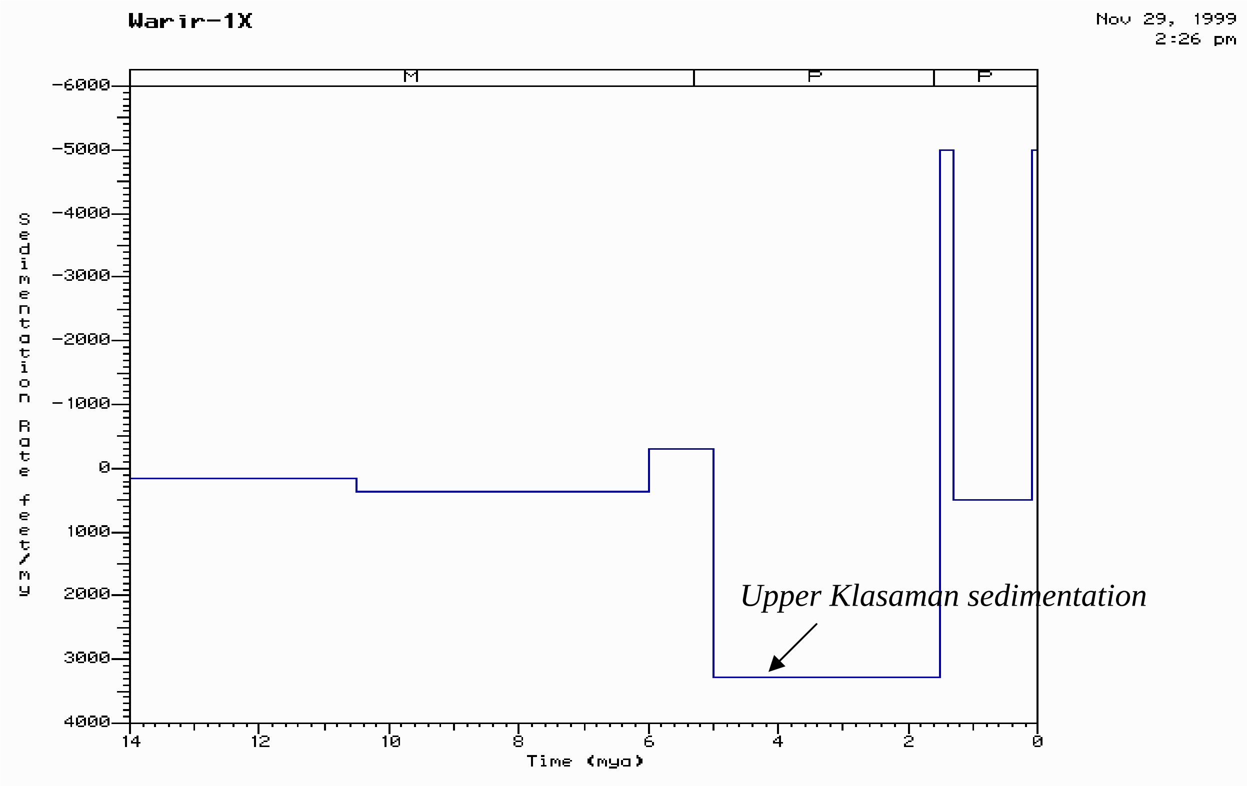


Figure 5 Upper Klasaman sedimentation. Deep-water setting took place in the northwestern partof the basin.



