Tectonic controls on the hydrocarbon habitats of the Barito, Kutei, and Tarakan Basins, Eastern Kalimantan, Indonesia: major dissimilarities in adjoining basins

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Abstract

The Barito, Kutei, and Tarakan Basins are located in the eastern half of Kalimantan (Borneo) Island, Indonesia. The basins are distinguished by their different tectonic styles during Tertiary and Pleistocene times. In the Barito Basin, the deformation is a consequence of two distinct, separate, regimes. Firstly, an initial transtensional regime during which sinistral shear resulted in the formation of a series of wrench-related rifts, and secondly, a subsequent transpressional regime involving convergent uplift, reactivating old structures and resulting in wrenching, reverse faulting and folding within the basin. Presently, NNE–SSW and E–W trending structures are concentrated in the northeastern and northern parts of the basin, respectively. In the northeastern part, the structures become increasingly imbricated towards the Meratus Mountains and involve the basement. The western and southern parts of the Barito Basin are only weakly deformed. In the Kutei Basin, the present day dominant structural trend is a series of tightly folded, NNE–SSW trending anticlines and synclines forming the Samarinda Anticlinorium which is dominant in the eastern part of the basin. Deformation is less intense offshore. Middle Miocene to Recent structural growth is suggested by depositional thinning over the structures. The western basin area is uplifted, large structures are evident in several places. The origin of the Kutei structures is still in question and proposed mechanisms include vertical diapirism, gravitational gliding, inversion through regional wrenching, detachment folds over inverted structures, and inverted delta growth-fault system. In the Tarakan Basin, the present structural grain is typified by NNE–SSW normal faults which are mostly developed in the marginal and offshore areas. These structures formed on older NW–SE trending folds and are normal to the direction of the basin sedimentary thickening suggesting that they developed contemporaneously with deposition, as growth-faults, and may be the direct result of sedimentary loading by successive deltaic deposits. Older structures were formed in the onshore basin, characterized by the N–S trending folds resulting from the collision of the Central Range terranes to the west of the basin. Hydrocarbon accumulations in the three basins are strongly controlled by their tectonic styles. In the Barito Basin, all fields are located in west-verging faulted anticlines. The history of tectonic inversion and convergent uplift of the Meratus Mountains, isostatically, have caused the generation, migration, and trapping of hydrocarbons. In the Kutei Basin, the onshore Samarinda Anticlinorium and the offshore Mahakam Foldbelt are prolific petroleum provinces, within which most Indonesian giant fields are located. In the offshore, very gentle folds also play a role as hydrocarbon traps, in association with stratigraphic entrapment. These structures have recently become primary targets for exploratory drilling. In the Tarakan Basin, the prominent NW–SE anticlines, fragmented by NE–SW growth-faults, have proved to be petroleum traps. The main producing pools are located in the downthrown blocks of the faults. Diverse tectonic styles within the producing basins of Kalimantan compel separate exploration approaches to each basin. To discover new opportunities in exploration, it is important to understand the structural evolution of neighbouring basins.

1. Introduction

Kalimantan is the Indonesian portion of the island of Borneo. It occupies more than two thirds of the island. Kalimantan is separated from Sarawak and Sabah (Malaysian portions of Borneo) and Brunei Darussalam by the ridges of the Central Ranges comprising from WSW–ENE the Kelingkang, Upper Kapuas, Iran and Semporna Highs (Figs. 1 and 2).

In Kalimantan, hydrocarbons are produced from three sedimentary basins located in the eastern half of

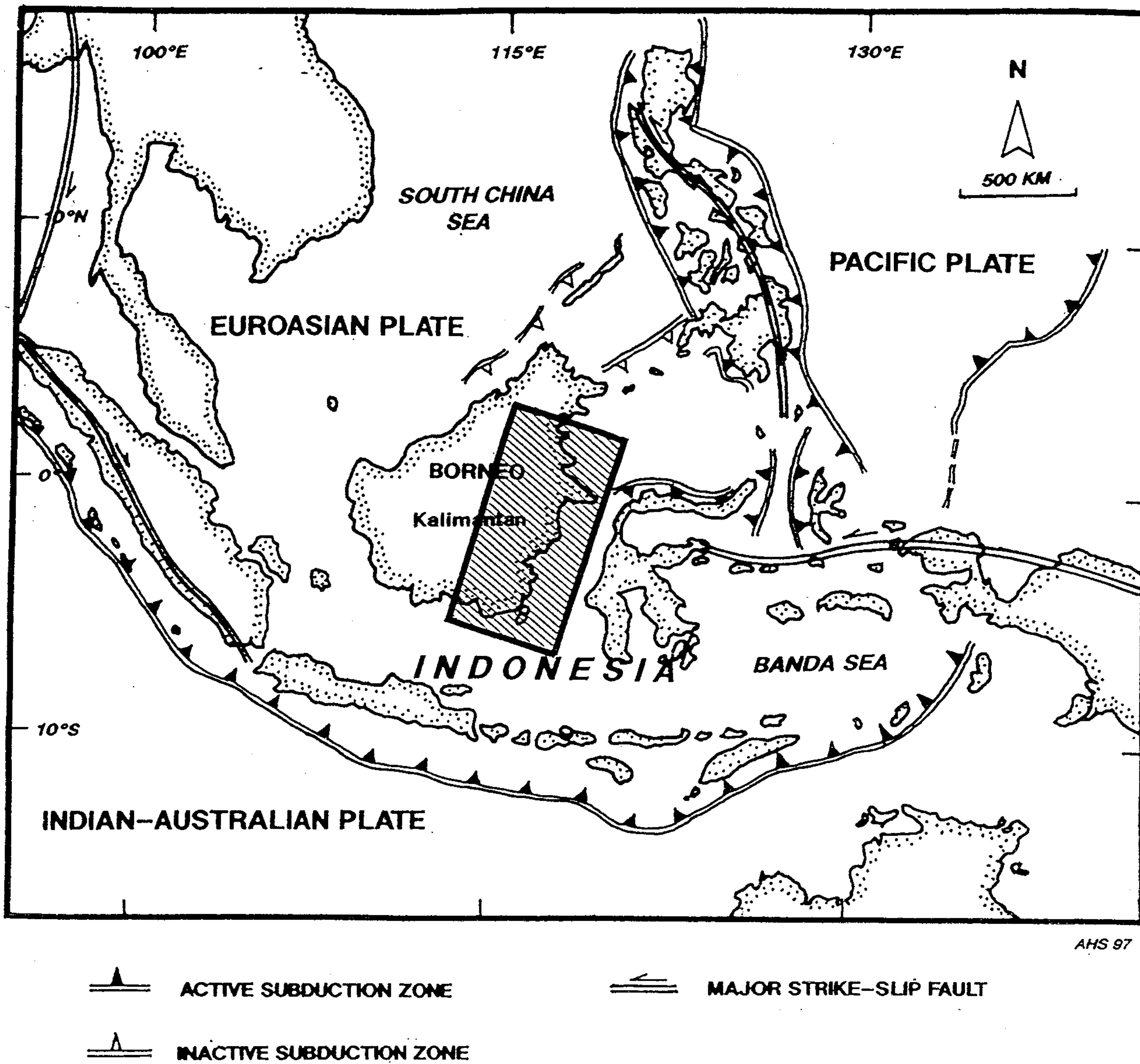

Fig. 1. The tectonic setting of the study area in eastern Kalimantan in Southeast Asia.

the island : Barito (since 1938), Kutei (since 1897) and Tarakan (since 1905) (Weeda, 1958) (Fig. 3). The history of oil exploration and production dates back to 1865 when Greve reported numerous oil seeps located in the Balikpapan–Samarinda area of the Kutei Basin. However, the oil and gas industry in Kalimantan began properly in 1891, when two petroleum concessions (Mathilde and Louise—both in the South Kutei Basin) were awarded to a private oil company by the Dutch Government. Nowadays, Kalimantan accounts for 18% of Indonesia's oil and condensate production and 32% of its gas production (Courteney and Wiman, 1991). One field in the Barito Basin and several fields in the Kutei Basin are classified as giant fields.

Almost all the oil fields in these three producing basins are due to the deformation undergone by the basins during the Tertiary and Pleistocene. In the Barito Basin, all fields are located in faulted anticlines. In the Kutei Basin, the Samarinda Anticlinorium is a prolific petroleum province. In the Tarakan Basin, anticlines fragmented by normal and growth-faults, prove to be the main petroleum traps. However, the tectonic style and origin within each basin is different, despite their neighbouring positions.

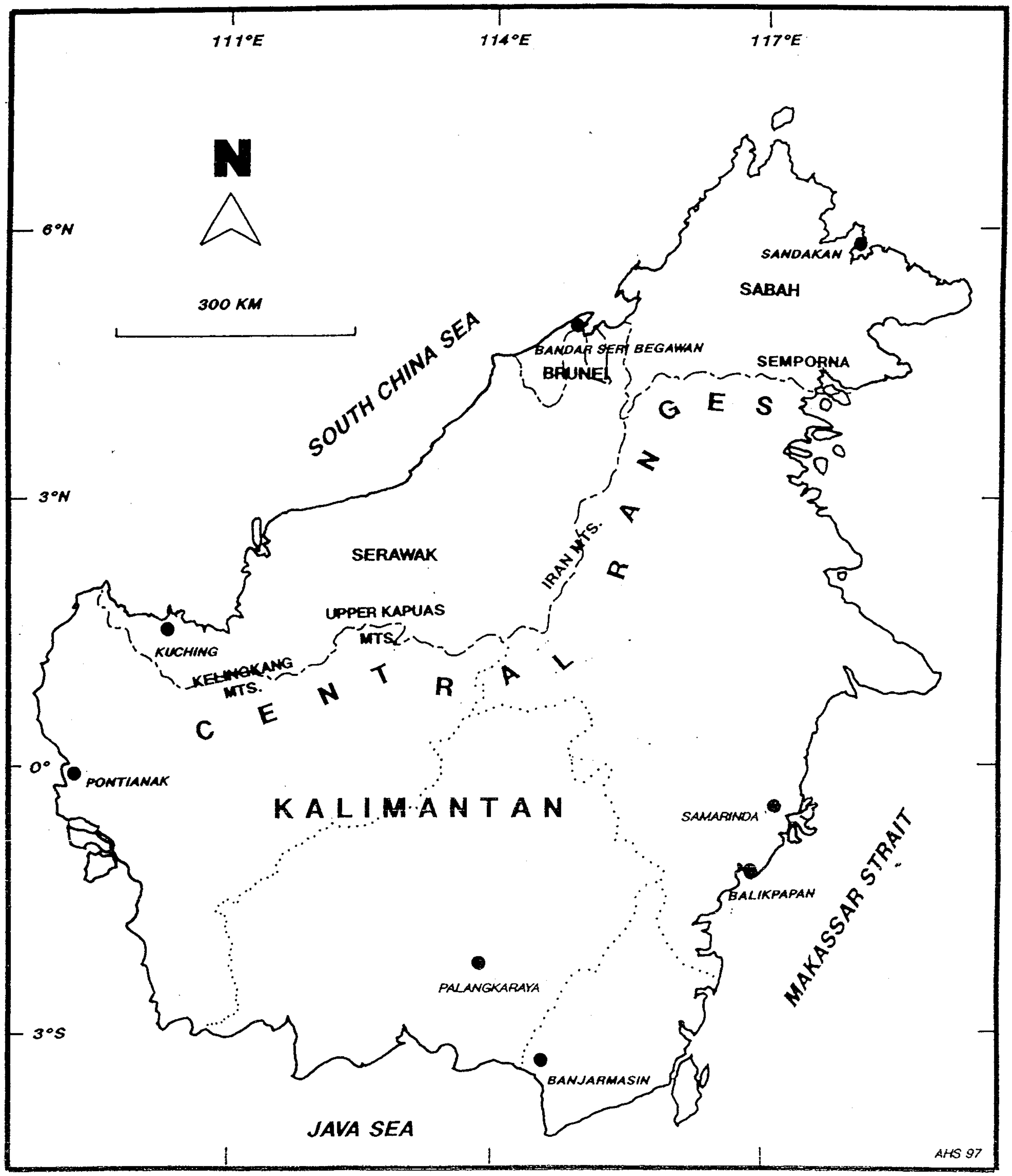

Fig. 2. Borneo–Kalimantan showing national and administrative boundaries, important cities and the mountainous areas constituting the Central Kalimantan Ranges.

