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The nature and significance of regional unconformities in the hydrocarbon–bearing Neogene sequence offshore West Sabah

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Abstract: The Tertiary West Sabah basin is a trench-associated sedimentary basin containing up to 12 km of predominantly siliciclastic sediments. The basin history can be divided into two phases:

1. Pre-Middle Miocene deposition of deep marine deposits with tectonic imbrication related to south southeastward convergence along the fore-runners of the Palawan Trough/NW Borneo Trench.
2. Middle Miocene and later deposition, after the cessation of subduction, by a series of northwestward-prograding shelf/slope sequences associated with important wrench-faulting in the basement.

Although a small amount of oil and gas has been discovered in the Pre-Middle Miocene deep water deposits, all commercial accumulations discovered to date are in the Middle Miocene and younger deposits.

The boundary between the two sequences is an unconformity at the landward margin of the basin, where deformation was the most intense, with terrestrial or coastal deposits directly overlying deep marine sediments. This major unconformity, the "Deep Regional Unconformity" is possibly related to the end of active subduction along the Palawan Trough/N.W. Borneo Trench in the Early Middle Miocene.

Deposition of the Middle Miocene and younger sequence was characterised by syn-depositional tectonic deformation. However, accelerated rates of deformation at certain times resulted in the formation of five regional unconformities which provide the correlation framework of the basin. These unconformities are: the Lower and Upper Intermediate Unconformities (LIU and UIU) in the late Middle Miocene, the Shallow Regional Unconformity (SRU) in the middle Late Miocene and Horizons II and I in the Pliocene and Pleistocene respectively. Each of these unconformities was the product of both local structure formation and a regional tilting down towards the northwest. Typically each unconformity passes from an erosion surface to an onlap surface towards the NW.

From the lateral extent of the unconformities it is argued that the inner part of the NW Sabah basin is underlain by at least six separate basement blocks which were internally deformed only at certain times and remain undeformed at other times.

The style of deformation also varied temporally. Erosion of the UIU and Horizon II were both being preceded by open flexural folding and tilting whereas the LIU and SRU were associated with tight folds and reverse or strike slip faulting.

The unconformity maps demonstrate, despite the local structural complexity, the seaward migration of successive unconformities as the landward basin margin was progressively uplifted. This pattern is familiar from other trench-related/fore-arc basins.

INTRODUCTION

The Tertiary basin offshore West Sabah (Fig. 1) is a 350 km long, 140 km wide NE-SW orientated sedimentary basin containing up to 12 km of predominantly siliciclastic sediments (Fig. 2). The basin history can be divided into two phases:

1. Pre-Middle Miocene deposition of deep marine deposits with tectonic imbrication related to southeastward subduction along the fore-runners of the Palawan Trough/NW

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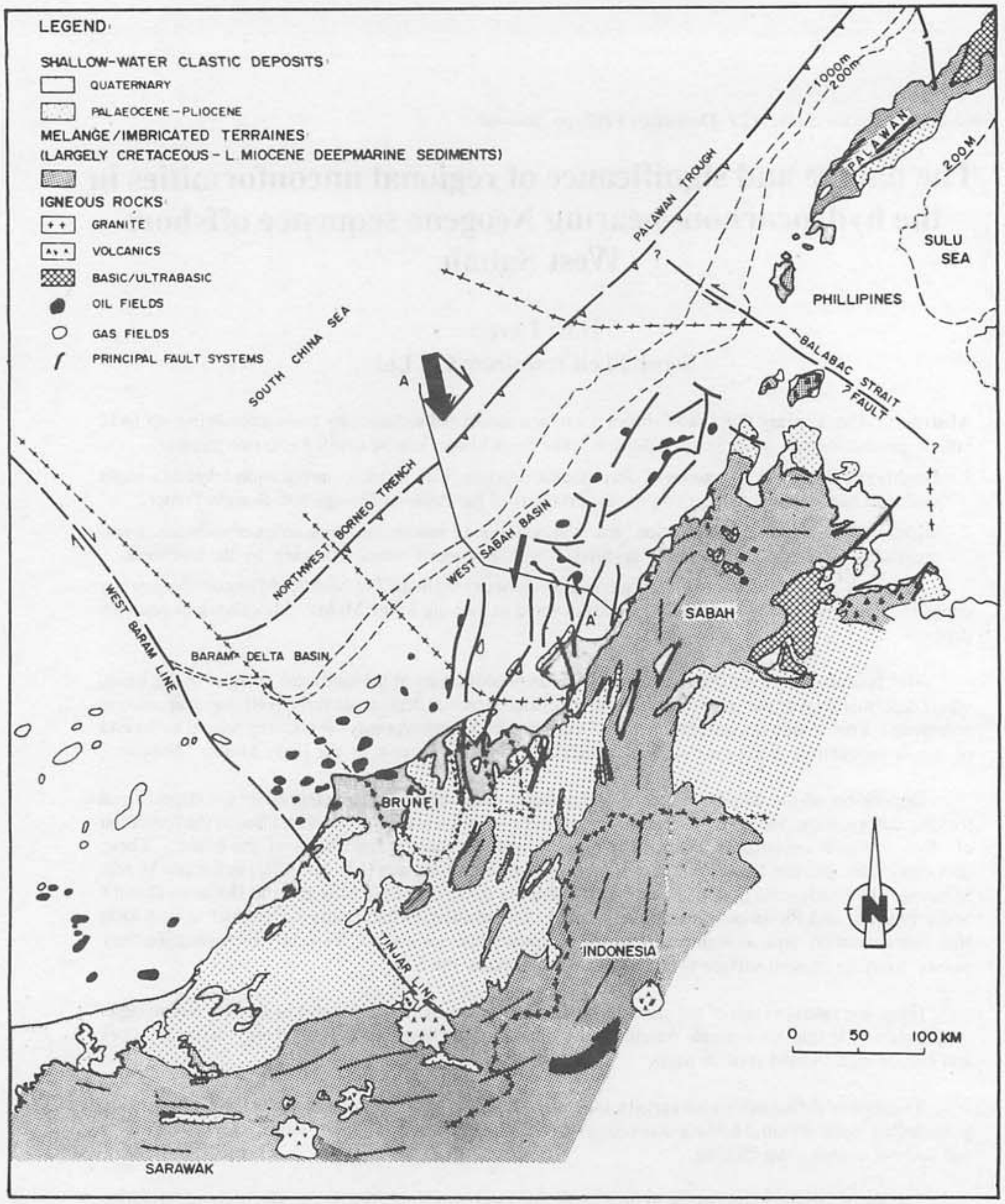


Fig. 1. The Geological Setting of the West Sabah Basin. The onshore geology of Northern Sarawak, Brunei and Western Sabah consists of a thick, deformed, series of deep marine sediments forming imbricated terraines related to south-eastward subduction (dense stipple) and a younger, less deformed, but also thick, sequence of largely shallow water sediments (light stipple) which, in western Sabah at least, were probably deposited in a trench-associated basin after major subduction had ceased. These two sequences are separated by unconformities which young, from Base Oligocene to Middle Miocene, towards the northeast.

Arrows indicate postulated relative movement directions. South-southeastward relative motion of the South China Sea Plate resulted in oblique subduction (vector diagram). Together with counter-clockwise rotation of Borneo this may have produced sinistral shear in the Sabah Ridges area in the south of the west Sabah Basin. These sinistral shears appear to have outlasted the end of major subduction along the NW Borneo Trench-Palawan Trough (which is believed to have become relatively inactive in the Early Middle Miocene) and persisted into the Pliocene.

Absolute overriding motion of the Borneo plate over the South China Sea plate off West Sabah could have resulted in extension in a 'V' shaped area bounded by the West Baram/Tinjar line and the South Sabah Ridge system, possibly accounting for the approximate 15 kms subsidence in the Baram Delta depocentre of North Sarawak and Brunei.

A-A' location of cross-section shown in Fig. 2.

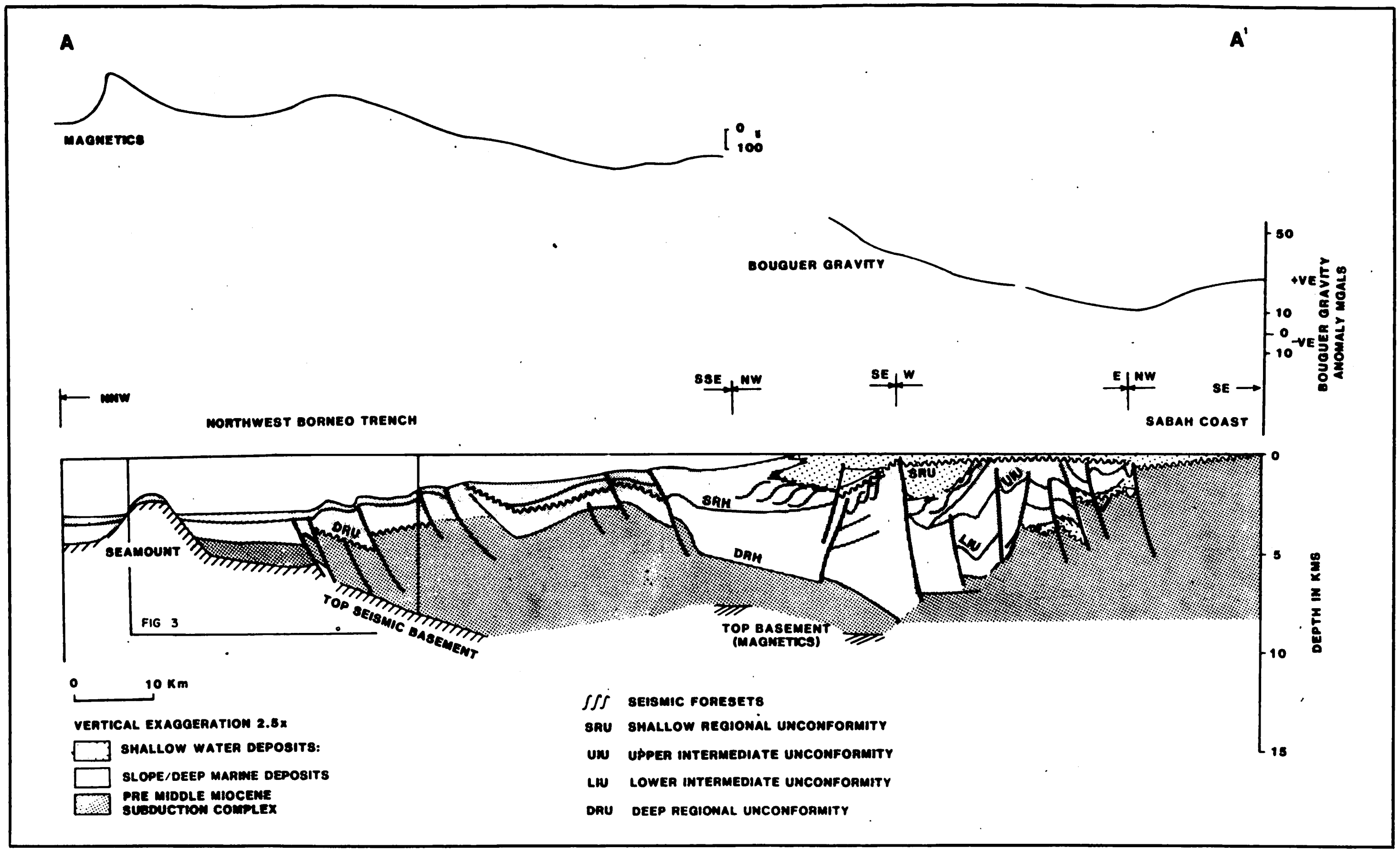


Fig. 2. Schematic geologic cross-section across the West Sabah Basin based largely on unmigrated seismic data. The cross-section illustrates the resemblance of the West Sabah Basin to a fore-arc basin, with an up-to-7 km thick sequence of largely shallow water clastics overlying and flanked by imbricate stacks of thrusted deep marine sediments. The fragmentary geophysical data appear, qualitatively at least, to be consistent with a dense slab dipping landward beneath the West Sabah continental margin.

Box locates seismic data shown in Fig. 3.

Borneo Trench.

2. Middle Miocene and later deposition, after the cessation of subduction, of a series of northwestward-prograding shelf/slope sequence contemporaneous with important wrench-faulting in the basement.

Although a small amount of oil and gas has been discovered in the Pre-Middle Miocene deep water deposits, all commercial accumulations discovered to date are in Middle Miocene or younger reservoirs.

Deposition of the Middle Miocene and younger sequence was characterised by syn-depositional tectonic deformation. However, accelerated rates of deformation at certain times resulted in the formation of five regional unconformities which provide the correlation framework of the basin. These unconformities are: the Lower and Upper Intermediate Unconformities (LIU and UIU) in the late Middle Miocene, the Shallow Regional Unconformity (SRU) in the middle Late Miocene, the Shallow Regional Unconformity (SRU) in the middle Late Miocene and Horizons II and I in the Pliocene and Pleistocene respectively. To date Sabah Shell Petroleum Co. Ltd. have drilled 57 exploration wildcats and exploratory appraisal wells in the basin. With the data from these wells, a refined basin stratigraphy has been established based on these unconformities and their correlative conformities. Each of the unconformities was the product of both local structure formation and regional tilting down towards the northwest. Typically, each unconformity passes from an erosion surface in the SE to an onlap surface towards the NW.

Repeated re-activation of basement wrench faults in response to varying regional stress fields on five occasions has led to a complicated tectonic and stratigraphic picture. Layer maps indicating which structures were active prior to the formation of a given unconformity, and the line along which that unconformity passes into a conformable sequence, demonstrate that the studied part of the NW Sabah basin is underlain by at least six separate basement blocks which were internally deformed only at certain times and remained undeformed at other times, presumably due to the relative orientations of the regional stress patterns and the block-bounding faults.

The evidence for separate basement blocks represents an example of the segmentation of a trench-associated (fore-arc) basin (Dickinson and Seely, 1979; Cross and Pilger, 1982; Kingston *et al.*, 1983). It is hoped that the description of these unconformities and the deformations preceding them will enable the Neogene geology of West Sabah to be fitted into the regional tectonic framework (e.g. Holloway, 1982).

PREVIOUS WORK

Individual structures formed during these tectonic phases have been illustrated by Bol and van Hoorn (1980). These authors differentiated three main deformation phases: an Upper Miocene phase which corresponds to the Shallow Regional Unconformity mentioned above, and two Pliocene phases which correspond to Horizons I and II (Fig. 3). In this paper attention is focussed on the nature of the unconformities associated with each tectonic phase rather than the structures themselves.

