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RE-EVALUATION OF THE SEDIMENTOLOGY AND EVOLUTION OF THE KAIS CARBONATE PLATFORM, SALAWATI BASIN, EASTERN INDONESIA: EXPLORATION SIGNIFICANCE

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ABSTRACT

Miocene Kais carbonates of the Salawati Basin have been productive reservoirs since 1936. There have been approximately 160 exploration wells drilled in the basin targeting the carbonates. As many as 30 fields have been discovered which have produced 375 MMBO and 175 BCFG through 2002. Because of extensive exploration, there is a large amount of data available on Kais carbonates and several studies on the carbonates, both of regional and field scales, have been published. Studies from the 1970s to early 1990s resulted in similar regional interpretations, mainly because the studies were conducted by the same operator.

Beginning in the mid-1990s, Santa Fe Energy Resources (later Devon Energy and now PetroChina) assumed operatorship within the Salawati Basin and Kais carbonates were re-evaluated. Regional studies from 1997-2000 have yielded new interpretations on the distribution, paleo-environments, and age of the Kais reefs and carbonates, based on regional seismic re-mapping, newly acquired seismic data, and petrographic-biostratigraphic data from 85 exploration wells within the basin. Studies of basin evolution, geochemistry, and structure have contributed to the understanding of the evolution of the Kais platform.

The revised interpretation concluded that the Kais carbonates of the Salawati Basin had continually developed within the shelfal area since the early-middle Miocene. The lagoonal facies of the carbonates, which are locally proven source rocks, was previously interpreted as basinal facies.

Productive reefs of the Kasim complex, previously interpreted as pinnacle reefs growing at the slope of the southern shelf, are actually lagoonal reefs which grew behind the Walio barrier carbonates. Basinal facies of the Kais were deposited to the south and southwest of the study area. These basinal facies were previously interpreted as carbonate shelf deposits. The changes in interpretation mainly resulted from recognition that the Salawati Basin was undergoing inversion (basin's polarity reversal) during Kais sedimentation. This was not taken into account in previous interpretations.

The re-evaluation of the Kais carbonates has provided the rationale for the discoveries in the lagoonal areas previously considered as basinal areas (Matoa, SWO, Matoa-20, Amuk) and opened opportunities for other prospective areas outside the classic Kasim-Walio area, as proven by the offshore Koi discovery in 2000. This study concludes that a new look at an old objective is important for reviewing exploration interest in a mature basin like the Salawati Basin.

INTRODUCTION

The Miocene Kais carbonates of the Salawati Basin, Bird's Head of Papua, Eastern Indonesia are the main objectives and the only producing reservoir in the basin. NNGPM (Dutch New Guinea Oil Company) drilled the basin's first well in 1936 (Klamono-1) on a surface anticline, later interpreted as anticlinal drape above a Kais reef, and flowed oil from the Kais limestones. There have been around 160 exploration wells drilled in the basin, resulting in the discovery of approximately 30 fields. Approximately 375 MMBO and 175 BCFG have been produced from the Kais carbonates through 2002.

Because the Kais is the main objective within the basin, it has been frequently studied by the operators working in the Salawati Basin (NNGPM, Pertamina, Phillips Petroleum, Petromer Trend, Santa Fe Energy Resources, Devon Energy, and PetroChina). NNGPM

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established the basic understanding of the basin's geological framework. Phillips Petroleum Teluk Berau and Petromer Trend Salawati explored most of the basin areas offshore and onshore, respectively. Most of the basin's geological knowledge derived from these two operators. JOB Pertamina-PetroChina presently operates the offshore area and PSC PetroChina operates the onshore area.

Vincelette (1973) published the first study on the Kais carbonates following the discoveries of the Kasim Field (1972) and Walio Field (1973). Later published studies on the Kais carbonates commonly referred to these fields (Vincelette and Soeparjadi, 1976; Redmond and Koesoemadinata, 1976; Gibson-Robinson and Soedirdja, 1986; Gibson-Robinson et al, 1990; Livingstone et al, 1992). Kasim and Walio Fields are important fields in SE Asia and commonly referred to in regional and global studies on Miocene carbonates (such as Longman, 1993; Sun and Esteban, 1994).

Interpretation of the sedimentology and paleogeography of the Miocene Kais carbonates of the Salawati Basin remained the same from Vincelette (1973)'s paper to Livingstone et al. 's (1992) paper, the most recent publication on the Kais carbonates until the present study. This uniform interpretation of the depositional setting may reflect the single operator which worked this basin during the period (Petromer Trend PSC and JOB). Since the mid-1990s, other operators have taken over the Petromer Trend, namely: Santa Fe, Devon, and PetroChina, and the Kais interpretation was modified. This paper summarizes the revised interpretation of the sedimentology and paleogeography of the Kais carbonates.

GEOLOGIC SETTING OF THE SALAWATI BASIN

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 the Ayamaru Platform, respectively. The Salawati Basin records the stratigraphic and tectonic history of the area from the Paleozoic to Recent.

Stratigraphic Framework

Figure 2 shows the generalized stratigraphy of the Salawati Basin. The oldest stratigraphic successions are the Siluro-Devonian Kemum metamorphics which are continental basement rocks and Carboniferous-Permian Aifam continental margin rocks. Overlying the basement are Mesozoic sedimentary rocks (Tipuma and Kembelangan groups), which are found only in the southern part of the basin because of the uplift in the northern part of the basin during the Late Cretaceous, resulting in erosion of the older sediments or non-deposition.

Tertiary sedimentation within the Salawati Basin began during the Paleocene with deposition of deep marine marly mudstones of the Imskin Formation in the southern area. In the late Eocene to early Oligocene, deposition of transgressive carbonates of the Faumai Formation took place. Overlying the Faumai carbonates are the late Oligocene, shallow-marine siliciclastics of the Sirga Formation. Thick carbonates of the Miocene Kais Formation were deposited following the Sirga siliciclastics.

Kais transgressive carbonates were deposited in various environments, from lagoonal, bank, to deeper water facies, resulting in various types of carbonate sediments from low-energy, organic-rich carbonate muds to moderate-high energy reefal carbonates. Contemporaneously with the Kais carbonate deposition, was the deposition of the Miocene lagoonal Klasafet fine calcareous siliciclastics. The Pliocene Klasaman siliciclastics are the youngest Tertiary stratigraphic sequences in the basin. Molassic deposits of the Sele conglomerates were deposited in the Pleistocene as erosional byproducts of the deformed zone along the Sorong fault.

Structural Framework

The main structural element 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. The present structural style of the basin is dominated by NNE - SSW normal faults formed as conjugates to the Sorong Fault. Movement along the Sorong fault has resulted in en echelon folds and synthetic left-lateral faults with normal slip (such as the "Line Six" Fault) trending through the Salawati Island. This movement has reactivated older normal faults which originated during rifting in the late Paleozoic - Mesozoic time, such as the Cenderawasih Fault, to become antithetic right-lateral faults. Satyana et al. (2002) have described the structural evolution of the Salawati Basin.

Basin Inversion (Polarity Reversal)

Regional studies from 1997 to 2000 (e.g. Satyana, 1999, 2001; Satyana and Setiawan, 2000; and Satyana et al., 2000) on basin evolution, structure, geochemistry, Kais paleogeography and sedimentology concluded that the Salawati Basin had undergone a polarity reversal from tilting southward during the Paleozoic to early Pliocene to tilting northward since the late Pliocene. Figure 3 summarizes the evolution of the basin and its polarity reversal mainly in the western basin. This reversal is related to 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 Groups, and early Tertiary to Mio-Pliocene Faumai, Sirga. Kais, Klasafet and lower Klasaman Formations compose the syn-reversal stratigraphy. Thick upper Klasaman rocks and the Sele molassic deposits compose the post-reversal stratigraphy. Reversal of the basin in the Mio-Pliocene was critical to the evolution and development of the Kais carbonate platform.

PREVIOUS INTERPRETATION OF THE KAIS CARBONATES

Previous interpretations of the depositional setting and evolution of the Kais carbonates of the Salawati Basin are typical of those of Gibson-Robinson and Soedirdja (1986), whose paper discussed the transgressive development of Miocene Kais reefs (Figure 4). The following discussion is from Gibson-Robinson and Soedirdja (1986).

During the Miocene, the Salawati Basin was the site of carbonate deposition in an embayment that was probably open to the northwest. In the southern and eastern parts of the basin, shallow shelf carbonates were deposited, apparently continuously during Miocene time. These carbonates form part of the Kais Formation and consist of bioclastic packstones and wackestones with numerous biohermal and biostromal build-ups.

In the central part of the basin, these shallow-water carbonates are absent and the early and middle Miocene section consists of relatively deep-water limestones, containing a fauna of planktonic foraminifera, and interbedded open-marine calcareous shales. These deposits form the Klamogun Formation and are overlain by middle to late Miocene shales and thin limestones of the Klasafet Formation. The Klamogun and Klasafet Formations were interpreted as the lateral equivalents of the Kais Formation developed on the shelf.

Between these two depositional areas a third province developed, probably beginning during middle Miocene time, as renewed transgression took place. In this area, termed the shelf margin, a series of pinnacle reefs and carbonate banks developed in the Kais Formation, and it is these that are productive oilfields. The reefs in the shelf margin area were identified by time-interval mapping between the top of Kais reef/carbonate and the regionally widespread seismic marker ("U" Marker) overlying the Kais reefs, supported by well data. The thinner the time-interval/isopach, the thicker the Kais reefs. It may indicate that the reefs grew up continuously, but biostratigraphic data were not used to confirm this. The Gibson-Robinson and Soedirdja (1986) model proposed at least three and possibly four transgressive cycles (called stages) during early middle to late Miocene Kais time.

Stage 1 (Kais Platform) passes basinward to the north into deeper marine limestones of the Klamogun Formation and shales of the lower Klasafet. Over the platform area, shoals probably developed which became sites for later reef growth. At the end of the Kais platform stage there was a broad division into an open marine basin to the north and a shallow shelf area to the south. Stage 2 (Cenderawasih-Kasim Utara) commenced with an abrupt change in sedimentation in off-reef areas from clean shelf carbonates to deeper water calcareous clays interbedded with argillaceous carbonates. During this stage, coral reefs such as Kasim Utara and Cenderawasih began to develop on the shelf margin. Vertical growth of the build-ups kept pace with sea level rise throughout the stage. During Stage 3, sedimentation in the south continued to be mainly in a shelf environment with local reef development and, in the northern part of the area, deeper water sedimentation dominated. The Walio, Kasim-Jaya and Moi areas became sites of coral reef development.