This paper first discusses the geologic setting of each basin and their tectonic implications for hydrocarbon habitats. Secondly, a comparative examination of the basins is given. Evaluation of the possibility of applying the understanding of the tectonic style of one basin to the other basins, in the search for new play opportunities, is also addressed in this paper.

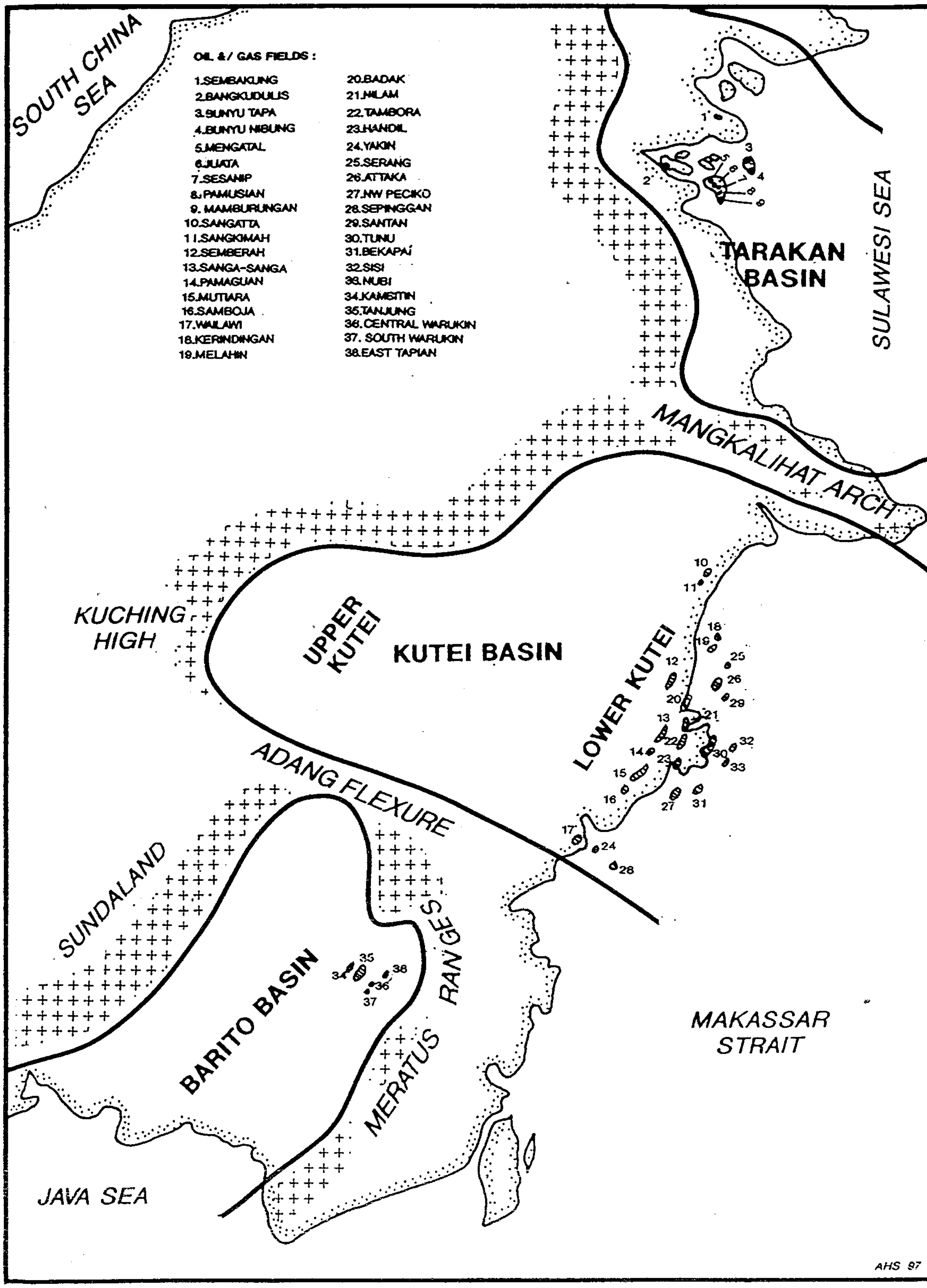

Fig. 3. Producing oil and gas fields (not differentiated) in the Barito, Kutei and Tarakan Basins.

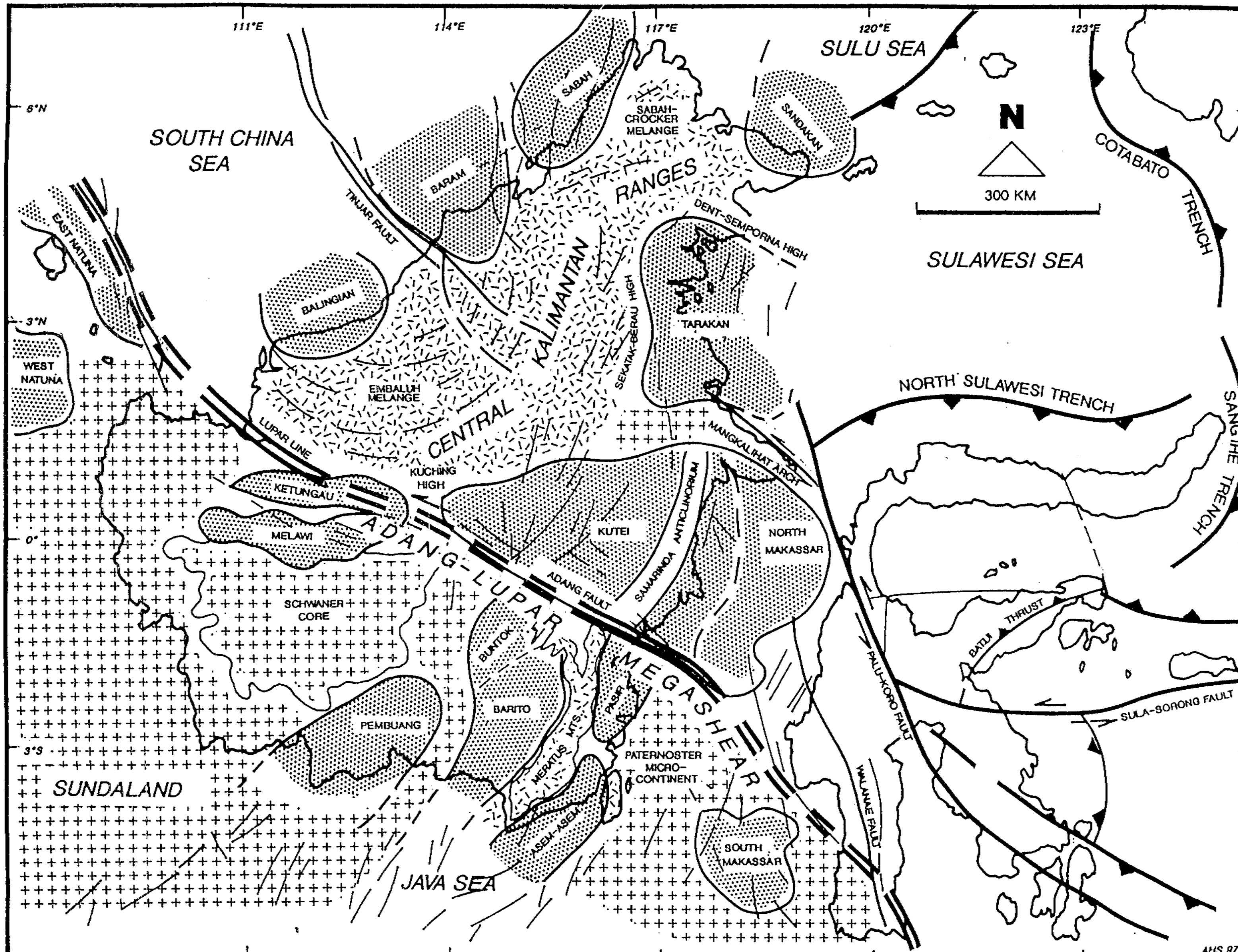

Fig. 4. The tectonic framework of Kalimantan and the surrounding areas. Note that the Barito, Kutei and Tarakan Basins overlie a variety of basement terranes (compiled from many sources).

2. Regional framework

2.1. Tectonics

Regionally, the island of Borneo is cored by a triangular-shaped nucleus (Latreille et al., 1971) pointing to the north, consisting of the Western Kalimantan–Schwaner continental shield at its base in the south, and of accreted crust, comprising the Central (Kalimantan) Ranges, to the north (Fig. 4). This triangular core forms the backbone of the island and plays a role as a dividing element separating two main basinal areas, to the NW and SE of the nucleus. The Balingian, Baram and Sabah basinal areas have developed to the NW of the nucleus, while the Barito, Kutei and Tarakan Basins have developed to the SE. The Melawi, Ketungau and Pembuang Basins occur within the area of the nucleus.

In the light of modern terrane concepts, the island of Borneo is made up by a variety of amalgamated basements : continental, oceanic and transitional (Fig. 4). The Barito Basin is situated between the Schwaner continental basement to the west and the accreted crust of the Meratus Mountains to the east. The Kutei Basin is terminated to the west and north by the accreted crust of the Kuching High (portion of the Central Ranges) and the continental basement of Mangkalihat, respectively. Onshore the Tarakan Basin is half encircled in a clockwise direction by the accreted crusts of Dent–Semporna, the Sekatak–Berau High (a portion of the Central Ranges) and the Mangkalihat continental basement. Relationships between these basement terranes are not fully understood. Some may represent suture lines, indicating collision zones, mobile belts or major fault zones (van de Weerd and Armin, 1992; Metcalfe, 1996; Satyana, 1996).

The Barito, Kutei and Tarakan Basins were part of a large and interconnected area of subsidence and sedimentation in the Early Tertiary. Miocene uplift segmented the area into separate basins (Weeda, 1958; van de Weerd and Armin, 1992). The Barito Basin is separated from the Kutei Basin by the Adang Flexure/Fault, a hinge line representing a major fault. The origin, evolution and economic significance of the Adang Fault has been discussed by Satyana (1996). The Kutei Basin is separated from the Tarakan Basin by the Mangkalihat Arch (Figs. 4 and 15).

Both the Tarakan and the Kutei Basins form embayments opening to the east towards the deep Makassar Strait (Fig. 14). Whereas, the Barito Basin is restricted towards the east by the Meratus Mountains. The rifting of the Makassar Strait in the Early Tertiary is considered to have controlled the inception of both the Tarakan and Kutei Basins (Biantoro et al., 1992; Lentini and Darman, 1996). Uplifted western borders cause the sedimentary fills of these basins to deepen and thicken asymmetrically towards the east.

The present structural configuration within the three basins is characterized by fold- and fault-belts trending parallel to the shoreline of Eastern Kalimantan (Fig. 5). The belts trend dominantly in a SSW–NNE direction, except in the Adang Flexure, the Mangkalihat Arch and the Semporna High areas, where they trend in a more E–W direction The origin of structures in each basin is completely different. In the Barito Basin, the structures are associated with the uplift of the Meratus Mountains to the east (Satyana and Silitonga, 1993; 1994; Satyana, 1994). In the Kutei Basin, the formation of the structures has been considered to have resulted from many causes: vertical diapirism (Biantoro et al., 1992), gravitational gliding due to the Kuching Uplift (Rose and Hartono, 1978; Ott, 1987), inversion through regional wrenching (Biantoro et al., 1992), detachment folds over inverted structures (Chambers and Daley, 1995) and inverted delta growth-fault system (Ferguson and McClay, 1997). In the Tarakan Basin, the origin of structures is closely related to sedimentary loading of successive deltaic deposits (Biantoro et al., 1996; Lentini and Darman, 1996). In the Tarakan Basin terranes from the Sulu Sea to NNE of Borneo, converging with the Semporna High are responsible for the formation of the structures.

The three basins show similar tectonic histories during the Tertiary, until the Pleistocene (Fig. 6). Extensional tectonics, resulting in rifts and commencing in latest Paleocene–Middle Eocene time, characterized structural styles during the Paleogene. Compressional tectonics dominated during Neogene and Pleistocene times, when older structures were inverted and uplifted, resulting in regressive sedimentation. Neogene and Pleistocene extensional faults, both in the Kutei and Tarakan Basins, were triggered by convergent uplift along the western margins of both basins.