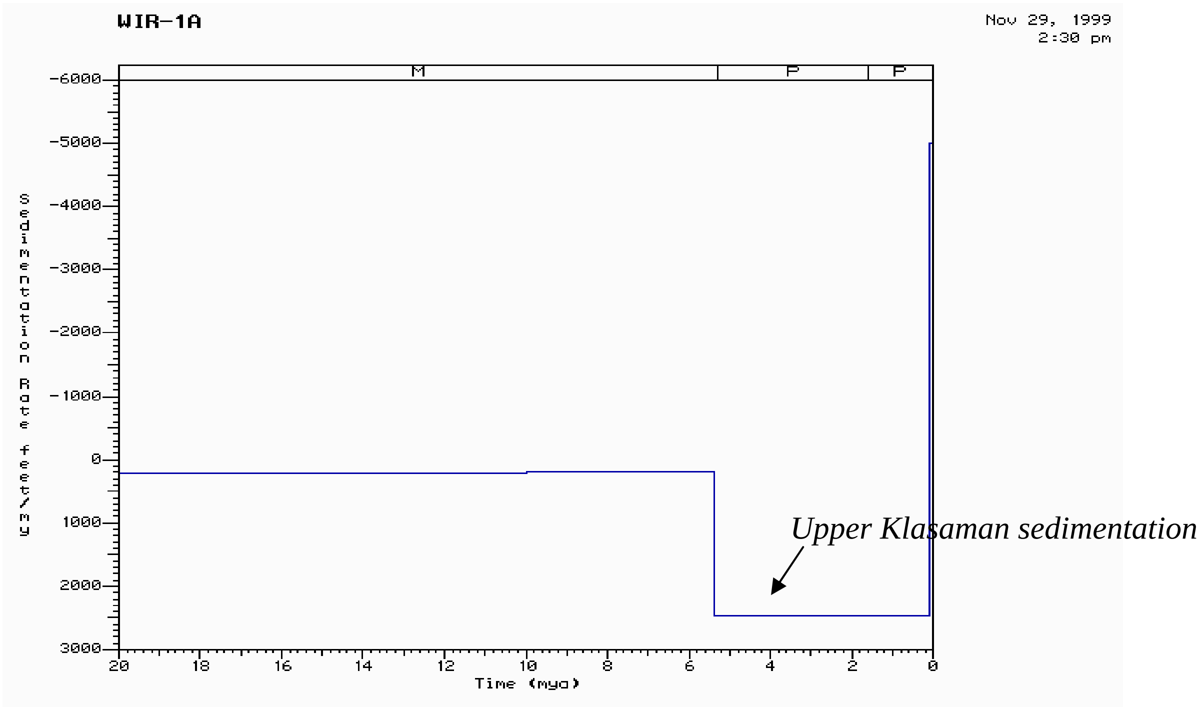


Figure 6 Rapid subsidence and deposition of Upper Klasaman sediments from 2300 to 3800 feet/million year. The wells are located in the Upper-Klasaman deep-water sedimentation.