During Stage 4, the Kasim reef continued to grow. Shale deposition dominated the remainder of the southern Salawati Basin with the exception of the Kasim reef. After Kais reef development, shales were deposited over most of the Salawati Basin, terminating reef growth.

RE-EVALUATION OF THE EVOLUTION OF THE KAIS CARBONATES

Methods of the New Interpretation

The present study was based on well and seismic data available up to 2000 and encompasses all parts of the basin, both onshore and offshore. The reef growth model described in the previous section is based only on data available in the southern part of the basin and focuses on the Walio Bank and its northern slope. The present study used biostratigraphic and petrographic data from approximately 85 exploration wells throughout the basin to date the stages of Kais reef growth and their relationships to the global cycles of sea level changes and to define the microfacies of the reefs. This was not addressed by previous interpretations.

Seismic mapping of the “U” Marker to top Kais interval is also adopted by the present study but, modified to include the time interval between the Textularia II Marker and top Kais. The Textularia II “marker” is a good time line at the top of the Klasafet Formation. It consists of blanket-like bioclastic limestones resulting in prominent seismic and log markers and is more easily identified than the “U” Marker. Where the time interval of Textularia II – top Kais is thin, reefal buildups are present in the Kais. Where the interval is thick, the Kais consists of deeper water facies overlying the basal platform limestone. Thin areas later were divided into three stages based on the thickness of the Klasafet Formation. The stages document the growth of Kais buildups. The buildups which continually grow will have thinner overlying Klasafet Formation. A series of seismic-based Kais paleogeographic maps were generated representing each stage of development (Figures 5-9).

Seismic-based Kais paleogeography is confirmed by biostratigraphic and petrographic data. Microfossil assemblages tell the relative age and depositional facies of the carbonates. Petrographic data tell the microfacies of the carbonates. All of these data were integrated with other regional studies, mainly a basin evolution study, which resulted in an interpretation of the evolution and development of the Kais carbonate platform and reefs.

Evolution and Development of the Kais Carbonate Stages

Figure 5 illustrates the definition of the development stages of the Kais carbonate platform and reefs based on seismic interval mapping. It recognizes three stages: Stages 1, 2, and 3. Stage 1 includes carbonate platform, intra-platform buildup (intra-Kais), and low-relief Kais reefs with thickness of the overlying Klasafet more than 1400 ft. Stage 2 includes moderately high relief carbonate buildups with thickness of the overlying Klasafet from 1400 to 800 ft. Stage 3 includes high relief carbonate buildups with thickness of the overlying Klasafet less than 800 feet.

Figures 6-9 show the development of the Kais paleogeography or the evolution of the Kais Platform from pre-Kais to post-Kais deposition including: Stage 1, Stage 2, and Stage 3.

a. Pre-Kais setting

Onlapping of the Eocene Faumai carbonates and late Oligocene Sirga siliciclastics northward indicate that the basin dipped to the south prior to deposition of the Miocene Kais carbonates (Figure 6a). Seismic and well data clearly show that both Faumai and Sirga Formations thicken to the south indicating the presence of a southern depocenter with depositional facies ranging from deltaic at the basin margin to shallow marine at the south. Northward from the onlap area was a landmass or ridge possibly composed of the Paleozoic Kemum-Aifam basement.

b. Stage 1 : Kais platform and low-relief reef (Figures 6a, 7)

Initial late Oligocene transgression during Sirga deposition continued to become a major transgression during the early and middle Miocene time. Carbonates were preferentially deposited during this period. The sea inundated almost all of the emergent areas of the Salawati basement including the northern landmass. The carbonates were deposited during progressive northward transgression and thicken to the south from approximately 200 feet in the northern area (WIR-1A) to 4000 feet in the southern area (Walio-69). The onset of Kais carbonate sedimentation in the Salawati Basin took place in the Oligo-Miocene, based on the presence of Lithothamnium/Mesophyllum type red algae and Amphistegina in WIR-1A. Fringing reefs of Klagagi-Klalin-Arar Complex developed to the south of the Arar High/Landmass. An extensive carbonate bank, the Walio Carbonate Bank developed in the south in an area free of siliciclastic input forming a barrier to the southern open sea. A broad lagoonal facies developed between the carbonate bank and the landmass. Marly carbonates were deposited within the lagoonal area. Low-relief reefal carbonates grew in various parts of the lagoon.

Behind the shelf margin on Walio Bank, shallow-water platform reefs grew on the platform (TBA, TBC, TBM, Salawati A-F, Kasim-Jaya Complex). Farther to the west (from TBM to the TBA/TBC), the influence of the open sea was was more pronounced. These buildups were previously interpreted as pinnacle reefs because they were thought to have been located basinward of the shelf margin. The present interpretation concluded that in this period, the open sea was to the south not to the north. Accordingly, these buildups are not the classic basinal pinnacle reefs of the open sea, but lagoonal "pinnacle" reefs.

c. Stage 2 : high-relief pinnacle reefs and Klasafet lagoonal deposition (Figures 6b, 8)

During the middle-late Miocene, the Salawati lagoon underwent significant tectonic change, possibly the result of plate readjustment around the northern Irian Jaya and southwest Pacific. The eastern lagoon (now onshore basin) subsided rapidly in response to uplifts of the Arar High to the north and the Walio Bank to the south. The western lagoon (now offshore area and Salawati Island) tilted to the southwest. Thus, the open sea shifted to the southwest and, consequently, the sea transgressed eastward/northeastward. The transgression inundated the Walio Carbonate Bank and the bank receded to the south. The fringing reefs located along the rim of the bank (TBA, TBC, TBM, Salawati A-F, Kasim complex) were being subjected to deeper water at the slope of the Walio Bank. These reefs aggraded to keep pace with the sea level rise and basin subsidence. During this period, the TBA, TBC, TBM, Salawati A-F, and Kasim reef complex attained their maximum growth.

With rising sea level, patch reefs grew on the Walio Bank. The Walio Field, South Walio, Koi, and buildups offshore to the west of the Walio Field are examples of patch reefs that grew on the Walio Carbonate Bank. In the lagoon, rising sea level terminated the growth of many reefs or mud mound in this area like SWO, Amuk, and other intra-Kais buildups. Klasafet sediments were continually deposited in the lagoon.

Reefs growing at the slope of the Salawati Ridge (Salawati K High) such as WIR and Salawati N kept pace with rising sea level similar to the "pinnacle reefs" growing at the slope of the Walio Carbonate Bank.

During this period, the eastern basin was being uplifted and, therefore, marine waters receded to the west. This is supported by regional biostratigraphy because the age of the Kais reefs are younger westward from the eastern basin where they are generally middle-lower late Miocene (N9-N16) to generally upper N16 age for upper Kais reefs in the western basin.

d. Stage 3 : Termination of most reefs and Klasafet deposition (Figures 6c, 9)

During the late Miocene, the Salawati Basin underwent significant tectonic changes, possibly resulting from the oblique convergence of the Australian and Philippine Sea (and Caroline) plates causing the Neogene Melanesian Orogeny within Papua Island. Plate re-organization resulted in inversion in the Salawati Basin’s polarity. The southern basin's depocenter was uplifted, and the northern landmass area began to subside to form a new depocenter.

The location of the open sea shifted from the southwest to the west-northwest. During this period, the Walio Carbonate Bank was uplifted terminating patch-reef growth over the bank and lagoonal "pinnacle" reefs growing at the slope of the bank. Some reefs to the south of Koi, however, continued to grow on the bank during the transgression southward. In the lagoonal area, reef growth was terminated except for those growing around paleo-highs, such as WIR and Salawati-N. Kasim. North Sele reefs also survived up to this period. Klasafet finer sediments were continually deposited in the lagoon area.

Farther south of the Walio Bank, pelagic carbonates of the equivalent Kais Formation were subaerialy exposed forming the permanent border for the Salawati Basin with the Seram area. This carbonate high is called the Misool-Onin Geanticline or Ridge. The exposure of equivalent Kais carbonates also occurred to the east of the Salawati Basin, forming the Ayamaru Platform, a border separating the Salawati Basin and the Bintuni Basin to the southeast. This uplifted Kais carbonate complex was the provenance for Klasaman sediments deposited rapidly into the basin, which was subsiding to the north/northwest. The northern subsidence, southern and eastern uplifts, and deposition of substantial siliciclastic debris flows terminated Kais carbonate growth in the Salawati Basin. This occurred at the N17/N18 foraminiferal zone (latest Miocene-base Pliocene), based on the youngest age of the Kais reef in the basin.

Basic Differences with the Previous Interpretations

The difference with the previous interpretation basically lies in the knowledge that the location of the basin's depocenter had changed from south to north during Kais deposition, as confirmed by seismic and well data. Previous interpretations did not recognize this change, - the depocenter had remained in the north during the Kais deposition (stages 1-4). Whereas, according to the present interpretation, the depocenter during the Kais deposition from stage 1 to 2 to 3 had changed from south to southwest to northwest, respectively. The deeper/basinal Kais facies of the previous interpretation is the lagoonal facies in the new interpretation. Geochemical data confirm this interpretation (Satyana et al., 2000). Proven source rocks of the Salawati oils are lagoonal shales not deep-water shales. The Kasim pinnacle reef complex in the previous interpretation, is actually backreef facies behind the Walio Carbonate Bank which aggraded because of down warping of the Walio Carbonate Bank slope. Longman (1993) concluded that the Kasim Field is dominated by skeletal packstones and wackestones forming what would commonly be considered a backreef facies. No true reef framework has been recognized although scattered corals, and some whole coral colonies, are present.

The present interpretation takes into account the basin dynamics during the deposition. This agrees with Sun and Esteban (1994) who stated that Miocene carbonates in the Indo-Pacific region, particularly in Southeast Asia, were controlled by tectonic styles and climate regimes and occurred in a variety of sedimentary basin types formed in response to tectonic collision between the Eurasian, Indian Ocean, Australian, Pacific, and Philippine Sea plates. Kais deposition was strongly controlled by the tectonic collision between the Australian, Pacific, and Philippine Sea plates, and during the deposition, the prevailing climate was relatively warm and humid, characteristic of open oceanic tropical-subtropical settings.

KAIS CARBONATE FACIES

Identification of the Kais carbonate facies is based on fossil assemblages and skeletal fabric (microfacies). At least, five broad facies subdivision can be made. They are : (1) Patch Reefs over the Arar High, (2) Lagoonal Mud/Reef Mounds, (3) Reefs over the Salawati Ridge, and (5) Patch Reefs over the Walio Bank. Figures 10 and 11 show the facies of the carbonates and representative microfacies based on petrographic data. Figure 12 shows the seismic section displaying the Kais reefal build-up and platform.