The palaeofacies development of the Neogene sequence was briefly discussed by Brolsma

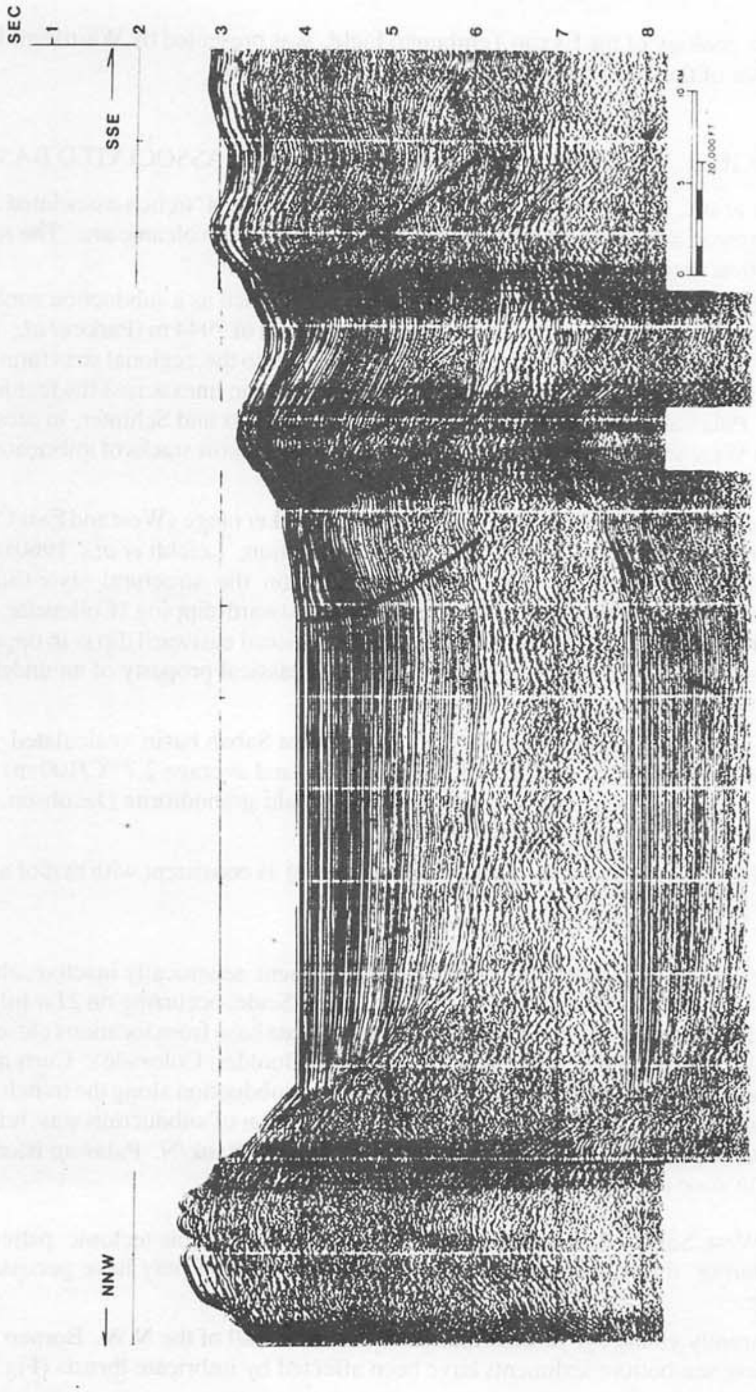


Fig. 3. The NW Borneo Trench. Unmigrated and strongly 'squeezed' seismic section across the nearly 3000 m deep NW Borneo Trench (for location see Fig. 2). Note the imbricate thrust slices in the inner wall of the trench which affect the sea bottom and a shallow pelagic drape. The "high" on the left-hand side is associated with a positive magnetic anomaly. Note also the landward dipping seismic basement descending to 7 secs two-way time in the SSE half of the section.

(1980), and some aspects of syn-depositional sedimentation in the basin were presented by Levell (1983) and Levell and Kasumajaya (1985).

The petroleum geology of the Exxon Tembungo Field, was presented by Whittle and Short (1978), and that of the Shell Samarang Field by Scherer (1980).

THE NEOGENE WEST SABAH BASIN AS A TRENCH-ASSOCIATED BASIN

Kingston *et al.*, (1983) have called the West Sabah basin a 'trench-associated basin' by which they mean a 'fore-arc' type basin without an associated volcanic arc. The reasons for this assertion may include the following:

(i) Interpretation of the Palawan Trough/N.W. Borneo Trench as a subduction zone: The bathymetric form of this feature, with a maximum depth of 2944 m (Parke *et al.*, 1971), is similar to that of other trenches. It also runs parallel to the regional structural strike over the larger part of the Sabah margin. Several seismic lines across the feature both offshore Palawan (Hamilton, 1979; Holloway, 1982; Hinz and Schluter, in press) and Offshore West Sabah (Shell proprietory data, e.g. Fig. 3) show stacks of imbricate thrust slices.

(ii) Interpretation of the deep marine sediments of the Crocker range (West and East Crocker Formation, Trusmadi Formation and Wariu Formation; Leichti *et al.*, 1960) as part of an uplifted accretionary wedge. This is based on the structural style (Stauffer, 1966) and the enormous aggregate thickness of eastward-dipping (Collenette, 1958) sediments. Wilson (1964) also argues that the regional eastward dip is in opposition to the regional westward younging direction, the classical property of an underthrust accretionary wedge.

(iii) The low to average geothermal gradients of the West Sabah basin (calculated geothermal gradients range from 2.3 to 3.65 °C/100 m and average 2.7 °C/100 m) which contrast with the young intrusion of the G. Kinabalu granodiorite (Jacobson, 1970) within the Crocker Range landward of the basin.

(iv) The evolution of the basin (as outlined in this article) is consistent with that of a trench associated basin.

The Palawan Trough/NW Borneo Trench is at present seismically inactive, although two earthquakes, the first of magnitude six on the Pascal Scale, occurring on 21st July 1930 and 8th March 1936, are recorded on the NOAA-EDIS data base from locations close to 7.5 °N Lat. 116.0 °E (National Geophysical Data Centre, Boulder, Colorado). Current plate tectonic reconstructions (Holloway, 1982) suggest that subduction along the trench ceased in the Middle Miocene (N13-N14). Possibly this cessation of subduction was related to the impingement of continental fragments such as the Reed Bank/N. Palawan Block with the subduction zone at this time (Holloway, 1982).

In the West Sabah Basin two features suggest that the same tectonic pattern that was active during the major pre-Middle Miocene subduction may have persisted into Pliocene time.

(1) The apparently young age of deformation in the inner wall of the N.W. Borneo Trench where near sea-bottom sediments have been affected by imbricate thrusts (Fig. 3).

(2) The sinistral wrench faults characteristic of the basin margin affect the post Middle Miocene sequence and yet can be understood in terms of stresses related to oblique subduction.

Possibly subduction, or over-riding, continued at a much reduced rate into the Upper Miocene and Pliocene.

Cross and Pilger (1982) have listed a number of factors which control the geometry of subduction zones and affect the position and extent of associated volcanism. Among the factors which they regard as possibly reducing the amount of volcanism, the following are perhaps relevant to the West Sabah case.

(1) Absolute motion of upper plate towards the trench, decreasing the angle of subduction.

(2) Young age of subducted lithosphere, which may be bouyant and hence subducts at a low angle.

(3) Thick accretion of deep water sediments which may flatten the subduction zone at shallow levels.

A limited duration of subduction in combination with the above might result in the subducted lithosphere not extending deep enough for large volumes to reach the zone of partial melting and generate a volcanic arc.

THE DEEP REGIONAL UNCONFORMITY

This unconformity marks a major break in the basin history. In the offshore area it separates a Late Eocene to Early Miocene period of continuous, rapid, deposition of a very thick sequence of deep marine shales and turbidite sands from a Middle Miocene and later period of NW prograding clastic wedges in which a large part of the sediment was deposited in shallow water (Figs. 2, 4).

In the onshore area, of southwest Sabah and northern Sarawak, there is an angular unconformity below the shallow water deposits of the Meligan Formation. This formation is, based on pollen data, believed to be partly of Early Miocene age (Wilson, 1964). The base Meligan unconformity apparently represents a similar break in deposition to the Deep Regional Unconformity. The unconformable break at the landward basin margin between the underlying deformed deep marine deposits and the overlying shallow marine clastic wedge thus migrated towards the northwest in at least two steps.

The Deep Regional Unconformity is however, areally, the more extensive of these two breaks (extending over about 3000 sq. km) and the latest. For these reasons it is regarded as the major break in basin history and the unconformity that is most likely to be related to the end of south-southeastward subduction along the NW Borneo Trench.

The angular unconformity has been dated by 19 exploration or exploratory appraisal wells and is closely constrained to occur within the *Globorotalia peripheroacuta* zone, i.e. Early Middle Miocene.

In the inner shelf area the DRU truncates either a reflective sequence of Early Miocene deep water deposits in which dips towards the SE predominate (Figs. 5, 6), or non-

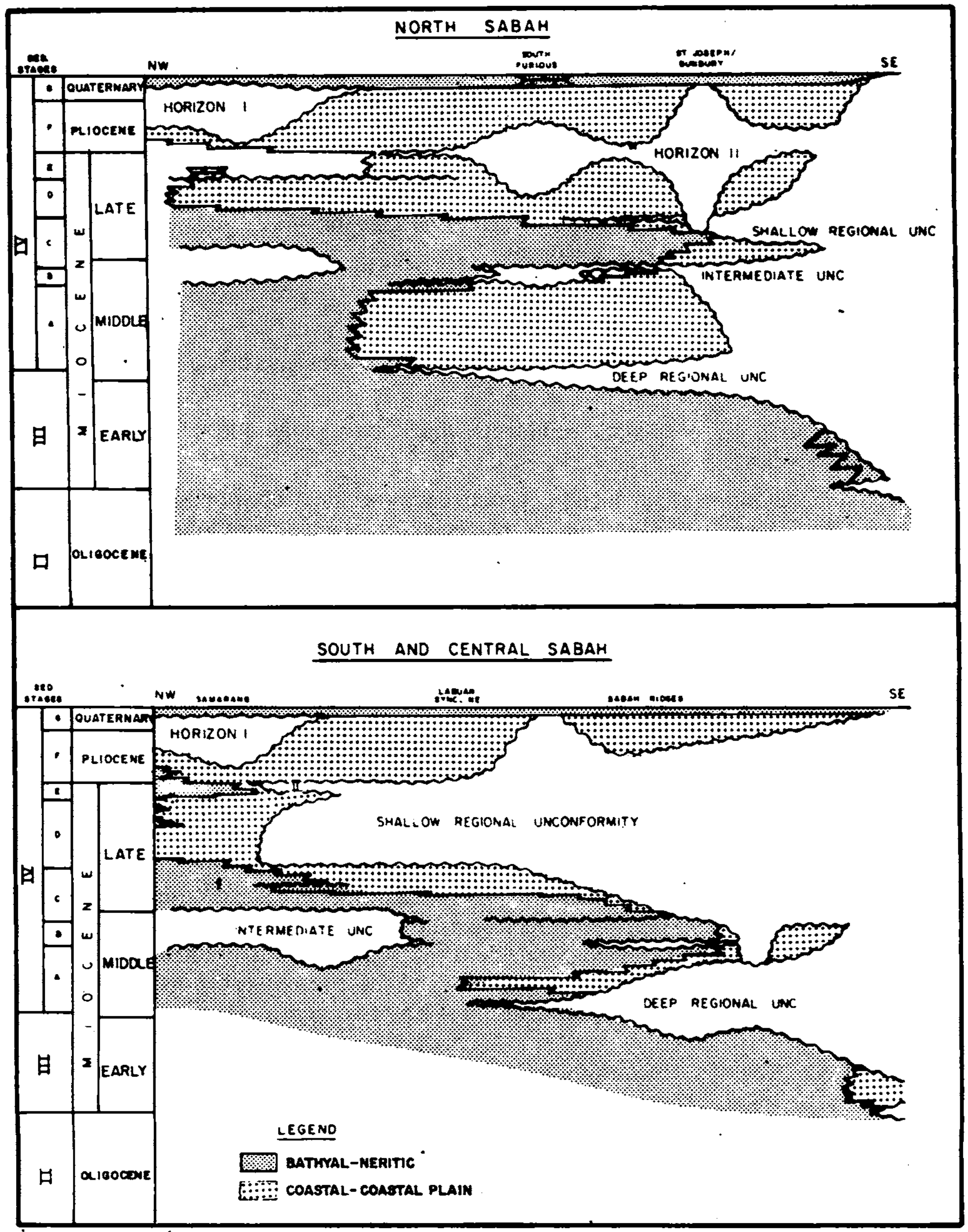


Fig.4. West Sabah Basin Time Stratigraphy. The two chronostratigraphic diagrams illustrate differences between the North and South/Central portions of the West Sabah Basin which are largely due to syn-depositional tectonics. Both diagrams can be simplified into a major early Middle Miocene uplift followed by a transgressive regressive cycle in the Middle and early Late Miocene.

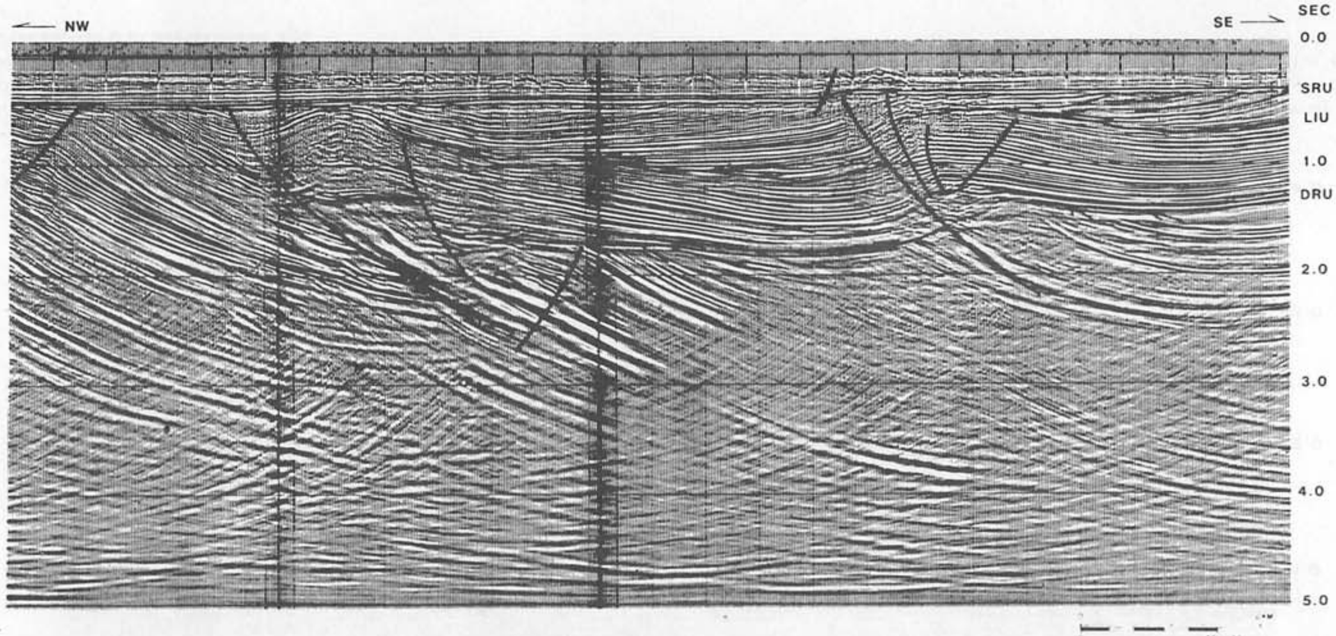


Fig. 5. Deep Regional Unconformity. The two major reverse-faulted structures shown on this migrated seismic line from the South Sabah Ridge area (SE Collins/ Kunau) clearly have long movement histories as shown by repeated truncation and onlap (arrows). Movement at Deep Regional Unconformity time (DRU) is indicated by dip changes with respect to this unconformity across the faults. Note that the DRU was associated with SE-dipping thrusts, SE-ward onlap and increase in angular truncation towards the SE. Submarine deformation at Lower Intermediate Unconformity time (LIU) is indicated by onlap without truncation. Strong erosion at Shallow Regional Unconformity time (SRU) was followed by a long period of tectonic quiescence during which deformation occurred in areas further to the northwest.