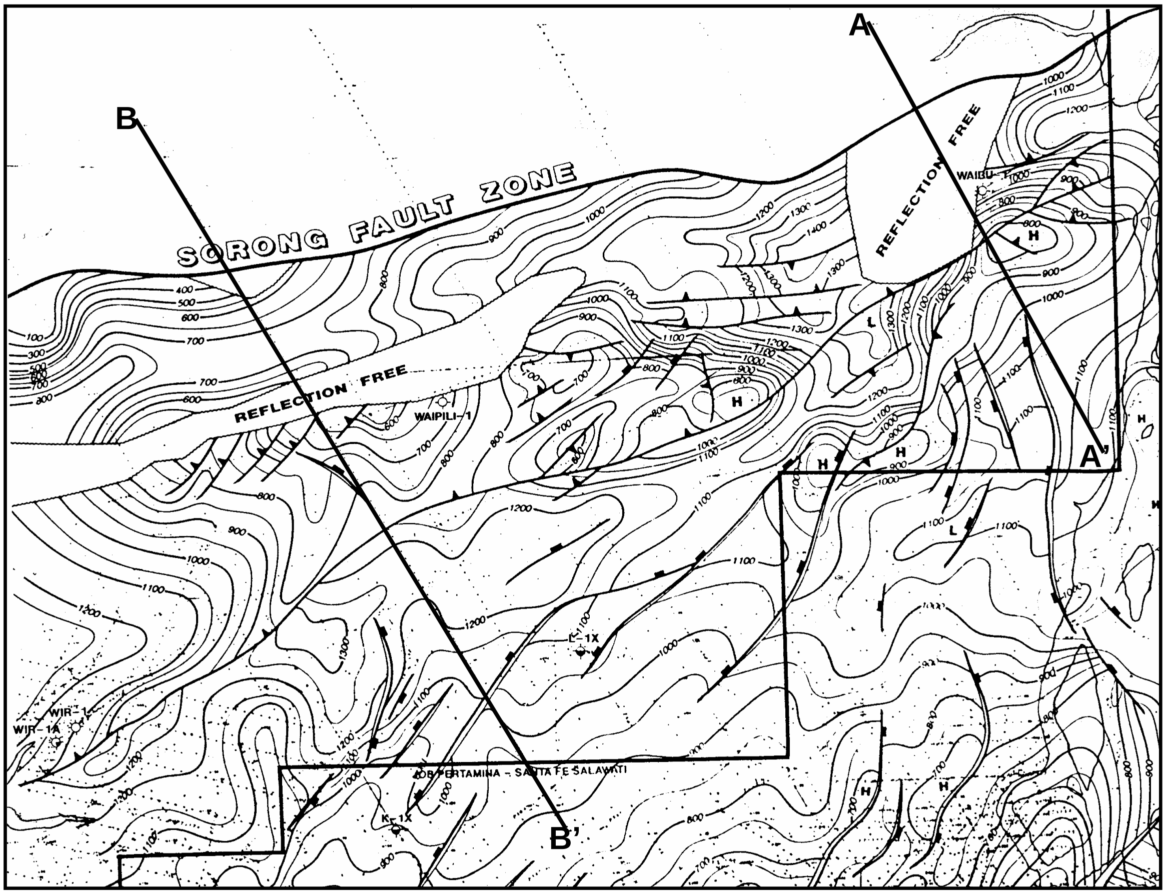


Figure 7 Top Intra-Klasaman time structure map showing the distribution of the Klasaman diapirs (reflection free area) which are