2.2. Stratigraphy

The Paleozoic and Mesozoic deposits of Borneo, preserved in cratonic areas, were metamorphosed and folded during pre-Tertiary orogenies. Tertiary and Pleistocene sediments were deposited in the basinal areas flanking the Borneo nucleus. Tertiary sedimentation took place under continental, transitional and open marine conditions (Latreille et al., 1971).

The depositional history of the eastern Kalimantan basins during the Tertiary is broadly one of subsidence, with the establishment of deep marine conditions, followed by filling up of the basins under shallower marine conditions (Figs. 6 and 7). In the

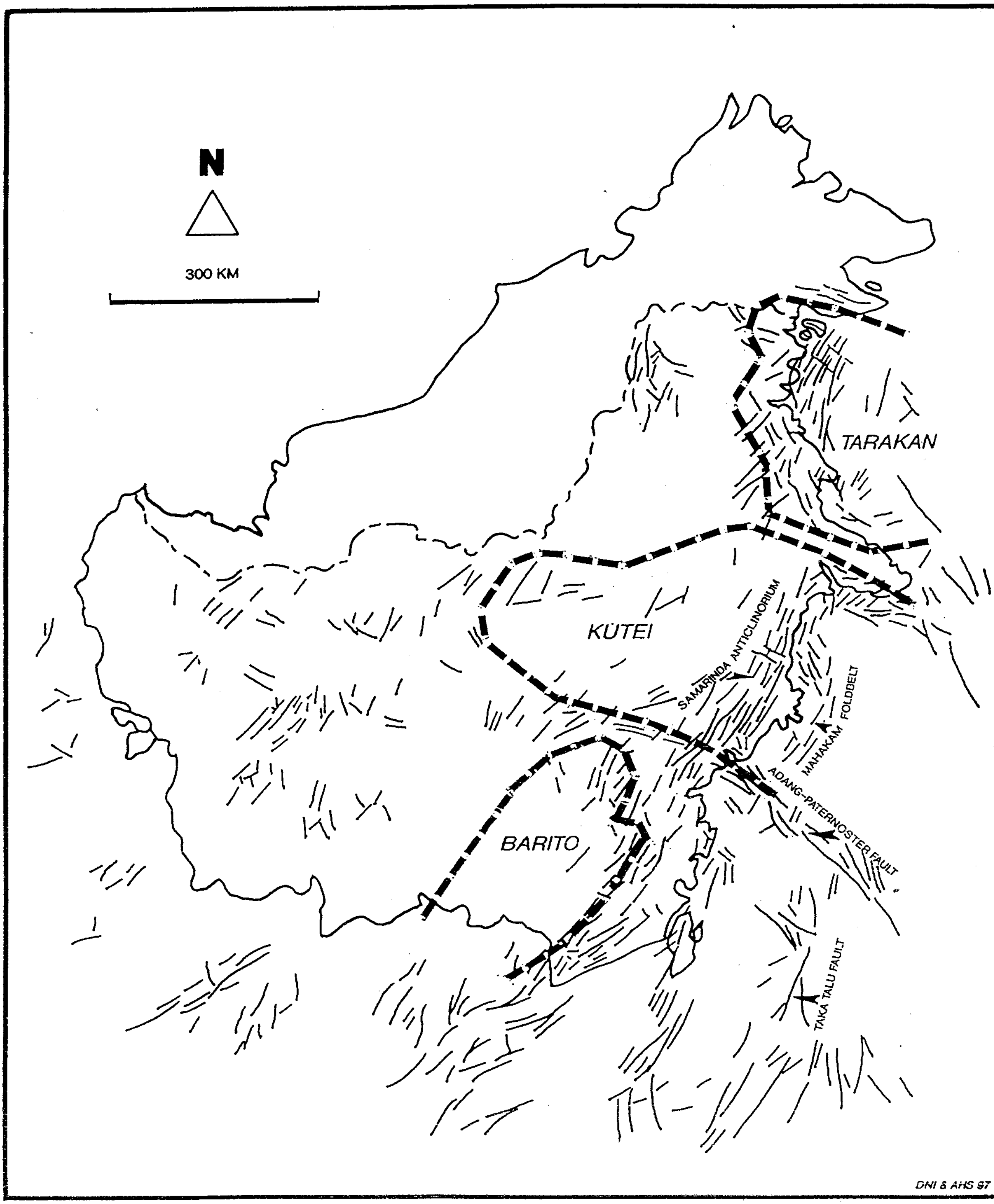

Fig. 5. The trends of present structural features in Kalimantan.

Tertiary, after the deposition of transgressive basal sands, a thick monotonous shale series was deposited in rather bathyal conditions. In the south (the Barito Basin), near the shelf, bathyal conditions were hardly ever reached. During the phase of the deepest immersion, in the late Oligocene, limestones were deposited. Northwards approaching Balikpapan, where subsidence was dominant, the basin reached greater depths

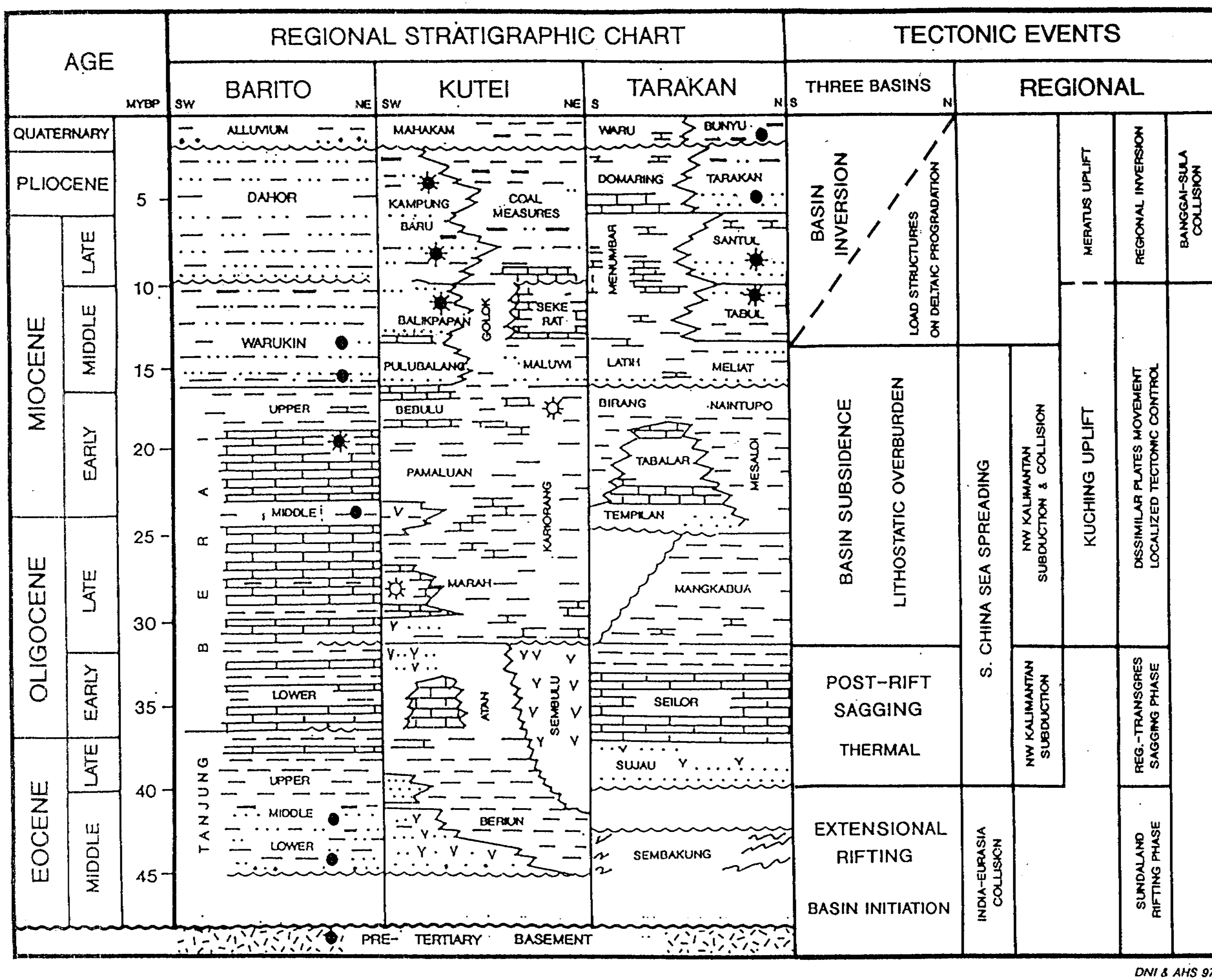

Fig. 6. The relationship of the stratigraphic successions in the Barito, Kutei and Tarakan Basins to tectonic episodes. The Palaeogene was characterised by extension–transgression; the Neogene–Pleistocene by compression–regression. Deltaic structures become more prominent from the Barito to the Tarakan Basin, while inversion structures become weaker in the same direction. Tectonic episodes are related to the broader regional picture.

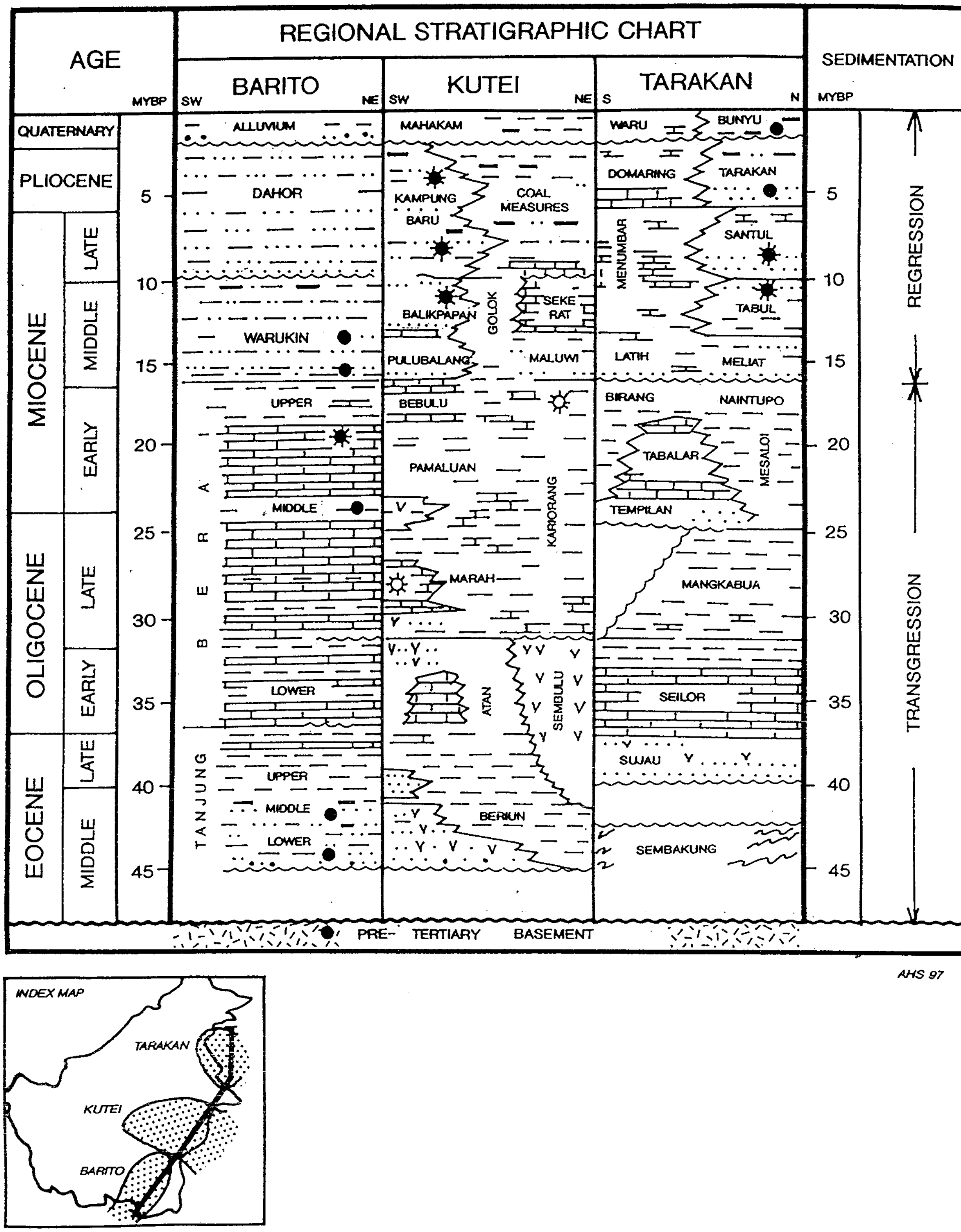

Fig. 7. The stratigraphic scheme of the Barito, Kutei and Tarakan Basins showing positions in the succession of hydrocarbon occurrences. Note that hydrocarbons occur in younger rocks from the Barito to the Tarakan Basin.

and during the same stages a clay series, thousands of meters thick, was deposited without limestones. Farther north, limestones again occur, but here they are not of the same importance as in the south, and appear only as intercalations in a predominantly clayey section (Weeda, 1958).