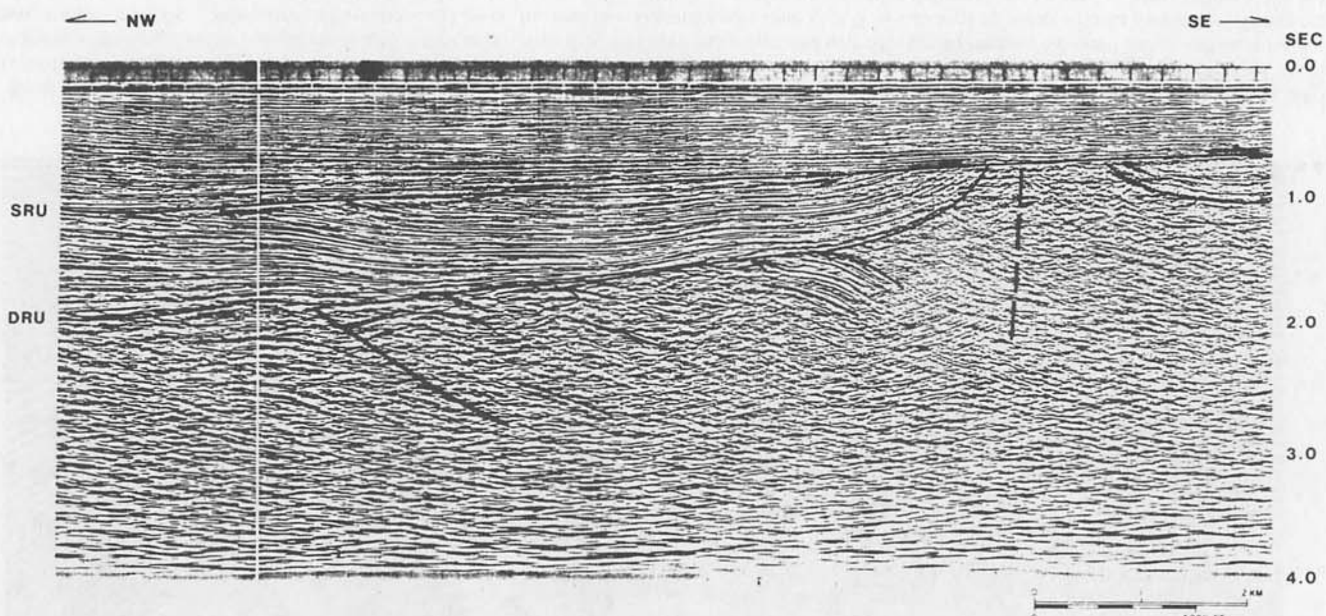


Fig. 6. The Deep Regional Unconformity. On this migrated seismic section (Bunbury Syncline) the DRU is again a clear erosional unconformity with onlap of the overlying Middle Miocene shallow water clastics towards the southeast. Note the SE-ward dip and possible thrusting within the deep marine deposits of the pre-Middle Miocene beneath the unconformity. The Shallow Regional Unconformity shows erosional truncation and SE-ward onlap. The ?fault related uplift at the SE end of the section is of indeterminate age.

reflective sequences which are probably intensely deformed. Characteristically, the dip discordance increases into fault zones, many of which show evidence of a reverse component (Fig. 5). Over this inner shelf area there is a regional southeastward to eastward onlap of the overlying Middle Miocene clastics (Figs. 5, 6, 7).

The outer margin of this area of truncation and onlap is bounded by a series of fault zones, which are nowadays intensely faulted anticlinal ridges (Fig. 8, see also Fig. 14). At DRU time this boundary line appears to have been a gently sloping flank, with a transition zone of some few kms over which the DRU gradually passed into a conformity. The line parallels to some extent the gravity isogals on the Bouguer anomaly map (Fig. 9), in particular the +20 isogal in South Sabah and the + 35 isogal in North Sabah. Segments of this boundary line were later reactivated many times and it is thought to approximately follow a set of important basement fractures.

At DRU times the tectonic movements may be summarised as follows:-

(i) Uplift of approx. 3000 sq. km of the inner shelf area from a deep marine to shallow marine/terrestrial depositional environment. The unconformity is a planar surface without palaeo-relief (Figs. 5, 6, 7) and was probably formed by marine erosion during this uplift.

(ii) Faulting along linear fault zones trending N-S or NE-SW within the inner uplifted terrain, including reverse faulting with tectonic transport towards the NW.

(iii) Regional tilting of this inner terrain down towards the NW leading to regional SE-ward onlap. Flexure down towards the NW along the boundary line discussed above.

(iv) Continuous subsidence with little deformation other than gentle flexural folding of the outer area to the northwest.

(v) Possibly uplift, related to thrusting, of the inner wall of the NW Borneo trench as expressed by an onlap unconformity (Fig. 2). (This correlation depends solely on seismic however.)

Unconformities of similar Early Middle Miocene age are widespread in the South China Sea region, and appear to represent a time of major tectonic re-organisation (Letouzey *et al.*, 1984). Possibly in our area this could relate to the end of sea floor spreading in the South China Sea which is dated by Taylor and Hayes (1980) on the basis of interpretations of sea floor magnetic anomalies as 17 Ma.

THE LOWER INTERMEDIATE UNCONFORMITY

An important increase in the rate of relative sea-level rise in the Middle Miocene resulted in a deepening over the larger part of the W. Sabah shelf. Consequently the tectonic deformation prior to formation of the LIU did not, generally, result in emergence of the uplifted structures but rather in submarine deformation. The LIU is therefore largely a marine onlap unconformity (Figs. 5, 10, 11). As such it passes rapidly off-structure into divergent reflection configurations and can be difficult to correlate.

Only seven exploration wells have penetrated the LIU in areas of clear angularity and these date it as Late Middle Miocene (within the *Globorotalia siakensis* zone).

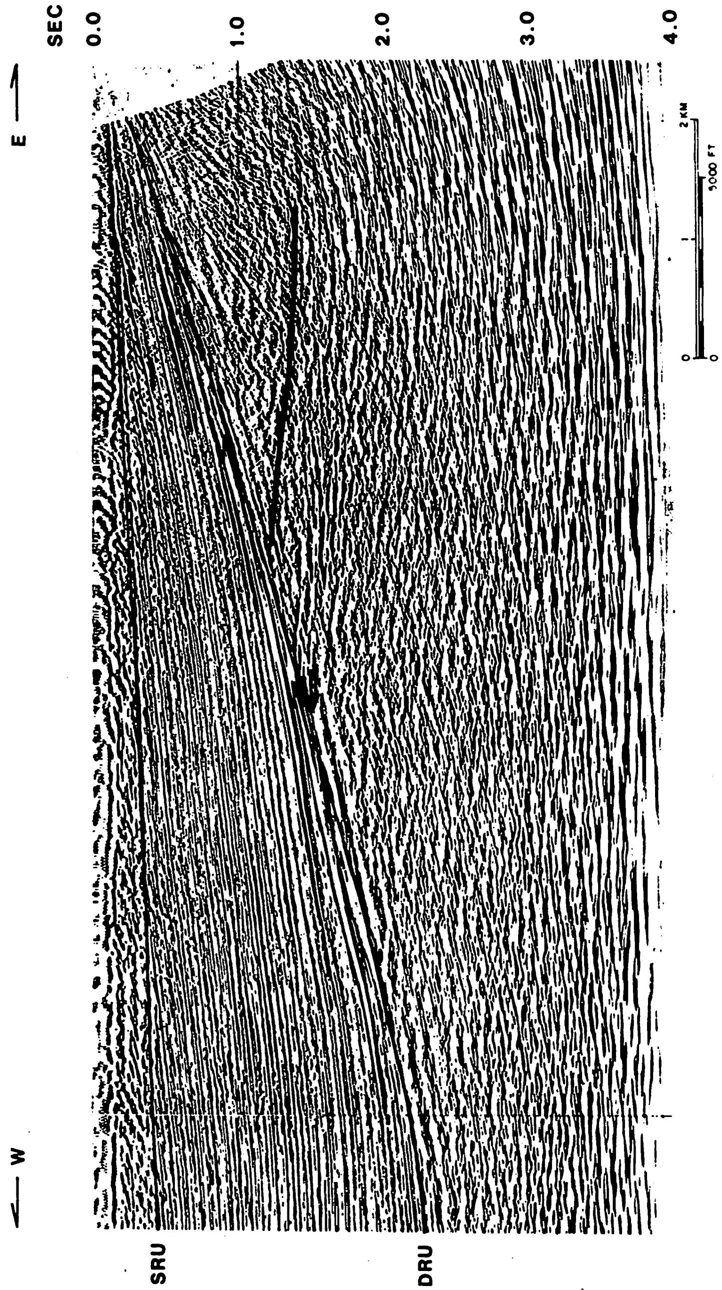


Fig. 7. The Deep Regional Unconformity (DRU) is, on this migrated seismic section (Kimanis Bay) visible chiefly due to the strong southeastward onlap. The overlying Middle Miocene is here developed in a coastal plain facies including conglomerates which are responsible for the strong onlapping reflectors. The deformation of the pre-Middle Miocene deep marine sequence is here more intense than Figs. 5 and 6 and is therefore less reflective.

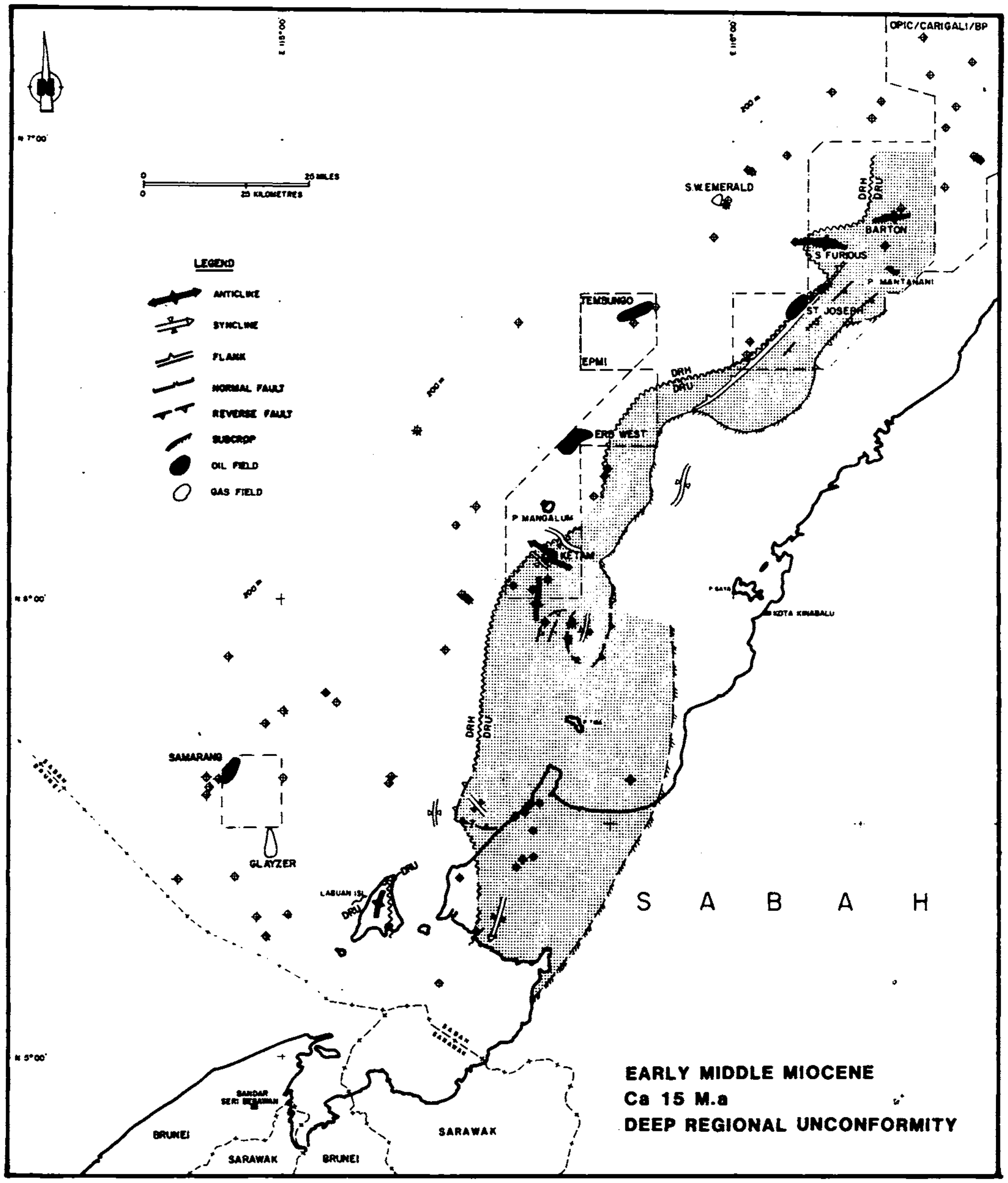


Fig. 8. This map illustrates the extent of the Deep Regional Unconformity (DRU) as an angular feature (either truncation or onlap). The inner boundary of the occurrence of the DRU is determined by subsequent uplift and erosion. The outer boundary marks the transition of the unconformity to a conformable horizon (DRU). In some areas, especially in the south this transition is very gradual. Hence, on Labuan there is field evidence for an unconformity but seismic data around the island show no angularity across the DRU.

The transition to a conformable relation to the NW indicates uplift of the imbricated stack of deep marine deposits which is also reflected in onlap towards the southeast and the fact that the main tectonic transport was towards the NW.

Only an incomplete picture can be obtained of the structures active at DRU time due to the masking effects of subsequent deformation phases which re-activated old structures.