Patch Reefs over the Arar High

The Arar High is a part of the northern landmass of the Salawati Basin. Parts of the Arar High were submerged when the Miocene sea transgressed northward during Kais carbonate deposition. Patch reefs grew locally on the Arar High. Their distribution was possibly controlled by pre-existing highs. Some of the reefal buildups are: North Sele, Arar, Klalin, West Klagagi, Klagagi, Klaifi, Rajawali, and Klagana. The limestones consist of mostly wackestones and packstones with less abundant mudstone, grainstones, dolomite which is of supratidal origin on the slope of the Arar High, and fringing reefal buildups such as Klagerik and Klamesin. The skeletal components are almost entirely planktonic foraminifera, indicating various environments from inner sub littoral to bathyal.

Lagoonal Mud/Reef Mounds

Central Salawati lagoon is the broadest carbonate facies belt in the Salawati Basin. Two subfacies of carbonates can be distinguished within this facies belt : (1) the eastern part: deeper lagoonal Kais carbonates, and (2) the western part : lagoonal mud/reef mound.

There are few Kais build-ups in the eastern part of the lagoon. This area started as shallow-water lagoon, but then subsided rapidly because of uplift of the Arar High to the north and the Walio Bank to the south. This subsidence resulted in deposition of pelagic carbonates and previously was interpreted as the depocenter of the basin. The Kais at Jeflio-1, Nurmana-1, and Klamogun-1 wells typify this facies. The limestones in this facies generally are dark, brownish grey, fine-grained lime mudstones and wackestones, locally argillaceous. The lithological and paleontological characteristics indicate low energy environment.

Many Kais build-ups grew in the western Salawati lagoon, possibly as a response to subsidence and tilting compared to its eastern counterpart. Generally low-relief carbonate build-ups both as intra-Kais build ups (Matoa-20 type, a build-up within Kais platform) and low-relief Kais build-ups (SWO type, a build-up above Kais platform) grew within this facies. Reefal lagoonal sediments (Matoa Field type) also developed in this area. These mounds consist of mostly wackestone to packstone. Grainstone is locally encountered, grading from packstone. Marl is commonly found to compose the uppermost part of the Kais Formation. Skeletal components consist of small planktonic and benthonic foraminifera, larger foraminifera, and local to common coral fragments. Based on the texture, lithological characteristics, benthonic foraminiferal assemblages, ratio of planktonic to benthonic foraminifera, and the presence of calcareous nannoplankton, the limestones in this area were deposited in littoral to inner neritic environments in close proximity to a reef complex. Limestones more to the west were deposited in a deeper-water environment (inner neritic), possibly in a moderate energy fore-reef setting.

Reefs over the Salawati Ridge

There are indications of the presence of paleo-ridges in the Salawati Basin around the area of Salawati K-1X, WIR-1, Salawati N-1X, and Salawati O-1X, based on seismic and well data. These paleo-ridges are thought to have influenced Kais sedimentation. Kais in the WIR-1A is an example of this facies. A mixture of Kais limestone and igneous rock fragments are present near tne base of the Kais. A dominant lime mudstone to wackestone texture almost throughout indicates a low energy depositional setting. Isolated coral fragments were locally observed. The presence of coral indicates proximity to some form of reefal development or could be as isolated coral heads.

Fragments of Amphistegina and coralline red algae suggest an inner to shallow middle neritic depositional setting.

Lagoonal "Pinnacle Reefs"

A belt of reefal buildups trending E-W exists behind the broad Walio Carbonate Bank. The reefs, from west to east include: TBA, TBC, TBM, Salawati C, Salawati E, Salawati F, Salawati F, Salawati D, Kasim Complex, Jaya, Cenderawasih, and Moi. The "pinnacle" reefs of TBA, TBC, and TBM were strongly influenced by the open sea. The reefs of Salawati C to Moi were true lagoonal "pinnacle" reefs.

Carbonate fabrics include skeletal wackestones, skeletal packstone, framestone, lime mudstone, and bindstone in order of decreasing occurrences. The skeletal grains are strongly modified by dolomitisation, but were originally dominated by corals and red algae, echinoderms, large and planktonic foraminifera. Lime mud matrix has been recrystallised. The widespread occurrence of corals and red algae is strongly suggestive of deposition in proximity to reefal buildups.

Patch Reefs Over Walio Bank

The broad Walio Carbonate Bank was a good substrate for patch reefs when the sea transgressed this area during the middle Miocene to lower Pliocene (Stages 1 to 3) from a west-northwest direction. Reefs of this type include are Koi, South Walio Complex, Lao-Lao, Maniwar, Payao, Walio Field, Linda, Sele, and other offshore buildups to the west of the Walio Field. Based on the skeletal fabric of the Walio Field, the depositional environments include reefs and intra-reef, inner sub littoral, shelf, and lagoonal deposits. Patch reefs over the western Walio Bank are usually characterized by a deeper water facies in the upper part of the reefs, indicating greater submergence at the end of reef growth.

EXPLORATION SIGNIFICANCE

Re-evaluation of the Kais carbonate evolution has provided some insights to the prospectivity of the Kais carbonates, mainly the western lagoonal facies and the offshore reefs over the Walio Bank. Previous exploration had overlooked this area because the area was mis-interpreted as basinal facies devoid of reefal buildups. New operators explored this area during the 1990s and discovered significant fields, namely : Matoa (1991, tested 1825 BOPD and 2.08 MMCFGPD), SWO (Southwest "O") (1995, tested 3564 BOPD and 12.49 MMCFGPD), Matoa-20 (1996, tested 601 BOPD), and Amuk (1998, tested 1667 BOPD and 0.40 MMCFGPD) Fields. The previously interpreted basinal facies area has become the focus of exploration since then.

"Intra-Kais buildup" is a special case in this facies. It is a build-up growing inside the Kais platform and proved to be productive through drilling of Matoa-20 well (1996). The buildups are dominated by bioclastic wackestones to packstones rich in planktonic foraminifera. These sediments are interpreted to have been deposited in a low-energy open marine environment of deposition. Larger foraminifera assemblages are fore-reef and back-reef forms. Recent seismic acquisition (2D and 3D) upgrades the prospectivity of this area to better define the reefs.

This type of reefal buildup developed in a relatively sheltered low-energy setting where micrite was easily trapped by the relatively delicate framework organisms. These micrite-rich shallow-water carbonate build-ups lack a rigid reef framework, but commonly contain abundant secondary porosity in the form of vugs and molds. They are particularly important in tectonically stable and sheltered settings or environments such as back-arc and foreland basins.

Increased prospectivity of the Kais carbonates outside the classic area of Kasim-Walio Complex is also suggested by patch reef facies over the Walio Bank. Koi-1 well (JOB Pertamina-Santa Fe Salawati, 2000) showed the prospectivity of this area; the well tested 898 BOPD and 2.89 MMCFGPD. The reefs grew during marine transgression of the Walio Bank eastward (Stage 2) and southward (Stage 3). There are many reefs identified in this area on the recent 2D seismic survey.

A geochemical study (Satyana et al., 2000) concluded that proven source rocks of the Salawati Basin are shales, marls, and carbonates of the Kais and Klasafet Formation deposited in the lagoonal area. Oil characteristics show that the source rocks are : Tertiary in age, organically very rich, contain dominantly marine algal kerogen, with minor terrestrial components, carbonate (lime mudstone) in parts, and very probably were deposited in an anoxic lagoonal (brackish water) environment (Satyana et al., 2000). The knowledge that the Kais/Klasafet lagoonal area is the main kitchen in the basin has provided a migration scenario. Hydrocarbons have been generated from the northern lagoonal Kais/Klasafet sources which are now in the oil and gas windows and migrated updip southward into traps within the lagoonal facies (Matoa, SWO, and Matoa-20 play types) and buildups over the Walio Bank (Koi play type).

A re-evaluation of the Kais carbonates has given new understanding and upgraded the prospectivity of the areas outside the long-known classic productive area (Kasim-Walio Complex). This study has opened new exploration opportunities within a mature basin.

CONCLUSIONS

The present study re-interpreted the Kais carbonates of the Salawati Basin using regional seismic re-mapping, newly-acquired seismic data, biostratigraphic and petrographic databases of Kais-penetrated wells, and was supported by a series of regional studies (basin evolution, Kais paleogeography, geochemistry, and structural re-visit). The new interpretation took into account the basin dynamics since the Kais deposition was contemporaneous with the collision of the Australian, Pacific, and Philippine Sea plates. The new interpretation resulted in significant differences with those of the previous interpretations in platform and reef evolution and facies definition.

New exploration opportunities are present, as evidenced by the discoveries of Matoa, SWO, Matoa-20, and Koi outside the classic productive areas of the Kasim-Walio Complex. The new Kais interpretation has contributed significantly to these new opportunities and it gives integrated understanding to the evolution and development of the Kais carbonate platform and reefs.