parallel with the Sorong Fault. Representative seismic sections A-A' and B-B' are indicated.

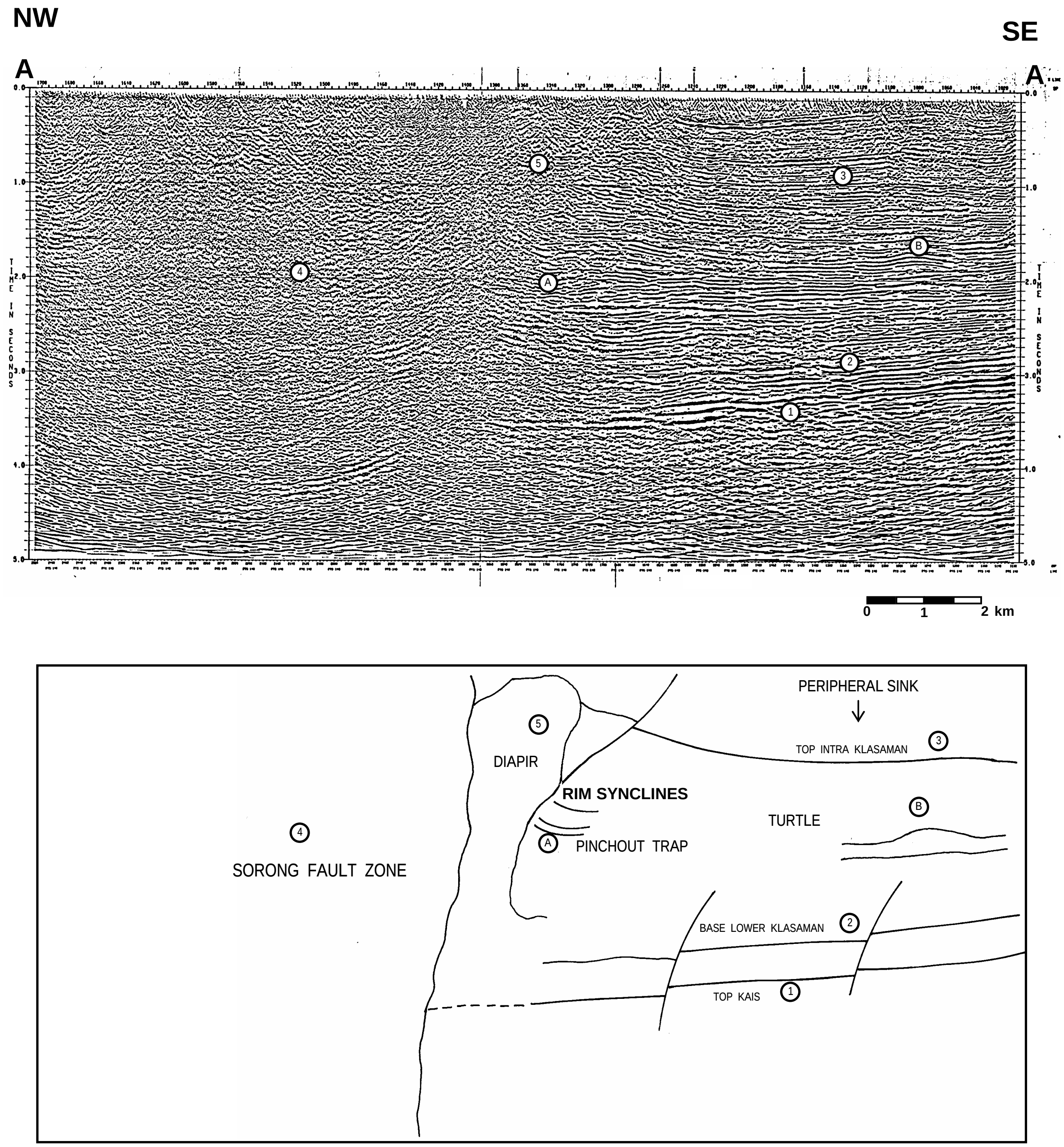
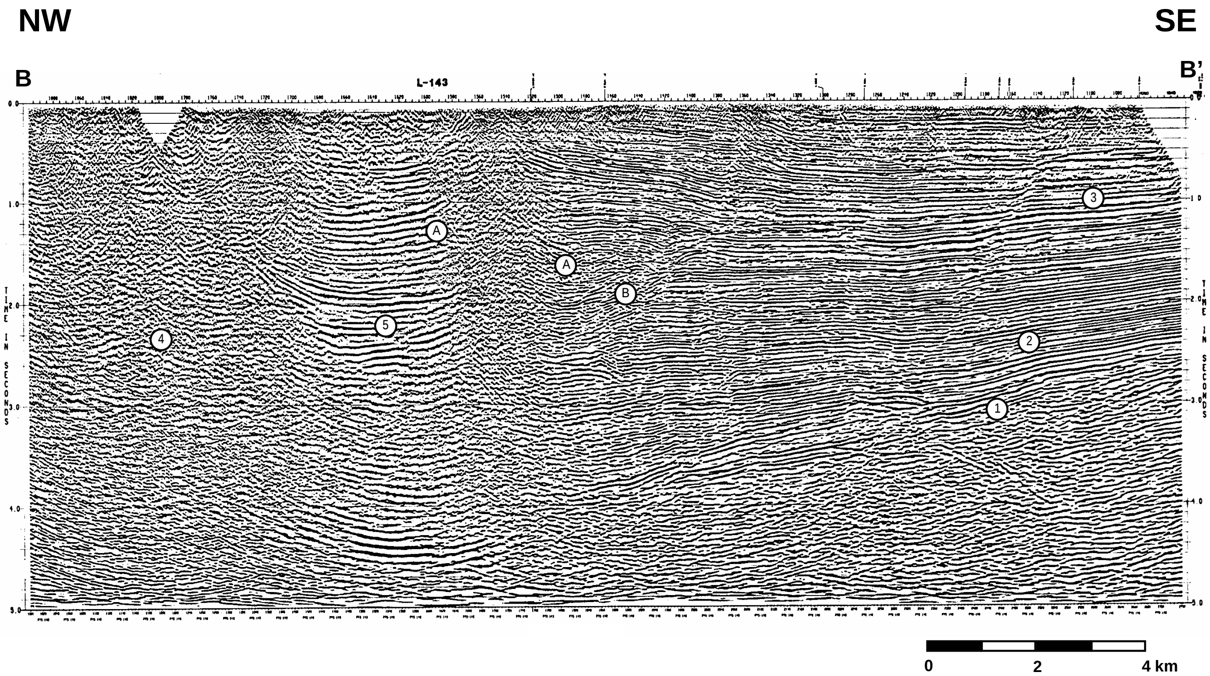