In early Middle Miocene time, a phase of regression commenced, during which sands were deposited. In the Barito Basin, very soon after the deposition of the early Miocene carbonates, paralic conditions prevailed, with the deposition of limestones and coals, together with sands, late in the Early Miocene. Near Balikpapan, early Middle Miocene deposits consist of clays with limestone intercalations, and it was only in the middle of Middle Miocene times that coarse sands were deposited. Farther north, near the Mangkalihat Arch, only the latest Middle Miocene is paralic, but on the Arch itself a fairly important carbonate of this age has been developed and coals are absent. Finally in the extreme north, in the Tarakan Basin, no coals or well-developed sands occur until after Middle Miocene time, although at Bunyu this stage does contains some coals and sands. After Middle Miocene time, the deposits became coarser over wide areas. In the extreme north and south of East Kalimantan, in the Tarakan and Barito Basins, younger deposits rest unconformably upon older deposits. In the Kutei Basin in the central part of eastern Kalimantan, this unconformity fades out. The thickness of the Tertiary deposits is considerable. Rough estimates are: in the Barito Basin—4000 m; in the Kutei Basin 12,000–14,000 meters; and in the Tarakan Basin 9000 m (Fig. 15).

3. Barito basin

3.1. Geologic setting

The Barito Basin is situated along the southeastern margin of the Schwaner Shield in South Kalimantan (Fig. 8). The basin is defined by the Meratus Mountains to the east and separated from the Kutei Basin to the north by a flexure related to the Adang Fault. The basin has a narrow opening to the south towards the Java Sea. The Barito Basin is an asymmetric basin, forming a foredeep in the eastern part and a platform approaching the Schwaner Shield towards the west (Fig. 9 and Fig. 14).

The Barito Basin commenced its development in the Late Cretaceous, following a micro-continental collision between the Paternoster and SW Borneo micro-continents (Metcalfe, 1996; Satyana, 1996). Early Tertiary extensional deformation occurred as a tectonic consequence of that oblique convergence. This produced a series of NW–SE trending rifts. These rifts became accommodation space for alluvial fan and lacustrine sediments of the Lower Tanjung Formation, derived from horst areas. In the earliest Middle Eocene, as the result of a marine transgression, the rift sediments becoming more fluviodeltaic and eventually marine, as transgression proceeded during the deposition of the Middle Tanjung Formation. The marine transgression subsequently submerged the rifts in late Eocene–earliest Oligocene time, resulting in the deposition of widespread marine shales of the Upper Tanjung Formation.

After a short-lived marine regression in the Middle Oligocene the development of a sag basin caused renewed marine transgression. The Late Oligocene is characterized by the deposition of platform carbonates of the Berai Formation (Figs. 6 and 7). Carbonate deposition continued into the Early Miocene, when it was terminated by increasing clastic input from the west. During the Miocene the sea regressed, due to the uplift of the Schwaner Core and the Meratus Mountains. Clastic input resulted in the deposition of the eastwards-prograding deltaic sediments of the Warukin Formation. In the late Miocene the Meratus Mountains re-emerged, followed by the isostatic subsidence of the basin which was situated in a foreland position in relation to the rising mountains. Sediments shed from this uplift were deposited in the subsiding basin, resulting in the deposition of thousands of meters of the Warukin Formation. The uplift of the Meratus Mountains continued into the Pleistocene and resulted in the deposition of the molassic-deltaic sediments of the Pliocene Dahor Formation. This structural and depositional regime still exists today.

The structural development of the Barito Basin is a consequence of two distinctly separate, regimes (Fig. 6). First, an initial transtensional regime, during which sinistral shear resulted in the formation of a series of NW–SE trending wrench-related rifts, and second, a transpressional regime involving convergent uplift, which reactivated and inverted old tensile structures and resulted in wrenching, faulting and folding. The kinematics and type of Barito tectonic inversion have been discussed by Satyana and Silitonga (1994).

Presently, the structural grain of the basin is characterized by the concentration of structures in the NNE part of the basin, typified by tight, parallel SSW–NNE trending folds, bounded towards the Meratus Mountains by high-angle easterly-dipping imbricate reverse faults, which involve the basement (Figs. 5 and 9). The presence of major wrench faults is indicated by drag or fault-bend folds and reverse fault traces. The unique concentration of structures in the NE part of the basin was interpreted by Satyana (1994) as the tectonic consequence of half-encirclement of the area by the two pre-Tertiary massifs: the northern Meratus Range and the North Meratus Massifs (Fig. 8). The western and southern parts of the Barito Basin was mildly tectonized and show almost no deformation structures. Thin-skinned tectonic manifestations, represented by decollement and ramp anticlines are only vaguely identifiable in this portion of the basin (Satyana and Silitonga, 1993). Along the northern

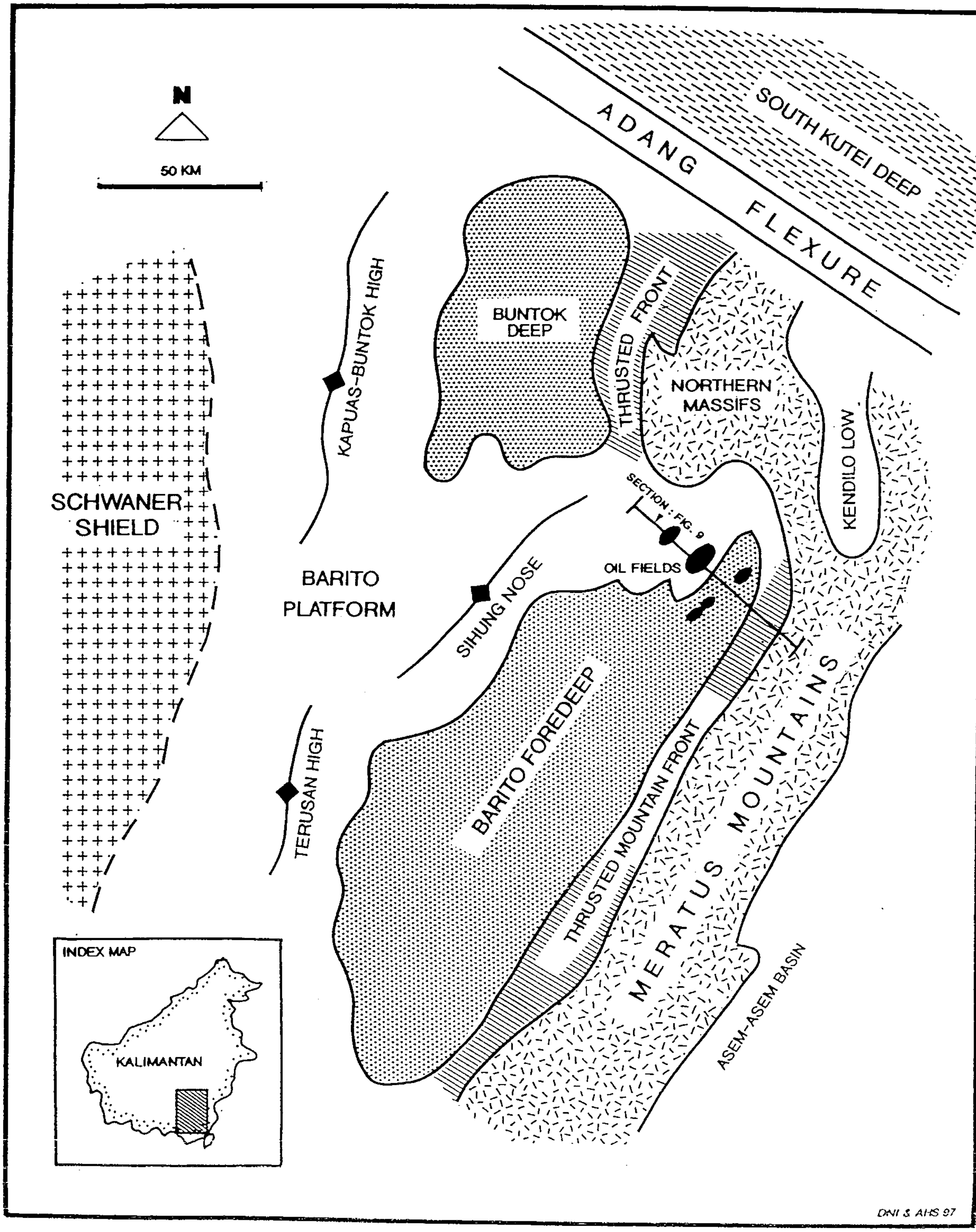

Fig. 8. Physiographic and tectonic setting of the Barito Basin, southeast Kalimantan showing producing fields.

margin the dominant structures are broad folds trending in an E–W direction. These folds are considered to be old folds of Paleogene age, originating in association with the Adang Fault Zone (Satyana, 1996).

3.2. Tectonics versus hydrocarbon habitat

In the Barito Basin, hydrocarbons are trapped in five fields: the Tanjung, Kambitin, South Warukin,

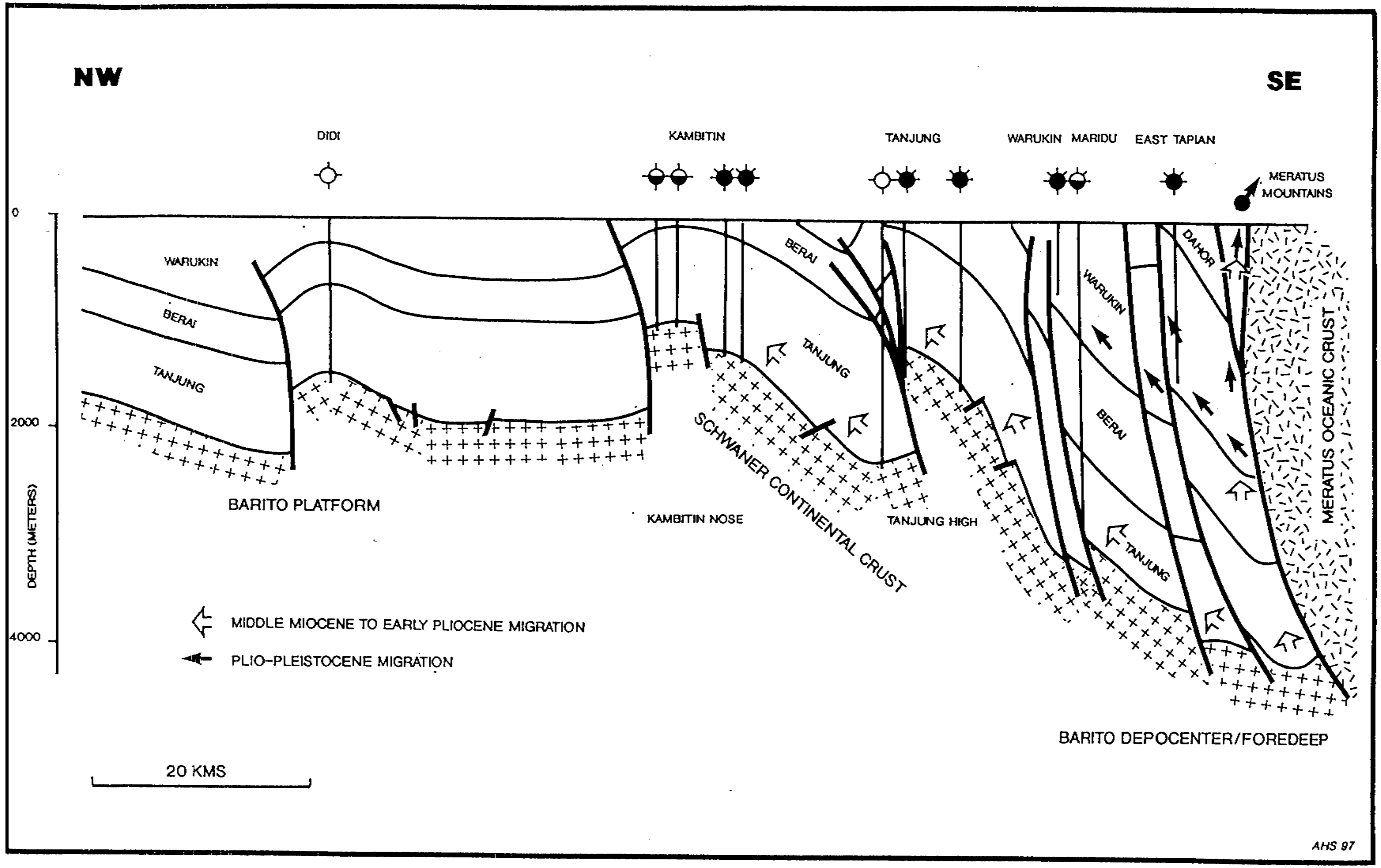

Fig. 9. Integrated structural section across the Barito Basin showing hydrocarbon entrapment. The Kambitin and Tanjung Fields were charged by Miocene migration, whereas the Warukin and East Tapian Fields were charged by Plio–Pleistocene migration. See Fig. 8. for the position of the line of section (modified from an unpublished joint study by PERTAMINA-Trend Kalimantan, 1988).