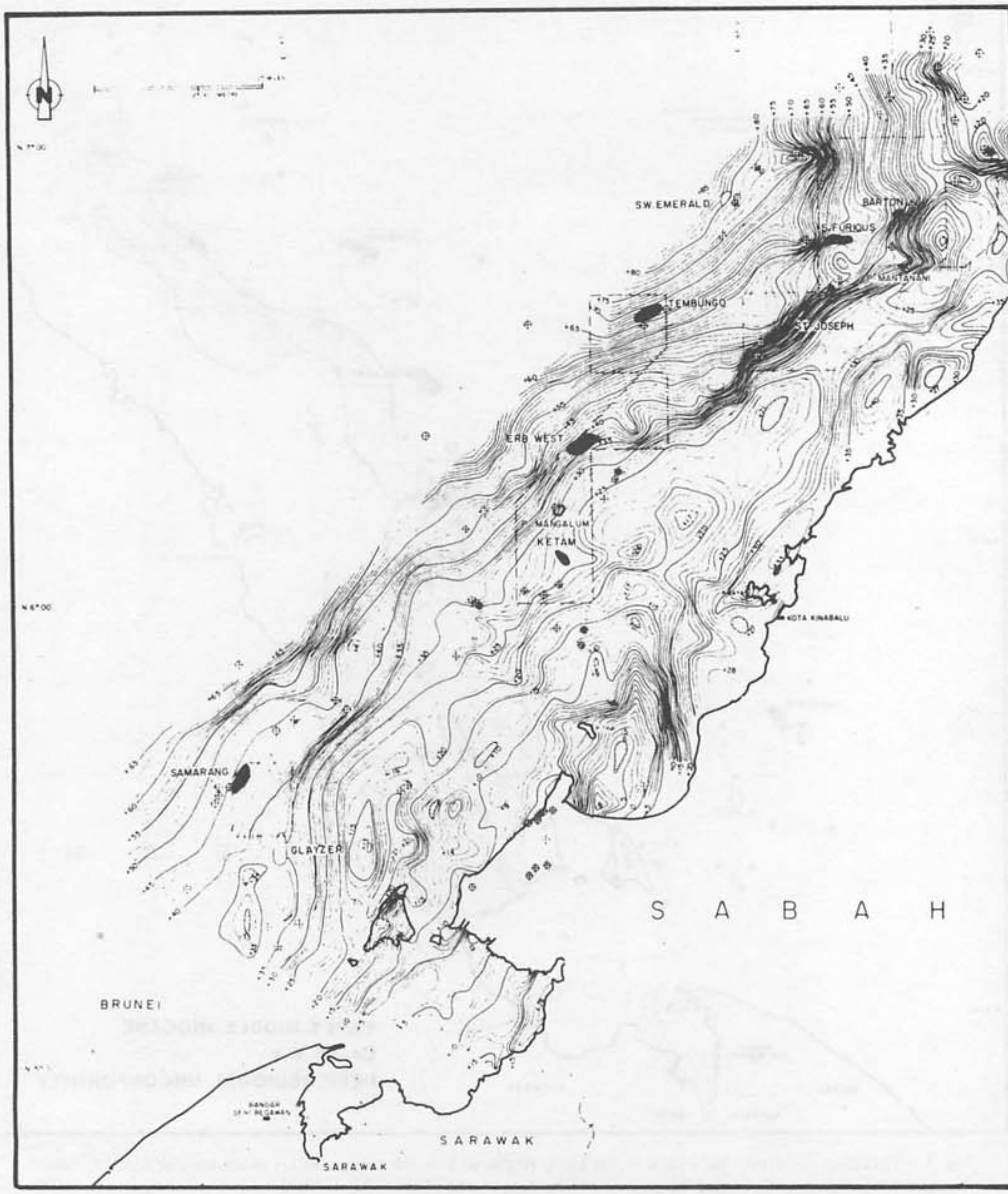


Fig. 9. Bouguer gravity anomaly map of the West Sabah Basin. Note the steady decrease in the positive Bouguer anomaly from the northwest towards the southeast. This regional trend is not related to the thickness of the post-Middle Miocene basin fill (see Fig. 2) and could reflect a deep dense basement which rises towards the NW., Possibly this is related to down-bending, due to loading, under the imbricate pile of pre-Middle Miocene deep marine deposit (the subduction complex), or even to a subducted basement slab. The northwestern, outer boundary of the DRU is related to steep changes in the anomaly pattern especially in North Sabah, indicating basement faults acting as boundaries to the uplifted and eroded blocks (e.g. in the St. Joseph area).

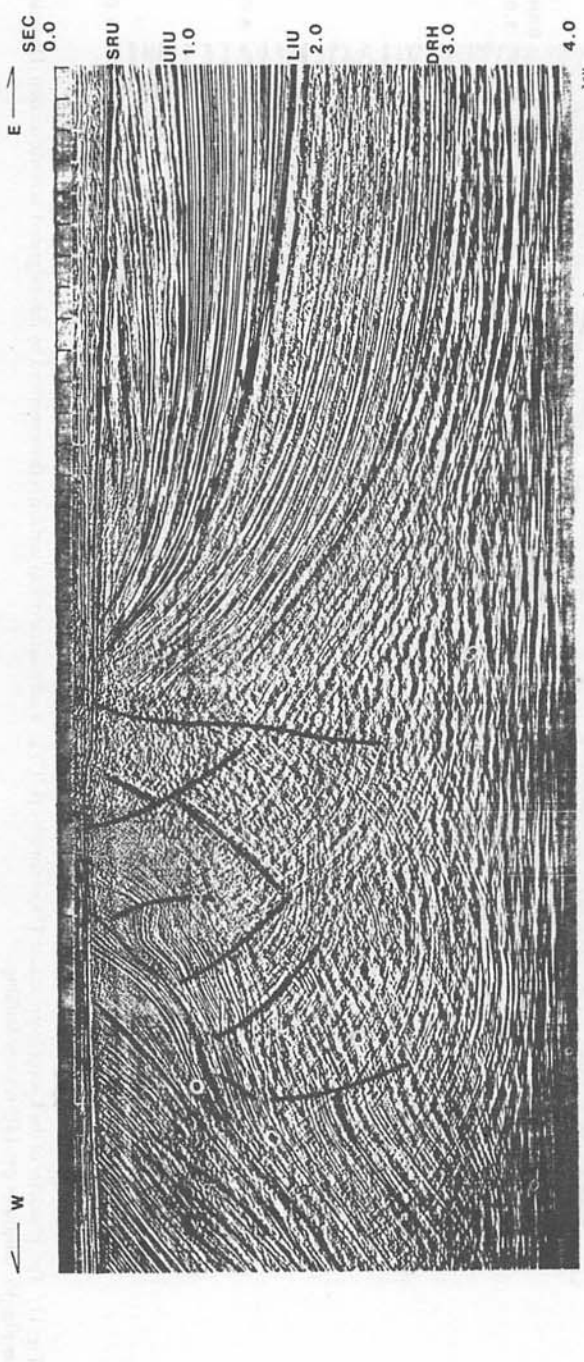


Fig. 10. The Lower Intermediate Unconformity (LIU) is on this migrated seismic section across one of the South Sabah 'Ridges' (Winchester Ridge) clearly developed as an onlap unconformity. Note that steep reverse faults on the western ridge flank pre-date the LIU. Commonly, as here, subsequent deformation of the ridges was along a slightly displaced axis. The importance of the Shallow Regional Unconformity movements and the subsequent stability of this structural province is, as in Fig. 5, vividly illustrated.

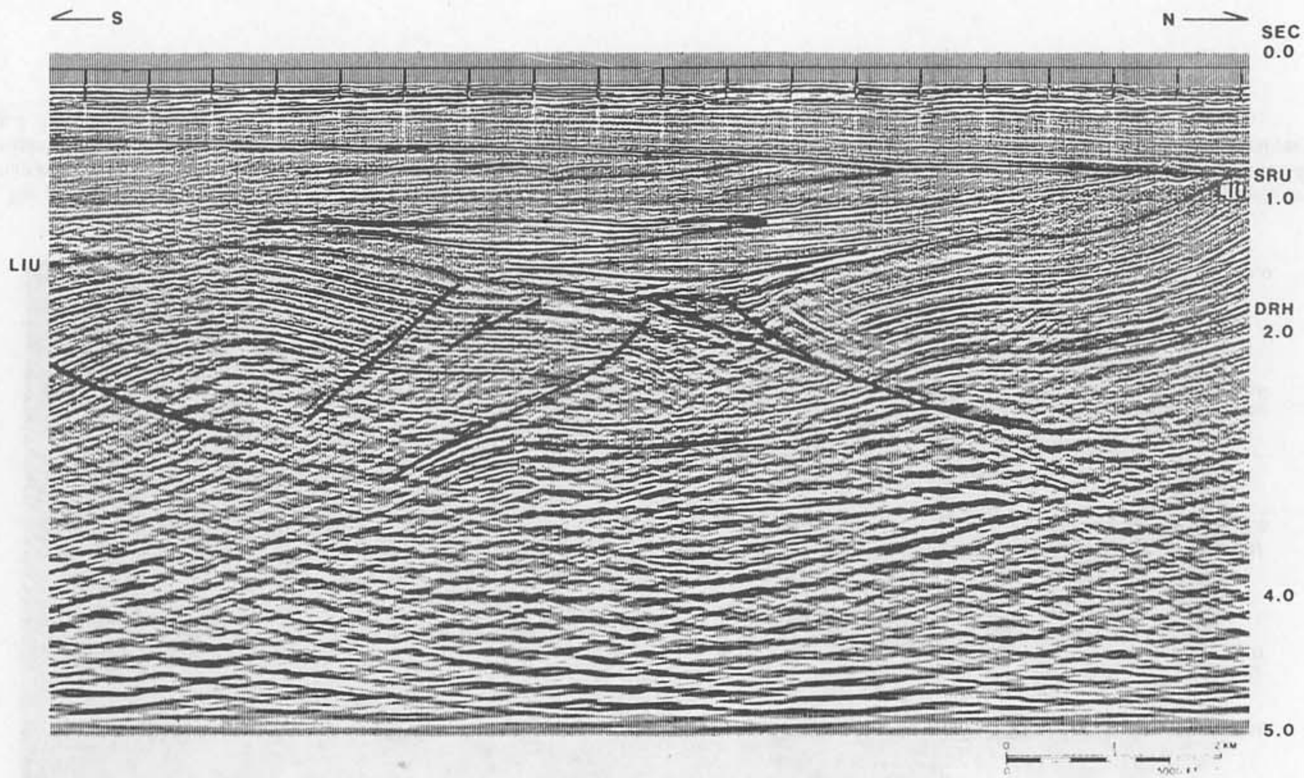


Fig. 11. The character of the Lower Intermediate Unconformity (LIU) as a submarine onlap surface is demonstrated by this migrated seismic section (Dampier) which, as Fig. 10, illustrates pre-LIU reverse faulting.

The mounded bodies infilling the depression between the two opposed reverse faults infilling the depression between the two opposed reverse faults are interpreted as small submarine fan lobes. The Deep Regional Horizon is, on this line, a conformable event which correlates further to the east with the angular unconformity of Fig. 5.

Deformation prior to formation of the LIU took two forms. In the inner shelf area where the DRU is also an angular unconformity, there was strong reverse faulting and uplift along the N-S trending South Sabah ridges (Fig. 10), which are probably the surface expression of deep compressional strike-slip fault zones (Bol and van Hoorn, 1980). At the same time reverse faulting along E-W trending lines occurred in Central Sabah (Fig. 11), and in both areas isolated, roughly elliptical synclines formed between the uplifted zones. Re-activation of both sets of faults during succeeding tectonic phases undoubtedly prevents the recognition of more LIU-age structures but in in some cases the pre-LIU folds and faults are slightly offset from later structures along the same trend which allows their recognition (Fig. 10).

To the west of this faulted area in the south and in the S. Furious area in the north, broad open anticlines and synclines were formed. The basement in these areas, where the DRU is also not developed, was apparently responding differently to the regional compressive stresses.

The NW boundary of the area where the LIU occurs as an angular surface is further west than that for the DRU (Fig. 12). There is little evidence for regional tilting at this time, except for the general westward passage into a conformable sequence.

THE UPPER INTERMEDIATE UNCONFORMITY

Reduced rates of relative sea-level rise in the late Middle Miocene mean that the UIU is developed virtually everywhere as a (marine) erosional unconformity.

The Upper Intermediate Unconformity (Fig. 13) is developed in three separate areas: the Glayzer High in the south, the western part of the South Sabah Ridges province and the S. Furious-Barton-St. Joseph area in the north. Dating in 18 exploration or appraisal wells, fixes the age of this unconformity as close to the top of the *Globorotalia siakensis* zone in the latest Middle Miocene.

Deformation prior to formation of the UIU is similar in its variety to that of the LIU. In the western part of the South Sabah Ridges province, southward thrusting along east-west striking reverse faults occurred in at least two small structures. Further east, any UIU deformation cannot be separated from later deformation phases. Again, the western boundary of the area of angular unconformity has shifted further west than that for the preceeding unconformity (Figs. 12, 15). In the Glayzer (Fig. 14) and S. Furious areas broad flexural folding with little or no faulting occurred, as at LIU time.

In the north the UIU truncates progressively more of the underlying sequence towards the east, indicating a gentle rotation down towards the basin. The western boundary of the unconformity passes into a conformity along the Bunbury-St. Joseph ridge (Figs. 14, 15) and the direct prolongation of this line towards the northeast. The westward tilting is even reflected in a marked southwestward pitch in the Furious and Prichard synclines, north and south of the South Furious structure respectively.