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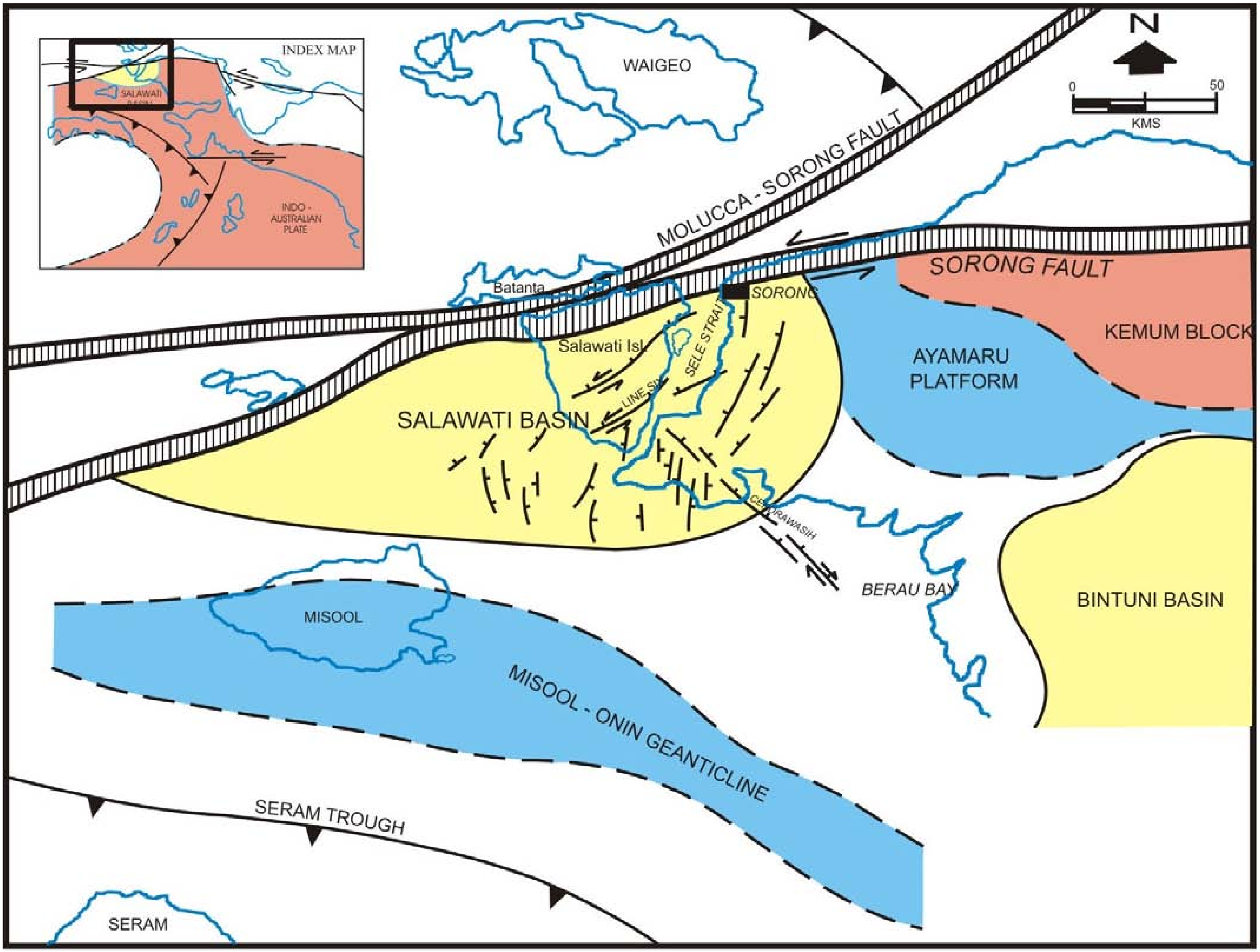


Figure 1 - Regional setting of the Salawati foreland basin relative to the Indo-Australian Plate. The basin is presently bounded to the north by the Sorong Fault. Misool-Onin Geanticline and Ayamaru Platform comprise late Miocene Kais carbonates uplifted in the Mio-Pliocene.

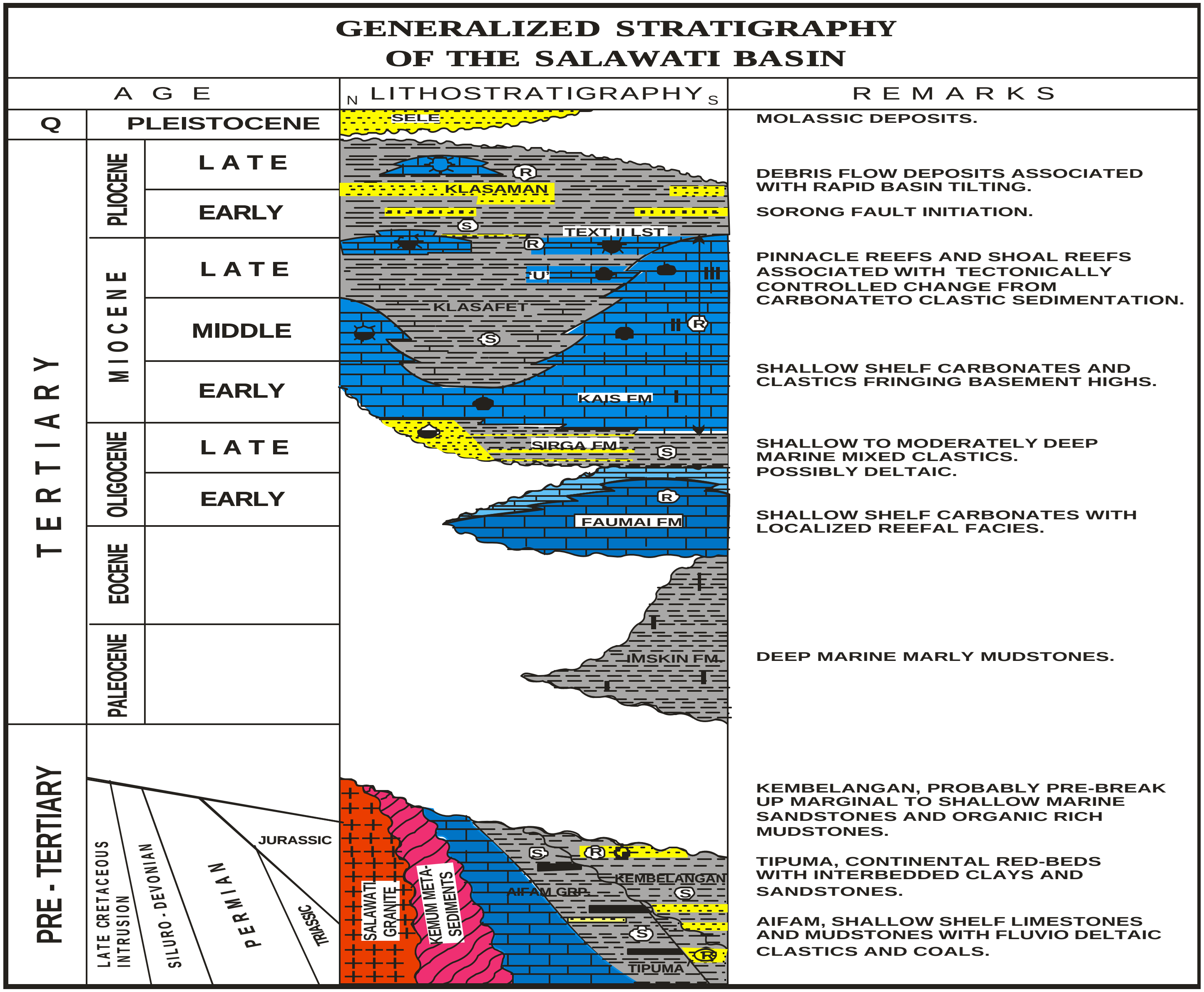


Figure 2 - Salawati Basin stratigraphy and related tectonic events forming the strata. The Kais and Klasafet Formations are partly coeval. Kais Formation is a part of the New Guinea Limestone Group.

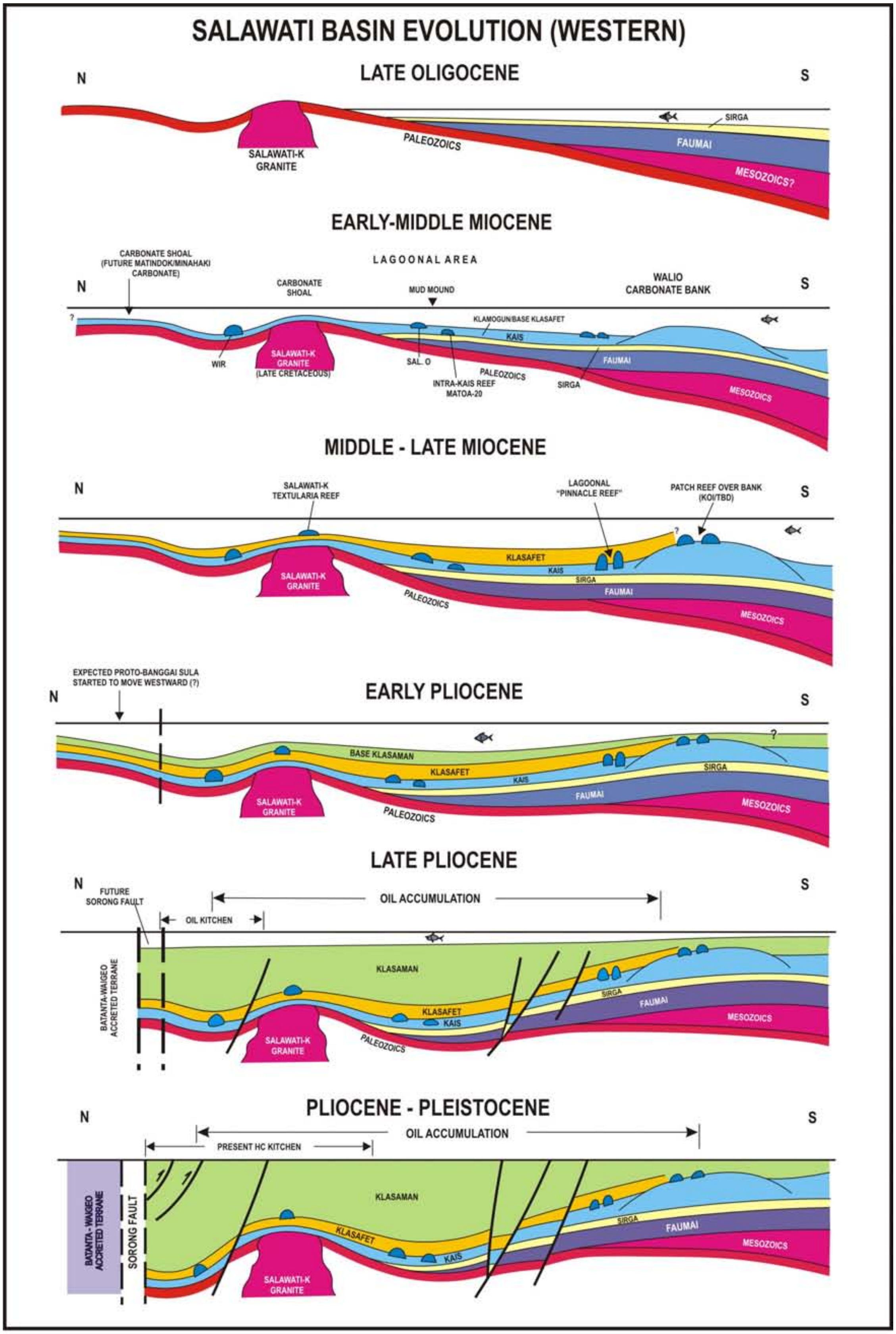


Figure 3a - Schematic diagram showing the evolution of the western Salawati Basin. Reversal of the regional basin's dip (basin's polarity) occurred in the west between late Miocene and late Pliocene. The east and middle part of the basin downwarped in response to uplift in the north and south, resulting in a deep lagoonal area.