Central Warukin and East Tapian Fields (Fig. 3). All of the fields occur in faulted anticlines dipping to the east. The Tanjung and Kambitin Fields are associated with basement-involved structures. The Warukin and East Tapian Fields occurred in structures developed by thin-skinned tectonics within the Warukin Formation (Fig. 9).

Hydrocarbons are reservoired in the Lower and Middle Tanjung Sands (Middle Eocene) and in the Lower and Middle Warukin sands (Middle Miocene) (Figs. 7, 14 and 15). Pre-Tertiary basement rocks and the Berai carbonates (late Oligocene–early Miocene), where they are fractured, have also proved to be good reservoirs, and may trap hydrocarbons if they are well positioned. The hydrocarbons were generated in, and migrated from, Lower and Middle Tanjung coals and carbonaceous shales, and Lower Warukin carbonaceous shales. The main kitchen is located in the present basin depocentre. The sealing rocks are mainly provided by the intra-formational shales. Generation, migration and entrapment of hydrocarbons has taken place since the middle Early Miocene (20 Ma).

The Barito Basin provides the best example of the effects of tectonic interaction on hydrocarbon habitat (Fig. 9). In this basin, tectonics controlled each component of the hydrocarbon habitat (petroleum system). Extensional tectonics in the Early Tertiary formed a rifted basin within which the lacustrine Tanjung shales and coals were deposited in graben areas. This lacustrine environment was responsible for the deposition of the Tanjung source rocks. As subsidence continued and the rifted structures were submerged, widespread shales were deposited, which became an important seal for the underlying reservoir rocks. This condition was also responsible for the deposition of the widely-distributed Middle Tanjung reservoir rocks. Extensional faults became conduits for the migration of hydrocarbons generated in the deeper graben areas.

The role of tectonics in hydrocarbon accumulation in the basin during Neogene and Pleistocene time is indisputable. The implications of basin reversal in the development of the petroleum system in the Barito Basin is discussed in Satyana and Silitonga (1994). During the Late Miocene the basin was inverted, in association with the Meratus Uplift, to produce an asymmetric basin; the Barito Basin, dipping gently in the NW, towards the Barito Platform, and steeply in the SE against the Meratus Uplift. Consequently the central part of the basin subsided rapidly, due to isostasy, causing the Tanjung source rocks to be deeply buried, so that they attained the depth at which hydrocarbons were generated.

Restored modelling for the Barito tectonics and petroleum generation (Satyana and Silitonga, 1994; Satyana, 1995; Satyana and Idris, 1996) has shown that inversion of the basin resulted from compressional tectonism (Fig. 9). Graben-fill sequences were actively inverted and asymmetric anticlines were generated along the reverse faults. Hydrocarbons generated from the basin depocentre were expelled to fill these structural traps. Structures such as the Tanjung Field were thus favorably positioned for the entrapment of early migrating hydrocarbons. Uplift of the Meratus Mountains was continuous during the Late Miocene, through the Pliocene, and peaked in the Plio–Pleistocene. Tanjung source rocks in the depocentre were already mature by the Late Miocene. Proto-inverted structural traps formed in the early Miocene time were continuously inverted as basin compression developed, resulting in strongly positive features. Hydrocarbons filled these traps through the faults and along permeable sands. It is considered that in the early Pliocene the Tanjung source rocks in this area had exhausted their liquid hydrocarbon generating capability. At this stage gas was generated and migrated to fill the existing traps.

Plio–Pleistocene tectonism caused the whole Barito Basin to be strongly inverted (Fig. 9). This tectonic event caused both the formation of new traps and the destruction of existing traps. Entrapped hydrocarbons probably remigrated to the newly-formed structures as old traps were tilted or breached by the Plio–Pleistocene inversion. At this stage the Tanjung source rocks had ceased to generate oil and gas in the depocentre, since the section was firmly within the dry gas window. The Lower Warukin Shales in the basin depocentre reached the depth of the oil window in the peak episode of tectonism during Plio–Pleistocene times. Oil was generated and migrated to accumulate in structural traps within the Warukin sands. The Warukin and East Tapian Fields were charged in this period.

The foregoing discussion depicts how critical tectonics are to the deposition of reservoir and source rocks, the maturation of source rocks, the formation of structural traps and oil field distribution. However, tectonics may also destroy pre-existing traps.

4. Kutei Basin

4.1. Geologic setting

The Kutei Basin is the largest (165,000 km^2) and the deepest (12,000–14,000 meters) Tertiary sedimentary basin in Indonesia. The basin is bounded to the north by the Mangkalihat High; to the south the basin hinges on the Adang–Flexure (Adang-Paternoster Fault); to the west it is terminated by the Kuching High—part of the Kalimantan Central Ranges; and to the east the opens into the Strait of Makassar (Fig. 10).

The Tertiary stratigraphic succession within the basin commenced with the deposition of Paleocene

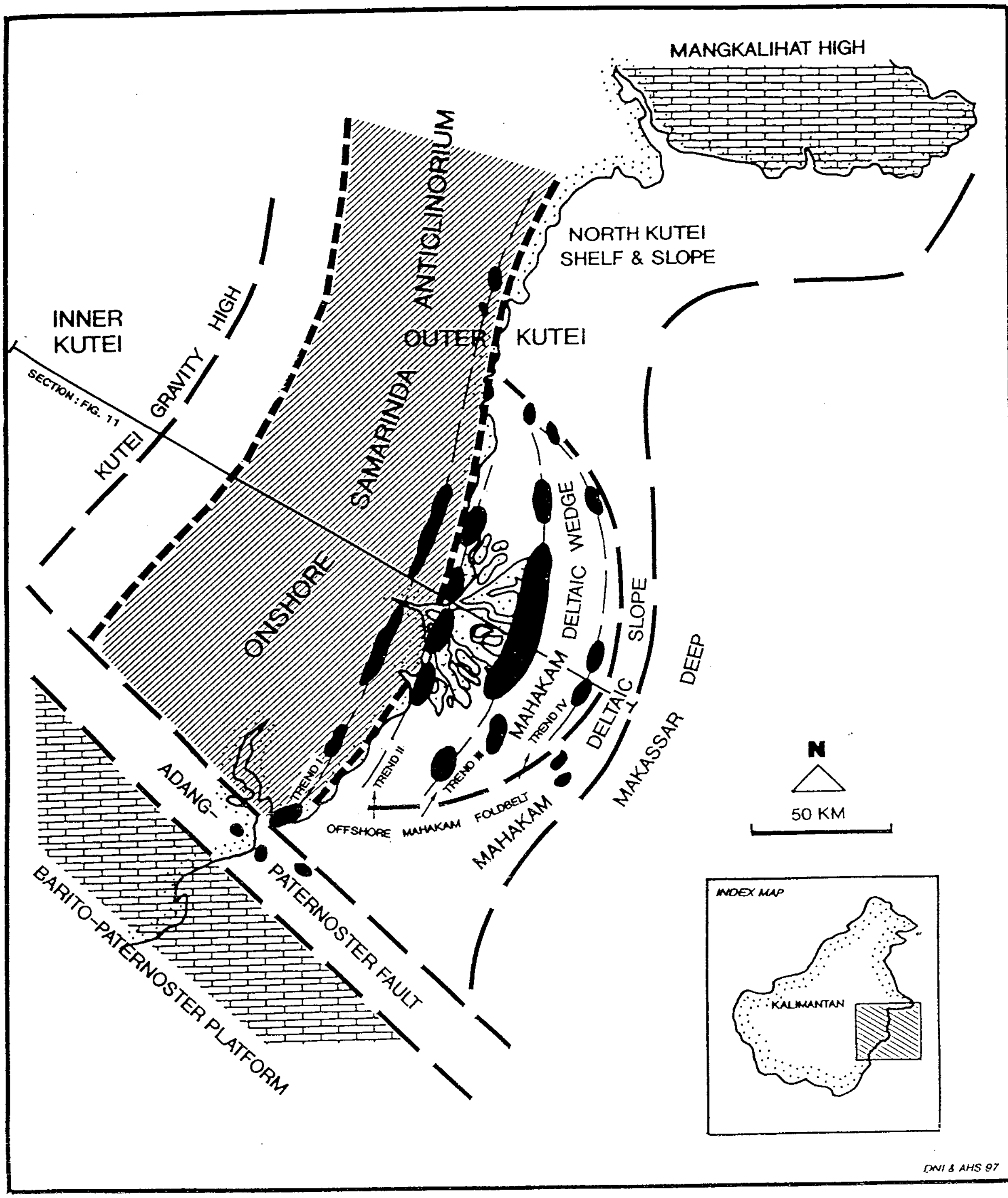

Fig. 10. Physiographic and tectonic setting of the Kutei Basin, East Kalimantan showing producing fields.

alluvial sediments of the Kiham Haloq Formation in the inner basin, close to the western border (Figs. 6, 7 and 14). The basin subsided during the late Paleocene–Middle Eocene to Oligocene, due to basement rifting, and became the site of deposition of the Mangkupa Shale in a marginal to open marine environment. Some coarser siliciclastics, the Beriun Sands, are locally associated with the shale sequence, indicating an interruption of basin subsidence by uplift. The basin subsided rapidly after the deposition of the Beriun Sands, mostly through the mechanism of basin sagging, resulting in the deposition of marine shales of the Atan Formation and carbonates of the Kedango Formation (Satyana and Biantoro, 1996).

Subsequent tectonic events uplifted parts of the basin margin by the late Oligocene (Figs. 6 and 7).

This uplift was associated with the deposition of the Sembulu Volcanics in the eastern part of the basin. The second stratigraphic phase was contemporaneous with basin uplift and inversion, which started in Early Miocene time. During that time, a vast series of alluvial and deltaic deposits were deposited in the basin. They comprise deltaic sediments of the Pamaluan, Pulubalang, Balikpapan and Kampung Baru formations, prograding eastwards, which range in age from the Early Miocene to Pleistocene times. Deltaic deposition continues to the present day, and extends eastwards into offshore Kutei Basin.

At present, the structural style of the Kutei Basin is dominated by a series of tight NNE–SSW trending folds (and subsidiary faults) that parallel the arcuate coastal line, and are known as the Samarinda Anticlinorium—Mahakam Foldbelt (Figs. 5, 10 and 11). These fold belts are characterized by tight, asymmetric anticlines, separated by broad synclines, containing Miocene siliciclastics. These features dominate the eastern part of the basin and are also identifiable offshore. The deformation is increasingly more complex in the onshore direction. The western basin area has been uplifted. A minimum of 1500 m to over 3500 m of sediments have been removed by a mechanism of inversion (Wain and Berod, 1989; Courteney and Wiman, 1991). Not much is known about the structure of the western basin area and, although large structures are evident, a similarity in structural trend and style is not apparent from the available data (Ott, 1987). In this region, the tectonics may involve the basement (thick-skinned tectonics). Tectonic reversal, in terms of origin and its strain response, is not as obvious as in the Barito Basin. Prograding deltaic sediments may have contributed to the mechanism of structural inversion, by a mechanism of diapirism or growth-faulting, these mechanisms are very different from those which affected the Barito Basin.