Figure 8 Seismic line and geologic interpretation of section A-A' showing structure and potential traps associated with the Klasaman diapirsm.



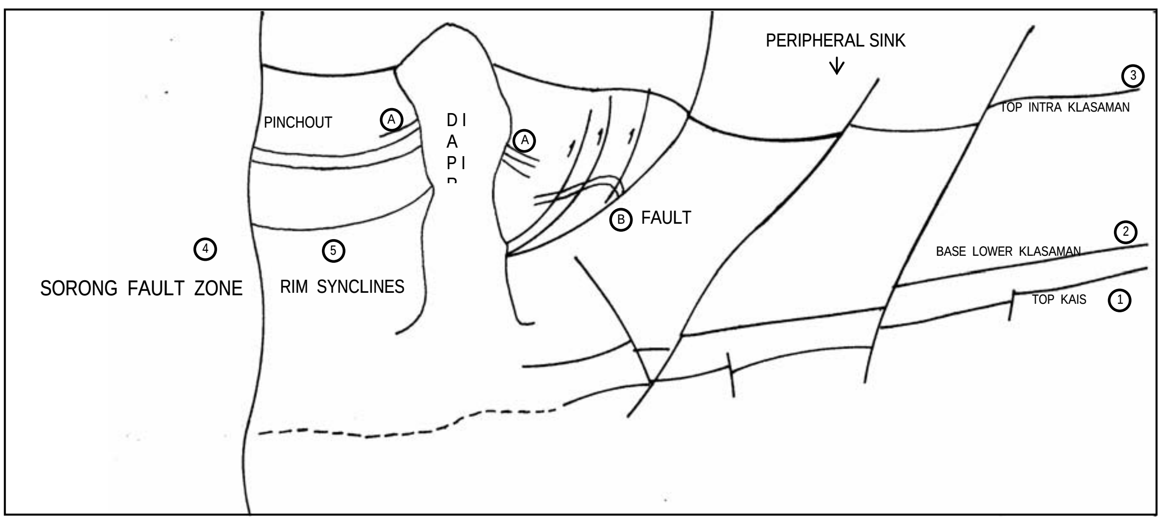


Figure 9 Seismic line and geologic interpretation of section B-B' showing structure and potential traps associated with the Klasaman diapirsm.

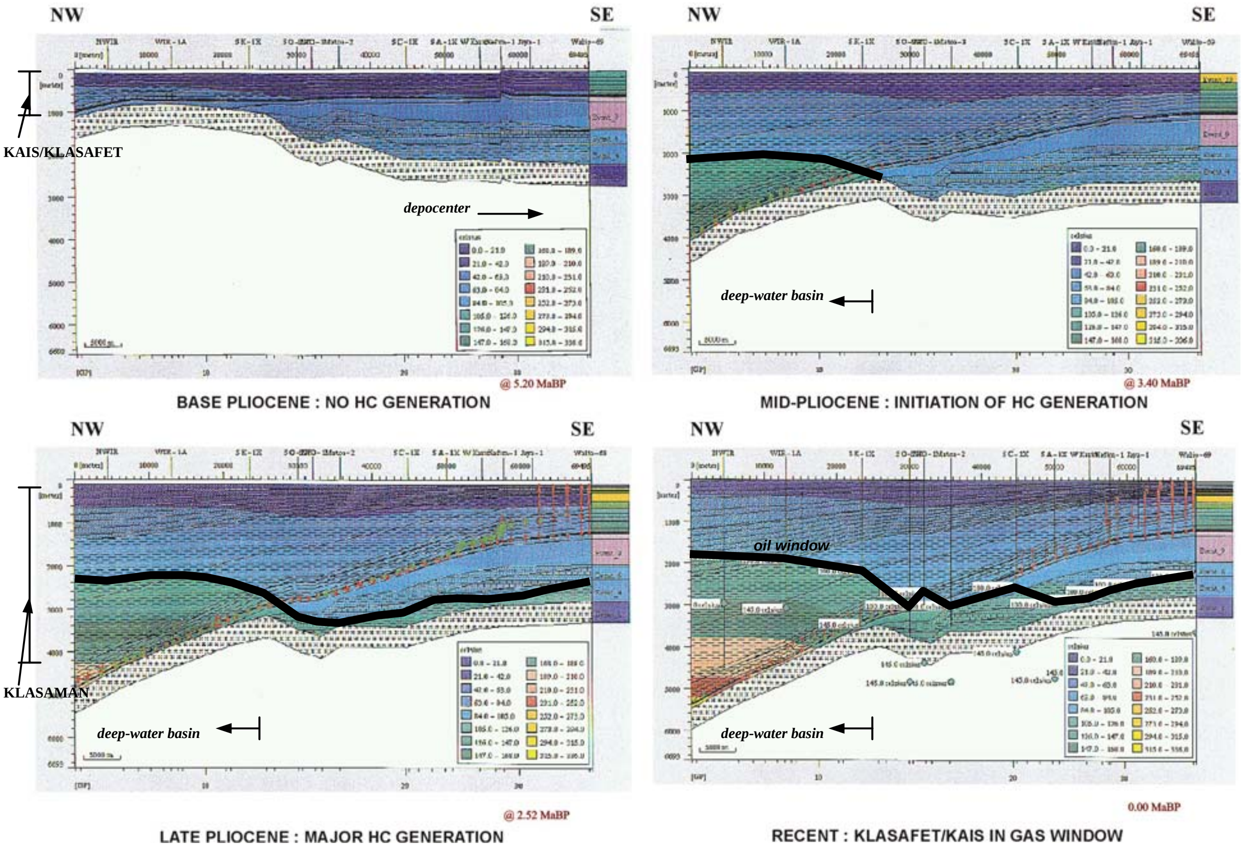


Figure 10 Basin modeling showing the effect of inversion of the Salawati Basin's polarity.