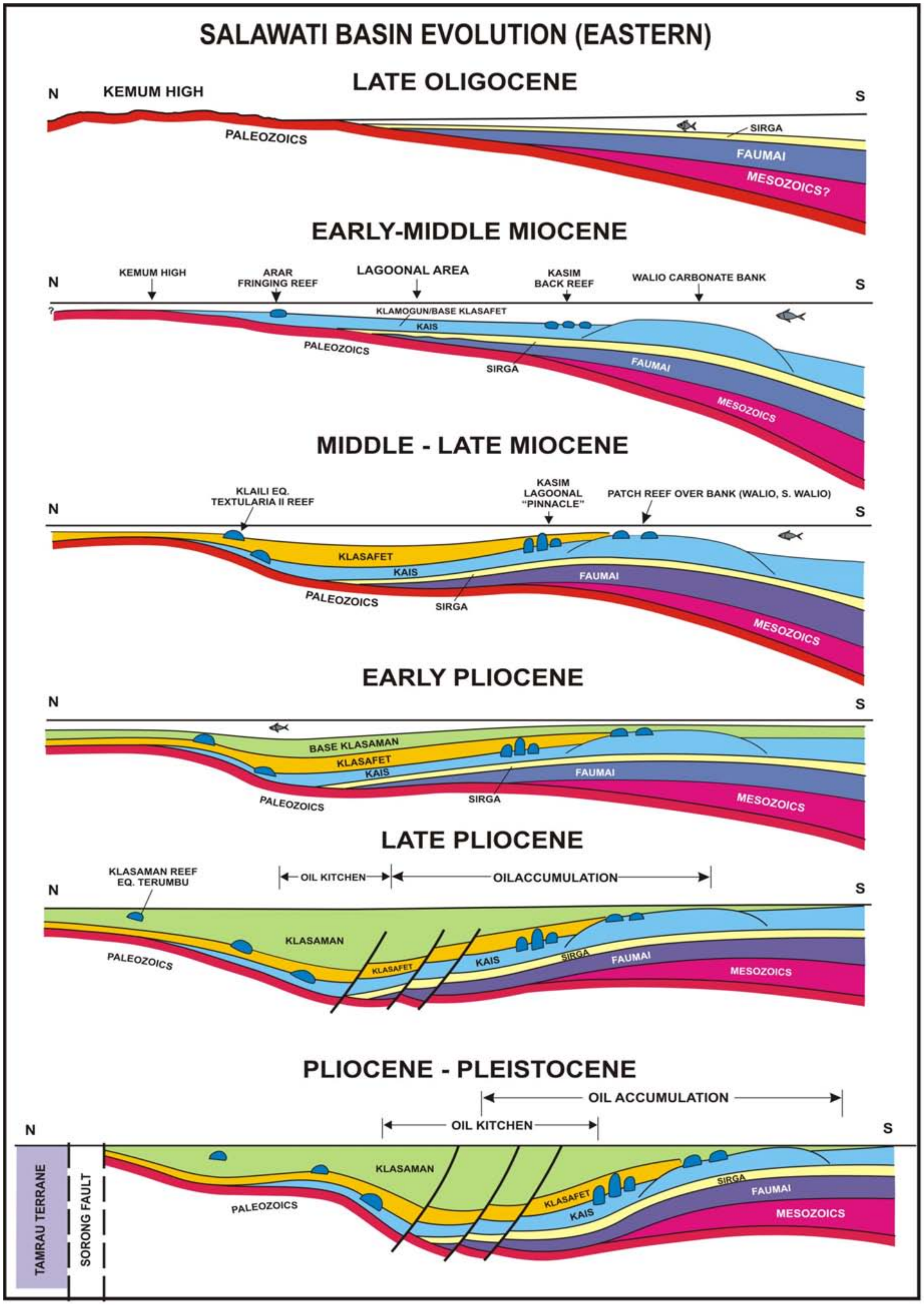


Figure 3b - Schematic diagram showing the evolution of the eastern Salawati Basin. Reversal of the regional basin's dip (basin's polarity) occurred in the west between late Miocene and late Pliocene. The east and middle part of the basin downwarped in response to uplift in the north and south, resulting in a deep lagoonal area.

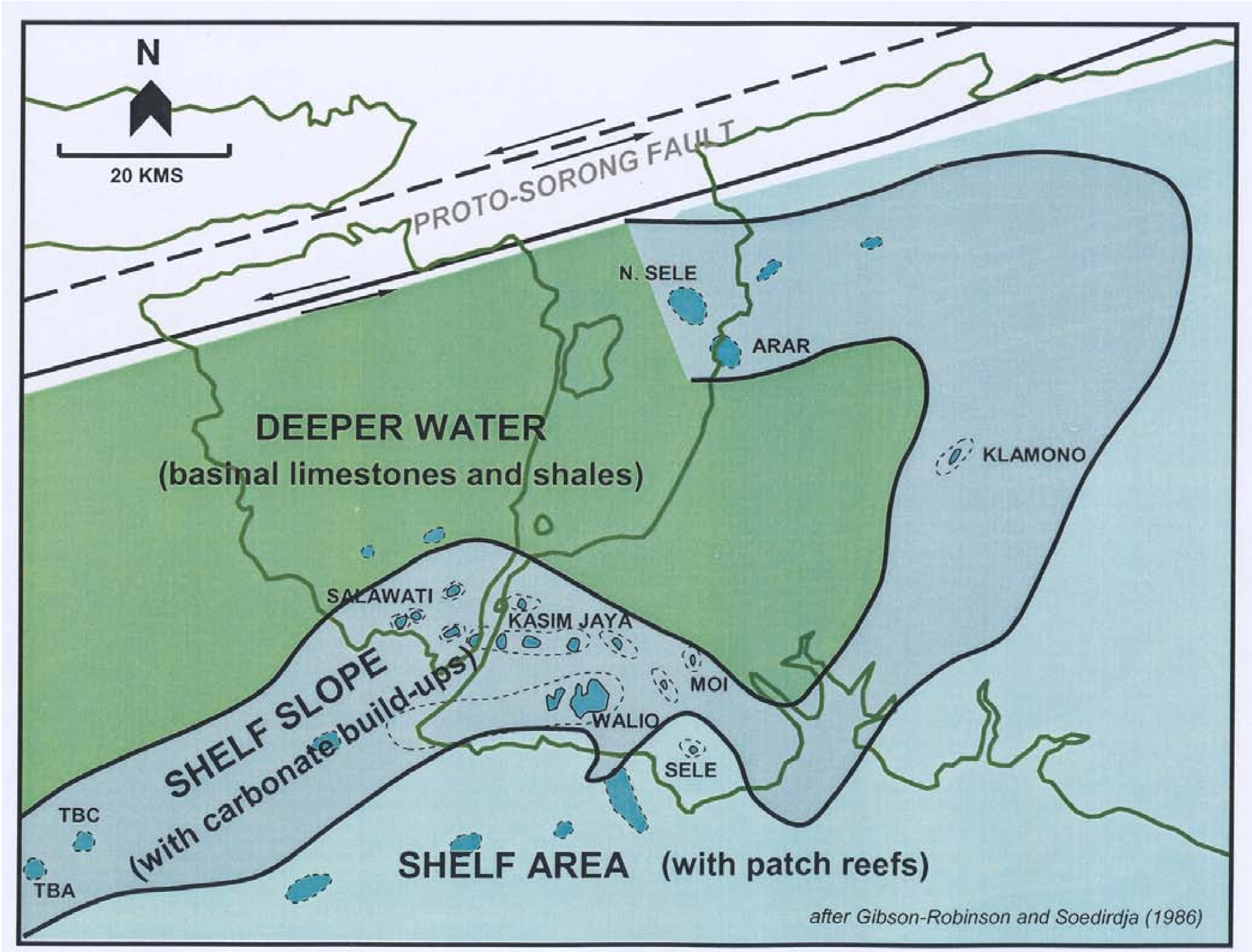


Figure 4 - Previous interpretation of Kais paleogeography. There was no interpreted change of paleogeography during the Miocene. The southern shelf area and northern deep-water area persisted through deposition of the Kais.