The origin of folds and faults in the Kutei Basin remains unresolved and concepts as diverse as vertical diapirism, gravitational gliding (Rose and Hartono, 1978; Ott, 1987), inversion through regional wrenching (Biantoro et al., 1992), micro-continental collision, detachment folding above overpressured sediments (Chambers and Daley, 1995), differential loading on deltaic sediments and an inverted delta growth fault system (Ferguson and McClay, 1997) have been invoked.

4.2. Tectonics versus hydrocarbon habitat

The Kutei Basin is the most prolific petroleum province in Kalimantan. No new commercial field has been discovered in the Barito and Tarakan Basins during the last few decades of exploration, but several new fields, some giants, have been discovered in the Kutei Basin during the last decade.

Producing oil and gas fields in the Kutei Basin are all concentrated in the outer (Lower) Kutei Basin (Figs. 3 and 10). Not one field is located in the inner (Upper) Kutei Basin. The non-producing Kerendan gas and condensate field is located in the transitional area between the Barito and Kutei basins, in the SW Kutei Basin, and cannot be related to the trend of the upper Kutei Basin. All the oilfields in the Kutei Basin occur in the Samarinda Anticlinorium–Mahakam Foldbelt. Some recently-discovered fields are stratigraphic traps, which are connected in some way with the tectonics. The 24 producing fields of the Kutei Basin are: Sangatta, Sangkimah, Semberah, Pamaguan, Sanga-Sanga, Mutiara, Samboja, Wailawi, Kerindingan, Melahin, Badak, Nilam, Handil, Yakin, Serang, Attaka, Tambora, Tunu, NW Peciko, Santan, Bekapai, Sisi, Nubi and Sepinggan. Giant fields are located along the present Mahakam River. The fields occur in parallel belts constituting four trends (Trend I to IV) across the onshore and offshore parts of the Mahakam Delta (Fig. 10).

Hydrocarbons are trapped in reservoir deltaic sands of the Balikpapan (Middle Miocene) and Kampung Baru (late Miocene–Pliocene) formations (Figs. 7, 11, 14 and 15). Pliocene carbonates form subsidiary reservoirs in the offshore area. The source rocks are the coals and carbonaceous shales of these two formations. Sealing is provided entirely by intra-formational shales. Each field is sourced by a proximal kitchen located in its down-dip synclinal area. The hydrocarbons generated in these areas migrated laterally updip to a maximum distance of 10 km (Paterson et al., 1997) to accumulate in anticlinal traps. The generation and migration of hydrocarbons started in the Late Miocene and peak oil accumulation has occurred since the late Pliocene. Trap formation took place from the middle Miocene to Plio–Pleistocene time.

Tectonics are responsible for the richness of the Kutei Basin. Convergent tectonics, which began in the late Oligocene, have uplifted/inverted the Kuching High and the Upper Kutei Basin (Ott, 1987) (Fig. 11). This uplifted area has become a major provenance for the deltaic sediments deposited in the Lower Kutei Basin since that time. These sediments provide reservoir, source and sealing rocks in the Kutei Basin. The presence of repeated synclinal kitchens and anticlinal traps within the Samarinda Anticlinorium/Mahakam Fold Belt demonstrates the role of tectonics in hydrocarbon accumulation. Recent papers by Paterson et al. (1997) and Ferguson and McClay (1997) stress the control of tectonics on early hydrocarbon expulsion of oil by fracturing of the source rocks, while in the generative stage.

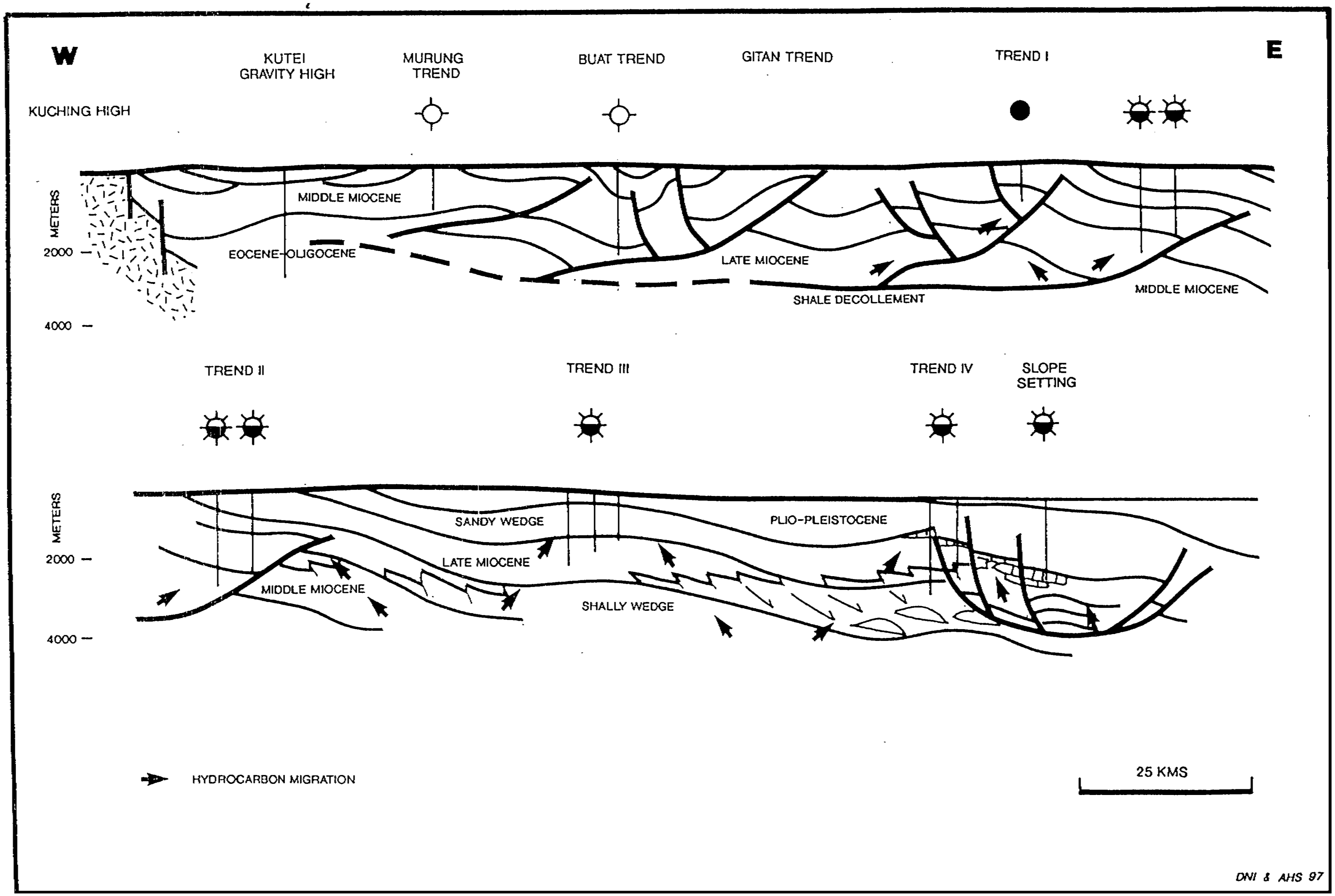

Fig. 11. Integrated structural section across the Kutei Basin showing hydrocarbon entrapment. Note: kitchens are located in each syncline of the Samarinda Anticlinorium. The location of the line of section is shown on Fig. 10.

Tectonics have also controlled the distribution of productive sands (Ferguson and McClay, 1997). At certain times, structural development controlled sedimentation patterns and channels ran parallel to the structures, instead of cutting across them, in a general W to E direction. This relationship is important in producing fields in delineating reservoirs, where paleochannel orientation may change from parasequence to parasequence, depending on the influence of structure on deposition. Tectonics are also responsible for the barrenness of the Upper Kutei Basin, due to excessive inversion and erosion.

5. Tarakan Basin

5.1. Geologic setting

The Tarakan Basin encompasses the basinal areas in NE Kalimantan (Fig. 12). Workers in this area usually subdivide the NE Kalimantan basinal areas into four sub-basins: the Tidung Sub-basin, the Berau Sub-basin, the Tarakan Sub-basin, and the Muara Sub-basin. The Tarakan Basin of this paper includes all four sub-basins. The boundaries between the sub-basins are not always effective borders, some are only hinges or fault zones.

The Tarakan Basin is separated from the Kutei Basin by the Mangkalihat High or Arch (Fig. 12). To the west the basin is terminated by the Sekatak–Berau High of the Central Ranges, the basin hinges on the Semporna High to the north, and opens eastwards and southeastwards into the Straits of Makassar.

Deposition in the Tarakan Basin commenced in the Middle Eocene, simultaneously with the rifting of the Makassar Straits which separates Sulawesi from Kalimantan (Lentini and Darman, 1996) (Figs. 6 and 7). The basin subsided and opened to the east. The sea transgressed westwards and shallow marine shales of the Sembakung Formation were deposited, overlying the older Danau basement rocks. The transgression was interrupted by the latest Eocene uplift which resulted in the deposition of coarse clastics of Sujau Formation. During Oligocene times a carbonate platform (Seilor Formation) developed and continued into the Early Miocene as the Mangkabua Shales and the reefal Tabalar Limestone. In the middle Miocene, the western basin margins were uplifted and caused open marine conditions to give way to widespread and rapid clastic deltaic deposition, which successively prograded eastwards with time. Periodic and cyclic regression—transgression during the middle Miocene to Pleistocene time caused sedimentary switching, leaving marine shales and limestones intercalated with coarse clastic deltaic sediments (The Naintupo shales, Meliat–Tabul–Santul–Tarakan–Sajau–Bunyu deltaics and the Domaring–Waru carbonates).

The present structural grain of the basin is characterized by folds trending NW–SE and by the faults trending NE–SW (Figs. 5 and 13). Structural deformation becomes increasingly complex northwards. The regular NE–SW trending faults, which are normal to the direction of sedimentary thickening, suggests that they were developed contemporaneously with deposition, and may be the direct result of sediment loading of successive deltaic sediments. All structures in the lower basin formed as the result of thin-skinned tectonics (Fig. 14). Involvement of the basement characterizes the structures of the upper basin, approaching the Sekatak–Berau High. Tectonic inversion is almost absent in this basin.

The tectonic history of the Tarakan Basin commenced with extensional tectonics in the Middle Eocene, initiating the basin by block faulting, similar to events in the neighbouring basins. In the Middle Miocene, the Sulu Sea, located to the north of the basin, was subducted below the accreted continental crust of North Kalimantan, and this resulted in the extrusion of Neogene volcanics in the Semporna Peninsula and was responsible for the formation of NW–SE trending, SE plunging folds in the Tarakan Basin. These fold axes are now represented by the islands of Sebatik, Bunyu and Tarakan. The folds become increasingly more complex towards the north as they approach the convergent margin. Some workers (Lentini and Darman, 1996; Biantoro et al., 1996) relate the formation of these folds to wrench tectonics in the basin itself. The thick progradation of a deltaic succession during Middle Miocene to Pleistocene time resulted in growth-faulting with rollover structures, aligned perpendicular to the sedimentary flow and subsiding towards the east.

5.2. Tectonics versus hydrocarbon habitat

Hydrocarbons in the Tarakan Basin were produced in the nine fields of Tarakan Island (Mengatal, Juata, Sesanip, Pamusian and Mamburungan fields), Bunyu Island (Bunyu–Nibung and Bunyu–Tapa fields) and in the onshore area of NE Kalimantan (Sembakung and Bangkudulis fields) (Figs. 3 and 12).