In all three areas submarine erosion of the UIU was, in part, caused by the incision of submarine slump scars along the western edge of the unconformity area. This activity is described in detail by Levell and Kasumajaya (1985). Elsewhere the planar unconformity

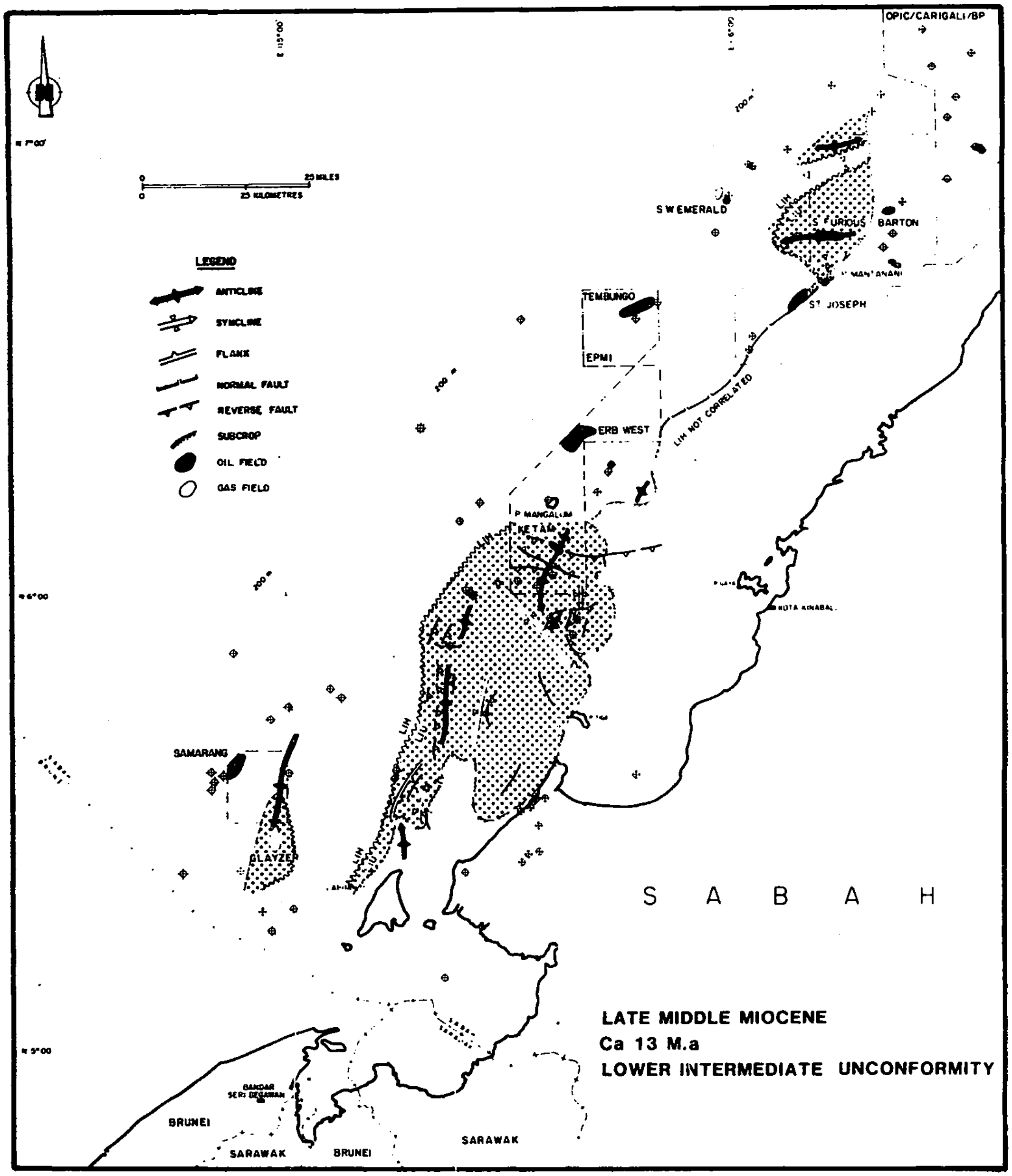


Fig. 12. The Lower Intermediate Unconformity, being a submarine deformation phase in which structures rarely reached erosional base level is developed only as an onlap surface even over the crests of growing anticlines. In the intervening synclines deposition was uninterrupted. Consequently the unconformity is evident in a number of separate area: the Glayzer anticline, the South/Central Sabah Ridges areas (from Labuan to Ketam), the S. Furious and Emerald anticlines. Palaeontological dating gives these four separate unconformities the same age.

Structures active prior to formation of the LIU include both the N-S and E-W trending reverse faults of the Ridges area and open folds. Compressive stresses in both north-south and east-west directions are implied. The area of LIU deformation extends slightly further to the NW than that affected by DRU movements. The inner boundary of LIU occurrence is again defined by subsequent erosion.

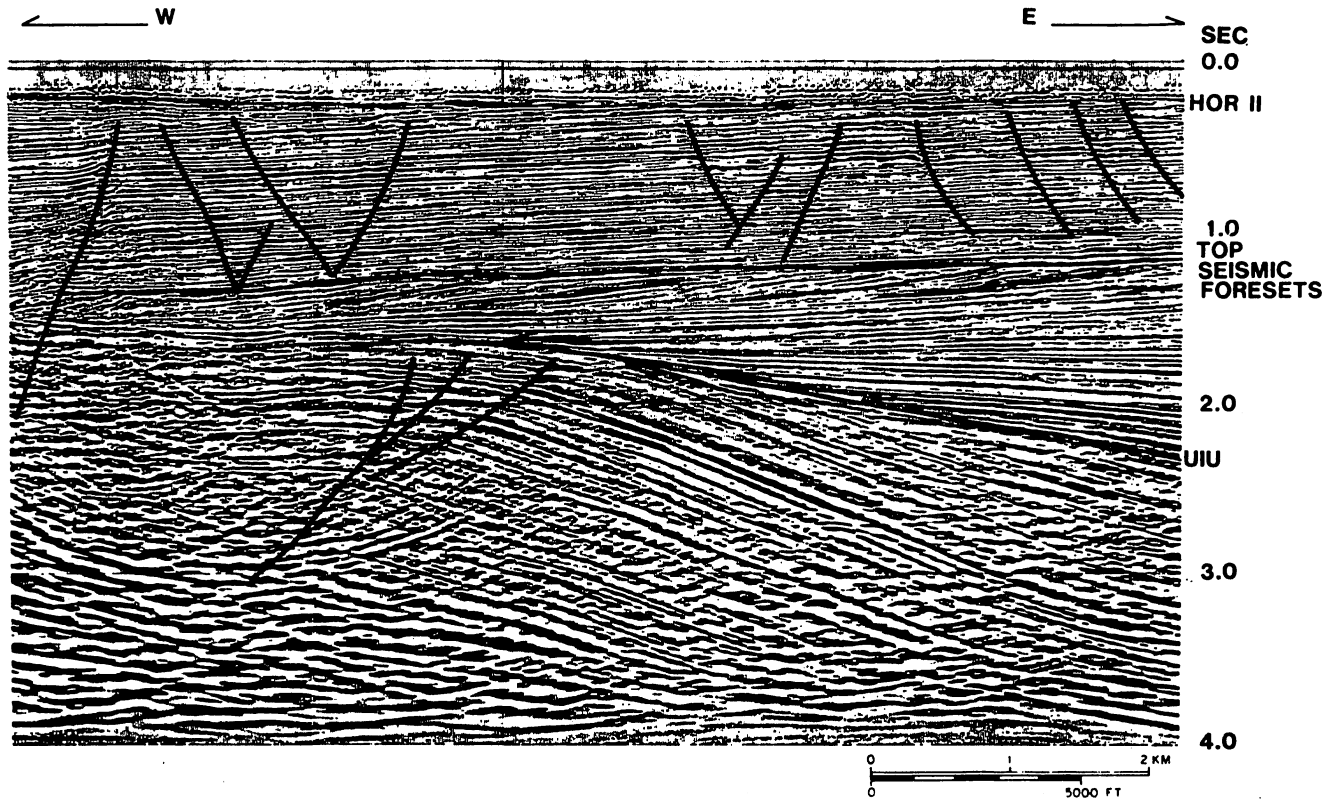


Fig. 13. The Upper Intermediate Unconformity is variable in character, but, although normally overlain directly by marine deposits, is marked by erosion over crests of growing structures as well as onlap on their flanks. This line from the Glayzer anticline in South Sabah illustrates well the passage from erosion to onlap to conformity passing down the flank of a syn-depositionally growing anticline. A wrong pick of the correlative conformity on the flank of the structure can lead to substantial correlation errors. In many cases erosion at UIU times was submarine and occurred through slumping (see Levell and Kasumajaya, 1985), and in other cases through shallow marine (shoreface) erosion.

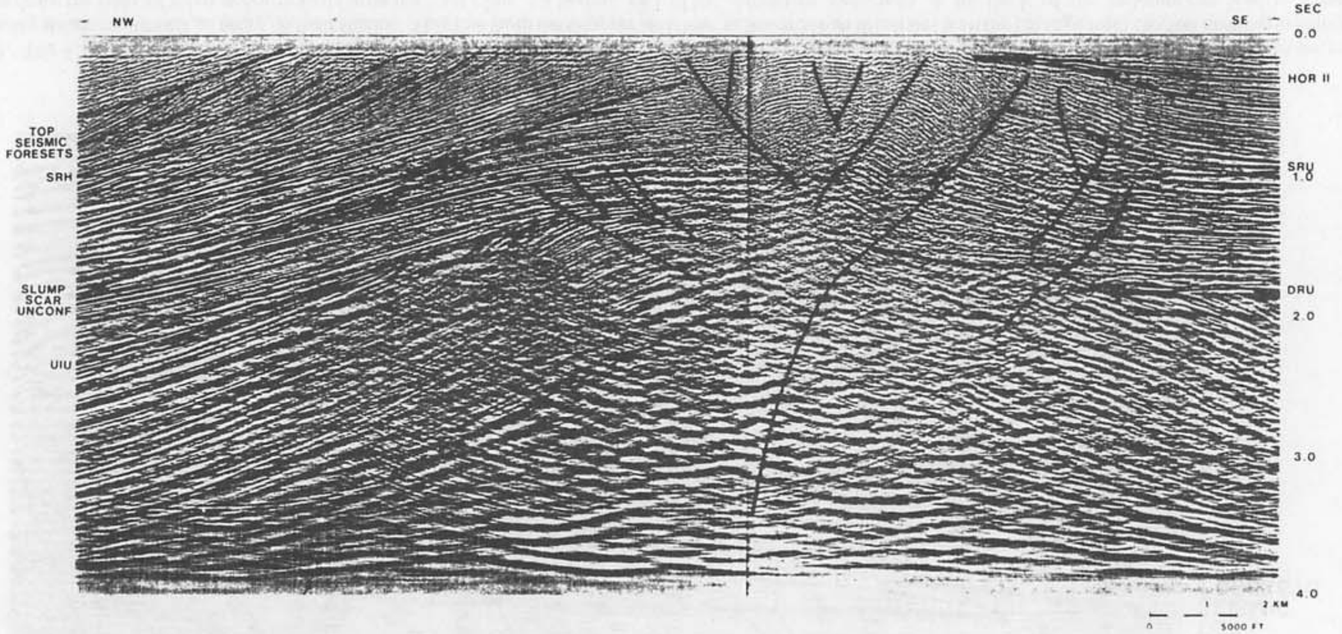


Fig. 14. The Upper Intermediate Unconformity is visible on this migrated seismic line as an erosional unconformity on the northwestern flank of the Bunbury-St. Joseph Ridge. At this particular point the slump scar unconformities only affect the younger sequence.

Note the DRU which is clearly expressed only on the southeastern (inner) flank of the ridge as an erosional unconformity with steep SE-ward dips in the pre Middle Miocene deep marine sediments. The SRU is also only evident on the inner side of the ridge. The interpreted Ridge fault pattern resembles a positive flower structure attributable to compressional strike slip. The axis of UIU uplift appears to be offset from the axis of later Horizon II/I uplift.

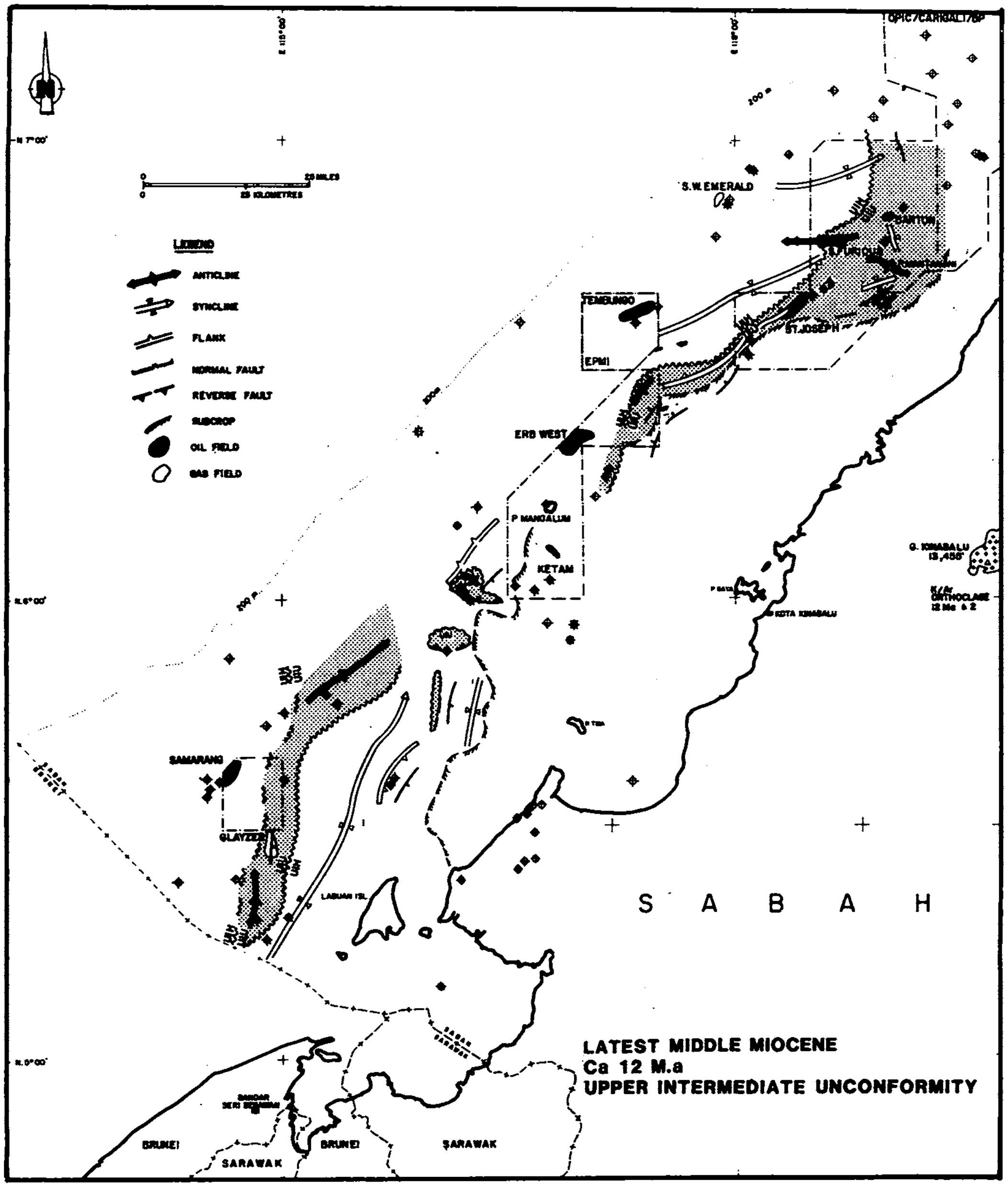


Fig. 15. The Upper Intermediate Unconformity is present throughout the West Sabah Basin. Due to its position immediately beneath the Shallow Regional Unconformity it has frequently been removed through the severe erosion at that time, hence the UIU structural pattern is not clear. However structures active at LIU time (Glayzer anticline, South Sabah Ridges, the S. Furious anticline) were reactivated and the Bunbury-St. Joseph Ridge became active for the first time since DRU movements.

is overlain by marine deposits, including some carbonate build-ups, and appears to be a shallow marine erosion surface.

The age of the UIU corresponds with the older ages (Jacobsen, 1970) from the G. Kinabalu granodiorite intrusion, but there is no direct evidence to link the intrusive event to this unconformity.

THE SHALLOW REGIONAL UNCONFORMITY

Movements prior to erosion of the Shallow Regional Unconformity (Fig. 16) clearly demonstrate the sub-division of the West Sabah offshore into areas of independently moving basement blocks (Fig. 17). In the northern area, to the northwest of the Bunbury-St. Joseph-Bambazon-Mantanani Ridges, no angular unconformity is recognised and the region was one of fairly uniform, continuous, subsidence which was mechanically detached from neighbouring areas.

To the southeast of the Bunbury-St. Joseph Ridge the SRU is a clear truncation unconformity cutting down towards the southeast and south (Fig. 14). It has not been penetrated by a well and is only dated by extrapolation from the Erb West area. Reconstructions of the Bunbury-St. Joseph Ridge show evidence of a pre-SRU steep, monoclinal, flexure most likely associated with faults.