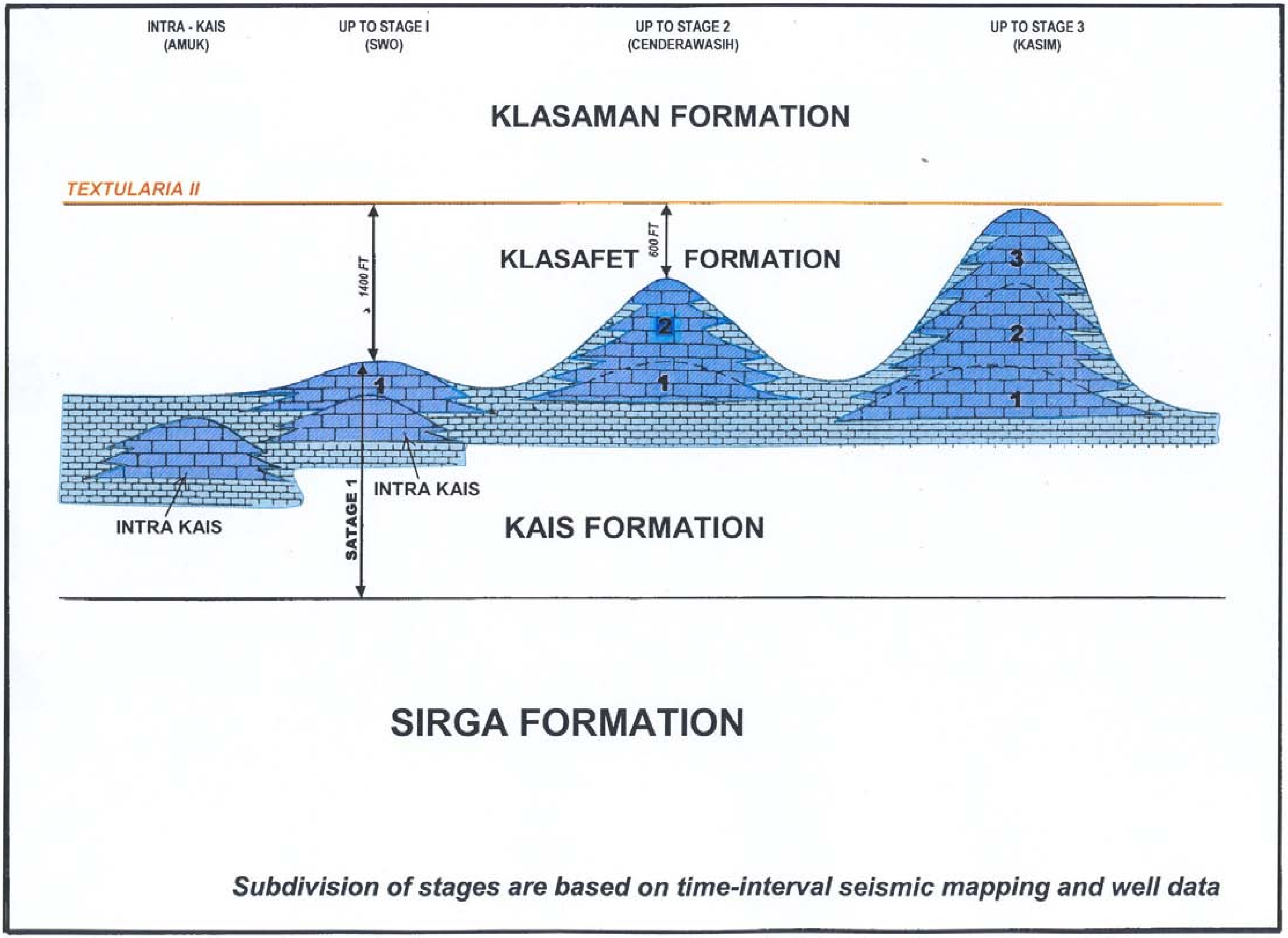


Figure 5 - Definition of the Kais stages (Stage – 1, Stage – 2, Stage – 3) as inferred from the seismic time-interval and isopach mapping. Thin area of Klasafet Formation indicate presence of underlying Kais build-ups.

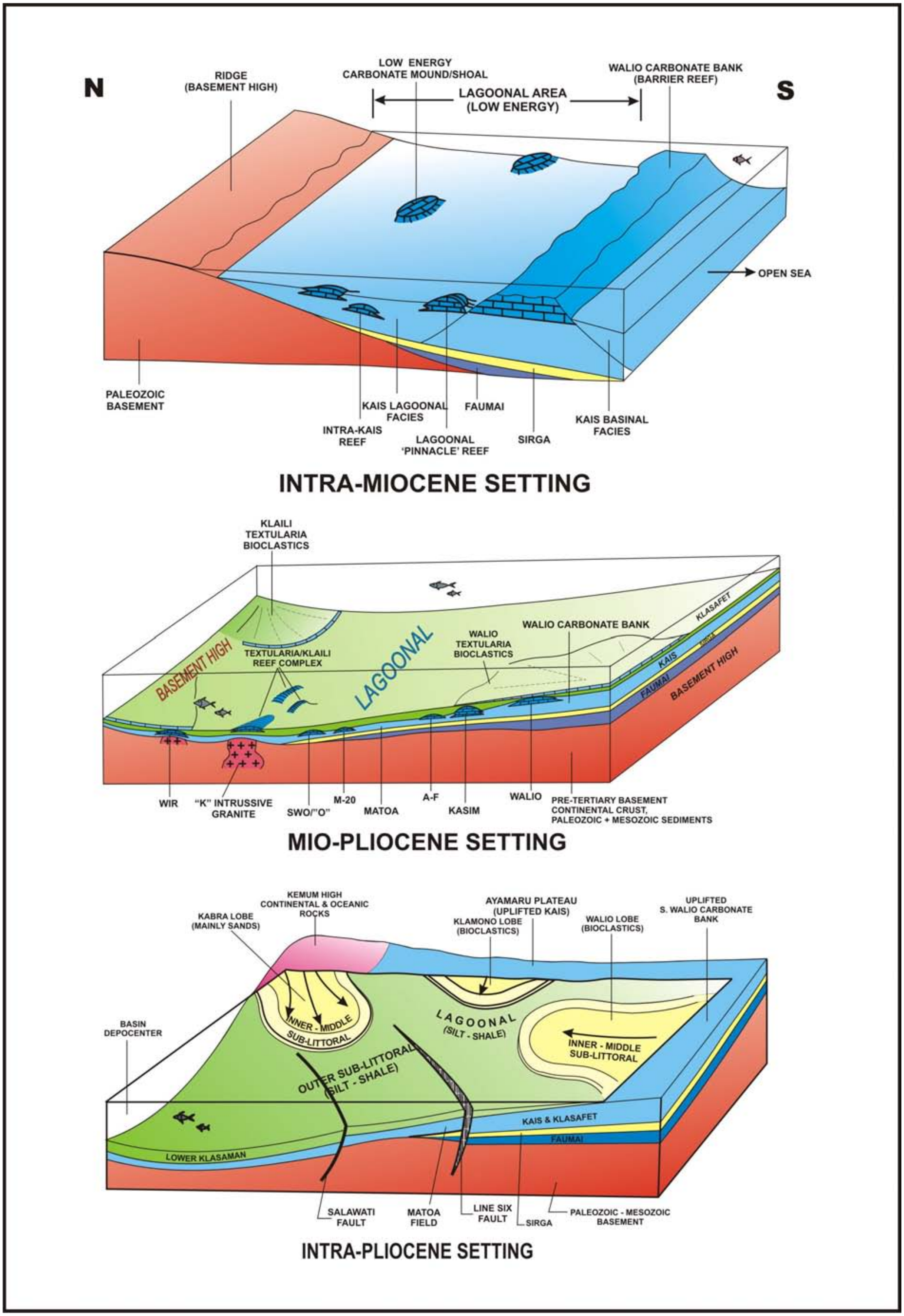


Figure 6 - Schematic diagram showing the reversal of the basin's polarity (basin dip) and related sedimentation.

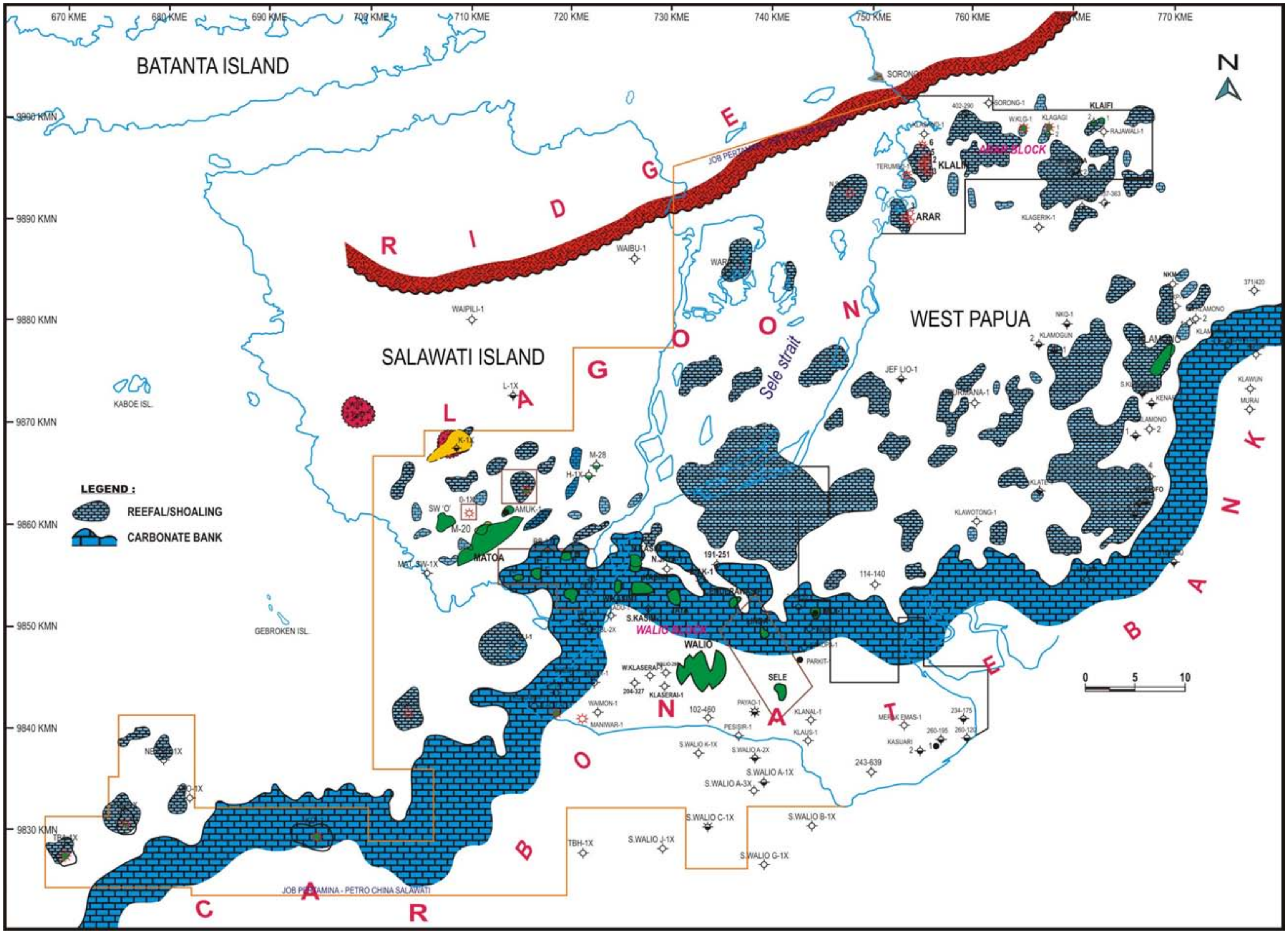


Figure 7 - Paleogeographic map of Kais Stage Three facies were recognized : ridge/ landmass, lagoon, and carbonate bank/shelf. Open Sea was to the south.