All hydrocarbons are reservoired in the deltaic sands of the Meliat, Tabul, Santul and Tarakan formations (Middle Miocene to Pliocene time) (Figs. 7 and 13–15). The hydrocarbons were generated from carbonaceous shales and coals in the Meliat and Tabul formations (Lentini and Darman, 1996) in two kitchen areas of the Sembakung–Bangkudulis Graben in the onshore area, and the Bunyu–Tarakan depocentre in

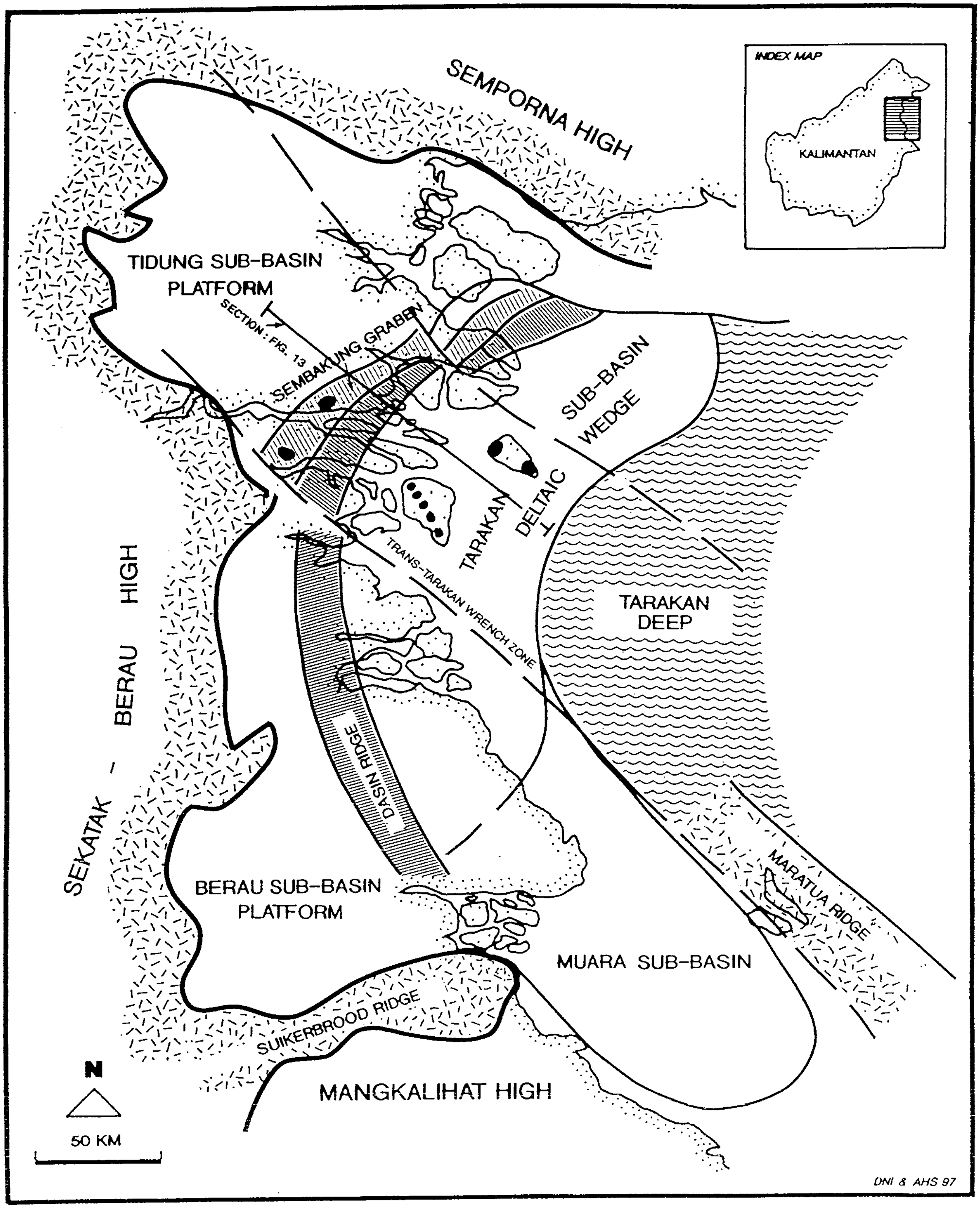

Fig. 12. Physiographic and tectonic setting of the Tarakan Basin, northeast Kalimantan showing producing fields.

the offshore area (Biantoro et al., 1996). Since the onset of generation in the late Miocene, both lateral and vertical migration have taken place along carrier beds and growth-fault in an updip direction towards the west. All the fields in the Tarakan Basin occur in faulted anticlines/faulted rollovers.

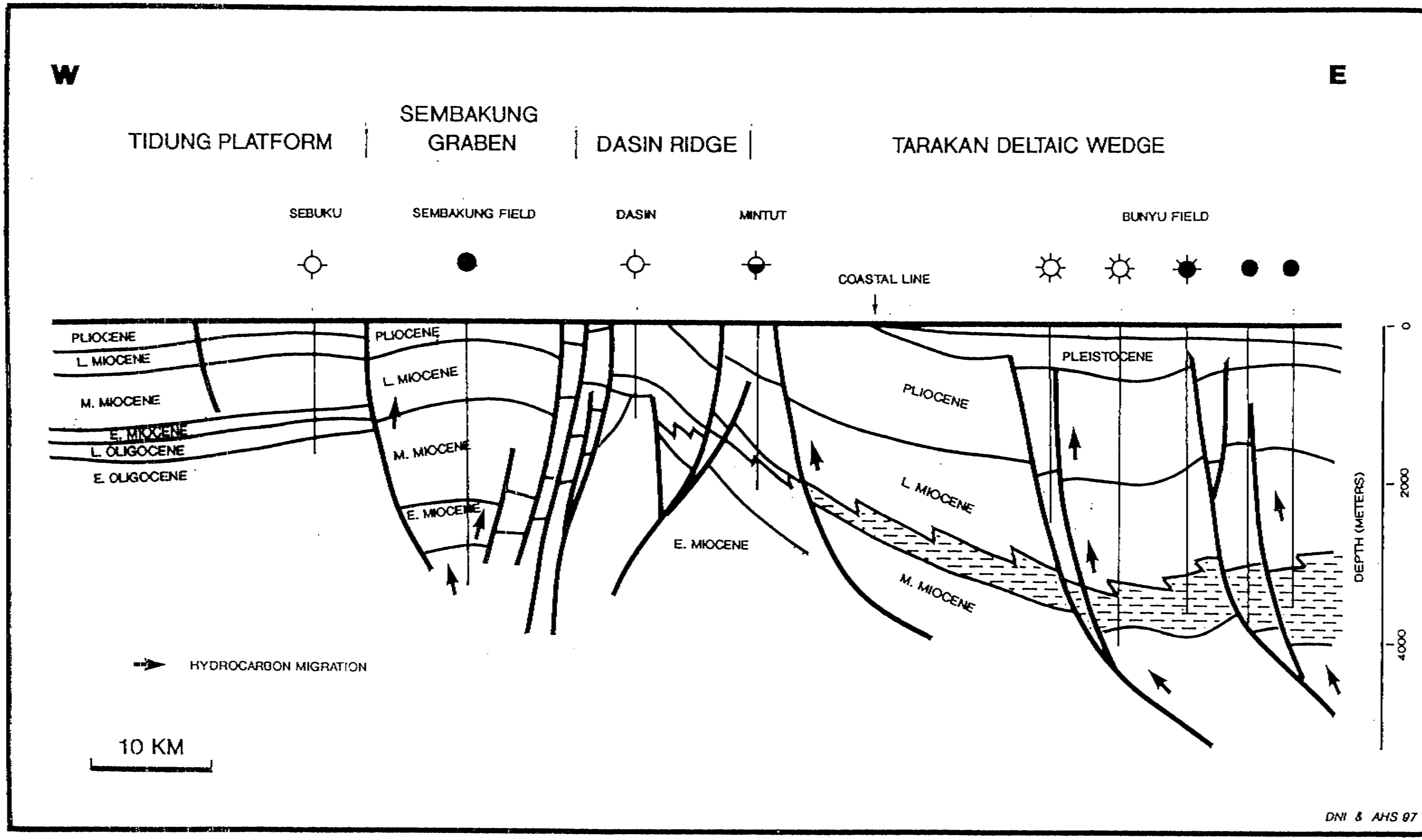

Fig. 13. Integrated structural section across the Tarakan Basin showing Hydrocarbon entrapment. Note that hydrocarbons are trapped in the rollovers of growth faults. The location of the line of section is shown on Fig. 12.

Syn-depositional faults play a major role in hydrocarbon accumulation in the Tarakan Basin. Biantoro et al. (1996) concluded that existing fields in the basin are very much dependent on the presence of growth-faults. The types of entrapment can be classified under the models of : four-way dip closure (Sembakung Field); rollover against fault (all Tarakan and Bunyu–Tapa fields); locally-upthrown block against fault (Bunyu Nibung Field); and unconformity-truncation against fault (Bangkudulis Field). Generally, hydrocarbons are trapped in the downthrown blocks of growth-faults. If hydrocarbons are found in the upthrown blocks, the reserves are generally not commercial. Faults may play a role either as conduits or as migration barriers. The maturation of source rocks was also a direct result of tectonics through subsidence until the rocks attained the depth of the oil window.

6. Major tectonic dissimilarities

The following discussion will show that although the Barito, Kutei and Tarakan basins are located in adjoining positions in the island of Kalimantan and have shared similar tectonic histories, they have major dissimilarities concerning some aspects of their tectonic development and the resultant hydrocarbon habitats (Figs. 14 and 15; Table 1).

6.1. Structural styles

The present structural grain of the Barito Basin is dominated by NNE–SSW trending faulted anticlines dipping to the east (west verging). Imbricate thrusts become more closely spaced towards the Meratus Mountains and involve the basement. These structures are concentrated in the northeastern part of the basin (Figs. 5 and 9). In the Kutei Basin at the present day the dominant structural features are a series of tightly folded, partly faulted, NNE–SSW trending anticlines and synclines of the Samarinda Anticlinorium, which dominate the eastern part of the basin and are identifiable offshore as the Mahakam Foldbelt. Structural growth is suggested by depositional thinning over the anticlinal structures (Figs. 5 and 11). In the Tarakan Basin, the present structural grain is typified by the NNE–SSW normal faults (growth faults) which mostly developed in marginal and offshore areas. These structures cross older NW–SE trending folds and are perpendicular to the direction of sedimentary thickening across the basin (Figs. 5 and 13).

6.2. Basement involvement

The Barito Basin is a shallow basin underlain by massive pre-Tertiary basement rocks (Figs. 9 and 14). The structuration involved the basement. Basement involvement increases eastwards and attains a maximum throw of 3200 m in the frontal area of the Meratus Mountains. To the west, approaching the Schwaner Shield, structuration may involve thin-skinned tectonics (Satyana and Silitonga, 1993). The basement of the Kutei and Tarakan Basins is very deep and has never been penetrated by wells (Figs. 11 and 13–15). The structuration of the Kutei and Tarakan Basins occurs only in the sedimentary cover of deltaic sequences (thin-skinned tectonics). Detachments are easily formed in the shale sequences within these basins. Chambers and Daley (1995) invoked detachment folds on overpressured sediments as the origin of folds in the Kutei Basin. To the west, approaching the Central Ranges, the Kutei and Tarakan Basins may show thick-skinned tectonics.