In the Erb-High/Mangalum area the pre-SRU movements created a very long, gentle, north to northwest sloping flank onto which post-SRU sediments onlap (Figs. 16, 18). Broadly speaking this flank area is a wider continuation of the monoclinal flexure along the Bunbury-St. Joseph Ridge and separates the basinal area in the north from a strongly uplifted eroded area to the south and east.

In the southern area there is marked planar unconformity across which there is a large hiatus, from Late Miocene to Middle Pliocene (Figs. 5, 6, 7, 10, 11). Erosion of this surface is thought to have started at SRU time because the Middle Pliocene Horizon II, above which sedimentation was resumed, onlaps this surface.

The whole South Sabah Ridges province was subjected to strong, mostly reverse, faulting along an intersecting set of N-S and E-W trending linear fault zones. The western edge of this province was again a flexure down towards an area of continuous deposition west of the axis of the Labuan syncline.

The wells that have penetrated the SRU have shown it to be overlain by marine deposits and it is most probably a shoreface or shallow marine erosion plane. Surprisingly no palaeo-relief has been observed even in the South Sabah Ridges area where the unconformity represents a time gap of several million years. Coastal erosion during the transgression associated with marine onlap in the flank area around Erb West is thought to be responsible for the development of the shallow marine sand reservoirs of the Erb West oil field.

The style of deformation associated with the SRU is clearly related to the individual basement blocks. However whereas in the northern area the blocks were tilted or subsided uniformly, in the south the 'Ridges block' was strongly deformed internally by compres-

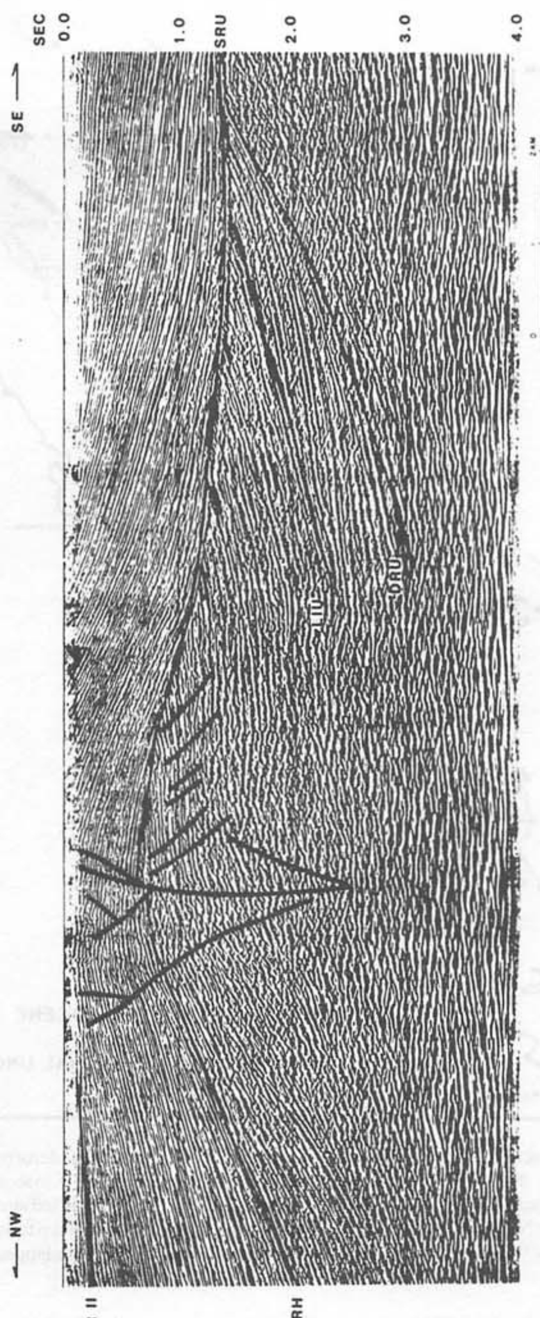


Fig. 16. The Shallow Regional Unconformity was eroded at a time of major uplift of the inner portion of the West Sabah Basin with a flank to an area of continuous deposition further northwest. This is clearly shown in this migrated seismic section (Erb High). Later Horizon II/I movements have led to uplift of the previous flank area. Note that the SRU passes from an erosional to an onlap to a conformable surface towards the NW.

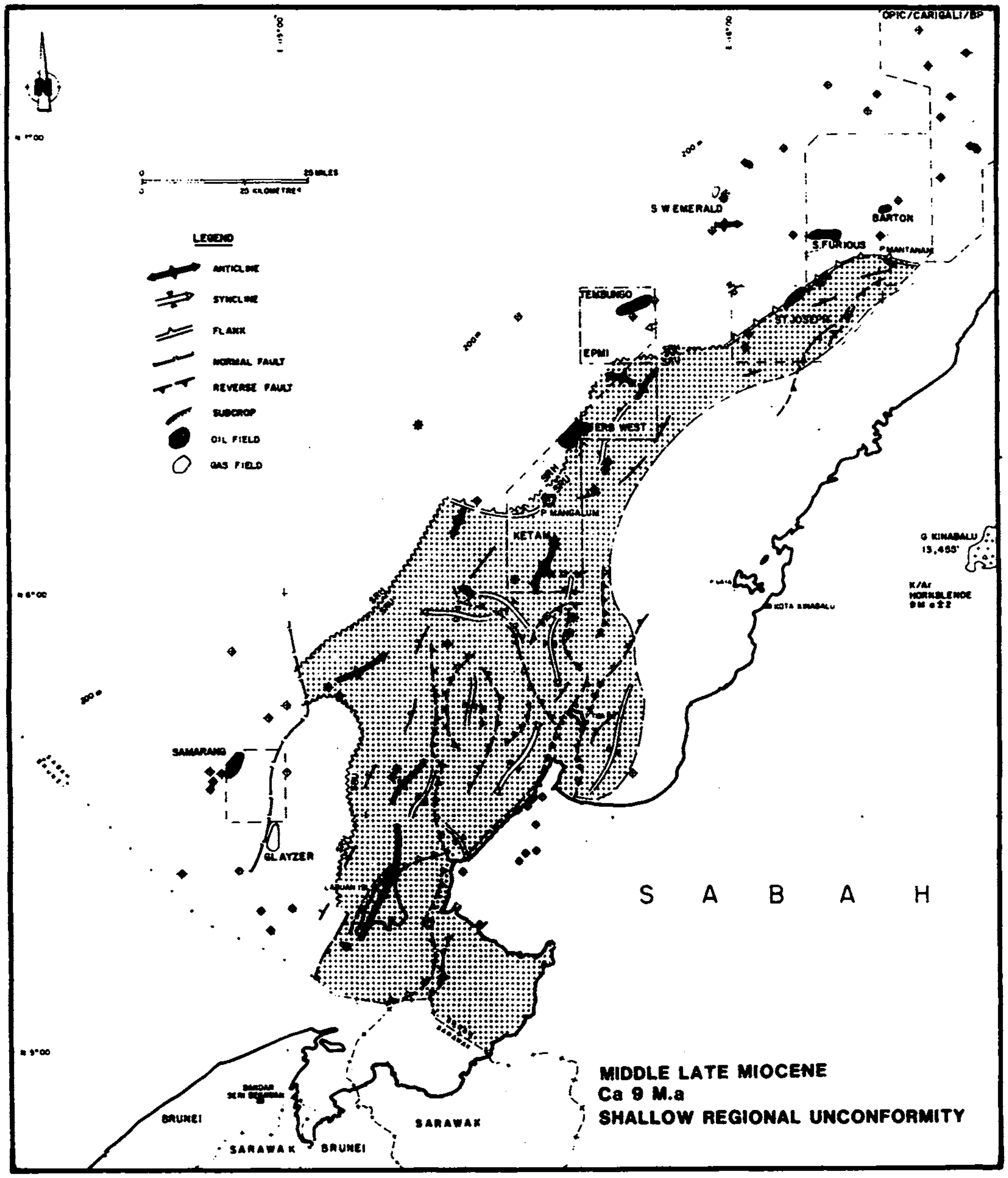


Fig. 17. The Shallow Regional Unconformity is evidence of an extension of the area of deformation further to the northwest than the preceding deformation phases. A broad area offshore of Kota Kinabalu was uplifted at this time with a more or less radially dipping flank. The South Sabah Ridge area was uplifted strongly following important reverse faulting along the N-S Ridge trends and was tilted with a steady regional dip towards the North. This structural province was largely "stabilised" after SRU movements and was passively onlapped by subsequent sediments.

The overall deformational style of the SRU structures is of compressive strike slip faulting. Comparison with the other deformation maps clearly indicates that areas of previous deformation were unaffected by SRU movements evidence for the fragmentation of the West Sabah Basin into discrete structural blocks mechanically detached from one another (Fig. 22).

sional strike-slip faulting. The style of deformation associated with the SRU has been described by Bol and van Hoorn (1980) who refer to it as the "Upper Miocene Phase".

The preferred date for major intrusion of the Gunung Kinabalu granite is 9 Ma ± 2 (Jacobson, 1970). Dating of the SRU in the 10 exploration or appraisal wells that have penetrated it in areas where the hiatus is small, gives an age of middle Late Miocene (i.e. ca 9 Ma). The formation of a wide, westward-dipping flank to the east of Erb West in the central area is related to uplift of a large area offshore of Kota Kinabalu known as the "Kinabalu culmination" possibly this uplift is an expression of the intrusion of the G. Kinabalu granodiorite.

HORIZON II

As pointed out by Bol and van Hoorn (1980) the Pliocene deformation differs from that of the Middle and Upper Miocene, and also affected a different area of the basin; an area further to the west and northwest. This can be seen as part of a continuing stepwise shift of the belt of uplift and deformation towards the 'exterior'.

The earliest of the two Pliocene folding phases has been dated in 12 exploration or exploratory appraisal wells as within the *Globoquadrina altispira* zone, close to the Early/ Late Pliocene boundary.

Horizon II is a gentle truncation or mild onlap unconformity and was associated with formation of open anticlines and synclines with a general NW-SE orientation (Figs. 16, 18, 19). The orientation of structures (Fig. 20) shows a higher degree of consistency than for the deformations preceeding the previous unconformities and suggests a NW-SE oriented horizontal principal compressive stress.

Independent movement of basement blocks is expressed at this time in the activity of major normal faults which were initated in the Late Miocene, and separate a folded terrain to the east from a growth-faulted terrain to the west. The boundary faults of these provinces, namely the Morris Fault in the south and the Emerald Fault in the North are not themselves classical listric growth faults but through-going, steeply-dipping, straight faults. Fault and fold patterns adjacent to these two faults suggest some (?left-lateral) strike slip movements.

In the inner area of open folding virtually all Horizon II structures are re-activated earlier features. Left lateral movements at this time are also suggested by a few displaced anticlines in this area.

HORIZON I

Major uplift, commonly of the order of 2-3000 ft. occurred over several structures in the Pleistocene. This was associated with tensional faulting over the crests of many structures but gentle open folding is the characteristic deformation style (Figs. 14, 16, 18, 19).

A striking feature of Horizon I folding is the parallelism of fold axes which can be interpreted as due to a NW-SE oriented principal compressive stress (Fig. 21).

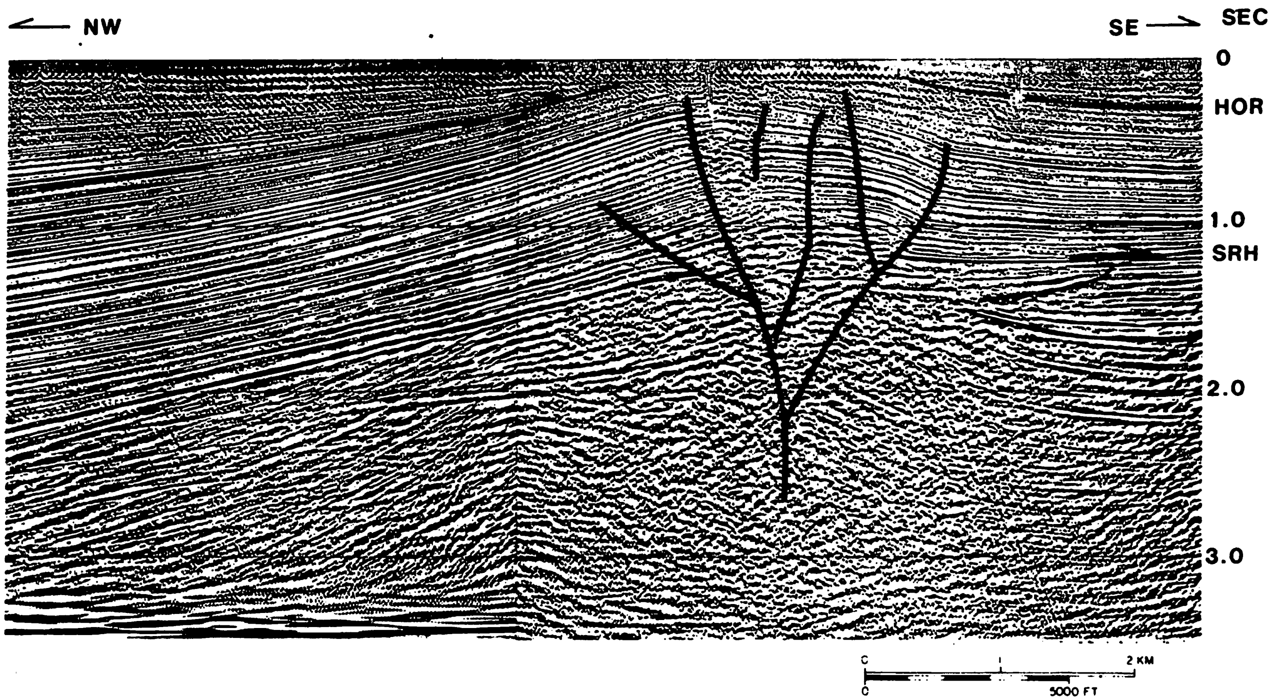


Fig. 18. Broad anticlinal uplift typical of Horizon II/I structures. This structure is closely comparable with that shown in Fig. 15. The fault pattern interpreted on this migrated seismic section is again indicative of compressional strike slip faulting. This is a section across the Mangalum line, which occurs at a significant swing in the predominant structural trends of the West Sabah Basin, from N-S in the south to NE-SW in the north (Fig. 22).