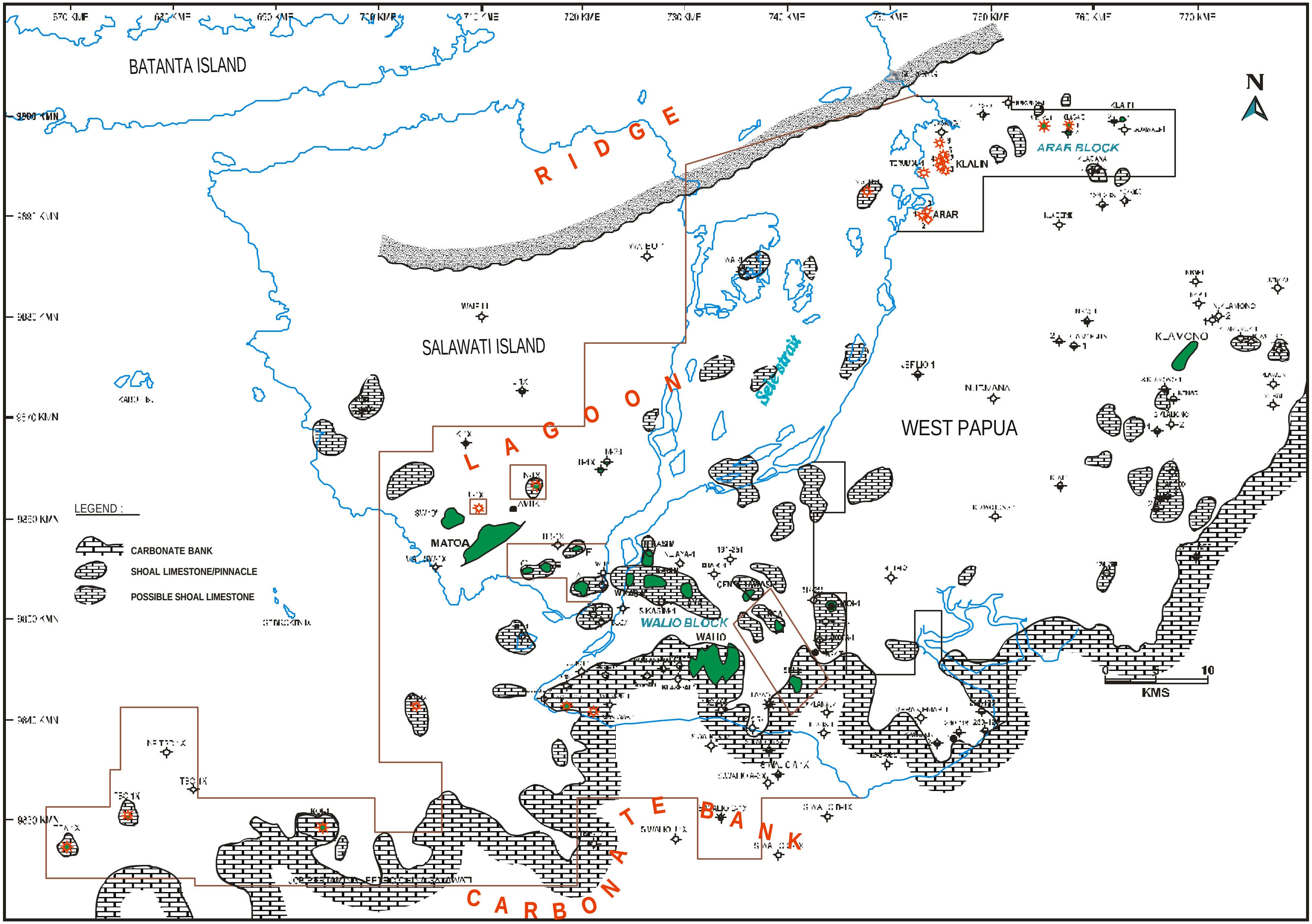


Figure 8 - Paleogeographic map of Kais Stage 2. Note that the lagoon area expanded south of the Stage 1 lagoon

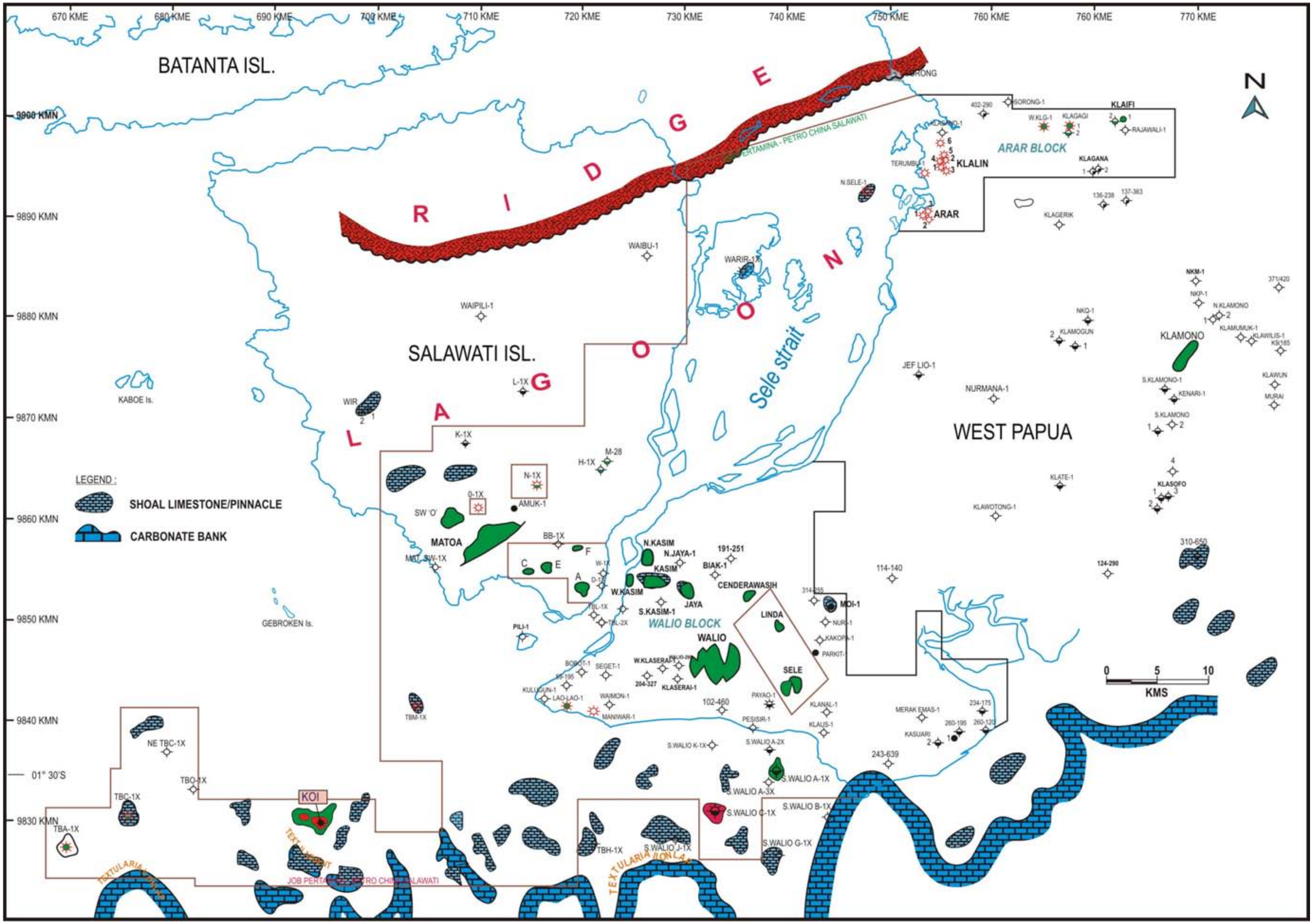


Figure 9 - Paleogeographic map of Kais Stage 3. Note that most of the Kais buildups of earlier stages ceased growth. Klasafet sediments onlapped to the south indicating the basin now dipped to the north. Transgressive reefs developed on the bank as the sea transgressed southward. The basin depocenter was to the north.

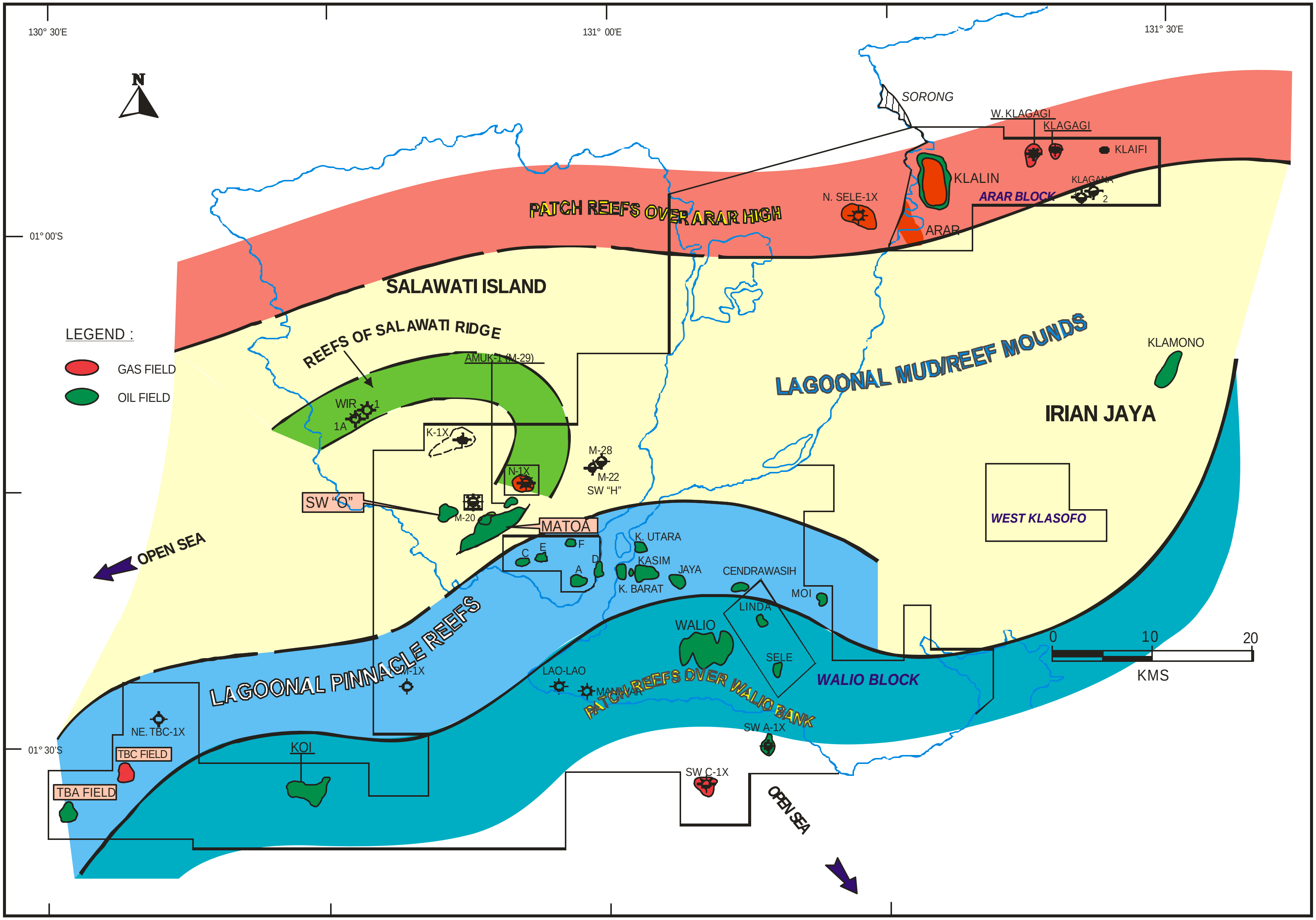
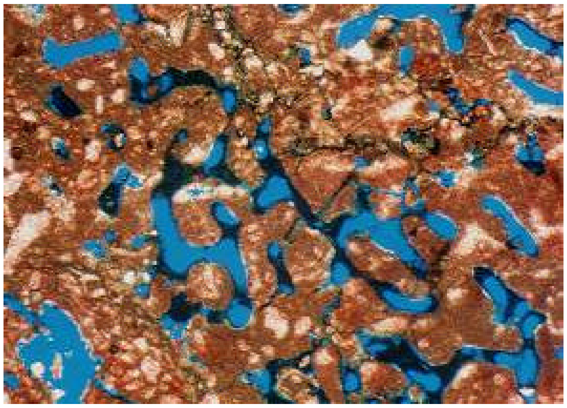