6.3. Tectonic inversion

Tectonic inversion decreases in magnitude from the Barito Basin to the Tarakan Basin. The present structures in the Barito Basin comprise inverted and reactivated structures. Inversion started in the Middle Miocene around the time of the Meratus Uplift. Further discussion of tectonic inversion in this basin

Table 1
Major tectonic dissimilarities between the eastern Kalimantan basins

Tectonic aspect	Barito Basin	Kutei Basin	Tarakan Basin
Structural style	NNW–SSW trending faulted anticlines imbricating and dipping to the east	NNE–SSW trending anticlines, partly faulted, increasingly more complex westwards, structural growth increasingly more obvious eastwards	NNE–SSW trending growth faults crossing NW–SE folds, structural growth increasingly more obvious eastwards
Basement involvement	Thick-skinned tectonics, in upper basin may thin-skinned tectonics	Thin-skinned tectonics, in upper basin may thick-skinned tectonics	Thin-skinned tectonics, in upper basin may thick-skinned tectonics
Tectonic inversion	Strongly inverted	Mildly inverted	Weakly inverted
Tectonic origin	Single origin by the Meratus Mountains uplift (passive)	Double origin by the Kuching High uplift (passive) and deltaic syn-depositional tectonics (active)	Double origin by the Sekatak–Berau High uplift (passive) and deltaic syn-depositional tectonics (active)

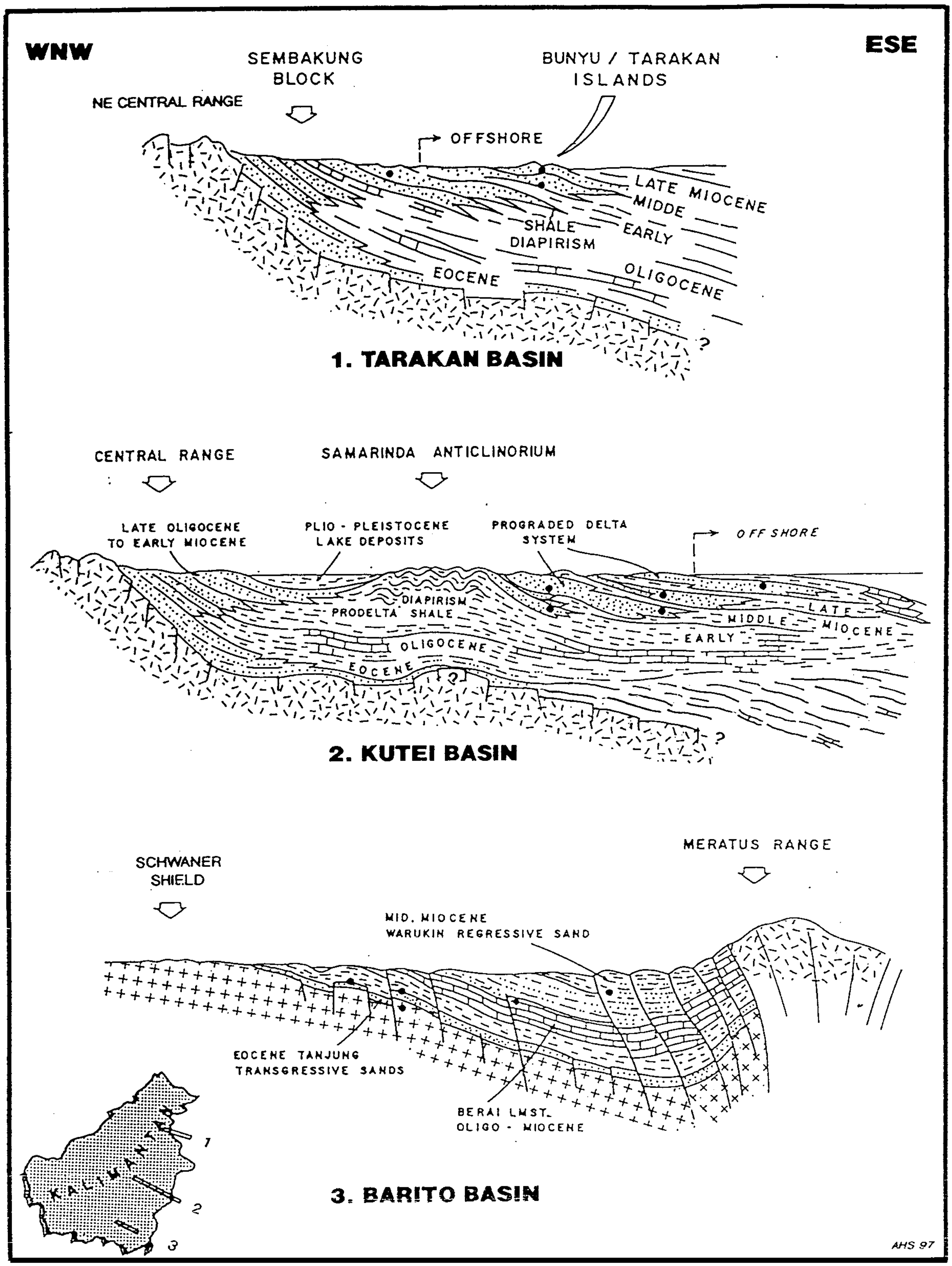

Fig. 14. Integrated dip sections of the Barito, Kutei and Tarakan Basins. Note that the Barito Basin is sedimentologically and structurally quite different from the Kutei and Tarakan Basins (modified from unpublished PERTAMINA Internal Reports).

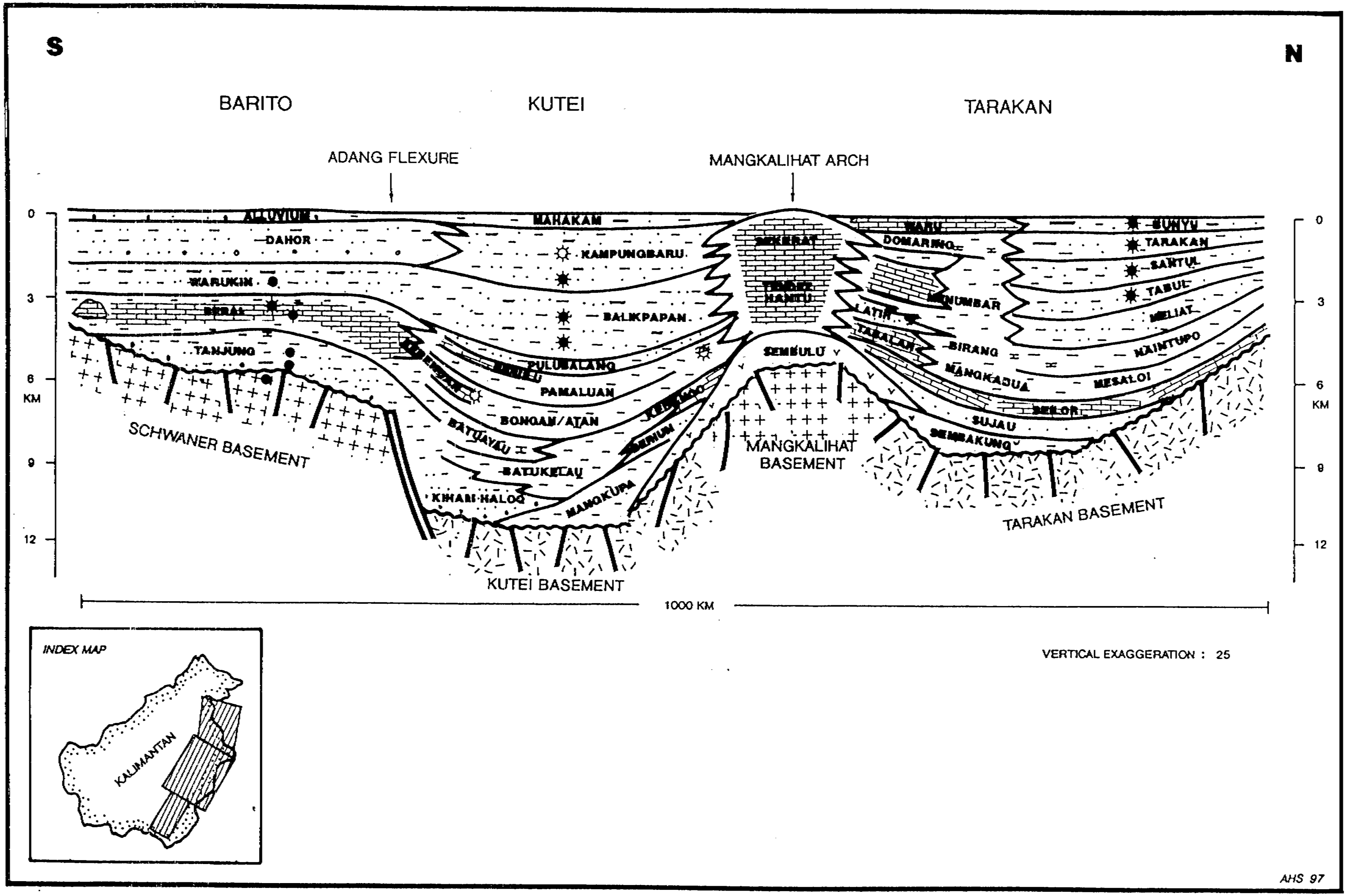

Fig. 15. Integrated strike section across the Barito, Kutei and Tarakan Basins. The Barito Basin is underlain by continental basement while the Kutei and Tarakan Basins are underlain by accreted oceanic basement. The Mangkalihat basement is a microcontinental terrane.

can be found in Satyana and Silitonga (1994). Most workers agree that inversion also took place in the Kutei Basin (Biantoro et al., 1992; Ferguson and McClay, 1997). However, extensional structures still imprint the tectonism strongly in some parts of the basin. Inverted structures in the Kutei Basin are different from those in the Barito Basin and were actively inverted as the deltaic sediments prograded. In the Tarakan Basin, the predominate structures are extensional growth-faults which show almost no overprint due to tectonic inversion.

6.4. Tectonic origin

Structures in the Barito Basin were caused by convergent uplift of the Meratus Mountains. This uplift compressed the basin obliquely towards the northwest. This is expressed by the westward vergence of all the structures and the imbricate system approaching the Meratus Mountains (Figs. 9 and 14). Structures of the Kutei Basin should be attributed first to the convergent uplift of the Kuching High, which subsequently contributed to very thick deltaic sequences in the lower basin, within which the present day structures developed actively through a number of mechanisms. The vergence of structures is various, and depends on the origin of the structures. Structures in the Tarakan Basin shared a similar origin to those of the Kutei Basin, where the Sekatak–Berau High to the west of the basin controlled the tectonism. However, further development of the structures was different, as the convergence of terranes located to the north of the basin controlled the development of their development. The last tectonic events in the Tarakan Basin are associated with the deposition of the deltaic sequence, the development of growth-faults and associated roll overs, as the deltaic sediments prograded eastwards across the basin.

7. Lessons from adjoining basins

Among the three producing basins in Kalimantan, the Barito Basin occupies a unique geologic setting and is tectonically isolated (Figs. 14 and 15; Table 1). The basin is terminated to the east, it has no thick sequence of deltaic sediments, it was deformed by thick-skinned tectonics, it has only a single tectonic generator, it produces oil from the basement and from the Paleogene section. The Kutei and Tarakan Basins show these aspects conversely: the basins open to the east, they have very thick sequences of deltaic sediments, they were structured in an environment of thin-skinned tectonics, they have double tectonic generators and they produce oil and gas only from the Neogene section.

These differences and similarities provide important lessons in the endeavor to improve exploration success. The Kutei Basin has Eocene sands, which in age and facies are equivalent to the productive Tanjung sands in the Barito Basin (Satyana and Biantoro, 1996). One should learn from the success of Paleogene exploration in the Barito Basin to look for a similar situation in the Kutei Basin. The Tarakan and Kutei basins are similar in several aspects of their tectonics and hydrocarbon habitat. However, exploration effort in the Kutei Basin, mainly in offshore Lower Kutei Basin, has had much greater success, by far, than in the Tarakan Basin.

Explorationists searching for hydrocarbons in the offshore Tarakan Basin will benefit from the experience of exploration success in the offshore Kutei Basin. Unfortunately, the lessons of Neogene success in the Kutei Basin cannot be applied directly to the Barito Basin, since these two adjoining basins were quite different in Neogene time. New exploration concepts should be developed for the Barito Basin, such as relict structures (Mason et al., 1993), Paleogene unconformities and structures (Satyana, 1995; Satyana and Idris, 1996) or stratigraphic traps within Tanjung Formation (Imanhardjo et al., 1993; Bon et al., 1996).

8. Summary

The Barito, Kutei and Tarakan basins shared a similar tectonic history during the Tertiary, characterized by an extensional regime in the Paleogene and a compressional regime in Neogene and Pleistocene time. However, their tectonic origins and styles are dissimilar. The effect of inversion—compressional stress decreases from the Barito Basin to the Tarakan Basin. The Barito Basin is tectonically isolated from the Kutei and Tarakan Basins.

Almost all existing producing fields in the Kalimantan basins occur as structural traps. Recently discovered fields in the offshore Kutei Basin are stratigraphic traps in which a structural component has, more or less, enhanced the traps.

Tectonics has played a major role in developing the habitats in the Kalimantan hydrocarbon-producing basins. In the Barito Basin it caused the subsidence of source rocks to depths for hydrocarbon generation, tectonics formed structural traps, it is responsible for the anomalous distribution of fields, it controlled the direction of migration and processes of entrapment. But also tectonics has destroyed old traps. In the Kutei Basin, tectonics is responsible for the richness of the basin, it expelled oil from source rocks, it caused the deposition of repeated sections of rich source and reservoir rocks, it controlled the distribution of productive sands, but it has also inverted the upper basin and rendered it barren. In the Tarakan Basin, tectonics formed growth-faults that solely controlled all hydrocarbon accumulations in the basin.

To lessen risk and increase success within each basin, it is necessary to learn from failures and successes in neighbouring basins.

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