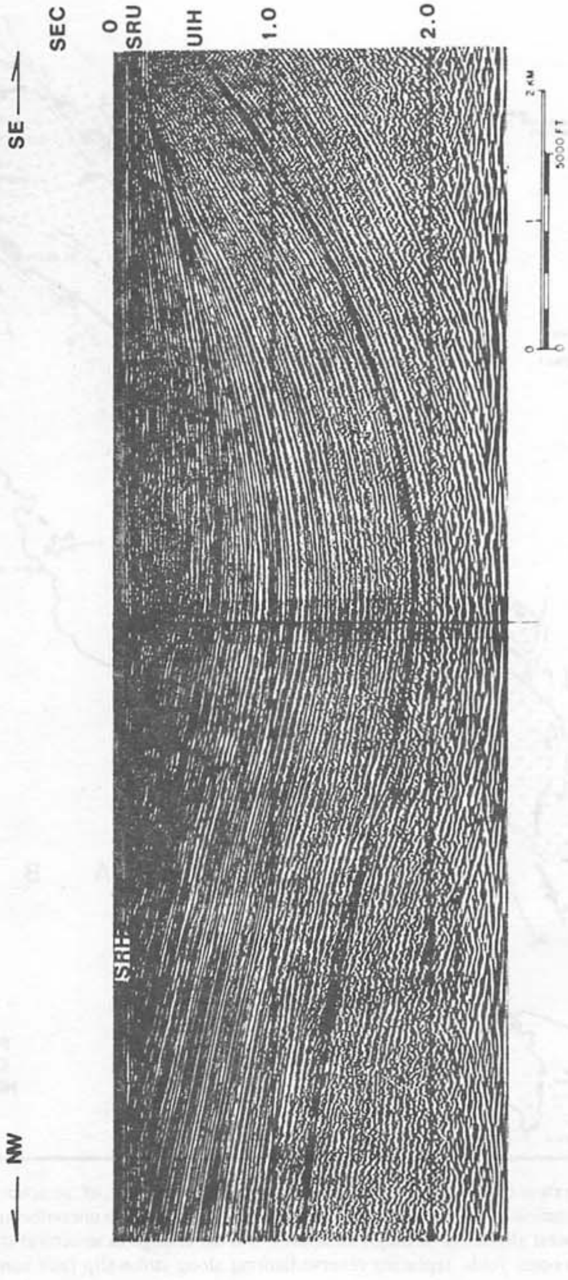


Fig. 19. The Horizon I and II deformations both saw renewed growth of the broad open synclines that were folded at LIU and UIU (but not SRU) times. This migrated seismic section (Keraman Area) also shows the NW-ward transition of the SRU to a conformity (as in Fig. 16).

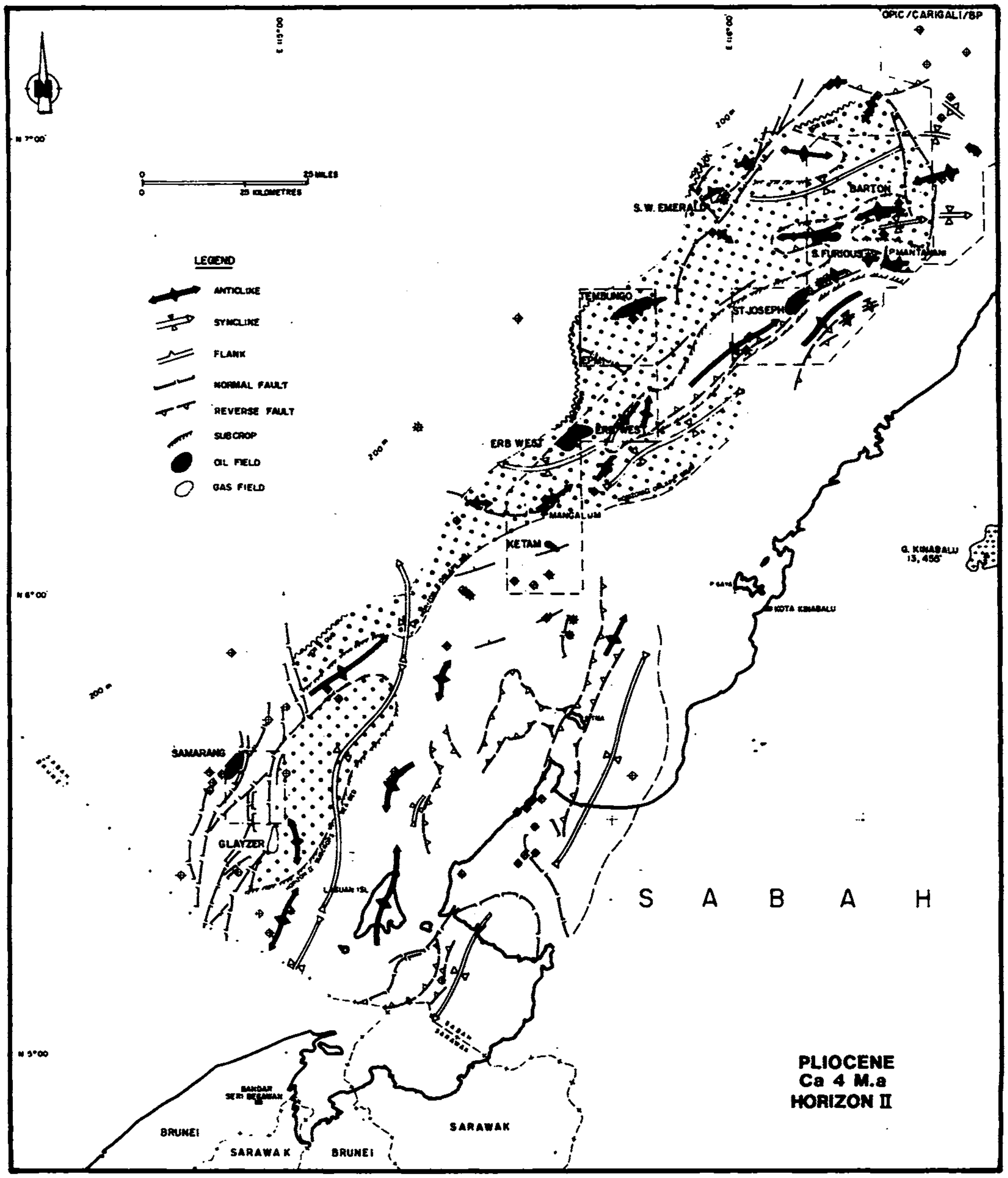


Fig. 20. This map of the extent of Horizon II as an angular unconformity and of structures active during its formation shows the continuation of the northwestward migration of successive unconformities. Also it clearly indicates a northeast-southwest alignment of major structures, and the change in structural style from the SRU deformation (Fig. 17) with open folds replacing reverse-faulting along strike-slip fault zones.

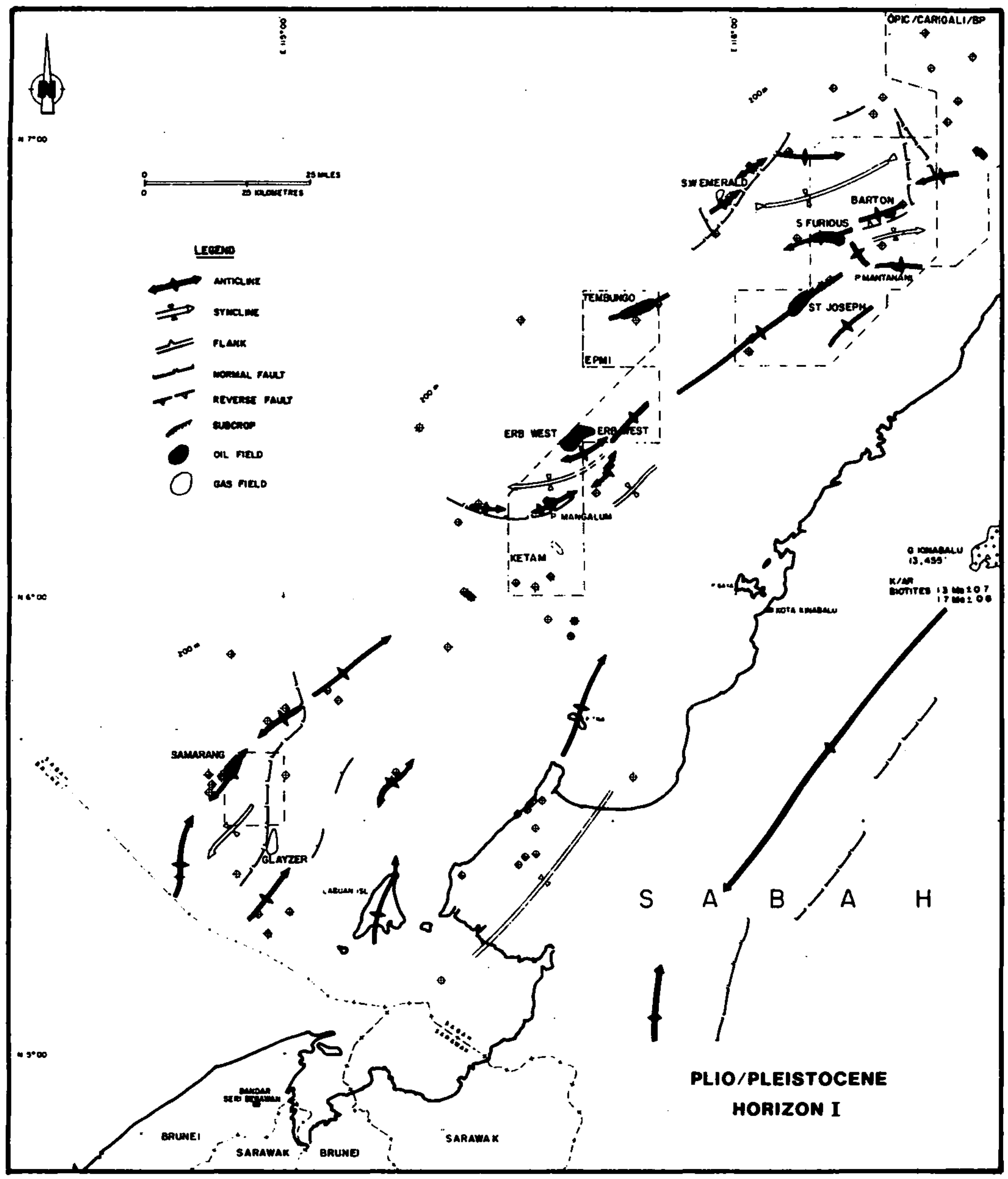


Fig. 21. The Horizon I unconformity cannot be mapped. Due to its shallow position it is often obscured by blanking at the top of seismic sections. Essentially the structural style and trend was a repeat of the Horizon II deformation phase. Commonly the Horizon I uplifts were more than those of Horizon II.

Possibly the uplifting of a Pliocene erosion surface over the Crocker Range (Liechti *et al.*, 1960; Wilford, 1967) and the K/Ar biotite cooling ages of 1.3 Ma ± 0.7 and 1.7 Ma ± 0.6 from Gunung Kinabalu (Jacobson, 1970) are related to the same deformation.

The age of Horizon I is however insecurely established by only one exploration well, primarily because it occurs in the shallow sections of exploration wells that are commonly not logged or sampled.

CONCLUSIONS

Progressive Regional Tilting

The following observations indicate that, despite the complexities of structural deformation introduced by independently moving basement blocks, and the intense internal deformation of individual blocks, the West Sabah basin was also affected by repeated uplift of its landward margin and migration of the sedimentation and deformation belts towards the exterior.

(1) The line along which each unconformity passes into a conformity is successively displaced towards the west or northwest (Fig. 22).

(2) The DRU, SRU and Horizon II all pass from being truncational unconformities in the southeast and east to being onlap unconformities in the northwest and west. Regional onlap is almost exclusively towards the east and southeast.

(3) After a period of strong deformation provinces became stabilised and were only weakly affected by later movements in a crude sequence from the southeast and east towards the northwest (e.g. the South Sabah Ridges province at SRU time, the area east of the Morris fault at Horizon II time).

(4) Although not specifically discussed in this report, depocentres migrated towards the west and northwest with time (e.g. the Middle Miocene depocentres are in the centre of the shelf whereas the Late Miocene to Pliocene depocentres are in the outer part of the continental shelf).

All these observations indicate that, considered on a large scale (± 100 kms laterally) the west Sabah area is underlain by a gently flexing basement subject to continual uplift of the landward margin possibly related to plutonism in, or isostatic compensation of, the thick accretionary wedge of Eocene to Lower Miocene deepwater deposits exposed onshore West Sabah.

Such behaviour appears to be characteristic of many basins, especially foredeep and fore-arc basins.

Independently Moving Basement Blocks (Fig. 23)

Superimposed on the regional flexural behaviour discussed above there is clear evidence for independent movement and separate deformation of individual structural provinces beneath the Neogene fill of the West Sabah basin (Fig. 24).

The characteristics of these provinces, whose boundaries are shown in Fig. 23, are summarised below:

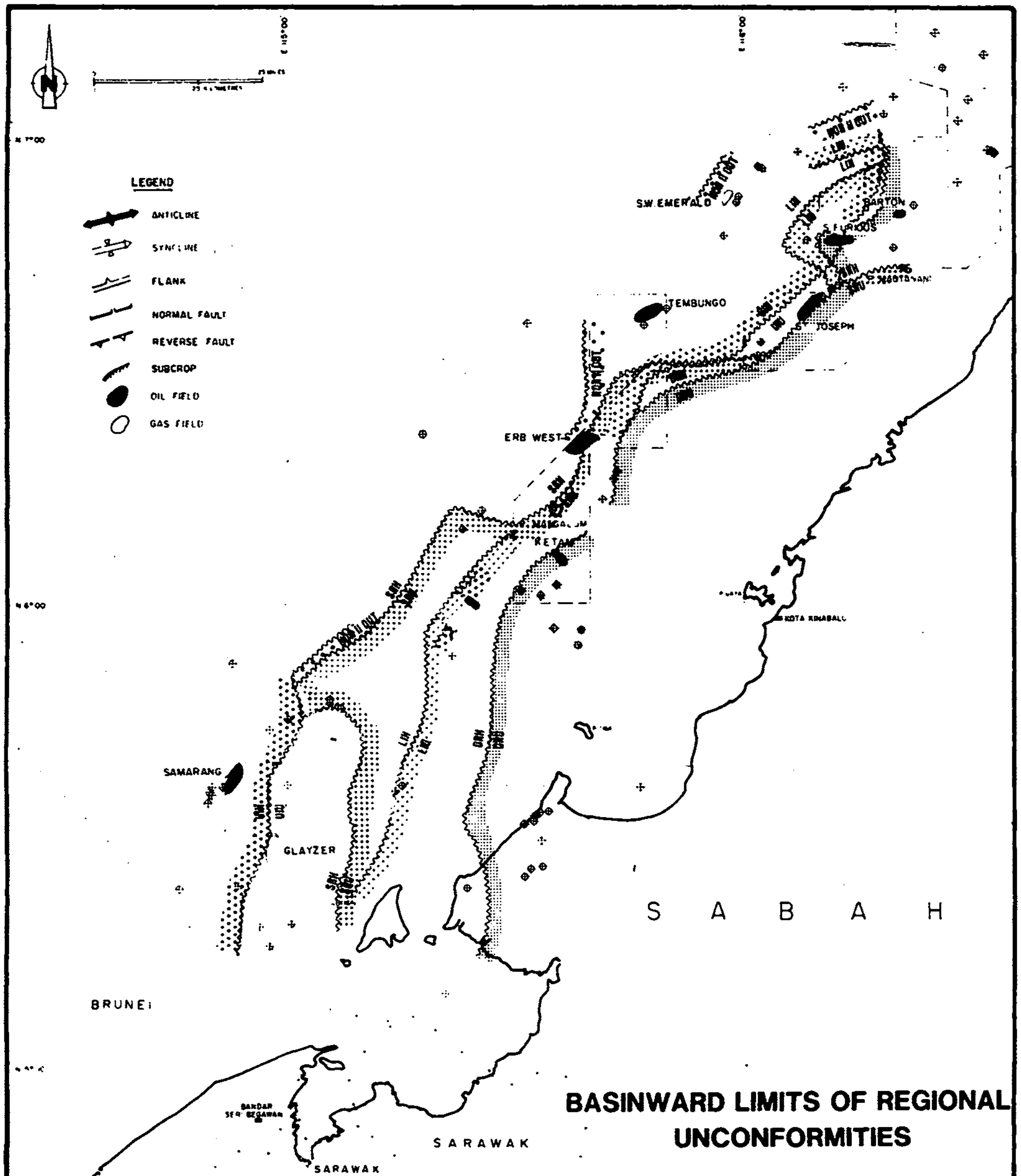


Fig. 22. Map showing the basinward limit of the five major unconformities. Note the overall successively basinward movement of uplifted and deformed blocks. This broad pattern indicative of progressive regional tilting is disrupted by the separate movement of individual structural province.