Figure 10 - Carbonate facies map based on Kais paleogeography and microfacies from petrography. No deep water facies were deposited during Kais deposition in the study area. Previously interpreted deep-water was a broad lagoon which deepened by downwarping in eastern area and tilting in western area during the evolution of the Kais platform.

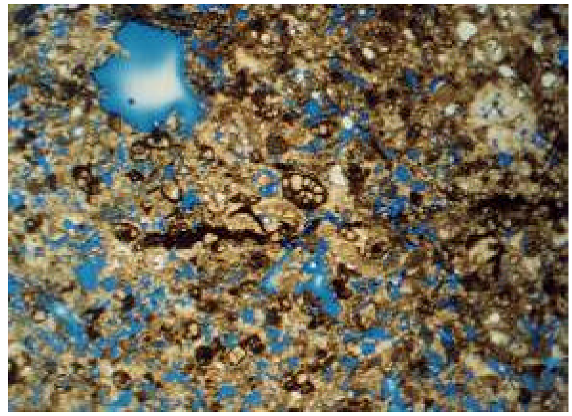
KASIM – 24 (3428 FT)

LAGOONAL BACK REEF



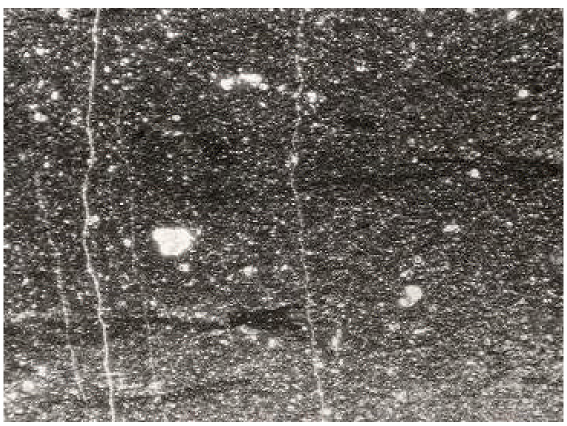
KLALIN – 3 (8473 FT)

FRINGING REEF ON THE ARAR HIGH



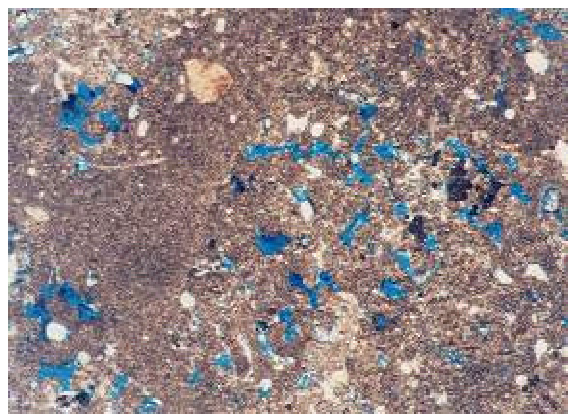
KLAMOGUN – 1

DEEP LAGOON AREA



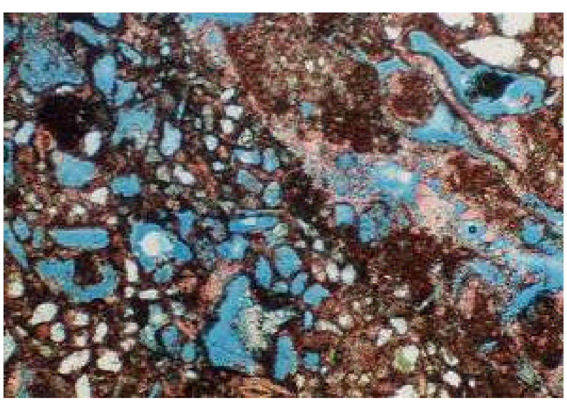
SOUTHWEST O – 2 (9824 FT)

LAGOONAL MUD MOUND



WALIO – 23 (2685 FT)

PATCH REEF OVER WALIO BANK



WEST ISLAND REEF – 1 (13250 FT)

REEF ON THE SALAWATI RIDGE

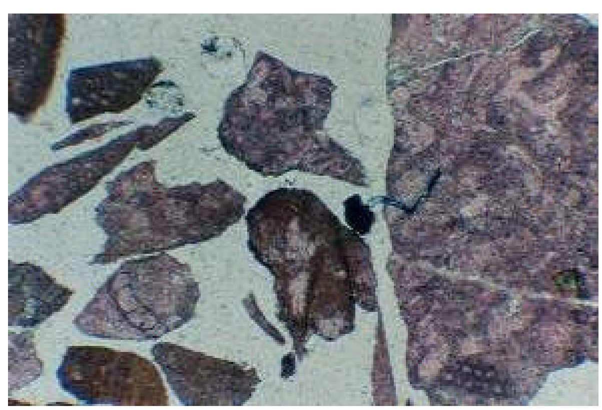


Figure 11 - Photomicrographs of facies recognized in this study. Blue dye epoxy indicates porosity.

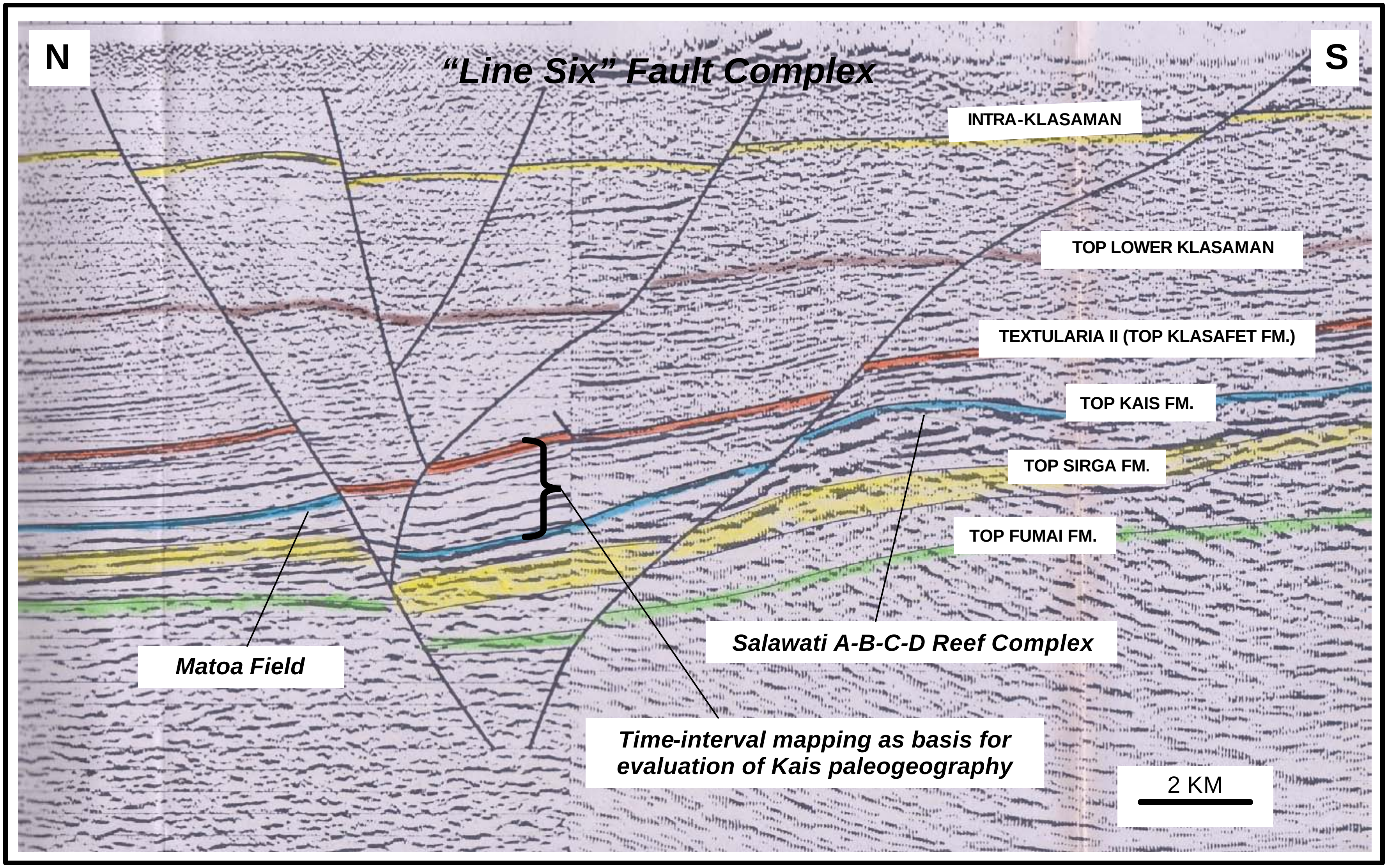


Figure 12 - Seismic section showing the Kais carbonates both as reefal build-up (Salawati A-B-C-D complex) and carbonate platform (Matoa Field). Time-interval map between top of Textularia II and top of Kais forms the basis for the paleogeographic mapping of the Kais carbonates (see additional information from figures 5, 7-9).