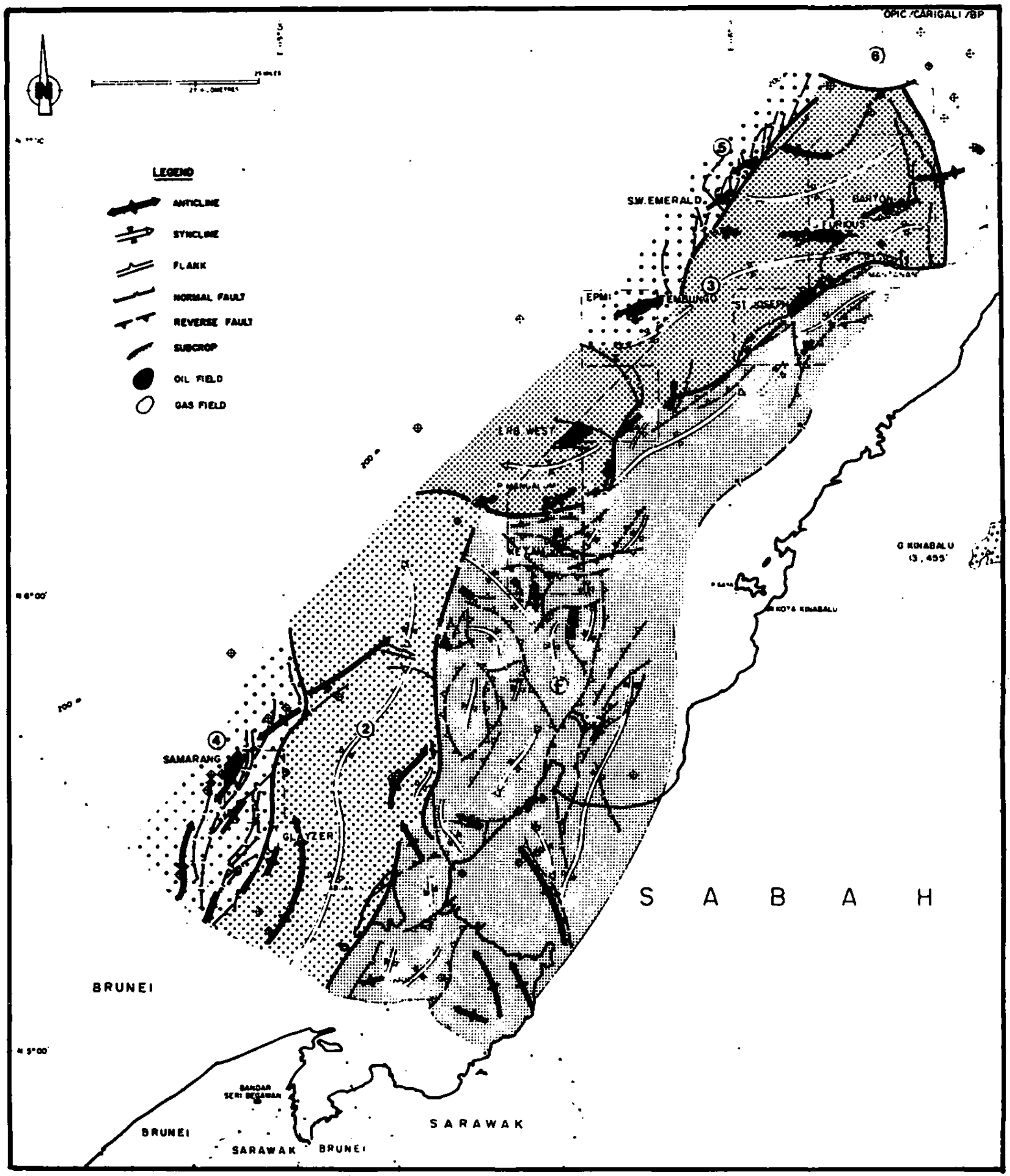


Fig. 23. West Sabah Structural Provinces. The changes in areas of active deformation from unconformity to conformity and the variations of structural style enable the Basin to be subdivided into structural provinces. Each province is thought to represent a fault-bounded block which was able to move with respect to its neighbours. The changing orientations of the regional stress patterns with respect to the block boundaries could have controlled the nature and extent of the deformation in any given province at any given time. There are two transverse elements: the Mangalum fault in the centre of the basin and the Bonanza fault between provinces 3 and 6 in the north.

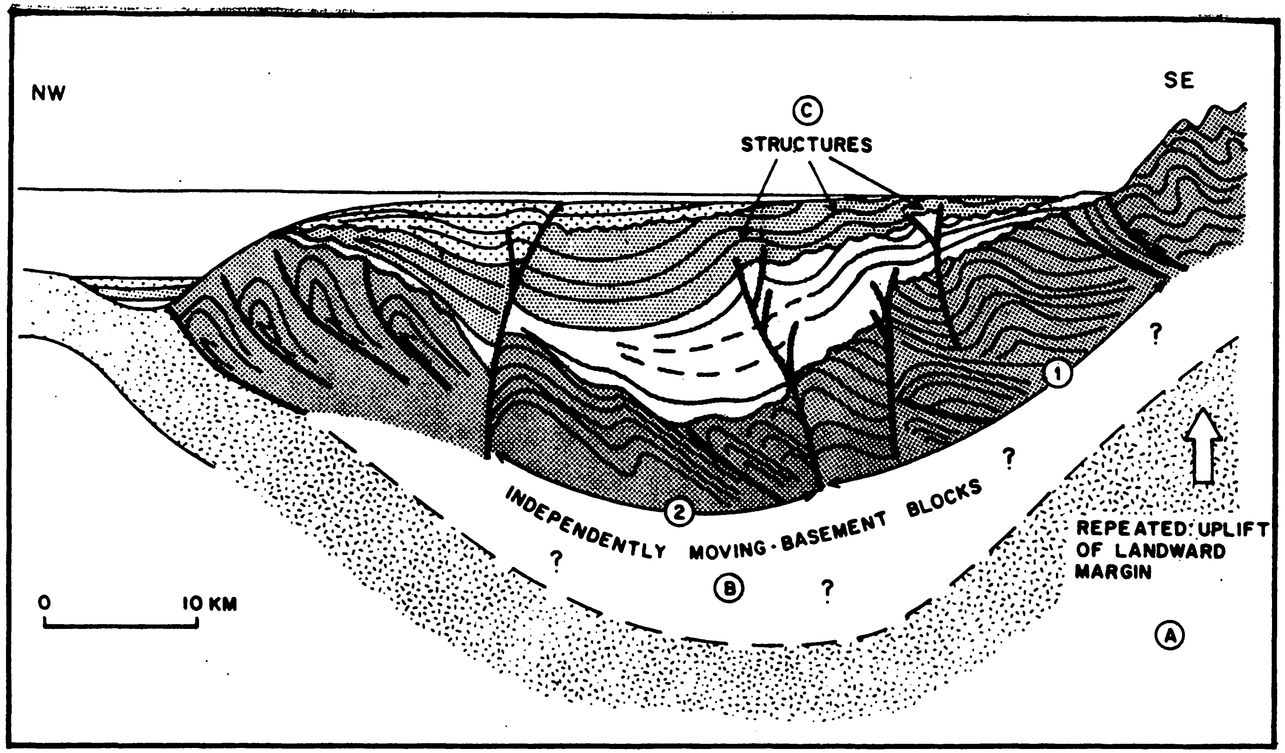


Fig. 24. This schematic cross-section illustrates the three scales of deformation which have affected the post Middle Miocene West Sabah Basin.

A. Repeated uplift of the landward basin margin is reflected in the northwestward transition from unconformity to conformable horizon, the south-eastward regional onlap pattern, and the shift of unconformities and depocentres to the northwest (exterior). This scale of deformation implies some elastic buckling behaviour of deep basement or lithosphere.

B. Independently moving basement blocks are evidenced by the structural provinces. Commonly these have sharp boundaries (e.g. Bunbury-St. Joseph Ridge, western margin of the Ridge province) and hence must be related to basement faults. An apparent structural problem arises from the consideration that this regional block movement is superimposed on the behaviour described under A above.

C. The smallest scale of structural movements is that of the individual structures.

Province 1:

Steeply dipping Lower Miocene, frequently with both beds and reverse faults dipping towards the southeast. Angular truncation unconformity at DRU time. Linear fault zones with evidence for compressional strike slip movements at DRU, LIU, UIU and SRU times. Little or no post-Upper Miocene deformation.

Province 2 and 3:

Sub-parallel Lower and Middle Miocene over most of the area with the DRU expressed as a truncation unconformity only in the S. Furious/Barton area. Flexural folding with gentle, open, synclines and tight, steep, anticlines, both with long sinuous axes. Severe faulting only in the cores of anticlines. The anticlines have been folded principally at LIU, UIU, and Horizon II and I times. Provinces 2 and 3 are separated, and slightly offset from each other by the Mangalum fault but together form a continuous longitudinal belt.

Province 4 and 5:

These two provinces were apparently not affected by significant deformation prior to the Pliocene, although lack of deep seismic data precludes a firm statement on this. The tensional faulting, including listric growth faults, of these provinces clearly distinguishes them from the other provinces.

Province 6:

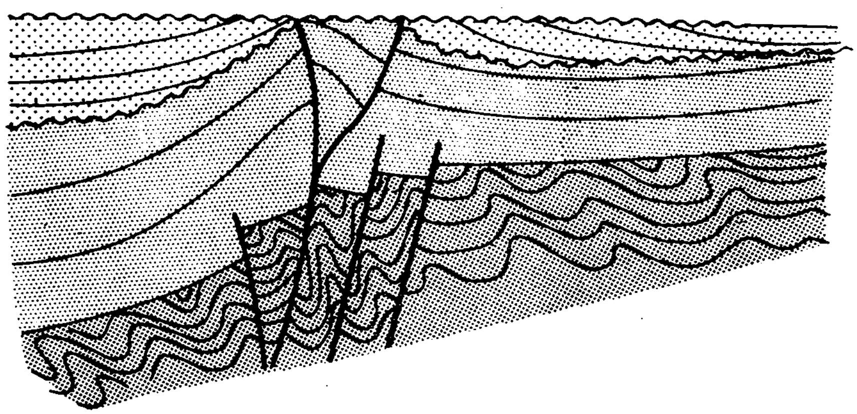
Little is known about province 6, but the E-W trending Bonanza fault line clearly represents an important structural break.

Provinces 1, 2 and 3 were lumped together by Bol and van Hoorn (1980) as a province of basement-controlled deformation. It is probable that although the province boundaries represent fragmentation of the basement, the structural style depends not only on basement type, but also on thickness of cover. This progressively increases towards the west across at least the present study area. Unfortunately the precise nature and depth of the basement are open to speculation.

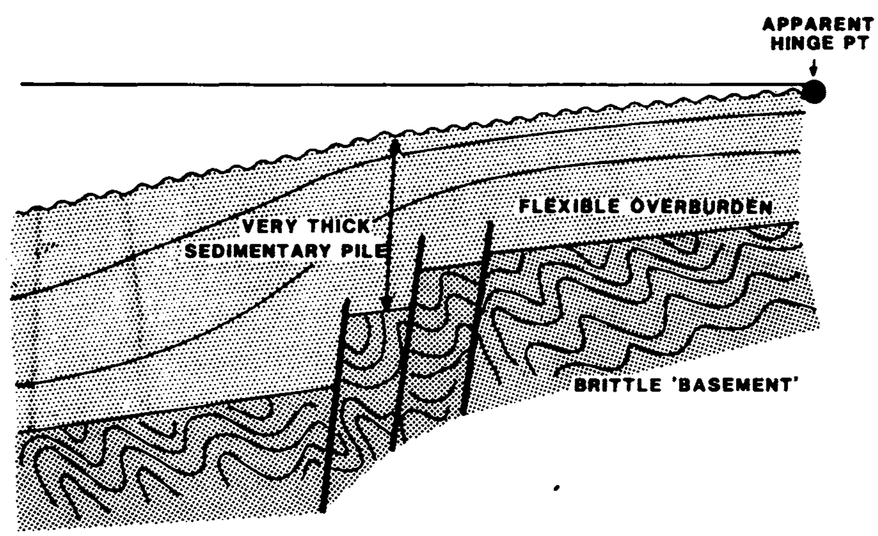
In many cases the boundaries between blocks are fault lines which in their early history were merely flanks (e.g. the Bunbury-St. Joseph Ridge, the Erb-High, the Mangalum Fault). Subsequently, commonly in the Horizon II phase, faults and folds were formed half-way down these flanks, the major faults do not occur at the apparent hinge points at the top of these rotating flanks possibly due to the mechanism sketched in Fig. 25. This behaviour is though to be due to the presence of a thick, initially ductile, cover above the basement fractures.

The Mangalum fault is a notable transverse element within the NW/SW oriented basin. The fault itself is a Pliocene (Horizon II) feature which occurs in the centre of a north-dipping flank formed at SRU time. The Mangalum fault line separates a southern region of N-S oriented structures from a NE-SW oriented set in the north (Fig. 23). It also displaces the boundary between structural provinces 1 and 2 in the south and 1 and 3, in the north. The Mangalum line occurs at the same latitude as the Gunong Kinabalu intrusion and the first evidence of its activity is at the same time as the main intrusion age preferred by Jacobson (1970). Unfortunately its eastern and western continuations are not known due to lack of data.

STRUCTURAL PROVINCE BOUNDARIES:



CONTINUED FAULT MOVEMENT MAY LEAD TO THROUGHGOING FAULT ZONE IN CENTER OF EARLIER FLANK



BASEMENT FAULT ZONE DEEPLY BURIED BENEATH VERY THICK SEDIMENTARY PILE EXPRESSED MERELY AS A FLANK AT THE DEPOSITIONAL SURFACE

Fig. 25. The structural province boundaries are frequently seen to be through-going faults in the centre of areas which were previously flanks (e.g. Figs. 14, 18). A possible explanation for this is sketched here.

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